Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar

Spanish Journal of Agricultural Research 2010 8(2), 472-480
ISSN: 1695-971-X

Biomass production and nutrient concentration of kenaf grown on sewage sludge-amended soil

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Abstract

Due to increasingly strict control of wastewater treatment, the production of sewage sludge is surging and the problem of its disposal is therefore also growing. Recycling this waste as a fertilizer is an economically and environmentally attractive option. Determining the availability of macro- and micronutrients in these sludges is important if such wastes are to provide sufficient nutrients to crops while causing minimal environmental damage. A greenhouse study with two kenaf cultivars ('Everglades 41' and 'Tainung 2') was designed to evaluate the effects of sewage sludge processing mode on plant development, biomass yield, and nutrient availability. Two different processing modes of sludges (digested dewatered and pelletized-heat dried) applied at two rates, 10 and 20 Mg ha^{-1} were compared with inorganic N and a zero-N control. Plant height, basal stems diameter and biomass production increased slightly with the sewage sludge treatments but in different manners depending on the kenaf cultivar in question. Both sludges were similar in their ability to supply N to the plants. Apparent N recovery and N fertilizer equivalent value were greater in the low dosage treatments. Of the two cultivars, 'Everglades 41' showed greater mean values for all the variables studied. No differences were found in leaf P, K, Ca, Mg contents among treatments. The Zn and Cu concentrations were the only trace elements that increased in the leaf tissues with sludge application, although the values recorded were well below critical environmental thresholds.

Additional key words: biomass yield, digested dewatered sewage sludge, dried-pelletized sewage sludge, fertilizer value, *Hibiscus cannabinus,* nutrients, trace elements.

Resumen

Producción de biomasa y contenido en nutrientes de kenaf cultivado sobre un suelo enmendado con lodos de depuradora

La eliminación de los lodos de depuradora supone un gran problema, debido al estricto control de los tratamientos de aguas residuales. El reciclado como fertilizante es una opción muy atractiva tanto económica como medioambiental. Es importante evaluar la capacidad de estos residuos para aportar nutrientes en dosis suficientes a los cultivos sin causar daños medioambientales. Se diseñó un estudio en invernadero con dos cultivares de kenaf ('Everglades 41' y 'Tainung 2') para evaluar los efectos de dos técnicas diferentes en el proceso de secado de lodos (deshidratado por centrifuga y secado térmico-pelletizado) sobre el desarrollo de la planta, la producción de biomasa y la disponibilidad de nutrientes. Se aplicaron dos dosis de lodos (10 y 20 Mg ha^{-1}), que fueron comparadas con un aporte de N inorgánico y con un control sin fertilizar. Los tratamientos con lodos aumentaron ligeramente la altura de la planta, el diámetro del tallo y la producción de biomasa, pero de forma diferente según el cultivar. La capacidad de aportar N a las plantas fue similar en los dos tipos de lodos. Los valores de recuperación aparente de N y de equivalentes de fertilizante nitrogenado fueron mayores en las dosis más bajas de los lodos. Los valores de todas las variables estudiadas fueron mayores en 'Everglades 41'. No hubo diferencias entre tratamientos en el contenido foliar de P, K, Ca y Mg. Los tratamientos con lodos sólo aumentaron los contenidos foliares de Zn y Cu, de todos los elementos traza estudiados, pero por debajo de los umbrales críticos.

Palabras clave adicionales: elementos traza, *Hibiscus cannabinus,* lodo de depuradora deshidratado, lodo de depuradora secado térmico-pelletizado, nutrientes, producción de biomasa, valor fertilizante.

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Received: 24-06-09; Accepted: 25-03-10.

Abbreviations used: ANRE (apparent nitrogen recovery efficiency), C (control with no fertilizer), DDS (dewatered digested sludge), MF (mineral fertilizer), NFEV (N fertilizer equivalent value), PDS (pelletized-dried sludge).

Introduction

Kenaf (*Hibiscus cannabinus* L.), a member of the Malvaceae family endemic to Africa (El Bassam, 1998) is an annual, herbaceous plant that produces high quality cellulose. Kenaf is a good source of low cost natural fibre for a wide range of industrial products, and the species has long been used to provide pulp for the paper industry (Taylor and Kugler, 1992). A high yielding plant, kenaf has the ability to tolerate periodic drought. Agronomic practices such as soil amendment may be able to improve its productivity and biomass quality (Muir, 2001, 2002; Alexopoulou *et al*., 2007).

In recent years, the production of sewage sludge has increased sharply in Spain due to the demand for better quality water and the imposition of more strict environmental laws. The accumulation of this type of biowaste poses a growing environmental problem. The application of stabilized sewage sludge to the land has become an attractive option since it could reduce a potential source of pollution as well as the need for synthetic fertilizers (Cuevas *et al*., 2003). Sludge products are a good source of plant nutrients and they have large amounts of organic matter that can also improve the physical and biological properties of soils; they therefore offer potential benefits in crop production.

One of the main concerns associated with the land application of sludge is the availability and mobility of macronutrients and trace metals (Korboulewsky *et al*., 2002; Shober *et al*., 2003; Mc Bride *et al*., 2004). A variety of sludge stabilization processes are available to reduce its mass, volume, odour and pathogen content, including composting, dewatering, pelletization and drying, and chemical stabilization, etc. The method in which sludge is processed may significantly change its trace element concentration and the availability of its macro and/or micronutrients (mainly N) (Misslebrook *et al*., 1996; Wen *et al*., 1997; Krogman *et al*., 1998; Richards *et al*., 2000; Walter *et al*., 2006). An inadequate N supply by sludge could reduce crop yields, while surplus N might reduce crop quality and lead to an accumulation of excess soil NO_3-N, which is subject to leaching (Shober *et al*., 2003; Cogger *et al*., 2004). Research is still needed to improve our understanding of the fate of mineralised N following the application of organic wastes.

Applications of sewage sludge based on crop N requirements can result in raised soil P levels (Sims and Pierzynski, 2000; DeLaune *et al*., 2006). Such increases may be associated with an increase in P in surface water runoff, which can contribute to the eutrophication of water bodies. Further, care should be taken that biosolids do not introduce an excess of heavy metals that become labile in the soil; these can have significant negative effects on groundwater, biological soil fertility and crop quality (McBride *et al*., 1999).

The present study was conducted in a greenhouse to evaluate the effect of two types of sewage sludge when used as soil amendments in the growth of two kenaf cultivars. The objective of this trial were: (i) to determine the effect of sewage sludge processing method on plant development and biomass yield, (ii) to assess the effect of processing mode on plant-available N, and (iii) to determine the concentrations of the major nutrients and trace elements supplied.

Material and methods

Experimental set-up and sludge preparation

An unfertilised, silty, clay loam soil was collected at a depth of 20 cm from the site of a field study designed to assess the effects of different sludges on soil quality and crop response in central Spain. Macronutrient (N, P, and K) concentrations of the original soil, classified as a Calciortidic Haplorexalf, were 0.44 g kg^{-1}, 10.7 g kg^{-1}, and 264.3 g kg^{-1} for N, P, and K respectively. Plastic pots, 30 cm diameter × 40 cm deep, were filled with a 3:1 mixture of this soil and coarse sand. The sludge products applied were derived from dewatered digested sludge (DDS) produced at a number of wastewater treatment facilities in Madrid. The primary and secondary sludges produced were anaerobically digested and subsequently dewatered in a belt filter press to a concentration of approximately 20-25% total solids. This DDS was used directly as one of the experimental sludges in the present work. The second experimental sludge —pelletized-dried sludge (PDS)— was produced from this DDS by introducing it into a pelletizer to produce pellets 1-4 mm in diameter. These were transferred to a rotating grate oven in which they were dried to a final solid content of approximately 94-98%. Thus, the sludge products used in the study were derived from the same original stock, thus allowing valid comparisons between the effects of the different processing methods to be made. The two sludge samples were dried at 50°C and finely ground in a mortar and pestle and analysed to determine their main physico-chemical characteristics (Table 1).

Table 1. Selected characteristics and trace/heavy element threshold values (Spanish legislation RD 1310/1990) of the sludges used in the study

Chemical properties	Trace/heavy elements threshold	DDS[1]	PDS[2]
Humidity[3], %		77.8 ± 1.8	4.01 ± 0.57
pH		8.00 ± 0.04	7.70 ± 0.01
EC[4], µS cm^{-1}		1,301 ± 100	1,070 ± 300
Total organic C, g kg^{-1}		475 ± 20	470 ± 8
Oxidizable C, g kg^{-1}		196 ± 12	271 ± 6
Total N, g kg^{-1}		43.8 ± 0.7	35.2 ± 1.0
Total P, g kg^{-1}		17.46 ± 0.6	15.96 ± 0.4
Total K, g kg^{-1}		9.48 ± 0.80	9.87 ± 0.45
Total Ca, g kg^{-1}		42.95 ± 1.05	48.32 ± 1.21
Total Mg, g kg^{-1}		11.67 ± 0.54	11.65 ± 0.98
Total Zn, mg kg^{-1}	2,500	1,124 ± 98	807 ± 75
Total Pb, mg kg^{-1}	750	158 ± 12	204 ± 15
Total Cd, mg kg^{-1}	20	1.99 ± 0.85	2.07 ± 1.02
Total Ni, mg kg^{-1}	300	56.7 ± 4.8	39.0 ± 4.2
Total Cr, mg kg^{-1}	1,000	102 ± 14	73.7 ± 8.7
Total Cu, mg kg^{-1}	1,000	250 ± 21	226 ± 19

[1] DDS: dewatered digested sludge. [2] PDS: pelletized-heat dried sludge. [3] With the exception of humidity, pH and EC all the data are expressed in terms of dry matter. [4] EC: electrical conductivity.

The experiment performed involved a trial with a randomised complete block design with six treatments, two kenaf cultivars and four replicates (each replicate consisted of four pots). The treatments included a control with no fertilizer (C), mineral fertilizer (MF) N treatment (NH_4 NO_3-N at 150 kg N ha^{-1}), and two rates of DDS and PDS (10 and 20 Mg ha^{-1} as dry matter). The kenaf cultivars studied were 'Tainung 2' and 'Everglades 41'. The inorganic fertilizer and organic amendments were incorporated into the soil and made a homogeneous mixture; the final mass of the soil mixture plus the amendments was 5 kg. The pots were wetted to 75% field capacity with distilled water to facilitate chemical equilibrium. After three days at field capacity, eight kenaf seeds were sown per pot. The pots were rotated and moisture added weekly to maintain the soil at 80% field capacity using the mass balance technique. Seven days after seedling emergence the best three seedlings were left to grow in each pot; the other five were removed. These plants were then grown in a controlled environment in a greenhouse under a 14-h photoperiod (a supplemental incandescent light was provided for the 14-h day^{-1}) at a temperature of 25°C day/18°C night, and at a relative humidity of 55% day/75% night.

Sixty days after sowing the height and basal stem diameter of the plants were measured. They were then removed from the pots and separated into their roots, stems and leaves to analyse biomass production. The tissues were washed with distilled water, dried in a forced-air oven at 65°C for 48 h, and then weighed. The dried tissues were later ground to pass through a 1 mm Wiley mill press for chemical analyses.

Analytical methods

The methods used for the analysis of the wastes were those described by Walter *et al.* (1989). Plant tissues were digested in a microwave oven (Anton Paar GmbH, Multiwave 3000) using HNO_3-HCl. Reagent blanks and BCR-CRM 281 standards (Community Bureau of Reference, European Commission) were routinely included in all analyses. Samples were analysed for P, K, Ca, Mg, Cu, Zn and trace metals (Cd, Cr, Ni and Pb) using inductively coupled plasma (ICP) spectrometry (Perkin Elmer Optima 3000). Total N was determined by the Kjeldahl method. Nitrogen uptake was calculated as the product of the total dry matter yield and the N concentration in each treatment. The apparent nitrogen recovery efficiency (ANRE) from the wastes and MF were calculated as the percentage of the difference between the total N uptake in each treatment and the control, divided by the total N applied (Ma *et al.*, 1999; Dean *et al.*, 2000; Rees and Castle, 2002; O'Neill *et al.*, 2004):

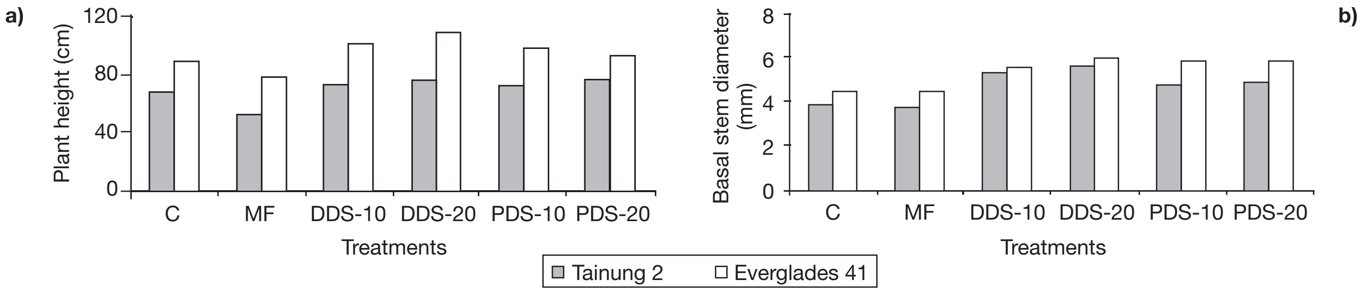

Figure 1. Plant height (a) and basal stem diameter (b) at the end of the growing period in each treatment and for both kenaf cultivars.

$$ANRE\ \% = \frac{Nt - Nc}{Na} \times 100$$

where Nt = N uptake by the plants in the fertilizer treatment; Nc = N uptake by the control plants; Na = N applied as amendment or MF.

The N fertilizer equivalent value (NFEV) was calculated as the ratio of the percent ANRE from the sewage sludge to the percent ANRE from the MF (Muñoz *et al.*, 2004):

$$NFEV\ \% = \frac{ANRE\ (org.t)}{ANRE\ (MF)} \times 100$$

where ANRE (org.t) = apparent nitrogen recovery efficiency from the organic treatment; ANRE (MF) = apparent nitrogen recovery efficiency from mineral fertilizer.

Data were analysed by standard ANOVA procedures for a randomised complete block design. Means were compared using the Duncan test; significance was set at $P \leq 0.05$ (SAS, 2001).

Results

Figure 1 shows the effect of the different treatments on plant height (a) and basal stem diameter (b). For Tainung 2 cultivar grown in the waste-treated soil the values for these variables were greater than those for the same cultivar grown in the MF and C treatments. For Everglades 41, no differences were seen among the different treatments or controls (Table 2). The height reached by Tainung 2 plants in the C and MF treatments was 69.7 cm and 50.4 cm respectively, whereas the mean for the four waste treatments was 74 cm. Everglades 41 plants reached a height of 89 cm and 79 cm in the control and MF treatments, and a mean of 101 cm in the four waste treatments respectively (Fig. 1).

The application of sewage sludge increased the total dry biomass production of Everglades 41 from 7.20 g per pot in the control to 12.51 g and 14.92 g per pot in the 10 and 20 Mg ha^{-1} sludge treatments (mean values for the two sludges) respectively. For Tainung 2 this increase was from 5.20 g per pot in the C treatment to 6.65 g and 9.25 g per pot for the low and high dose sludge treatments respectively (means for the two sludges) (Table 3).

With respect to Everglades 41, differences in biomass production were seen between the waste amendment treatments and control and MF treatments, but none were seen among the four waste treatments themselves ($P > 0.05$). For Tainung 2, differences were only seen

Table 2. Summary of ANOVA (p-value) of the growth —height (cm) and basal stem diameter (mm)— of the two kenaf cultivars studied

Source of variation	DF[1]	Height		Basal stem diameter	
Cultivar (C)	1	0.0010		0.0060	
Treatment (T)	5	0.0001		0.0012	
C * T	5	0.7853		0.8125	
		Tainung 2		Everglades 41	
		Height	Diameter	Height	Diameter
Treatment	5	0.0311	0.0221	0.0600	0.0956

[1] DF: degrees of freedom.

Table 3. Effect of treatment on dry biomass production (g) in the two kenaf cultivars (mean of four replicates)

Treatment	Tainung 2				Everglades 41			
	Leaf	Stem	Root	TB[1]	Leaf	Stem	Root	TB[1]
Control	1.70[bc]	2.54[a]	0.96[a]	5.20[ab]	2.10[b]	3.90[bc]	1.23[a]	7.23[b]
MF[2]	1.33[c]	1.80[a]	0.55[a]	3.68[b]	2.03[b]	2.83[c]	0.90[a]	5.75[b]
DDS[3]-10	2.75[abc]	3.03[a]	0.98[a]	6.75[ab]	4.33[a]	6.30[ab]	1.83[a]	12.47[a]
DDS-20	4.03[a]	4.53[a]	1.40[a]	9.97[a]	5.10[a]	7.70[a]	2.13[a]	14.93[a]
PDS[4]-10	2.63[abc]	3.05[a]	0.88[a]	6.55[ab]	4.65[a]	6.23[ab]	1.68[a]	12.55[a]
PDS-20	3.62[ab]	3.88[a]	1.00[a]	8.53[ab]	6.00[a]	7.10[a]	1.80[a]	14.90[a]

[1] TB: total biomass. [2] MF: mineral fertilizer. [3] DDS: dewatered digested sludge. [4] PDS: pelletized-heat dried sludge. Mean values within a column followed by different letters indicate significant differences at $P \leq 0.05$ according to Duncan's multiple range means separation.

between the DDS 20 Mg ha^{-1} and MF treatments (Table 3). The dry biomass production of the Tainung 2 plants was less than that of Everglades 41 plants under all treatments (including the control) ($P \leq 0.05$).

The N concentration of the plant tissue samples of both cultivars of kenaf was greater with all fertilizer treatments compared to the control (Table 4). The interaction between cultivar and waste treatments had an effect on these N concentrations. In all three tissues analysed the N concentration was always somewhat great in Everglades 41 than in Tainung 2.

Similarly, the total plant N uptake of both kenaf cultivars increased (and similar) in both sewage sludge type treatments at both doses (Table 5). In the case of Tainung 2, N uptake in the MF treatment was similar to that seen for the controls, whereas in Everglades 41 it was more than double that shown by the control (61 and 140 mg per pot in the control and MF treatments respectively).

The ANRE values obtained in this study (Table 5) with the different types of waste (at both doses) were very low for both kenaf cultivars. The ANRE obtained with Tainung 2 was lower than with Everglades 41 in all the treatments, including the MF treatment (which was associated with the lowest ANRE values for this cultivar).

The N fertilizer equivalent value (NFEV) for Tainung 2 could not be determined because the ANRE from the MF was lower than that obtained with the organic treatments. For Everglades 41, the NFEVs obtained were 60% and 44% for the low and high rates of sewage sludge (mean values for the two types of waste).

In comparisons with the respective controls, the P, K, Ca and Mg concentrations of the kenaf leaf samples were not affected ($P > 0.05$) by the treatments applied (Table 6). The average P concentration ranged from 1.93 to 2.52 g kg^{-1}. No differences were seen in leaf K concentration between the controls and treatments in either cultivar; values averaged from 17.2 to 24.0 g kg^{-1}.

Leaf micronutrient concentrations showed no abnormalities, although the Cu and Zn concentrations were slightly higher in the plants subjected to the sludge treatments than those subjected to the MF and control treatments (Table 7). The results obtained with the DDS and PDS sludge were similar, and no differences

Table 4. Effect of treatment on N content (g kg^{-1}) of the leaf, stem and root of the two kenaf cultivars

Treatment	Tainung 2			Everglades 41		
	Leaf	Stem	Root	Leaf	Stem	Root
Control	28.44[c]	4.64[d]	10.64[b]	29.56[b]	4.80[c]	8.43[c]
MF	37.20[ab]	15.35[a]	13.23[ab]	43.43[a]	13.63[ab]	14.60[ab]
DDS-10	39.35[ab]	10.48[bc]	11.85[ab]	42.85[a]	13.05[ab]	15.20[ab]
DDS-20	38.47[ab]	10.70[bc]	11.30[ab]	43.48[a]	15.10[a]	16.13[a]
PDS-10	33.55[bc]	6.48[cd]	10.58[b]	41.70[a]	10.85[b]	13.63[b]
PDS-20	41.68[a]	12.98[ab]	15.45[a]	44.75[a]	13.93[a]	16.28[a]

Mean values within a column followed by different letters indicate significant differences at $P \leq 0.05$ according to Duncan's multiple range means separation.

Table 5. Effect of treatment on N uptake and apparent nitrogen recovery efficiency (ANRE) in the two kenaf cultivars

Treatment	Tainung 2		Everglades 41	
	N uptake (mg pot^{-1})	ANRE (%)	N uptake (mg pot^{-1})	ANRE (%)
Control	70^{d}	—	61	—
MF	84^{d}	3.7	140	21
DDS-10	152^{b}	7.5	190	12
DDS-20	219^{a}	6.8	241	8
PDS-10	117^{bc}	5.3	171	13
PDS-20	218^{a}	8.4	243	10

Mean values within a column followed by different letters indicate significant differences at $P \leq 0.05$ according to Duncan's multiple range means separation.

were seen with respect to application rate. The leaf Cd, Cr, Pb and Ni concentrations of both kenaf cultivars in all treatments were near or below the detection limit of the plasma ICP method, and were therefore largely unreproducible.

Discussion

Our results indicate that the sewage sludge treatments increased plant height and basal stem diameter of kenaf plants slightly, but in different manners depending on the kenaf cultivar in question (Fig. 1). For Tainung 2 grown in the waste-treated soil, the values for these variables were greater than those for the same cultivar grown in the MF and C treatments. For Everglades 41, no differences were seen among the treatments or controls (Table 2). Similar results were found by Alexopoulou *et al.* (2007) in a three years field experiment to study the effect of nitrogen fertilizer on the growth of the same kenaf cultivars.

The application of sewage sludge increased the total dry biomass production of kenaf plants (Table 3). These increases were mainly manifested as a greater production of leaf and stem biomass and might be attributed to a beneficial effect of the wastes on the soil's biological and physical properties, plus the improvement of soil fertility. The reason for the lack of response in the MF treatment, which returned the lowest productions of dry biomass in both kenaf cultivars, is unclear. However, a nutritional imbalance may have been responsible since nitrogen was the only nutrient supplied by the MF.

The results have shown that the N concentration of the kenaf tissue samples was greater with all fertilizer treatments compared to the control, and the N concentration was always somewhat greater in Everglades 41 than in Tainung 2 (Table 4). In the same way, the total plant N uptake of kenaf plants increased in both sewage sludge type treatments (Table 5). This supports the idea that the sludge processing mode did not affect N availability to the plant.

Table 6. Leaf macronutrient (P, K, Ca and Mg) contents (g kg^{-1}) for the two kenaf cultivars in each treatment

Treatment	Tainung 2				Everglades 41			
	P	K	Ca	Mg	P	K	Ca	Mg
Control	2.13	19.6	18.4	4.69	2.51	17.2	17.1	4.43
MF	1.93	21.5	20.4	4.77	2.52	24.0	23.1	5.95
DDS-10	2.42	20.8	19.8	3.99	2.16	20.1	19.3	5.74
DDS-20	2.12	19.4	18.6	4.63	2.26	19.6	19.2	4.86
PDS-10	2.23	19.8	17.2	4.62	2.35	19.2	16.7	5.19
PDS-20	2.06	21.4	18.1	5.56	2.46	20.8	20.2	5.55
p value	0.5464	0.9903	0.9196	0.7013	0.6207	0.3561	0.1286	0.2688

Mean values within a column followed by different letters indicate significant differences at $P \leq 0.05$ according to Duncan's multiple range means separation.

Table 7. Leaf Cu and Zn contents (mg kg^{-1}) for the two kenaf cultivars in each treatment

Treatment	Tainung 2		Everglades 41	
	Cu	Zn	Cu	Zn
Control	10.6^{bc}	27.2^{b}	11.6	29.6
MF	9.5^{c}	25.1^{b}	12.5	45.0
DDS-10	13.1^{ab}	32.7^{b}	11.2	36.9
DDS-20	14.5^{a}	42.9^{a}	10.4	44.4
PDS-10	11.4^{abc}	32.7^{b}	10.0	37.7
PDS-20	12.3^{abc}	34.3^{ab}	13.4	39.5
p values	0.0566	0.0197	0.5285	0.1599

Mean values within a column followed by different letters indicate significant differences at $P \leq 0.05$ according to Duncan's multiple range means separation.

The ANRE represents the fraction of fertilizer N recovered in the harvested plant (Cogger *et al.*, 2001); the ANRE values obtained in this study with the different types of waste were very low for both kenaf cultivars (Table 5). This might be explained in that only a small fraction of the N from organic residues (the most labile) may have become available for plant uptake during the short experimental period (60 days). The ANRE obtained with Tainung 2 was lower than with Everglades 41 in all the treatments, including the MF treatment. This was unexpected; the ANRE from organic N sources is usually less than that obtained with MF sources since the N from the former is released slowly over time (Cogger *et al.*, 2001). Certainly in Everglades 41, the MF treatment was associated with the greatest ANRE values. With this cultivar, N recovery with the low application rates for both sewage sludges was greater than at the high rates. Similar results were reported by Cogger *et al.* (2001) who applied different rates of biosolids to forage grasses, and by Hirzel *et al.* (2007) in a field trial investigating the effect of poultry litter on silage maize. The ANRE values obtained with the low and high rates of DDS were similar to those obtained with the corresponding rates of PDS. This again suggests that, in the short term, both wastes supply the same amount of plant-available N. Other authors have reported similar results (Smith and Durham, 2002; Cogger *et al.*, 2004; Hirzel *et al.*, 2007). For Tainung 2, the sewage sludge rates appeared to have no such consistent effect on ANRE.

The N fertilizer equivalent value (NFEV) for the organic amendments reflects the percentage of amendment N that behaves as inorganic N fertilizer (Smith and Durham, 2002; Gilmour *et al.*, 2003; Bowden *et al.*, 2007). It therefore provides a way of estimating the fertilizer N value for organic wastes. The NFEV for Tainung 2 could not be determined, but the NFEVs obtained for Everglades 41 were 60% and 44% for the low and high rates of sewage sludge. Although the ANRE values for the two wastes were similar, the NFEV was slightly greater for the PDS than the DDS (data not shown). This implies that the PDS waste was a little more effective in supplying N under the current experimental conditions. Nevertheless, the values obtained with both kenaf cultivars were quite similar and were within the range reported by other authors in field and greenhouse experiments with different organic wastes and crops (Cogger *et al.*, 1999; Bowden *et al.*, 2007).

The leaf macronutrient (P, K, Ca and Mg) concentrations of the kenaf were not affected by the waste treatments applied (Table 6). The P values are within the range reported by Muir (2001) for three cultivars of kenaf grown under dryland conditions with applications of 10 and 20 Mg ha^{-1} dairy manure compost. When applied at N-requirement rates, the amount of K supplied by sewage sludges is often much lower than the amount needed by crops (Shober *et al.*, 2003). This is due to the fact that K is water soluble and is therefore removed from the sludge during dewatering (Pierzynski, 1994). Nevertheless, the data obtained were within the normal range for K in kenaf cultivars (Hollowell, 1997).

With regard to the leaf micronutrient concentrations, only Cu and Zn were slightly higher in the plants subjected to the DDS and PDS sludge treatments than those subjected to the MF and control treatments (Table 7). The values for both microelements in both kenaf cultivars were well below the phytotoxicity threshold for leaf tissue (Kabata-Pendias and Pendias, 1984). Leaf concentrations of the trace elements (Cd, Cr, Pb and Ni) indicate that heavy metal phytoavailability is low with both types of wastes, at least over a 60-day growing period.

In conclusion, under greenhouse conditions (*i.e.,* optimal temperature and moisture conditions), both sewage sludges had a positive effect on kenaf production and quality. These wastes could be a good substitute for synthetic N fertilizer and cause no apparent crop damage nor do they result in toxic plant tissue. The DDS and PDS sludges were similar in their ability to supply N and other macro and micronutrients. Although the N uptake and ANRE values were similar for both sludges, NFEV values obtained with Everglades 41 with the PDS were slightly great than those obtained with the DDS. Generally, Everglades 41 showed the greatest values for all the variables analysed, although the reasons for this cannot be discerned given the present experimental design.

Although temperature and moisture conditions for organic decomposition in the field are often suboptimal, the results obtained in this study provide an indication of the amounts of N that might be supplied by sewage sludges at the rates applied. Nevertheless, long-term field studies are needed to obtain more accurate assessments of their fertilizing capacity and environmental impact, especially excessive accumulation of nutrients in the soil following repeated application.

Acknowledgements

We thank Fabián García for his technical assistance during various phases of this work. This study was funded by European Community programme through the contract nº: QLK5-CT2002-01729 BIOKENAF.

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