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Vermicomposting as a Sustainable Procedure for the Reduction of Carbon Dioxide Emissions

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ABSTRACT

The burning of wood to dispose thereof generates large amounts of carbon dioxide (CO_2), one of the critical greenhouse gases. However, vermicomposting of woodchips is a desirable and safe disposal method that requires no combustion and has the additional benefit of being a potential organic ameliorant. This study evaluated the cumulative amount of CO_2 produced during vermicomposting of *Quercus rubra* (*QR*) and *Pinus sylvestris* (*PS*) compared to the amount of CO_2 that evolved from burning the wood. The experiment was conducted over a period of 100 days in plastic pots in a greenhouse. The compost temperature, CO_2 produced, degree of biodegradation and ash content were measured during the composting period. Also, the amount of CO_2 evolved by combustion of wood was determined. The results show that CO_2 produced increased over the decomposition period. Higher cumulative amounts of CO_2 were produced from *QR* compared to *PS* wood compost. The cumulative amount of CO_2 produced for both types of wood over the composting period, was lower than that produced by combustion. Ash content, used as an indicator of compost stability, increased over the incubation period; this trend was more pronounced for the *QR* than the *PS* wood compost.

Keywords: earthworms, *Pinus sylvestris*, *Quercus rubra*, woodchips
Abbreviations: C/N, carbon to nitrogen; **CO_2**, carbon dioxide; **DB**, degree of biodegradation; ***DV***, *Dendrobaena veneta*; ***EF***, *Eisenia fetida*; ***PS***, *Pinus sylvestris*; ***QR***, *Quercus rubra*

INTRODUCTION

Emissions from the burning of biomass represent an important global source of particles and gases released to the atmosphere. These emissions cause significant detrimental effects on air quality and human health and it is estimated that biomass burning contributes about 50% of the total direct CO_2 emissions globally (Mieville *et al.* 2010). The burning of wood emits more CO_2 per unit energy than combustion of any other fuel (William 2006). Currently, many industrial countries use wood as a source of energy while disposing of it through combustion. However, disposal without combustion would be preferable in order to avoid the release of CO_2, which is one of the critical greenhouse gases. The CO_2 released when burning wood, is about 1700-1900 g of CO_2 for each 1000 g of wood burnt (Radke *et al.* 1991). Aerobic composting provides an alternative approach to dispose of wood while mitigating the reduction of CO_2, methane and nitrogen oxide emissions (Abrigo 2008). Furthermore, it provides the additional benefit of producing a soil conditioner that supports humus formation (Hermann *et al*. 2011). The derived mathematical equations for CO_2 emissions of agricultural solid wastes suggested by Abrigo (2008) are:

$$Y_B = 1.275 \times X \quad (1)$$

$$Y_C = 0.665 \times X \quad (2)$$

where: Y_B = CO_2 emitted by burning (tonnes); Y_C = CO_2 emitted by composting (tonnes); X = biodegradable solid wastes (tonnes).

Over and above the importance of composting processes in reducing CO_2, the addition of compost can improve soil properties such as porosity, bulk density, aeration, water-holding capacity, buffer capacity and cation exchange capacity (CEC) (Lynch *et al.* 2005). Application of compost can result in agronomic benefits due to beneficial changes in the soil chemical characteristics (Singh *et al.* 2011). An increase in total carbon in the form of organic matter leads to an increase in CEC, thereby increasing the number of exchange sites for mineral nutrients available for plant uptake (Ouedraogo *et al.* 2001). Composts can increase the pH in most acid soils, reducing the potential for aluminium and manganese toxicity (McConnell *et al.* 1993).

Compost can be produced by using earthworms through the process of vermicomposting, which involves the bio-oxidation and stabilisation of organic material by earthworms and microorganisms (Wang *et al.* 2005). Through this process, organic waste resources can be converted into nutrient rich plant growth media i.e. vermicompost. The earthworms fragment the organic waste substances, stimulate microbial activity and increase rates of mineralization, thereby rapidly converting the wastes into humus-like substances with a finer structure than compost (Atiyeh and Domínguez 2000). The major drawback in the vermicomposting process is that it must be maintained at temperatures below 35°C, since exposure of worms to higher temperatures will kill them. This means that the process temperature is not high enough for acceptable pathogen kill and hence the product does not pass the regulations of the Environmental Protection Agency (EPA) for pathogen reduction. In addition, the major problems associated with thermophilic composting are the duration of the process, loss of nutrients during the prolonged composting process and the frequency of turning of the material (Alidadi *et al.* 2005). In addition, woodchips are difficult to decompose because of the complex chemical structure of lignocelluloses. Previous efforts have developed methods of producing wood composts from sources such as bark (Kawada 1979), saw dust and wood shavings (Fujiwara 1988; Zoes *et al.* 2001; Suzuki *et al.* 2004), as well as methods of estimating compost matu-

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Table 1 Physical and chemical properties of the woodchips and lake mud (LM).

Properties	Units	*QR*	*PS*	LM	Reference
Organic matter	%	98.47	98.22	24.94	DIN 19684 (2000)
Ash		1.53	1.78	75.06	
Organic carbon		47.73	46.63	14.46	Navarro *et al*. (1993)
Total carbon		50.75	50.73	18.27	Tabatabai and Bremner (1991)
Total nitrogen		0.16	0.14	1.17	
C/N ratio		317.18	362.35	15.62	-
Phosphorus	mg kg^{-1}	153.45	152.91	412.14	Rodriguez *et al*. (1994)
Potassium		382.80	301.40	7310.90	DIN ISO 11466 (1997), Havezov (1996)
Calcium		320.10	315.20	17754.00	
Magnesium		89.30	73.70	1564.20	
Copper		3.64	4.82	13.32	
Iron		279.37	281.40	7708.80	
Manganese		53.78	48.04	471.90	
Zinc		4.69	6.94	64.19	

QR *Quercus rubra*; PS *Pinus sylvestris*; LM Lake mud; C/N carbon/nitrogen

Table 2 Chemical properties of tap and compost water.

Properties	Units	Tap water	Compost water	Reference
Electrical conductivity	dS m^{-1}	1.15	12.33	APHA (1998)
pH	-	7.45	5.14	
Phosphorus	mg L^{-1}	0.20	1407.21	Watanabe and Olsen (1965)
Potassium		235.00	2510.00	APHA (1998), Havezov (1996)
Calcium		107.00	2490.00	
Magnesium		13.00	420.00	
Copper		0.08	0.44	
Iron		0.01	10.88	
Manganese		Traces	19.00	
Zinc		0.50	8.10	

rity. However, there have been few reports on composting methods for woodchips and uncertainty remains regarding the mixing ratio of the initial ingredients and determining the maturity of the final compost (Suzuki *et al*. 2004). Important parameters for compost maturity and stability are CO_2 emission, compost temperature, ash content and rate of biodegradation (Wang *et al*. 2005). When maturity parameters are low, it may indicate the presence of organic matter that is hard to biodegrade or it may be due to the presence of toxic organics inhibiting microbial activity. Therefore, it is of the essence to employ multiple measurement parameters for maturity and stability of compost to ensure that compost quality is measured accurately.

A combined composting approach suggested by Alidadi *et al*. (2005), included vermicomposting and combined compost vermicomposting processes of sludge. The sludge was mixed with sawdust to provide a carbon to nitrogen (C/N) ratio of 25:1 and *Eisenia fetida* was the earthworm species used in the vermicomposting process. The results obtained indicated a reduction in the amount of volatile solids, total carbon and C/N ratio with the vermicompost age, which indicates the reduction in the biodegradable organic content and mineralization of the sludge. There was also an increase in the phosphorus concentration by the end of the process due to mineralization of organic matter. The results indicate that a system that combines the two processes not only shortens stabilisation time, but also improves product quality. In another study combining two composting systems, the resultant product was more stable and homogenous and the product met the pathogen reduction requirements. The authors suggested that a combined compost vermicomposting process was more efficient in stabilising sludge than the vermicomposting process alone (Frederickson *et al*. 2007).

The objective of this investigation was to apply a combined composting (first 30 days) and vermicomposting (remaining 70 days) approach to two types of wood, *Quercus rubra* (*QR*) and *Pinus sylvestris* (*PS*), to compare the amount of CO_2 produced during composting to that evolved by burning the wood. In addition, the effect of wood type, water type, mixing ratio and earthworm inoculum on compost maturity and stability was also evaluated.

MATERIALS AND METHODS

Experimental design

The experiment was conducted in a greenhouse in pots with a depth of 21.8 cm and diameter of 18.7 cm. The pots were lined with plastic mesh (0.5 mm aperture) and a layer of gravel (1.0 cm thick) was added. Two types of vermicomposted woodchips were used – pine (*Pinus sylvestris*; *PS*) and oak (*Quercus rubra*; *QR*) – the wood was crushed to form woodchips of 2 × 0.2 cm and soaked in water for 24 h before use. After soaking, lake mud (70% moisture content) was used to make two mixtures of each type of woodchips to a ratio (w/w) of 1: 1 and 1: 3 (wood: mud). These ratios were applied in order to obtain a C/N ratio for each mixture of 20: 1 and 30: 1, respectively (McClintock 2004). The pots were filled with the respective mixtures of woodchips and lake mud and covered with net. To maintain porosity, the mixtures were turned at three-day intervals (Hellal 2007). A summary of the physical and chemical properties determined for the lake mud and the woodchips from *QR* and *PS*, respectively, is provided in **Table 1**. Each ratio of the mixtures (woodchips and mud) was repeated in 18 pots, which was divided into two plots (9 pots/plot). The first plot was irrigated with tap water for the duration of the experiment (100 days). The second plot was irrigated with compost water for the first 30 days, followed by irrigation with tap water for the duration of the experiment. The compost water was obtained from Pro Arkades (Neuendorf, Brandenburg). The chemical properties of the tap and compost water are provided in **Table 2**.

One month after the start of the composting process, each of the plots was divided into sub-plots of 3 pots each. This was done to avoid exposure of earthworms to the possible high temperatures during the initial thermophilic phase of composting (Frederickson *et al*. 2007). The first sub-plot was left without an earthworm inoculum; the second sub-plot was inoculated with *Eisenia fetida* (*EF*), at a rate of 25 earthworms/kg mixture (Maboeta and Van Rensburg 2003) and the third sub-plot was inoculated with *Dendrobaena veneta* (*DV*), also known as *Eisenia hortensis*, at the same inoculation rate. The moisture level of all pots was maintained at 55% during the composting and 75% during the vermicomposting period, where the relevant type of water was added to the pots to maintain the required moisture level.

Analytical methods

1. Temperature

The temperature (°C) of the pots was measured daily for the duration of the experiment using a digital probe thermometer (HI 8314 portable pH/mV/°C meter, HANNA instruments). The average temperature of the replicates of each treatment was calculated.

2. Carbon dioxide

Carbon dioxide evolved by burning wood, was calculated from total carbon determined by flash combustion on a Thermo Finnigan, Flash 1112 Series elemental analyser in standard mode. Fine powdered wood (1-2 mg) was ignited in a tin cup in O_2 at 1000°C (Tabatabai and Bremner 1991). The oxide produced was analysed using a thermal conductivity detector. The amount of CO_2 was calculated using equation (3), where TC is total carbon (g) and 44 and 12 (g/mol) are the molecular masses of CO_2 and carbon, respectively.

$$CO_2\,(g.kg^{-1}) = TC \times (44/12) \tag{3}$$

3. Microbial respiration rate

The microbial respiration rate was measured on a weekly basis using a modified procedure (ADAS 2005). Approximately 100 g (dry weight) of compost at 60% (w/w) moisture content was sealed in a 1.0 L vessel along with a beaker containing a known volume of 1M sodium hydroxide (NaOH) solution. Air was pumped at a rate of 2–4 L/h, initially through a 1M NaOH solution to remove atmospheric CO_2, then through the compost incubation vessel and finally through a diffuser at the base of a 150 ml test tube filled with 50 ml 1M NaOH. Any CO_2 produced by the compost was flushed through and trapped by the 1M NaOH as sodium carbonate. The samples were incubated for 7 days at room temperature (24 ± 2°C). During the incubation, the released CO_2 was trapped by the NaOH solution, which was then analysed titrimetrically at regular intervals with 1M hydrochloric acid (HCl). The collected sodium carbonate was precipitated as barium carbonate after addition of 4 ml 1M barium chloride. The CO_2 evolved was calculated using equations (4) and (5). Since there was a large variation in the evolution of CO_2 during incubation, the peak CO_2 evolution rate was used to represent compost stability. Determination of a blank value was carried out in parallel with the determination, by the same procedure using the same quantities of all reagents but omitting the test portion.

$$CO_2\,(mg \cdot kg^{-1} \cdot day^{-1}) = [B_{vol} - S_{vol}] \times (44/12) \times (1000/w) \tag{4}$$

$$Total\ .CO_2\,(mg \cdot kg^{-1} \cdot 7\,days^{-1}) = \sum (d_1 + d_2 + \ldots\ldots + d_7) \tag{5}$$

where: B_{vol} = volume in ml 1M HCl for the blank titre; S_{vol} = volume in ml 1M HCl for the sample titre; 44 and 12 = molecular mass (g/mol) of CO_2 and C, respectively; w = dry weight of the sample per gram (at 105°C); d = time per day.

4. Degree of biodegradability

The degree of biodegradability (DB, %) was calculated according to equations (6) and (7) (ISO-14855 1999). The theoretical amount of carbon dioxide ($ThCO_2$) was calculated from total organic carbon (C_{TOT}) measured (Navarro *et al.* 1993), assuming that all the organic carbon of the test material was transformed to CO_2:

$$ThCO_2 = C_{TOT} \times (44/12) \tag{6}$$

$$DB(\%) = \frac{\left[\sum (CO_2)_T - \sum (CO_2)_B\right]}{ThCO_2} \times 100 \tag{7}$$

where: $\sum(CO_2)_T$ = the cumulative amount of CO_2 evolved from the test material between the start of the test and time *T*; $\sum(CO_2)_B$ = the cumulative amount of CO_2 evolved from the blank between the start of the test and time *T*.

RESULTS AND DISCUSSION

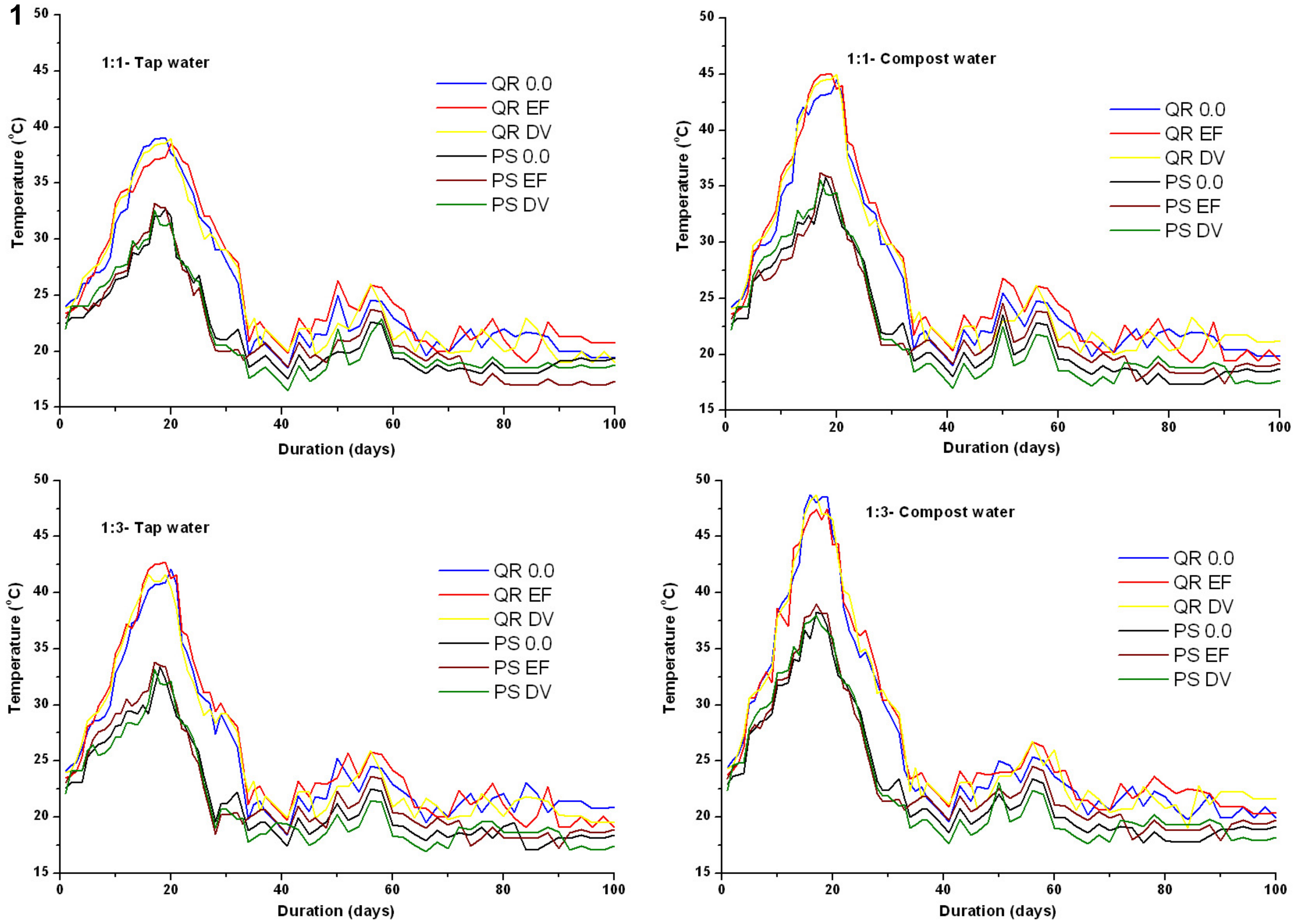
Changes in temperature during composting of wood

The changes in the compost temperature over the study period are indicated in **Fig. 1**. Large variations were observed in the measured temperature over the study period. The temperature increased from the start of the experiment to 21 days and decreased after that, with relatively little fluctuation from day 63, indicating that the compost entered a stability phase (Grigatti *et al.* 2011). Increased temperature at the beginning may be due to high available carbon content which provides a favourable condition for the growth and biological activity of microorganisms. These results are in agreement with the findings of Ndegwa and Thompson (2000, 2001).

The effect of the water type (tap or compost water) on compost temperature was visible by the higher temperature observed for the compost treated by compost water compared to the compost treated with tap water. This indicates that treatment with compost water enhanced the decomposition processes more than of tap water treatments (Wang *et al.* 2005). This trend was found with different mixing ratios of woodchips and lake mud. The highest temperature was found in the compost of the 1: 3 mixtures (wood: mud) followed by the 1: 1 mixtures. These findings may be due to a higher bulk density associated with the mixtures that contained a higher portion of lake mud which reduced temperature loss. These results are in agreement with those obtained by Mason and Milke (2005) and ROU (2007). Finally the data of **Fig. 1** show the clear differences between compost of the two types of wood and between different mixtures. The inoculation treatments (*EF* and *DV*) did not show a clear trend for different compost mixtures.

Changes in cumulative carbon dioxide during composting

The cumulative amount of CO_2 produced from woodchip compost under different treatments is illustrated in **Fig. 2**. The results show that the cumulative amount of CO_2 produced under different experimental conditions, increased from the start of the experiment to 21 days and decreased after that until day 77, after which it become relatively stable. If the CO_2 produced is considered a function of the humification rate, a higher rate would be expected during the first weeks of the experiment (Majumdar *et al.* 2009), with declining rates present in the following weeks. Similar results were obtained in other studies (Eiland *et al.* 2001; Agnew and Leonard 2003; Wang *et al.* 2005). The amount of CO_2 produced (g kg^{-1}) for *QR* woodchips compost was higher than those for *PS* woodchips compost in the different treatments. This could be ascribed to the high content of soluble carbon and nutrients present in the *QR* woodchips (**Table 1**), which may contribute to an increase in the decomposition rates and the activity of microorganisms in the compost (Singh and Sharma 2003; Tiquia 2005). Poor decomposition of *PS* woodchips was probably caused by the presence of toxic substances such as tannins and turpentine in the wood which means that ingestion of this wood type by earthworms were low (Venner *et al.* 2009). The earthworm inoculums (*EF* and *DV*) resulted in a slight increase in the CO_2 produced (**Fig. 2**), which was more pronounced for those treatments with *EF* than for *DV*. Similar results were found by Edwards and Domínguez (2000) and Maboeta and Van Rensburg (2003). These findings could be attributed to the fact that *DV* has a lower reproductive rate and longer maturation rate compared to *EV* (Edwards 1988). In this regard, *DV* seems to be a less successful earthworm species for vermicomposting (Viljoen *et al.* 1991). Another observation from the data presented in **Fig. 2**, is that those compost mixtures treated with the compost water, had a higher amount of CO_2 produced than the mixtures treated



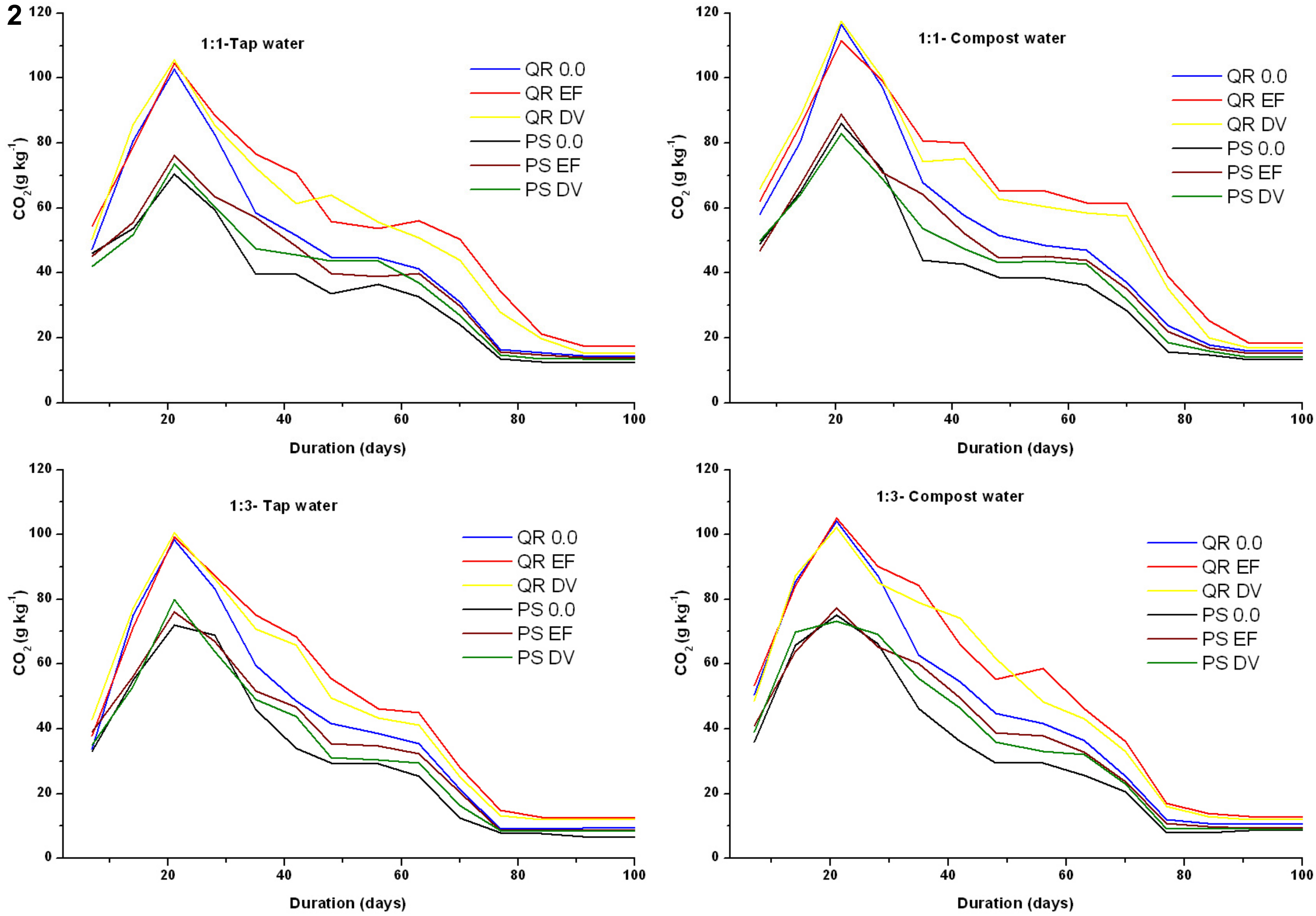


Fig. 1 Daily mean of temperature (°C) during composting of woodchips under different treatments. QR, *Quercus rubra*; PS, *Pinus sylvestris*; EF, *Eisenia fetida*; DV, *Dendrobaena veneta.*

Fig. 2 Cumulative amount of CO_2 (g kg^{-1}) produced from composting of woodchips under different treatments. QR, *Quercus rubra*; PS, *Pinus sylvestris*; EF, *Eisenia fetida*; DV, *Dendrobaena veneta.*

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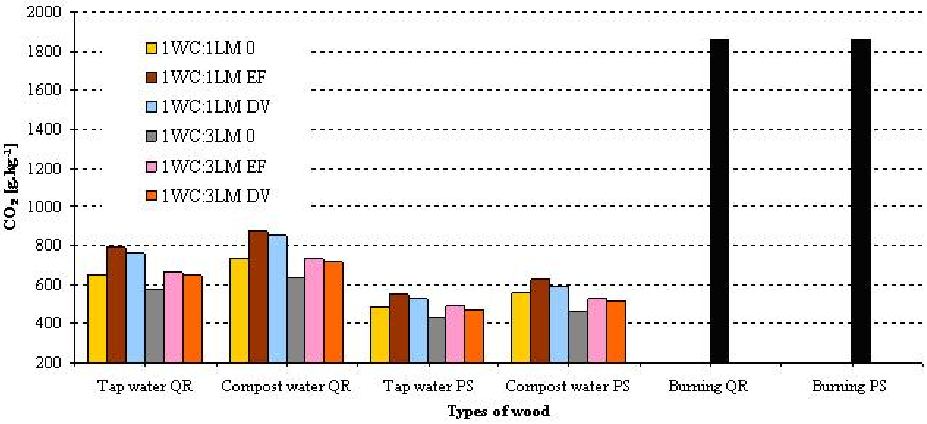

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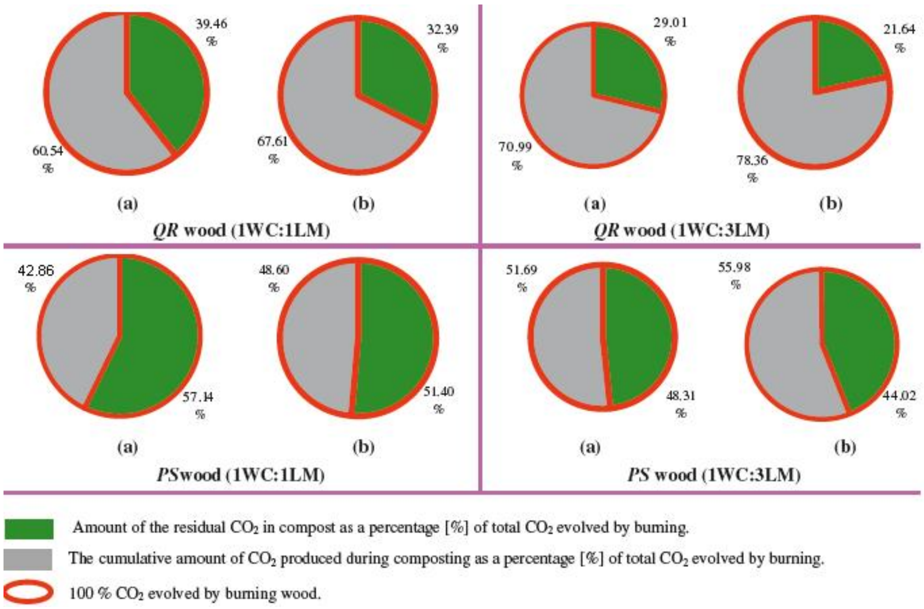

Fig. 3 Cumulative amount of CO_2 during the composting period for different treatments and CO_2 evolved by the burning of two types of wood. WC, woodchips; LM, lake mud; QR, *Quercus rubra*; PS, *Pinus sylvestris*; EF, *Eisenia fetida*; DV, *Dendrobaena veneta.*

Fig. 4 Relative percentages of the cumulative amount of CO_2 produced during vermicomposting and the residual amount of CO_2 stored in compost. WC, woodchips; LM, lake mud; QR, *Quercus rubra*; PS, *Pinus sylvestris.*

with tap water. This can be attributed to the higher content of nutrients present in the compost water (Adani *et al.* 2003; Nathan 2004). These results correlate with those for the changes in temperature. However, the 1: 1 mixtures showed higher amounts of CO_2 than the 1: 3 mixtures. This may be due to a higher proportion of wood in the 1:1 mixture.

A comparison of the cumulative amount of CO_2 produced during vermicomposting and the amount of CO_2 evolved by combustion of wood is presented in **Fig. 3**. The data show that the cumulative amount of CO_2 produced by vermicomposting was significantly lower than that produced by combustion. The highest amount of CO_2 produced during any of the composting processes was found in the *QR* woodchips compost, mixed at a ratio of 1: 1 with lake mud, inoculated with *EF* and irrigated with compost water (873.42 g kg^{-1}). The lowest amount was recorded for *PS* woodchips compost, mixed at a ratio of 1: 3 with lake mud, not inoculated with earthworms and irrigated with tap water (434.62 g kg^{-1}). The burning of both the *QR* and *PS* wood produced CO_2 in excess of 1800 $g.kg^{-1}$. What should be considered is that the CO_2 produced during vermicomposting, originated from the organic carbon present in both the woodchips and lake mud (**Table 1**) and not from the woodchips alone. This is based on the assumption that microbial activity would have an equal degradation impact on the organic carbon from both these sources. The difference between the amount of CO_2 produced from the vermicomposting of a specific type of wood and the CO_2 evolved from combustion of the same wood, represents the amount of residual CO_2 stored in the compost and is indicated in **Fig. 4**. For example: the cumulative amount of CO_2 produced from 100 g of *QR* woodchips in a 1: 1 mixed ratio and irrigated by tap water was 112.62 g. This amounted to 60.54% of the amount of CO_2 evolved from the combustion of the *QR* wood. The data presented in **Fig. 4** show that different treatments did not contribute equally to the reduction in CO_2 emissions. The percentage of residual CO_2 in *QR* wood compost was lower than in *PS* wood compost. These results could be related to the higher biodegradation and humification rates of *QR* wood. The stored CO_2 in the treatments irrigated by tap water was higher than those treated with compost water. When compost is finally applied to soil, those composts with higher amounts of residual CO_2 will be most beneficial to improve the chemical and microbiological properties of soil.

Degree of biodegradation

The degree of biodegradation (DB, %) of the *QR* and *PS* woodchips used as composting material under different treatments is shown in **Fig. 5**. The results show that the DB of *QR* compost was higher than that of *PS* compost in all treatments. The DB increased over the composting period, with a tapering off in this trend after day 70, signifying that the compost entered a stability phase. This could be related to the exhaustion of easily degradable carbon substrates over the composting period and the results correspond to those obtained in other studies (Ndegwa and Thompson

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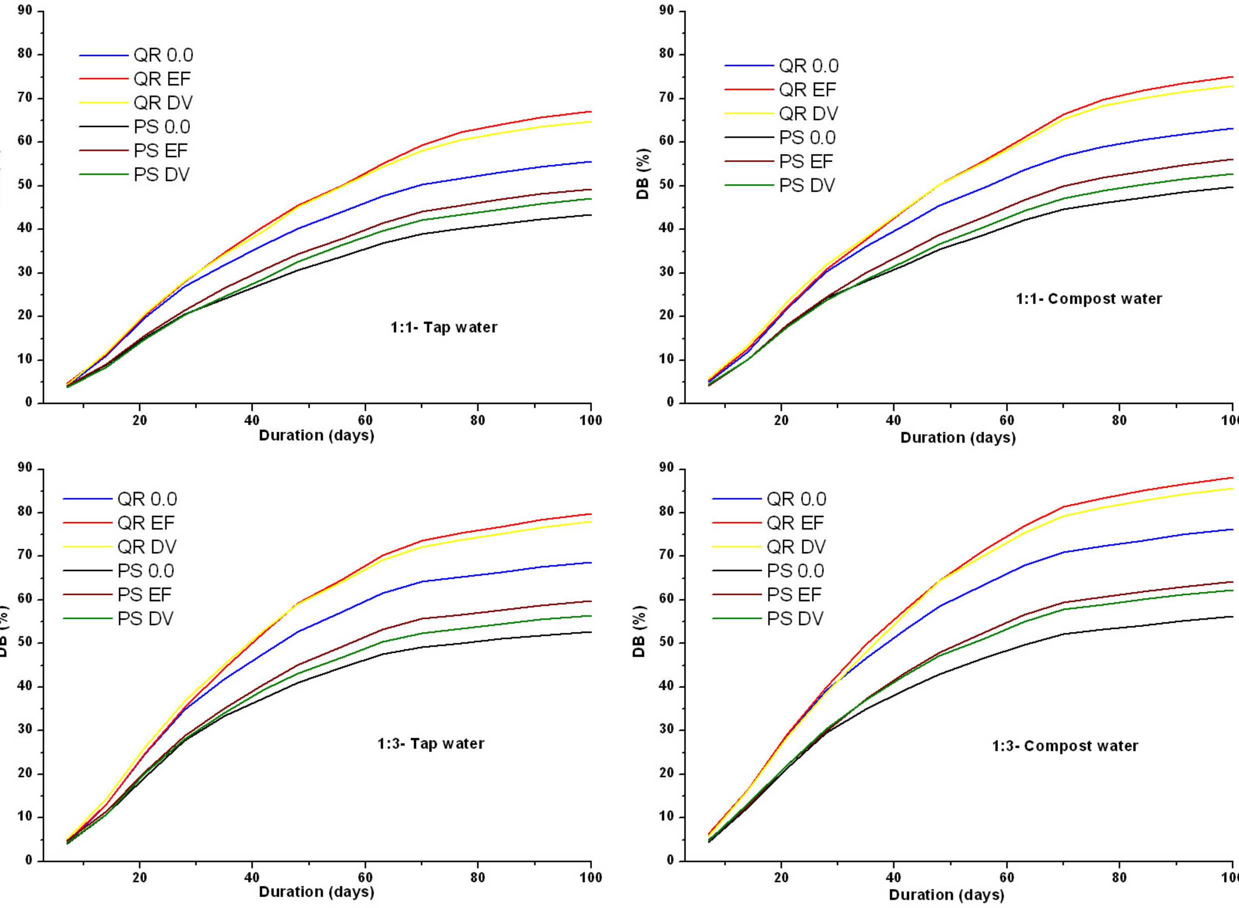

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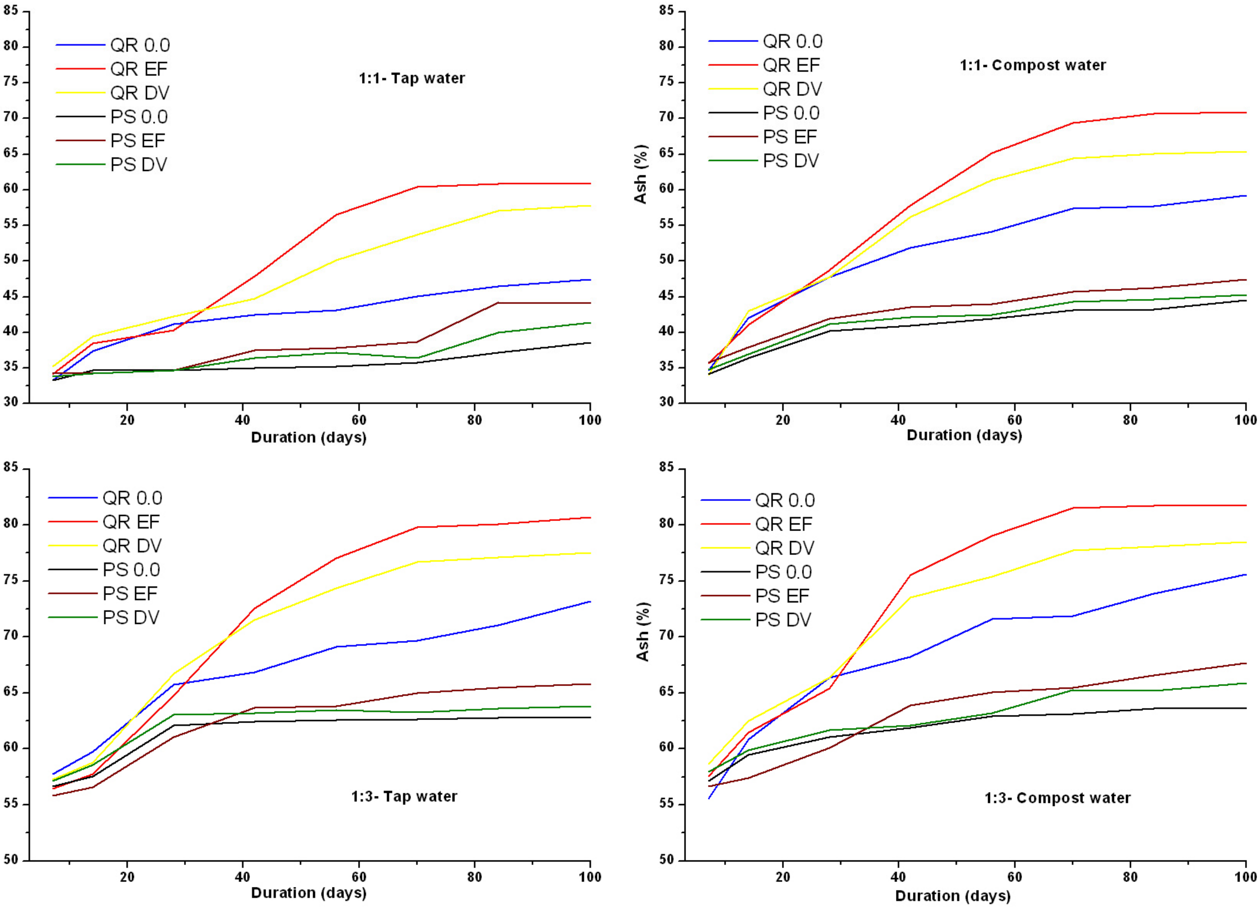

Fig. 5 Degree of biodegradation (%) during composting of wood under different treatments. QR, *Quercus rubra*; PS, *Pinus sylvestris*; EF, *Eisenia fetida*; DV, *Dendrobaena veneta.*

Fig. 6 Ash content (%) during composting of wood under different treatments. QR, *Quercus rubra*; PS, *Pinus sylvestris*; EF, *Eisenia fetida*; DV, *Dendrobaena veneta.*

2000; Tuomela *et al.* 2000; Tiquia 2005). The effect of irrigation with compost water compared to tap water is also visible in **Fig. 5**, with those treatments irrigated by compost water having higher DB percentages. These results show that irrigation with compost water enhanced the biodegradation process during vermicomposting since it acts as an inoculum (Romero *et al.* 2001).

In terms of the different mixing ratios, higher DB percentages were found for the mixed ratios of 1: 3 (wood: mud) than of the 1: 1 ratios. This may be due to the higher content of N, P and other nutrients in the 1: 3 mixtures originating from the lake mud (**Table 1**). This provides a favourable environment for microbial activity (Adani *et al.* 2003; Wang *et al.* 2005) and leads to better humification of the compost. Finally, those treatments inoculated with *EF* had higher DB percentages than uninoculated treatments and slightly higher percentages than treatments inoculated with *DV.* These results are in agreement with the findings of Kaushik and Garg (2003) and Singh and Sharma (2003).

Ash content

The ash content as a percentage of the composting material of all treatments was monitored over the study period (**Fig. 6**). All treatments showed a relative increase in the ash content of the composting material as degradation of organic matter occurred. However, there was a notable difference in these increases between the different treatments. As in the case of the degree of biodegradation, the ash content of *QR* compost was higher than that of *PS* compost and those treatments irrigated with compost water and inoculated with *EF* had higher ash content percentages than the other treatments. These results confirm that better degradation of organic matter occurred in these treatments. The 1: 3 composting mix showed a higher ash content overall, compared to the 1: 1 mixture. This can be attributed to the higher content of lake mud in the 1: 3 mixture, since lake mud had a high ash content (**Table 1**). As in the previous results, monitoring of the ash content indicated that the compost reached stability after approximately 70 days. These results are in agreement with the results obtained by McClintock (2004) and Suzuki *et al.* (2004).

CONCLUSION

Composting of *QR* and *PS* woodchips for 30 days followed by vermicomposting for 70 days resulted in the compost reaching stability after 70 days from the start of experiment. It was demonstrated that under different treatments, the compost temperature increased up to 21 days, after which it stabilised over the last 30 days of the experiment. The amount of CO_2 generated from wood composting was lower than that evolved by combustion of the same wood. The degree of biodegradability and ash content increased over the composting period until the compost reached the stability phase around day 70. From the results obtained during this investigation, it is clear that composting of wood is a better procedure to dispose of wood than combustion. First, CO_2 emissions are greatly reduced and second, the compost produced can be applied as a soil conditioner to degraded soils.

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