Composting of washed *Ulva reticulata* seaweed: process parameter variations and compost quality

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Abstract: Co-composting process of unwashed (Run A) and washed (Run B) seaweed *Ulva reticulata* with bagasse and broiler litter was studied. Peak temperatures of 48.9°C and 55.2°C were recorded for Runs A and B, respectively. For Run A, the starting wet bulk density was 43.31 kg m\(^{-3}\) and increased by 5.2 times on day 23. Net biodegradable Volatile Solid (VS) reductions were 2.19 and 11.44% for Runs A and B, respectively. Beyond day 37, the respiration rate of both composts had decreased to 8.87 mg CO\(_2\).C day\(^{-1}\) g\(^{-1}\) VS and 8.09 mg CO\(_2\).C day\(^{-1}\) g\(^{-1}\) VS (Runs A and B, respectively). Washing treatment lowered the chloride content by 3–5 times in Run B. Final compost from Run B had a better fertilising capacity with its higher N, P and K contents.

Keywords: composting; *Ulva reticulata*; washings; compost quality.


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1 Introduction

Solid wastes management, and particularly its organic fraction, is becoming a global problem in developed countries. At present, different technologies are being applied to reduce landfill destination of organic wastes, as this management is responsible for a considerable contribution to global warming (Mor et al., 2006) and is not environmentally sustainable. Among the bioremediation technologies to treat the organic fractions of solid wastes, anaerobic digestion and composting are environmentally friendly technologies that allow treatment and recycling (Artola et al., 2009). Composting is defined as the biological decomposition and stabilisation of organic substrates under conditions that allow the development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, has a limited number of bacterial counts when compared with the raw materials or waste, and can be beneficially applied to land (Haug, 1993). A composting system is hence inherently complex and therefore dynamic, with very intense biological activity and various interdependent interactions amongst the various process parameters (Agnew and Leonard, 2003). Many factors that affect the composting process performance are determined by process design and substrates preparation, but some can be influenced by external control during the process (Mohee et al., 2009). Many studies of the aerobic composting process have been reported over the last three decades and many researchers have preferred the use of laboratory or pilot-scale composting reactors (Mudhoo and Mohee, 2007). Composting is now emerging as an \emph{ex situ} biological technology that is potentially applicable to non-volatile and semi-volatile organic compounds in soils and to a variety of solid residues. Composts have been derived from green wastes (Antizar–Ladislao et al., 2005), lagooning sewage sludge (Atagana, 2008), spent mushrooms (Lau et al., 2003), yard wastes (Carlstrom and Tuovinen, 2003), textile sludge (Garg et al., 2006, 2009), alkaline tissue digester effluent with yard trimmings (Das, 2008) and municipal solid wastes (Lourencetti et al., 2007).

Seaweeds are large algae (macro-algae) that grow in saltwater or marine environment. Yan (1998) stated that marine algae are a good candidate to increase the carbon assimilation capacity from the atmosphere, by virtue of their strong photosynthetic ability and owing to their potential huge culture area. Seaweeds can also be used in
wastewater treatment to reduce the nitrogen and phosphorus levels (Troell et al., 1999) and to remove heavy metals from effluents (Davis et al., 2000). Nevertheless, seaweeds when left unused or untreated pose a serious environmental nuisance on beaches in terms of bad odour generation and propagation, and eye sores (Leatherman, 1997). Seaweed management (especially of the Ulva sp., brown-algal Fucus serratus and Undaria pinnatifida species) by composting has also been a recent area of applied research (Mazé et al., 1993; Vendrame and Moore, 2005; Greger et al., 2007; Wosnitza and Barrantes, 2006; Tang et al., 2007, 2008). In their study to evaluate the potential of composting seaweeds, Eyra et al. (1998) deduced that although the quality of the seaweed compost was limited by excessive amounts of sand and low nitrogen content, it proved to be a good amendment that improved both physical and nutritional characteristics of local sandy loam soils used in intensive horticulture. Seaweed composting is important in both marine waste disposal and production of fertiliser with good quality. Until now, there are only few papers reporting the composting of seaweed. In general, green seaweed composting has been assessed in Brittany by Mazé et al. (1993) and in Italy by Vallini et al. (1993). From a technological, economical or environmental point of view, composting has been considered one of the best techniques to utilise this algal biomass (Cuomo et al., 1995). Seaweed composting, however, presents some problems that should be solved before the resulting compost may be used as an amendment in horticulture, flower production, or forestry. In particular, high compost salinity inherited from residual seawater on the seaweeds and an excessive sand content can seriously limit plant growth and development (Mazé et al., 1993; Vallini et al., 1993; Taylor et al., 2001). In this line of thought, comparisons of composting process with washed and unwashed seaweed waste are meaningful for the field application. This study was conducted to investigate the effects on the composting process when using water-washed green Ulva reticulata seaweed as substrates. In Mauritius, the pile up of seaweeds (average of 13–20 tonnes per year) does constitute a form of environmental problem on the beaches, and especially for beaches that are near to or directly connected to tourist hotels. The prolonged stay or uncontrolled disposal of the seaweeds piling up ashore these places hence tend to limit the economic and leisure space associated with the hotels. The specific objectives of the study have been to determine an optimum washing efficiency, which would both reduce the salinity and produce a limited volume of saline wastewater; to monitor the changes in temperature, Moisture Content (MC), bulk density, pH, VSs, chloride ions content, Electrical Conductivity (EC) and respiration rate during the composting experiments and, finally, to assess the quality of the final composts produced from the composting matrices monitored in terms of the particle size distribution, water-holding capacity, porosity, nitrogen/phosphorus/potassium ratio, heavy metals content, phytotoxicity and germination performance on seeds of compost produced.

2 Materials and methods

2.1 Composting substrates

Drifted seaweed Ulva reticulata was collected at Trou d’Eau Douce Public Beach (Flacq District, Mauritius), located in the eastern coast of Mauritius and sugarcane bagasse was obtained from the F.U.E.L. Sugar Factory (Union Flacq, Flacq
District, Mauritius). The bagasse was used as a source of carbon for the microorganisms, as a bulking agent for providing sufficient porosity and hence aeration in the composting matrices under experimental analysis. Broiler litter obtained from Chanteleer Farm (Moka, Moka District, Mauritius) was also added to the initial composting mixes as an additional substrate to enhance the fertiliser values of the final compost. The three composting materials were physically and chemically characterised and the results are summarised in Table 1. Oven-dried samples of each substrate were finely ground and were used, in triplicates, for determining the carbon and nitrogen contents from a CHNS–932 analyser.

<table>
<thead>
<tr>
<th>Property</th>
<th>Units of measurement</th>
<th>Ulva reticulata</th>
<th>Bagasse</th>
<th>Broiler litter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content</td>
<td>%</td>
<td>78.71 ± 2.35</td>
<td>48.32 ± 3.01</td>
<td>21.81 ± 2.13</td>
</tr>
<tr>
<td>Volatile solids</td>
<td>%</td>
<td>66.68 ± 1.69</td>
<td>96.32 ± 2.03</td>
<td>70.50 ± 3.54</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>6.3 ± 0.3</td>
<td>5.6 ± 0.4</td>
<td>8.3 ± 0.3</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>mS cm⁻¹</td>
<td>7.50 ± 0.32</td>
<td>0.52 ± 0.28</td>
<td>3.31 ± 0.21</td>
</tr>
<tr>
<td>Bulk density</td>
<td>kg m⁻³</td>
<td>78.81 ± 3.24</td>
<td>90.96 ± 4.31</td>
<td>379.31 ± 4.98</td>
</tr>
<tr>
<td>Carbon</td>
<td>%</td>
<td>37.04 ± 0.02</td>
<td>53.51 ± 0.07</td>
<td>39.17 ± 0.03</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>%</td>
<td>1.82 ± 0.02</td>
<td>0.35 ± 0.03</td>
<td>1.79 ± 0.04</td>
</tr>
</tbody>
</table>

The MC, VSs, carbon and nitrogen contents are given on a dry mass basis. On the basis of the physico-chemical characteristics of the feedstock materials, a final substrate to substrate mix ratio on a weight mass basis was calculated to achieve a C/N ratio approximating 30. A ratio of 7:3:1 was determined for the seaweed:bagasse:broiler litter composting mix. The optimum mix consisted of 35 kg seaweed, 15 kg bagasse and 5 kg broiler litter. This mix was selected since it prioritised the seaweed portion in the composting matrices. The overall composting mix had a carbon to nitrogen ratio of 31.7 and a wet basis MC of 65.2%.

2.2 Batch composting reactor design

The batch composting reactor used for the composting experiments was a horizontal plastic cylinder, 55 cm in diameter and 90 cm in length, with a volume of approximately 0.2 m³ (Figure 1). An opening (aperture) at the top of the drum allowed the substrate to be loaded and unloaded. The same outlet was used for periodic sampling for different experimental analyses of process parameters. There were three holes for aeration each 5.0 cm in diameter on top of the drum and one other hole (underdrain) at the bottom centre for leachate drainage. At both ends of the cylinder, 5 cm near the bottom were two holes each 5 cm in diameter. Two polyvinyl chloride tubes having a length of 110 cm each, with a diameter of 5 cm, had been fitted alongside. Each tube had a number of perforations. Each perforation had a diameter of 0.2 mm and was situated along the whole length of the pipes. The reactor is not equipped with additional insulation in the form of foam materials or a polystyrene envelope of a specific thickness. More details of
the experimental reactor may be obtained from Mohee et al. (2008), Mudhoo and Mohee (2005, 2008). The latter three studies have demonstrated that a reliable composting process pattern of the substrates does take place in the batch reactor and the overall results of the composting process do provide some useful indication on the potential to scale up the batch composting of the substrates to windrow systems.

### 2.3 Washing and seaweed to wash water ratio

The washing efficiency was determined on a laboratory scale. This test consisted of obtaining the ratio of seaweed (on \textit{in situ} mass basis) as collected from the seashore to water (in mL) for an efficient washing and determining the number of washings needed to reduce the salt concentration of the seaweed using an optimum quantity. The quantification of the reduction of salt from the seaweed comprised monitoring the EC and chloride ions content. Three samples of seaweeds (these were \textit{in situ} samples, which were just moist to the touch), 20 g each, were taken and their respective chloride ions contents and EC determined before any washing. Afterwards, a basis of 1:10 \textit{w/v} (seaweed to wash water), 1:15 \textit{w/v} and 1:20 \textit{w/v} were considered (i.e., three samples of same mass were washed with 200 mL, 300 mL and 400 mL of double Distilled Water (DW)). After washing, the same samples were again tested for chloride ions content and EC. This method was repeated with increasing number of washings using fresh samples each time. The chloride ion and EC tests were measured in triplicates each time. A schematic diagram of the method used for carrying out the washings is shown in Figure 2.

### 2.4 Composting experiments

The composting experiments were carried out in two batches (Runs A and B, and in duplicates) in the batch mode in the composting reactor described earlier. Run A
consisted of composting unwashed seaweeds with bagasse and broiler litter while in Run B, washed seaweeds were composted with bagasse and broiler litter. The broiler litter was taken from Chantecler Farm (Moka, Moka District, Mauritius) and the bagasse had been obtained from a local sugarcane processing factory.

Seaweeds were washed based on the washing ratio obtained from the laboratory tests before setting up of Run B in the composting reactor. 35 kg of seaweeds were subsequently washed with 700 L (for two washings and each being with 350 mL) double distilled water in a 500 L plastic tank with a wooden bar as a stirrer. After washing, the wastewater was drained through the drain valve in the tank, and a sample of the wastewater tested for chloride ions and EC to verify whether it was within the limits of the local wastewater standards prior to being discharged as effluent. The physico-chemical characteristics of the composting mixes for the two runs are given in Table 2. The composting experiments had all been conducted in the SugarTech Laboratory of the Department of Chemical and Environmental Engineering, University of Mauritius to eliminate the effects of rain and excessive heating from direct sunlight. The batch reactors were rotated over one complete turn every 7 days to keep conditions aerobic.
2.5 Measurement techniques for composting process parameters

Samples for analysis of MC, VSs, bulk density, respiration rate, EC, chloride ions and pH were taken on Days 1, 8, 15 and 22. Sampling of two grab samples (10–20 g each) was done at three different spots (middle and at two extremities) in the reactor at a depth of 5–10 cm from the level surface of the compost matrix in the reactor to obtain representative sample and used to calculate an average value for generating graphs for parameter variations. Temperature was monitored in situ everyday. To maintain aerobic composting conditions, the reactors were turned three to five complete rolls every 7 days for aeration and homogeneity.

The analytical methods employed to measure MC, VSs, bulk density, respiration rate, EC, chloride ions and pH were adapted from the quality and testing procedures of the Methods Book for the Analysis of Compost and Test Methods for the Examination of Composting and Compost (TMECC, 2001). These adapted procedures are now outlined. The temperature of the compost pile was recorded using a thermocouple (CheckTemp1, ±0.1°C) with a probe of 1 m dipped at three different openings namely T1, T2 and T3 along the surface of the pile (Mudhoo and Mohee, 2008). The initial wet bulk density and MC of the samples were determined according to Agnew and Leonard (2003). The pH was determined electrometrically in a slurry of the homogeneously ground oven-dried compost and calcium chloride solution (1:10 w/v sample: calcium chloride extract) using a calibrated EcoScan pH (buffer 4, 7 and 10) meter. EC was determined using a calibrated electrical conductivity meter (Model Lutron pH–201 Hand Held Digital pH meter). The VSs content of each sample was determined using the BS1377 method. VS was calculated using the following equation:

\[
VS(\%) = \frac{M_{\text{dry}} - M_{\text{burnt}}}{M_{\text{dry}} - M_{\text{crucible}}} \times 100\%
\]  
(1)

where \( M_{\text{dry}} \) = mass of sample and crucible before burning (grams), \( M_{\text{burnt}} \) = mass of sample and crucible after burning (grams), \( M_{\text{crucible}} \) = mass of empty crucible (grams). The masses for VS determination were recorded to the nearest 0.001 g on the Mettler PM400 top balance. Also, the respiration rate was measured as per the experimental method described by Mohee et al. (2008). The mass of CO2 generated by the compost sample was calculated using the following expression:

\[
CO_2.C(mg) = 12 \times (HCl_b - HCl) \times [HCl]
\]  
(2)
where $HCl_b = mL$ HCl used in titration of blank, $HCl_s = mL$ HCl used in titrating sample from jar containing compost, $[HCl]$ = concentration of hydrochloric acid used (mol L$^{-1}$), and $CO_2_C$ = mass of $CO_2$- Carbon generated (mg). The value for mg $CO_2_C$ g$^{-1}$ organic carbon day$^{-1}$ was determined using the relationship mg$CO_2_C$ g$^{-1}$ organic carbon day$^{-1}$ = mass of $CO_2_C$ (mg day$^{-1}$) g$^{-1}$ organic carbon, where the organic content (g) was itself deduced from the equation organic carbon (g) = (wet weight of sample) (100-% wet moisture) (%Carbon). The %Carbon was estimated from the equation %C = 0.55 (% VS) (Haug, 1993).

The chloride ions concentration was determined using the Argentometric method and the concentration of chloride, in mg L$^{-1}$, was calculated from equation (3) where $A =$ titrant for the sample (mL), $B =$ titrant for the blank (mL) and $M =$ normality of silver nitrate (mmol mL$^{-1}$).

$$Cl^-(mgL^{-1}) = \frac{(A - B) \times M \times 35.5 \frac{mgCl}{mmol}}{25mL \times \frac{L}{1000mL}} \tag{3}$$

2.6 Determination of final compost quality parameters

The particle size of the compost was determined using a Ro–tap testing sieve shaker for sieves having mesh sizes 18.86, 13.34, 6.68, 3.33, 1.65 and 0.34 mm. The maximum water-holding capacity, $WK_{max}$, was calculated from equation (4) where $E_{dry} =$ mass of dry sample, $g = (M_e - M_0) (1 - (MC/100)); E_{moist} =$ mass of wet sample, $g = M_{moist} - M_0; MC =$ moisture content of sample, %; $M_0 =$ mass of cylinder + wet filter paper, $g$; $M_e =$ mass of cylinder + weighed-in sample, $g$ and $M_{moist} =$ mass of cylinder + wet sample, $g$. Porosity was determined following procedures described by Mohee et al. (2008) by the water pycnometer method. The advantages of this method over the more accurate air pycnometry method (Su et al., 2006) were that it was overall a simpler procedure. Porosity was calculated from equation (5) where $V_{T,15} =$ total volume of water added in 15 mL increments (mL), $V_s =$ volume of sample and $L_f =$ final water level (mL; read to the nearest 10 mL) (Mohee and Mudhoo, 2005).

$$WK_{max} = \frac{E_{moist} - E_{dry}}{E_{dry}} \times 100\% \tag{4}$$

$$Porosity = \frac{(V_s + 1000 + V_{T,15}) - L_f}{V_s} \times 100\% \tag{5}$$

To determine the heavy metals (lead, cadmium, chromium, copper, nickel and zinc), 30 g were dried and ground to <0.25 mm, and treated with aqua regia (3 parts of $HCl_{con}$ + 1 part of $HNO_3_{con}$) (i.e., 18 mL of $HCl_{con}$ and 6 mL of $HNO_3_{con}$). The heavy metals concentrations were determined by atomic absorption spectrophotometry (mg L$^{-1}$), applying the corresponding standard calibration series. The heavy metal content in mg kg$^{-1}$ DS was calculated from equation (6) where $SM_{al} =$ heavy metal content in the treatment solution, mg L$^{-1}$, $F_{al} =$ dilution factor, $V_{mk} =$ volume of treatment solution, mL and $E =$ mass of sample, g.

$$Heavy \text{ metal (mg} kg^{-1} DS) = \frac{SM_{al} \times F_{al} \times V_{mk}}{E} \tag{6}$$
The organically bound total nitrogen content was determined using the Kjeldahl treatment of the dry compost. The available phosphorus was determined by the modified Troug Method (Chang and Juo, 1963; Vaughn Weseloh and Brown, 1971). To determine the exchangeable potassium, a mixture of 5 g of dry compost and 50 mL of ammonium acetate was shaken in an automatic shaker for 1 h. After filtration of the mixture, the clear filtrate was used for analysis in a flame photometer, which was previously calibrated with standard solutions of potassium.

Phytotoxicity bioassay was used to determine whether the compost contained substances that could inhibit seed germination or seed radicle elongation. The equivalent amount wet compost to 100 g dry compost was calculated from wet compost, g = 100 g dry compost/MC (%). The germinated seeds were counted, the length of radicle and germination index (GI) were determined from equations (8) and (9) where $G_t = \text{mean germination for treatment}$, $G_c = \text{mean germination for distilled water control}$, $L_t = \text{mean radicle length for treatment (mm)}$ and $L_c = \text{mean radicle length for distilled water control (mm)}$. The following phytotoxicity ratings were used to assess the phytotoxicity of the final composts by comparing GI for the composts: germination index of 0.8–1.0 implies ‘No inhibition of plant growth’, germination index of 0.6–0.8 implies ‘Mild inhibition’, germination index of 0.4–0.6 implies ‘Strong inhibition’ and germination less than 0.4 implies ‘severe inhibition’.

\[
\%\text{Germination} = \frac{G_t}{G_c} \times 100 \tag{7}
\]

\[
\%\text{Radicle.Length.Elongation} = \frac{L_t}{L_c} \times 100 \tag{8}
\]

\[
GI = \frac{G \times L}{10000} \tag{9}
\]

Germination tests were used to determine the effect of the composts on plant germination and growth in soil, a mixture of soil and compost and compost only. The soil and compost were sieved to 10 mm. No water was added at a latter stage. 2 cups (200 mL-cup) of soil only, 2 cups of compost only, 2 cups of mixture of 75% soil with 25% compost, 2 cups of 50% compost with 50% soil and 2 cups of mixture of 25% soil with 75% compost were prepared from composts from Run A (referred to as CS) and Run B (referred to as CSW). 5 Brassica Rapa L. Var. Rapa seeds were placed in each cup at 2.5 cm depth and the cups were placed in a cool, well-ventilated place of the laboratory.

### 3 Results and discussions

The following sections present and discuss the variations of the composting process parameters monitored over the 26 days and the final composts characteristics for their quality and suitability to be used as soil amendment. Since literature is scanty in published research on the composting of Ulva reticulata (with and without washing), the present findings are fresh to the compost literature and hence novel in their own right. An attempt has nevertheless been made to compare the present findings with the very few relevant reported data that could be distilled.
3.1 Washing and seaweed to wash water ratio

Figure 3 shows the efficiency of the reduction of soluble salts as well as chloride ions in seaweed *Ulva reticulata* after washings. Samples undergoing one washing (denoted by ‘1 Washing’ in Figure 3) showed a decrease in chloride ions below 90%. The results of samples that had been washed twice showed a fair decrease in EC and chloride ions, which were between 92 and 94%, respectively. With three washings, the results showed highest washing efficiencies of 92-94% for chloride ions and from 94-96% for EC. However, interim results also showed that it was more convenient to wash the seaweeds with two washings with a ratio of 1:10 (seaweed to water (w/v)). The single washing process did not reduce salts concentration efficiently compared with the two washings and three washings as shown in Figure 3. On the other hand, despite results showed very good decrease in chloride contents and EC with samples undergoing three washings, it was not appropriate owing to high amounts of wastewater that were produced (700 L with ratio of 1:20 for 35 kg of seaweed, single washing). Hence, washing two times the seaweeds was more suitable. With two washings, the efficiencies for the three different ratios of seaweed to water were more or less the same (around 92% for chloride ions removal and between 93 and 94% for soluble salts removal). Thus, the ratio 1:10 (seaweed to water on w/v basis) and two washings were chosen for subsequent use in the composting experiments.

![Washing efficiency of seaweeds](image)

3.2 Temperature variation

Temperature was monitored daily from the start of the experiments until stabilisation near ambient values, which averaged at 30.2°C. The temperature profiles for mean temperatures for Runs A and B are shown in Figure 4. The data show that the average temperature of the composting materials changed according to typical temperature profiles though variations in temperature within the compost mixture...
were frequently noted after an initial rapid rise in temperature. Tang et al. (2007) have also noted a rapid increase in temperature to over 54.9–55.7°C after 18–20 h during the degradation of the Seaweed Wakame (*Undaria pinnatifida*) by composting with the inoculation of *Bacillus* sp. HR6. The peak temperatures for Runs A and B were 48.9°C and 55.2°C, respectively on day 5. The temperature remained above 50°C for about 4–6 days in both composting matrices (The horizontal dark line represents the mesophilic–thermophilic threshold). This indicated that the composting process in both mixes had experienced from sufficiently high thermophilic temperatures (Das and Keener, 1997; Raviv et al., 1999; Mohee and Mudhoo, 2005) for prolonged time periods. The difference in temperature trends can be explained by the fact that Run A had a higher salt concentration that have inhibited thermophiles growth and reproduction since temperature is a direct indicator of microbial activity (Haug, 1993; Epstein, 1997). Other important observations from the temperature profiles are that the end of the thermophilic phase occurred with a drastic drop in temperature of about 9°C for both runs. Saludes et al. (2007) stated that temperature falls down when most of the easily biodegradable materials are consumed and the rate of heat generation becomes less than rate of heat loss. It was also noted that the temperature was not uniform across the piles for both runs, but with same general trend. The temperatures in the middle sections (both transverse and longitudinally the reactors) had always been the highest temperatures as it was the core of the composter, denoting the region of highest microbial activity and highest degradation rates. This corresponded to Epstein’s (1997) statement that temperature is rarely uniform throughout the composting mass and the centre of the mass tends to be hotter and the outer edges cooler.

### 3.3 Wet moisture content

Figure 5 shows the variation of wet basis MC for Runs A and B for three weeks of composting.
The initial moisture was 69.8 and 72.5% for Runs A and B, respectively. The high moisture mix was acceptable as there was presence of enough lignocellulosic material (bagasse) in the ratio of 2.33:1 (seaweed to bagasse). From Figure 5, it can be observed that the MCs oscillated during the composting process for 3 weeks. This was mainly due to evaporation of water from the matrices. The broiler litter and mainly bagasse added as bulking agent, absorbed most of the free water on the first 5 days for both mixes. Leachate was collected and approximated 1.03–1.17 L for the experimental runs investigated.

3.4 Wet bulk density

Bulk density is the measure of the amount of the solid material occupied by a certain volume. The bulk density was found to have increased to a great extent during the 22 days of the composting process in both mixes. For Run A, the starting wet bulk density was 43.31 kg m$^{-3}$ and the final bulk density was 225.4 kg m$^{-3}$ (Figure 6). For Mix 2, the starting wet bulk density was 46.93 kg m$^{-3}$ and the final density reached 280.4 kg m$^{-3}$ at the end of week 3. Larney et al. (2000) stated that bulk density should normally increase with composting time based on a mass decrease usually accompanied by more pronounced volume reductions. As supported by the results in Figure 6, the initial feedstock materials, their physical preparation and the mix ratio used have favoured the biodegradation of the substrates in both matrices, inducing settlement of the piles and ultimately causing the bulk densities in both experiments to increase.

3.5 pH

Figure 7 illustrates the variation of pH for the three weeks of composting for Runs A and B. The pH rose from 6.2 to 7.1 for Run A, and for Run B, the pH increased from 6.8 to 7.4 during the composting process. This could be mainly due to the microbial...
decomposition of the organic matter, proteins and amines that produced ammonia gas (detected from its characteristics irritating smell). Ammonia being alkaline in nature caused the pH to rise. These results, therefore, show that the average pH (for both composting mixes, which varied from 6.2 to 7.4) of the composting materials was acceptably within the normal range (6.5–8.5) for optimum microbial activity. pH was thus not a limiting factor for the compost set-ups studied.

3.6 Volatile solids

VS is a good indication on how biological degradation occurred with time. The data for the change of VSs with composting days have been presented in Figure 8. This set
of data indicates the randomness in variation for the VS content within the parent compost piles. It can also be observed that there was a general decrease in the VS % throughout the composting process for both runs of composting experiments. The initial VS content for Run A was 77.95% and the final VS content was 75.4%. For Run B, the starting VS content was 84.47% and the VS content after 22 days was 72.7%. The net rates of organic matter degradation, $OMDR$, determined from equation (10) (Haug, 1993; Saludes et al., 2007) are 11.59 and 50.20% for Runs A and B, respectively.

$$OMDR = 100\% \times \left[1 - \frac{VS_{final} \times Ash_{initial}}{Ash_{final} \times VS_{initial}}\right]$$  \hspace{1cm} (10)

Run B hence had a higher organic matter degradation rate thereby showing that it had more favourable composting conditions than in Run A. Also, the net degradation of the compost piles in terms of net VS reduction is 2.19 and 11.44% for Runs A and B, respectively, over the 3 weeks. It can be hence deduced that the mix containing washed seaweeds decomposed more rapidly than the one with unwashed seaweed, upholding the inference that the degradable substrates for Run B were more readily available when compared with Run A. These net decreases in VS contents also indicate that adequate microbial degradation of the substrates had taken place in both mixes but nearly fives times more in Run B. Hence, washing of seaweeds seemed to have favoured the microbial activity in Run B as the salinity was far less in this mix.

3.7 Electrical conductivity

Figure 9 shows the variation of EC for Runs A and B. It can be observed that there was a general increase in the EC of the composting mix for Run A during the composting period but that in Run B mix was varied over a much narrower range (2.6–3.6 mS cm$^{-1}$). The large increase in Run A may be set on account of the fact
that EC varies significantly with many factors among which the type and relatively amounts of materials composted, the soluble salt content in the compost (Krogmann, 1999), the time of composting and the amounts of leachate drained off (Khoshgoftarmanesh and Kalbasi, 2002) are the most important. It may also be noted from Figure 9 that a decrease in EC (hence, salt content) occurred in the thermophilic stage (Days 1–8). This decrease might be due to the uptake of soluble salts by thermophiles. After the thermophilic stage, the EC increased significantly in Run A as the degradation of substrates may have most seemingly liberated soluble salts from the substrates in the compost pile. Yan (1998) found that sodium and chloride ions were rather high in the Ulva species compared with other marine algae. However, for Run B, the salt concentration remained close to the initial value of the mix during the entire composting process. This showed that rate of uptake of soluble salts by the microbes matched the release of salts from the decomposing materials and hence EC changed by little.

3.8 Carbon dioxide evolution

Figure 10 shows the respirometric activity (mg CO$_2$.C day$^{-1}$.g$^{-1}$ VS) of Runs A and B with composting time. The respiration test is a measure of the activity of the microorganisms in the compost heap, and thus of the stability of the compost produced. As the composting process proceeded, the organic matter present in the pile was decomposed, in the presence of oxygen to release carbon dioxide as one of the major gaseous products. Initially, carbon dioxide generated was negligible indicating no active composting. On day 1, the respiration rates were at a maximum in both mixes at 17.5 mg CO$_2$.C day$^{-1}$.g$^{-1}$ VS and 20.0 mg CO$_2$.C day$^{-1}$.g$^{-1}$ VS for mixes in Runs A and B, respectively. The rises observed in respirometric activity during the first 26 h of the composting process coincided perfectly with the initial temperature rise (Figure 4) for the first day of composting from ambient temperatures. This confirmed the early onset of active composting.
The respirometric activities then decreased gradually for both runs of composting experiments. On day 28, the respirometric activity had reduced to 10.14 mg CO₂·C day⁻¹ g⁻¹ VS and 11.03 mg CO₂·C day⁻¹ g⁻¹ VS for mixes in Run A and Run B, respectively. After day 28, the carbon dioxide generation remained quite low and below 10 mg CO₂·C day⁻¹ g⁻¹ VS for both matrices. Comparison of the mg CO₂·C day⁻¹ g⁻¹ VS values on day 28 for both composts (Run A compost and Run B compost) with the California Compost Quality Council Standards (http://www.crra.com/ccqc/) for CO₂ respiration tests indicated that the compost from Runs A and B were just moderately stable. (The California Compost Quality Council Standards states that a value of 5–10 mg CO₂·C day⁻¹ g⁻¹ VS corresponds to ‘moderately stable’ compost while values in the range 2–5 mg CO₂·C day⁻¹ g⁻¹ VS refer to ‘stable compost’). The respirometric activity of both composts was again determined on day 38 (curing phase of composting). Run A compost and Run B composts gave 8.87 and 8.09 mg CO₂·C day⁻¹ g⁻¹ VS, respectively, and were hence stable.

3.9 Chloride contents

Figure 11 shows the variation of chloride ions over time in both Runs A and B. Although the chloride ions content was 3–5 times more in Run A composting matrix than in Run B’s (thus showing that washing of seaweeds has greatly reduced the chloride ions contents), these chloride ions levels remained quasi constant and close to their respective initial value (the variations being almost linear and horizontal, Figure 11) in both mixes. This may be accounted by two possible reasons:

- the physical effects of ions release owing to the degradation in both experiments may have not affected the net matrix chloride contents,
- the release of chloride ions has been negligible in both mixes.
3.10 Statistical analysis of variations of composting parameters

This study consisted in analysing the effects of washing one of the three substrates being used in one of the mixes in two composting experiments. While it is evident from Figure 11 that washing reduced the chloride ions content in Run B composting matrix, it is important to verify whether the washing has been (or not) equally and solely responsible to affect the other above-mentioned composting process parameters. In this respect, a Single-Factor ANOVA analysis has been performed to compare the physical treatments (in this specific case, ‘treatments’ refers to the ‘washing of seaweeds for one mix and no washing for the other’).

The ANOVA test statistics have revealed that for $P < 0.05$, the null hypothesis made by ANOVA was not rejected. Since the null hypothesis by ANOVA states, in principle, that the data sets in the two columns are same and come from the same population, a no rejection of the null hypothesis, in context, implies that the treatments have not given different sets of values for the composting process parameters. This inference is supported by the test result $F$-values of the ANOVA tests for the two mixes for the composting parameters given in Table 3 whereby the $F$-test statistic is less than the critical value for $F (F_{crit})$. It may be hence deduced that the washing of seaweeds did not significantly affect the variations of key process parameters (temperature, bulk density, pH and VSs) of the composting process.

![Figure 11 Variation of chloride ions contents in Runs A and B](image)

### Table 3  ANOVA results for treatments

<table>
<thead>
<tr>
<th>Composting Parameter</th>
<th>Range of values tested for single-factor ANOVA over stated time line for Runs A and B</th>
<th>F-test statistic</th>
<th>$F_{crit}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Day 1 to Day 10</td>
<td>2.083</td>
<td>4.494</td>
</tr>
<tr>
<td>Bulk density</td>
<td>Day 1 to Day 22</td>
<td>0.316</td>
<td>5.987</td>
</tr>
<tr>
<td>pH</td>
<td>Day 1 to Day 22</td>
<td>2.733</td>
<td>5.987</td>
</tr>
<tr>
<td>Volatile solids</td>
<td>Day 1 to Day 22</td>
<td>0.151</td>
<td>5.987</td>
</tr>
</tbody>
</table>
experiment in Run B. However, the assessment of the quality of the composts produced from the experiments conducted has shown a different set of findings. These are discussed downstream.

3.11 Compost quality assessment

3.11.1 Particle size distribution

Figure 12 shows the particle size distribution of dry composts produced from composting mixes from Runs A and B. The distributions are observably similar for both composts. For compost from Runs A and B, the % passing the sieve of 13.34 mm mesh size was 92.9 and 94.1%, respectively. This implies that more than 90% of both composts can be used for horticultural and agricultural application purposes since the overwhelming proportion of both composts was very fine.

3.11.2 Porosity, water-holding capacity, nutrients value and heavy metals

The final porosities were 82.8% and 76.5% for composts from Runs A and B, respectively. On the basis of the initial matrix porosities, there was thus a net decrease of 10.3% and 16.5% in porosity for Runs A and B, respectively, after 27 days of composting. The standard deviations associated with the porosity values being low at 1.56–2.57 support that these values are reliable even though the air pycnometer method may have given more accurate results (Su et al., 2006). These decreases in air porosity are fully supported by the large volume reductions that were noted throughout the process for both mixes and increase in bulk densities. The net decrease in porosity can be accounted as the result of settlement and organic matter degradation occurring simultaneously during the composting process.

The maximum water-holding capacity for composts obtained after 26 days of composting process was 4.68 and 5.69 for Run A and Run B compost, respectively,
indicating for Run B compost, that every 100 g of the well-mixed compost could hold as much as 569 g of water. Work carried out by Levanon et al. (1988) on mixed cattle manure and biosolids gave a water-holding capacity as high as 9.00. If the water-holding capacities from this study are compared with the result from Levanon et al. (1988), it is clear that the difference is very large. One possible reason could be the considerable difference in compost permeability (owing to varying compost compaction and compost composition) for the two composts that were tested. The water-holding capacity of 4.68 and 5.69 nevertheless still remain a good index for the compost quality of the composts produced from the present experiments since the corresponding temperature and CO₂ evolution profiles convincingly indicate high compost stability and maturity, respectively.

The nutrient levels for nitrogen (N), phosphorus (P) and potassium (K) being relatively higher in compost from Run B than from Run A indicate that the final compost produced with washed seaweeds had a better fertilising capacity (N and P contents for Run B compost were 2.04 and 0.70 mg kg⁻¹, respectively). The heavy metals content for lead, chromium, cadmium, copper, nickel and zinc in both composts were all well below the limits set by reference standards. Cadmium was undetectable for both composts and lead for compost produced from washed seaweeds. Compost from washed seaweeds contained lower levels of all heavy metals than in compost from Run A. This might be due to either the initial washings, which may have washed away a certain level of these heavy metals.

### 3.11.3 Phytotoxicity bioassays

It was deduced that the CS compost contained more phytotoxic substances than in the CSW compost, which may be attributed to the high salt content. Phytotoxins can be salts, heavy metals, pesticide residues or other toxic compounds. It was observed that using CS compost with seeds or plants caused severe inhibition while CSW compost causes mild inhibition. Also, at full strength (no dilution), the inhibition was stronger in CS compost than in CSW compost as washing had significantly reduced the salt (chloride) concentrations (Eyras et al., 2008) (for data in Figure 11, $F_{\text{statistic}} = 368.05 > F_{\text{crit}} = 5.99$ for $P < 0.05$ from a Single-factor ANOVA analysis), thus, reducing phytotoxins level. Hence, the composts can be leached before use or can be applied well before planting to allow for leaching.

### 3.11.4 Germination performance

It was found that only seeds with mixtures of CSW compost and soil had germinated (Figure 13). No seeds germinated with CS compost only and combination of CS compost and soil thereby showing that compost derived from Run A contained high level of phytotoxins (as supported by the severe inhibition result from the phytotoxic bioassay result), which severely inhibited germination. Moreover, seeds develop the root system within soil only during the 15 days of germination test run as soil had most probably a much lower nutrient content, lower moisture and lower water-holding capacity relative to compost. It was also observed that with 100% CSW compost, seeds did not germinate. This corresponded to the phytotoxic
bioassay results that with full extract of CSW compost, there was mild inhibition. Hence, to use CSW compost effectively for agricultural purposes, it is recommended to apply the compost in soil well before use to permit leaching, which would lower the phytotoxins level. It can be inferred from Figure 13 that using 25% CSW compost and 75% soil (dry mass basis) is adequate for potting plants and vegetables.

Figure 13  Germination performance of compost/soil mixture

![Germination performance of compost/soil mixture](image)

4 Conclusions

This present study compared the batch composting process of mixed Ulva reticulata, bagasse and broiler litter in two composting experiments with one mix containing double distilled water washed seaweed. The success of the experiments in being typical to other reported composting experiments in terms of the evolution of the main composting parameters (temperature, bulk density, carbon dioxide evolution rate and pH) supports that the aerobic batch composting of Ulva reticulata seaweeds is feasible. Although the statistical results from the Single-factor ANOVA analyses showed that the variations of composting parameters did not differ significantly between the treatments, the quality of compost produced from the matrix containing washed seaweed was superior to that produced from the composting mix containing unwashed seaweeds in terms of finer compost particle size, higher nutrients (N:P:K) content, lower concentrations of heavy metals (Cd, Cr, Ni, Cu, Pb and Zn), reduced phytotoxicity and hence better seed germination performance.
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