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Test Equipment

Design considerations for high-temperature respirometric biodegradation of polymers in compost

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ABSTRACT

As interest in the field of biodegradable plastics grows so too must the methods to accurately assess them. The use of respirometric units to control and monitor in-situ degradation is one popular method to achieve this, however little is understood about the consequences of their design when applied to high-temperature large-scale replications of bioreactors. In this paper we discuss the design characteristics of a laboratory scale aerobic biodegradation unit and compare a number of key design features with a particular focus on the effect of internal bioreactor design and aeration rate on the compost moisture content and overall sample biodegradation. The internal design of the bioreactors was shown to produce different air and moisture circulation patterns within the bioreactor compost-sample mix. Optimised design of the bioreactor systems to maximise biodegradation was shown to increase the biodegradation of base cellulose from 72 to 81% over a 90 day period.

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1. Introduction

Over the last decade there has been an increase in the research and use of bio-derived or bio-based polymers as substitutes for conventional fossil fuel-based polymers. Societal pressures for renewable carbon-neutral, environmental-friendly biodegradable polymers are just a few of the reasons for the renewed interest and drive in this field of material science. Unfortunately, improvements in the processing technology to extract and thermoform these biopolymers, as well as knowledge about their resultant physio-chemical properties, has far exceeded the understanding of how these novel biopolymers, blends and composites biodegrade after their end-of-service life. Without this knowledge the design of future biopolymers is incomplete.

Investigations of biodegradation aspects of these novel biopolymers have centered on immersing these materials into likely waste mediums and measuring the resultant physiochemical changes. However, this approach is still incomplete as it looks more at the material at discrete time points and excludes the overall biodegradation behaviour between these time points. Without this overall information, critical transitions in biodegradation behaviour remain unknown and the links to the physio-chemical information collected can only be hypothesised.

To address this, international testing standards (ISO) and regional standards, such as ASTM (USA), CEN (Europe) and JIS (Japan) were created to provide a broad guideline on methodology for polymer biodegradation over a specified time in a variety of media [1–3], such as soil, compost [4,5], aqueous [6,7] and sludge [8,9]. These testing standards attempt to measure the biodegradation in-situ by measuring the carbon dioxide evolved from the medium. They rely upon the assumption [Equation (1)] that the organic carbon initially present in the biopolymer is consumed by micro-organisms in the media and respired as carbon dioxide (CO_2) that is quantified either discretely or continuously.

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$$\textbf{Aerobic:}\quad C_{SAMPLE}+O_2\rightarrow CO_2+C_{BIOMASS}+C_{RESIDUAL}$$
$$\textbf{Anaerobic:}\quad C_{SAMPLE}+H_2\rightarrow CO_2+CH_4+C_{BIOMASS}+C_{RESIDUAL} \qquad (1)$$

This requires a gas flow rate through the sample-medium mix, whether continuous or refluxed, to extract the evolved gases so that they can be directly analysed by gas chromatography, infrared spectroscopy, or absorbed into alkaline solutions (such as $Ba(OH)_2$ and NaOH) for liquid titrations. The gas profile of the sample-medium mix is converted into a percentage biodegradation by subtracting the medium-only profile and dividing by the theoretical CO_2 that could be produced if all organic carbon in the sample was converted to CO_2 (refer to Equation (5)).

Recent interest to further characterise and understand the full biodegradation behaviour of polymers has seen an increase in publications that provide a detailed outline of the construction of their units [10–12] designed to comply with the biodegradation testing standards. Other authors describe their units and focus on the stability and accuracy of the chosen setup, such as CO_2 determination by IR, alkaline solutions and gas chromatography [13,14], or improved control through the addition of a pycnometer [15]. Others have focused on the environmental and physio-chemical properties [16] of the media to produce the most stable or optimum biodegradation kinetics, such as aeration rates [12,17–19], compost moisture, pH and temperature profiles [20,21] (using both constant temperature and a temperature profile). Vermiculite or perlite has also been added in several instances [22–27] to improve the signal-to-noise ratio between the compost/soil baseline and compost/soil-sample mix.

However, the effect of the internal design of the bioreactor on maintaining the stability of the compost environment or the respirometric rate has not been studied. In this paper we have designed a robust laboratory scale aerobic biodegradation unit and compared a number of key design features with a particular focus on the effects of internal bioreactor design and aeration rate on the compost moisture content and overall sample biodegradation.

2. Method

2.1. Materials

Microcrystalline cellulose powder (20 μm, Sigma–Aldrich) was used as a positive reference and three-month old compost (Natural Recovery Systems, Bangholme, Victoria) was used as a source of inoculum. The compost was further sieved through an 8 mm sieve to remove large debris and inert material, and distilled water was added to increase the moisture content up to 45–50%. The characteristics of the compost at the start of the respirometric test are presented below in Table 1.

Table 1
Compost characteristics.

Parameter	ISO 14855 Requirements	Test data
Initial dry weight	50–55% dry/wet weight	51% dry/wet weight
pH	7.0 to 9.0	7.2
Solid volatile content (on dry weight basis)	Greater than 30%	45%
Particle size	Less than 10 mm	Less than 8 mm

Table 2
Descriptions of bioreactors tested in the respirometer.

Mix name	Compost (dry, g)	Cellulose (dry, g)	Bioreactor design	Air flow rate (mL/min)
Compost-Nil-150	600		Nil	150
Cellulose-Nil-150	600	100	Nil	150
Compost-Tube-150	600		Tube	150
Cellulose-Tube-150	600	100	Tube	150
Compost-Plate-150	600		Plate	150
Cellulose-Plate-150	600	100	Plate	150
Compost-Plate-100	600		Plate	100
Cellulose-Plate-100	600	100	Plate	100

The compost and cellulose powder were later subdivided into sample mixtures outlined in Table 2 then decanted into 3 L glass jars (called Bioreactors). Three replicates of each bioreactor composition were analysed and all weights are based on dry weight equivalents. A schematic of the three types of bioreactor design used (i.e. Nil, Tube, Plate) are described in more detail later and can be seen in Fig. 3.

2.2. Respirometric operation

The bioreactors were conditioned using an in-house constructed Respirometric Unit seen in Figs. 1 and 2. The unit and its operation have been NATA certified and are compliant with ISO 14855. The unit collectively conditions all bioreactors with a humidified air stream as well as holding bioreactors at a constant temperature to simulate a desired industrial composter environment via the partial submersion of the bioreactors inside a dark communal water bath. The unit also individually records from inlet and outlet sensors attached to each bioreactor.

Each bioreactor has a 0–250 mL/min air flow regulator to control air entering the bioreactor and set of condensation glassware to collect excess moisture from the respired air streams prior to analysis. The air exiting the condensation

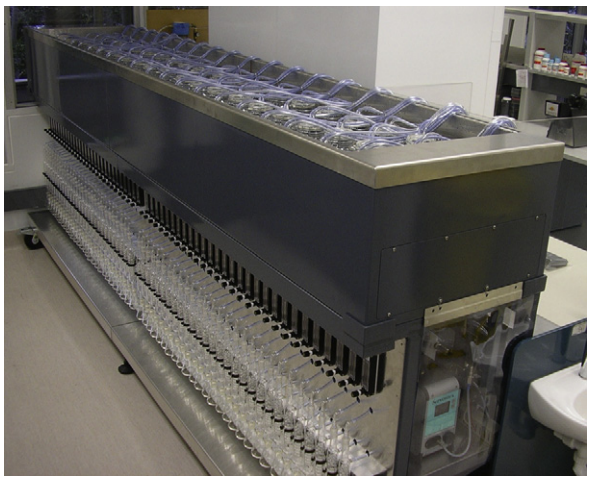

Fig. 1. Photo of the respirometric unit.

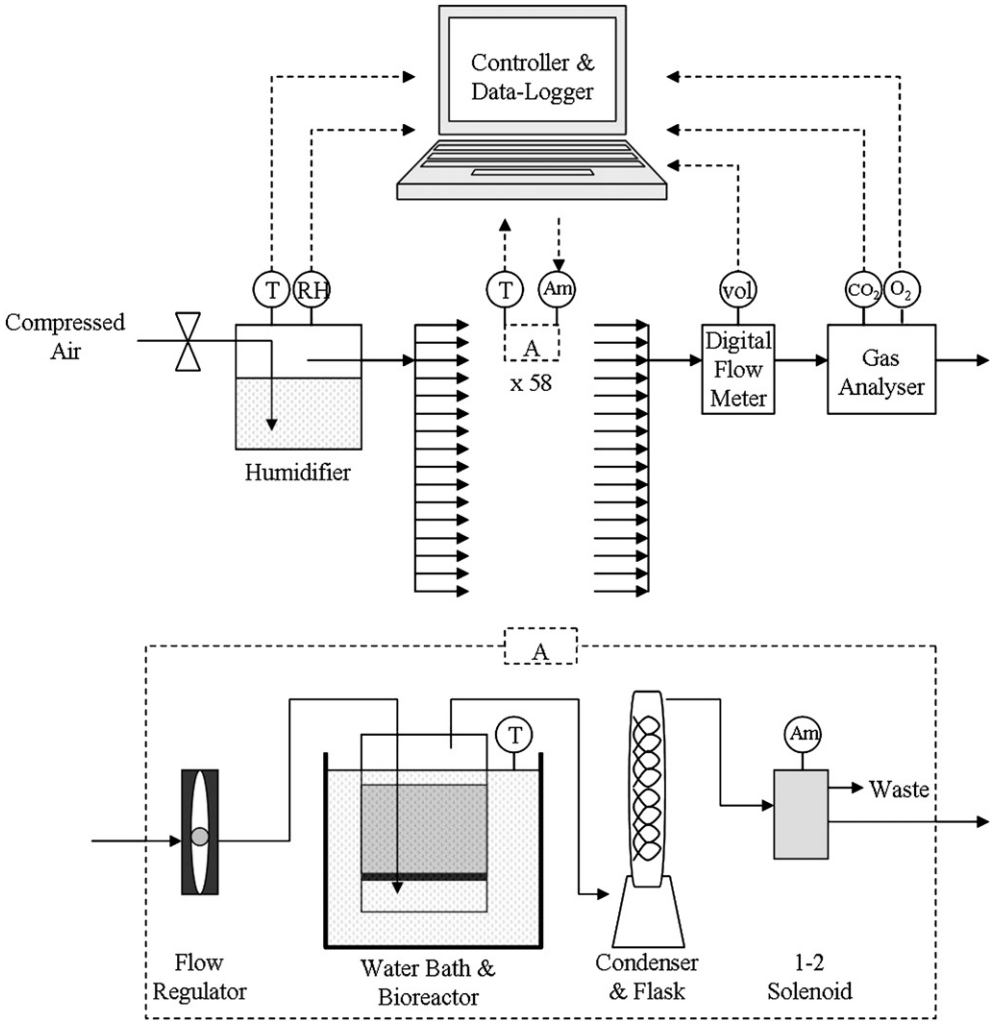

Fig. 2. Schematic of respirometric unit.

glassware flows into a 1–2 way solenoid where it is either discarded or analysed. All the solenoids are controlled by NI LABVIEW software which automates the timing and sequencing of the bioreactor gas streams and data-logging of the unit sensors. When a bioreactor is sequenced for analysis, the associated solenoid directs respired air into an air manifold then to a digital gas flow meter and infra-red gas analyzer. The LABVIEW software records the various unit sensors (air flow rate, CO_2%, O_2%, water bath temperature, air temperature, air humidity) and operator observations to a data file associated with that respective bioreactor before sequencing the next bioreactor. The software also automatically generates warnings when the sensor readings fall outside desired operating limits.

The unit is routinely checked for air leaks and the unit sensors are calibrated at least weekly. The O_2/CO_2 gas analyser is calibrated with certified gas mixtures purchased from BOC Gas and the water bath temperature is checked against a NATA certified thermometer. A summary of the respirometric unit conditions can be seen in Table 3.

2.3. Determining the purge time for bioreactors

Before running the respirometric test, the unit was assessed to determine a suitable sample purge time. To do this the entire gas collection network and gas analysis sensors were purged with 100% N_2 for 8 min and the gas concentration in the line checked. Simultaneously, the

Table 3
Condition settings used in the respirometric unit.

Parameter	Setting
Inlet air humidity	90–95% RH at 20–23 °C
Air flow to each bioreactor	100 ± 20 or 150 ± 30 mL/min at 23 °C
Water bath temperature	58 ± 2 °C
Water condensation of the respired air	Through glass condensation columns re-circulated with chilled water
Respired air flow	Factory calibrated digital flow meter
Respired air composition	Infra-red CO_2/O_2 gas analyzer calibrated with certified gas mixtures

bioreactor air line (set for bypass) was purged with the CO_2 calibration gas (8.54% CO_2 in N_2). The bioreactor air line was activated for analysis and the time, flow rate and CO_2 concentration were recorded until the gas concentration plateau was reached. The gas collection network was configured with both 29 or 58 bioreactor lines connected, and a gas flow rate of either 100 or 150 mL/min. The time elapsed value for all data was normalized to reflect the desired flow rate as per Equation (2). Three replicates were used to determine the mean time for the analysis concentration to fall within 10, 5, or 2% of the calibration medium.

$$Time_{T=t} = \sum_{T=i}\left(\frac{FLOW_{ACTUAL}}{FLOW_{DESIRED}}\right) \quad (2)$$

where $Flow_{ACTUAL}$ is the flow rate recorded by the digital flow meter and $Flow_{DESIRED}$ is the flow rate desired (of either 100 or 150 mL min^{-1}).

2.4. Bioreactor designs used for the study

Three internal bioreactor designs (seen in Fig. 3) were investigated for their effect on the biodegradation of the compost/cellulose samples. The first bioreactor design ('Nil') has no internal down pipe tubing to disperse the inlet air. The second ('Tube') is the commonly seen setup with a tube directing all inlet air to the base of the bioreactor. The third ('Plate') had a tube that directed all inlet air to the base of the bioreactor and then a standoff perforated plate in the base to diffuse the air back up through the bioreactor. All bioreactors consisted of a 3 L glass jar with a hinged lid (for easy filling and access) into which plastic tubing connectors were inserted to facilitate entry of fresh air into and removal of respired air out. The bioreactors were selected as they had a large throat diameter. The large throat allows the operator easy access to the compost mix to rehydrate and remove samples for subsequent physiochemical analysis.

2.5. Sample handling and collection schedule

Twice a week the bioreactors were disconnected from the respirometric unit and had water replenished to maintain the moisture content of the compost. This was achieved by weighing the water collected in the respective condensation flask for each bioreactor and adding an equivalent weight of distilled water back into the bioreactor. For the 'nil' and 'tube' setups, the water was replenished using a fine misting spray. For the 'plate' setup, the water was replenished by injecting the water down the inlet tube into the base of the bioreactor. After water replenishment, all bioreactors were shaken to homogenise the contents before the bioreactor was reconnected to the respirometric unit.

Additionally, on days 14, 28 and 49, compost samples were removed from the top 2 cm region and bottom 2 cm region of each bioreactor, and were later subjected to dry weight analysis.

2.6. Analysis of evolved carbon dioxide

The data collected from the gas sensors for each of the bioreactors were used to calculate the quantity of carbon dioxide evolved between successive data points, according to Equation (3).

$$vol(CO_2) = \Delta Time \times vol\ rate(air) \times conc[CO_2] \quad (3)$$

This was further used to calculate the cumulative carbon dioxide evolved over daily intervals according to Equation (4).

$$Cumulative\ vol(CO_2) = \int_0^t vol(CO_2)\cdot dt \quad (4)$$

Finally, the percentage degradation of the cellulose with respect to time was calculated according to Equation (5).

$$Cellulose\ Degrad\ (\%) = \frac{Cumulative\ vol(CO_{2,CELLULOSE}) - Cumulative\ vol(CO_{2,COMPOST})}{Theoretical\ vol(CO_{2,CELLULOSE})} \quad (5)$$

Mean and standard deviation of each sample were calculated using the three replicates according to Equation (6).

$$Mean\ Degradation = \frac{Degrad_1 + Degrad_2 + Degrad_3}{3} \quad (6)$$

2.7. Dry weight analysis

Approximately 15 g–30 g samples of wet compost collected directly from the bioreactors were weighed on aluminum trays and dried at 105 °C until no further weight loss was observed. The dry weight of the compost (relative to the wet weight) was calculated according to Equation (7).

$$W_D(\%) = \frac{W_{V,T2} - W_{V,T0}}{W_{V,T1} - W_{V,T0}} \times 100 \quad (7)$$

where W_D is the dry weight of the compost relative to the original wet weight (%), $W_{V,T0}$ is the empty weight of the drying tray, $W_{V,T1}$ is the weight of the drying tray including the wet compost and $W_{V,T2}$ is the weight of the drying tray including the dry compost.

2.8. Statistical analysis

All *t*-test values mentioned were calculated using a 2-tailed distribution of paired data relative to the 'Plate-150' bioreactor setup under the same conditions.

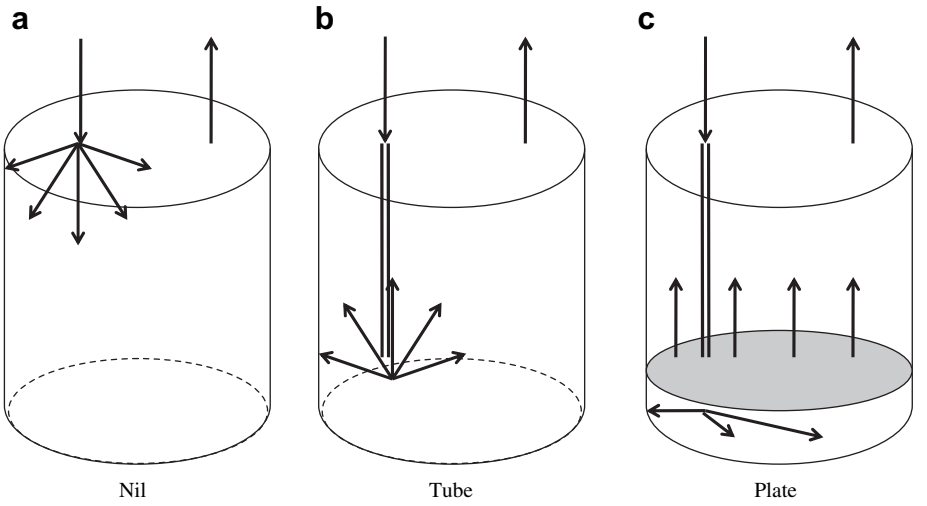

Fig. 3. Schematic of bioreactor setups.

3. Results and discussion

The results presented focus on the accuracy of the respirometer setup, the effects of selecting an air flow rate for a bioreactor and the effect of three different bioreactor designs focusing on the condensed water collected, moisture imbalances throughout the compost and the resultant respirometric activity.

3.1. Accuracy of the respirometer unit

The respirometer unit constructed and used in this study is comparable to other units [10,11], although it contains more bioreactors and records more sensor parameters. The larger sensor array allows for improved monitoring of compost conditioning parameters such as inlet air humidity, air temperature, water bath temperature and outlet air flow rate, and air composition (CO_2 and O_2). An example of the data collected for a compost sample can be seen in Fig. 4.

Fig. 4 shows an initial disturbance in the CO_2 signal during the first 5 days as it equilibrates to the new compost conditions, which is then followed by a steady decline over the remainder of the test. The O_2 signal mirrors the CO_2 signal reflecting the declining microbial activity in the compost with the absence of any food source, and the

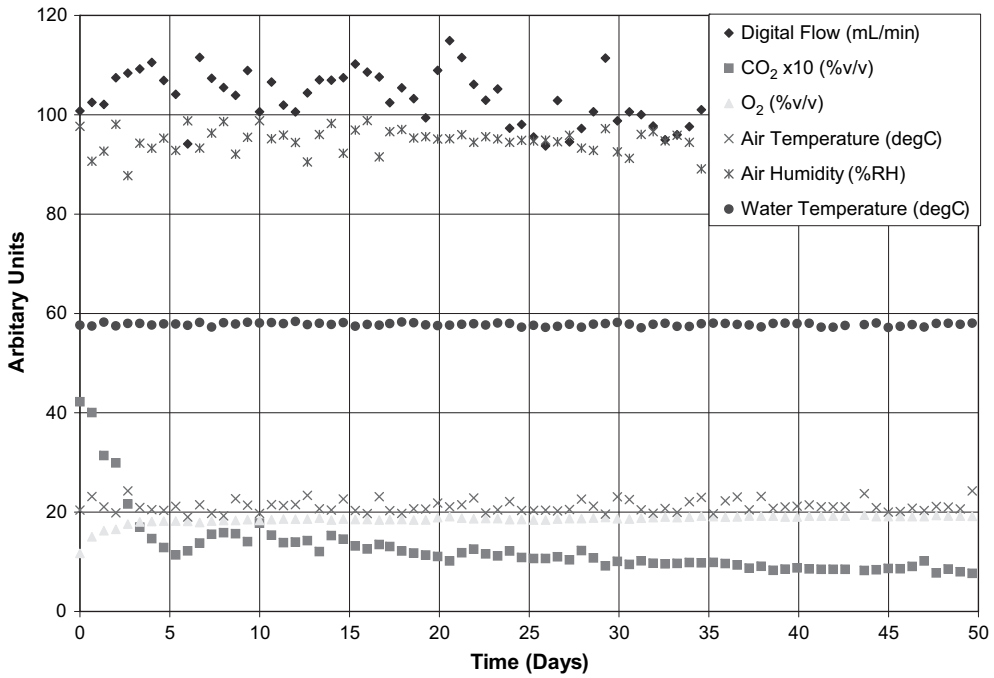

Fig. 4. Example conditioning of a compost sample (Plate design with 100 mL min^{-1} flow rate).

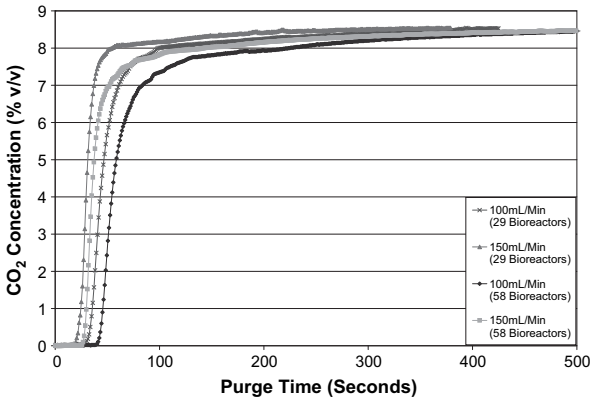

Fig. 5. Purge flow characteristics of the respirometer unit with 29 or 58 bioreactors.

signal plateaus at roughly 20%. The inlet air humidity and temperature are stable at 93 ± 5 %RH and 21 ± 2 °C respectively. The inlet air flow rate showed more than the desired fluctuation (at 100 ± 20 mL min^{-1}) due to fluctuations in the source flow rate and pressure. Minor fluctuations in inlet flow using this method for determining percentage biodegradation are not significant as all offsets away from the mean flow rate were reflected in slight increases or decreases in the CO_2 signal. These offsets in flow and CO_2 percentage later correct each other when using Equation (3). The water temperature remained well within the required 58 ± 2 °C, reflecting the efficiency of the multiple heaters throughout the water bath and the recirculation pump. All unit sensor readings were within their calibrated limits.

3.2. Bioreactor air flow rate

Increasing the inlet air flow rate to the bioreactor can have an effect on the compost conditioning, the gas sensor accuracy and overall unit function.

Increasing the air flow rate enables a more rapid purge time for the respired bioreactor gases to pass through the collection manifold and flow through gas sensors. Fig. 5 shows the purge time required for respired bioreactor gases to pass through to the infra-red gas analyser and display the correct CO_2 concentration. As the infrared analyser is the last item in the analysis network it determines the required purge time for each bioreactor before data can be collected for analysis.

The purge characteristics in Fig. 5 are summarised in Table 4 and reveal that for all setups analysed, a 10% confidence threshold was achieved in less than 130 s, but significantly more time was required to reach 5% and 2% confidence. It also shows that doubling the number of bioreactors in the collection manifold almost doubles the manifold volume and, thus, time to purge. Likewise, increasing the flow rate (from 100 to 150 mL min^{-1}) decreases the time to purge. Consequently, the required purge time for all future respirometer tests was set using the 2% confidence threshold plus at least 30%.

Table 4
Purge flow characteristics of the respirometer to be within 10, 5, or 2% of the actual purge gas concentration.

Setup	Time to reach threshold concentration (Seconds)		
	10%	5%	2%
100 mL/Min (29 Bioreactors)	78 ± 1	139 ± 5	265 ± 19
150 mL/Min (29 Bioreactors)	44 ± 1	80 ± 8	167 ± 4
100 mL/Min (58 Bioreactors)	127 ± 1	251 ± 10	416 ± 10
150 mL/Min (58 Bioreactors)	80 ± 4	182 ± 1	354 ± 1

Ultimately, any condition that increases the required purge time also increases time to sequence through all bioreactors and the number of times a bioreactor is analysed per day. Using the 2% confidence threshold, all 58 bioreactors can be sequenced and analysed at least twice daily (which fulfils ISO 14855 requirements). The use of the automated sampling sensors and control program became particularly useful here as these would otherwise be too time consuming for the operator.

Increasing the air flow rate also has an effect on the compost conditioning inside the bioreactor. Increasing the air flow rate will ultimately result in decreased CO_2 and increased O_2 composition in the respired air stream. Care must be taken to choose an air flow rate that prevents the respired gas composition falling outside the limits of the gas analysers as well as providing a realistic value from the environment being simulated. This will be discussed later with respect to the different bioreactor designs.

3.3. Choice of bioreactor design

The different internal designs for the bioreactors were investigated as it was believed they would invoke various degrees of heterogeneity in the compost-sample mixture in terms of dryness, aerobic activity and ease of operator handling. The three setups chosen were intended to reflect the worse case setup ('Nil'), the commonly used setup ('Tube') [10,21] and optional replacement setup ('Plate') [11,12,15,17,28]. The perforated 'Plate' design, although a simple extension to the 'Tube' design, can potentially offer several important advantages in terms of air flow through the compost, moisture content of the compost and operator effort.

Firstly, the air flow is improved as the plate separates the compost from the exit of the tube down pipe and thus keeps the end of the tubing down pipe free of obstructions. The plate also maintains the position of down pipe tubing at the bottom of the bioreactor and prevents it from coiling up or moving within the compost when the compost mix is routinely homogenised. Once the inlet air reaches the bioreactor base it is pre-warmed (by the water bath) before reaching the compost mix, thus preventing a cooling effect from the air. The air flow through the compost is further improved as the air is spread over the entire base of the bioreactor before moving upward thus preventing the channeling effect seen in the 'Tube' design [12].

The 'Plate' design also allows the operator to more efficiently replenish the compost water. This can be achieved by injecting the water directly into the base of the bioreactor (via the down pipe) and letting the inlet air naturally absorb the water on its way through to the compost. Adding water to the air stream, as opposed to the

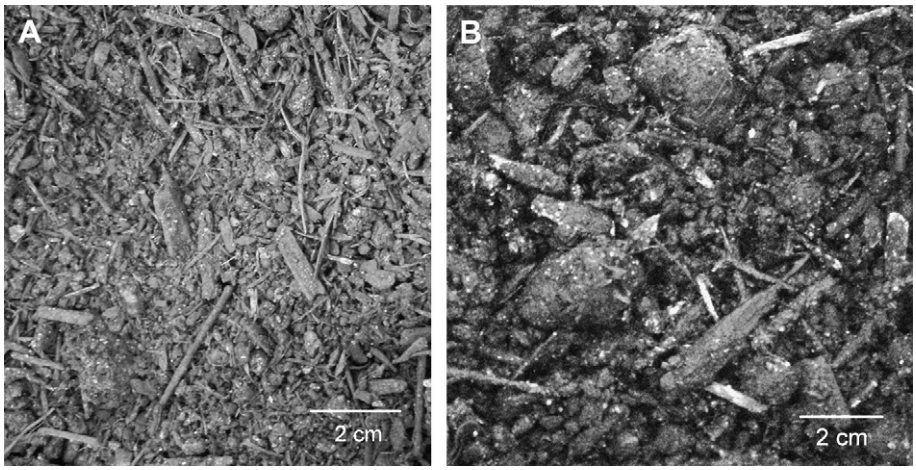

Fig. 6. (left) Compost at day 35 with the plate-150 Setup, (right) compost at day 35 with the tube-150 setup.

compost directly, means that the drying effect that normally comes from upward air flow is minimised as the air is at its hygroscopic limit and cannot absorb water from the compost. However, water added to the base of the bioreactor is quickly evaporated into the air stream and, once depleted, the air steam resumes its drying effect as normal.

Adding water to the air stream also helped to minimise the 'clumping' effect that occurs in over-damp compost (seen in Fig. 6). The plate helps safeguard against this by allowing excess moisture in the compost to drain into the space below the plate and away from the compost (which has also been used to collect leachates [15]). This prevents rotting and anaerobic conditions forming in the compost and recycles the water for future air flow.

Several attempts were made to humidify the inlet air stream, using air mixers and other humidification devices [11,15,21,28,29], to achieve the optimal relative humidity to prevent any drying effect on the compost. However, this proved unsuccessful as it needs to be done close to the bioreactor inlet at the operating temperature of the bioreactor to prevent moisture from condensing out and interfering with air regulators and sensors. This would be best achieved if the humidifier was installed after each individual bioreactor air regulator, but that would be too expensive to install on such a large bioreactor array. Humidifying the inlet air at close to optimum is also problematic as it is more difficult for the operator to detect if a moisture imbalance occurs. Thus, having a system that is designed to be slightly drying is easier to rectify as it is easier to identify, quantify and correct.

Adding water to bioreactor in this way is beneficial to the operator as it is rapid uncomplicated and eliminates the need to manually spray water onto the compost. It also prevents the need to open the bioreactor and expose the operator to the risks from the microbes in the compost. In addition, maintaining a closed bioreactor does not disturb the aerobic conditioning of the compost.

3.4. Water collection

The degree of drying on the compost mixes was determined by the amount of condensate collected from the bioreactor by the operator twice weekly. The water collected was due to the cooling of the moist air leaving the bioreactor (at 58 °C) to ambient temperature (~22 °C). The lower

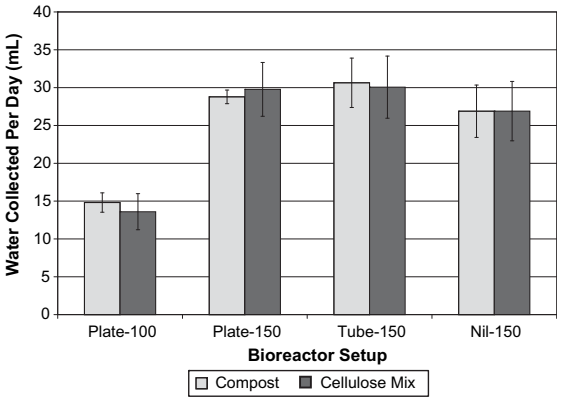

Fig. 7. Average amount of water collected per bioreactor setup.

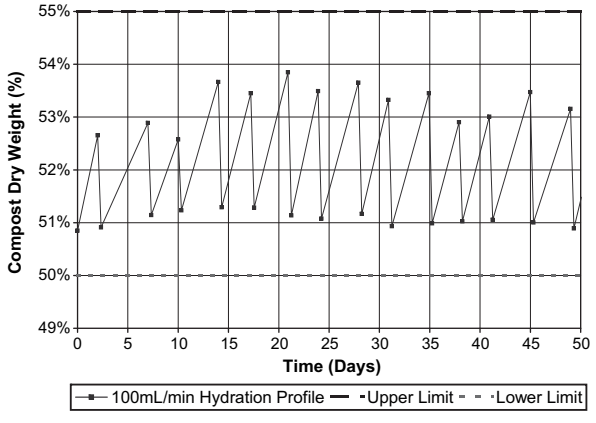

Fig. 8. Estimated compost dry weight profile with a 100 mL/min flow rate.

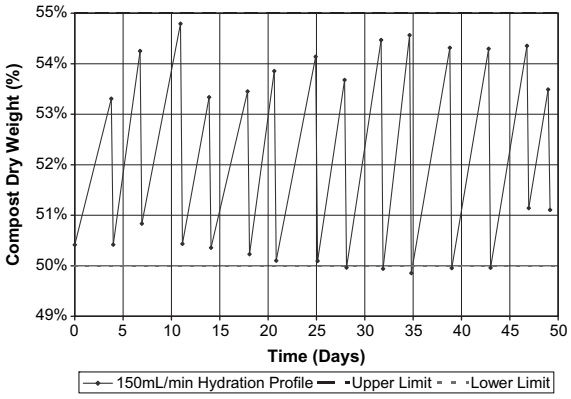

Fig. 9. Estimated compost dry weight profile with a 150 mL/min flow rate.

temperature lessens the moisture holding capacity of the air and the excess moisture is condensed out. This water is collected and replenished into the bioreactor to maintain uniform moisture levels throughout the test. This condensation stage also protects the operation of the electronic solenoids and maintained the accuracy of the gas sensors.

The amount of water collected from a bioreactor is affected by a variety of parameters associated with the compost, air and bioreactor, such as moisture content, quantity, porosity and depth of the compost as well as the flow rate, inlet humidity, moisture capacity (and temperature) of the air, and even the shape of the bioreactor lid and air outlets. Fig. 7 shows the average amount of water collected per day from various bioreactors. This average is based on the three replicates of each sample during week's two to four. The figure reveals very little difference in the amount of water collected between the three design types at 150 mL/min flow rate (t-test p value 0.07–0.3), but the 'Plate-100' design resulted in approximately half the water collected compared to the 'Plate' design at 150 mL/min (t-test p value < 0.01). Based on this information, it appears that the absolute amount of water collected is primarily due to the convective evaporation of air through the compost and not the natural evaporation from the compost.

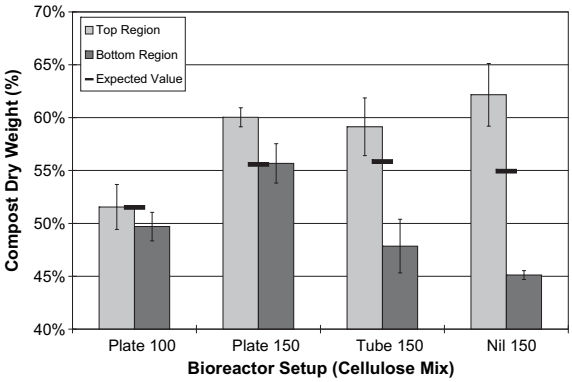

Fig. 10. Compost dry weight in the top and bottom bioreactor regions that result from various bioreactor setups.

Table 5
Composition of respired air exiting the bioreactors.

Parameter	CO_2 evolution (%v/v)	O_2 emission (%v/v)
Test limits	10% max limit for IR gas analyser	More than 8% required by ISO 14855
Compost – Plate – 100	0.5–2	15–20
Cellulose – Plate – 100	0.5–6	14–20
Compost – 150	0.5–2	18–20
Cellulose - 150	0.5–4	16–20

3.5. Compost dry weight profile

The water collected twice a week was used to estimate the overall dry weight content in the compost over the course of the respirometric test. The simple mass balance on the compost water is shown in Figs. 8 and 9. It is apparent that the 100 mL/min flow rate results in a lesser fluctuation in the compost moisture content (52 ± 1.5 %RH) compared to the 150 mL/min flow rate (52 ± 2.5 %RH). Lower fluctuations led to greater stability in the compost conditioning or, conversely, a greater time interval could be used between re-hydrations and still maintain the desired 50–55% compost dry weight. These figures also show that the re-hydration schedule of twice a week maintained the desired 50–55% compost dry weight. Decreasing the frequency, particularly for the 150 mL/min flow rates, would have moved the compost dry weight outside of the desired 50–55% window and may have led to reduced aerobic biodegradation activity.

3.6. Water imbalance within the bioreactor

Fig. 7 suggested that the internal bioreactor design or flow pattern within a bioreactor had little effect on the absolute quantity of water collected per day. However, closer examination of the compost moisture from the top and bottom regions of the bioreactor revealed a moisture imbalance. Fig. 10 shows that the 'Plate' designs (at both 100 and 150 mL/min) in the top and bottom regions of the bioreactor are quite close to their estimated means. In contrast, the variation between the top and bottom regions of the 'Tube' design was greater and the 'Nil' design even greater. The majority of this moisture imbalance is seen as an increasing wetness of the bottom region of the compost for the 'Tube-150' and 'Nil-150' (t-test p values <0.05) compared to their top regions (t-test p value 0.4–0.5).

The uniformity in the compost moisture between the top and bottom region can be best explained by comparing the internal flow pattern within the bioreactors. The 'Nil' setup produced a drier compost region at the top of the mixture (also noted by Spence et al. [30], who suggested that it leads to slower mineralization) as this is the region where all the air flows through this bioreactor. A wetter region thus developed at the base where there was no air flow or moisture uptake into the air. In contrast, the 'Tube' setup produced a slightly less moisture imbalance between the top and bottom regions as there was air flowing upward from the tube outlet in the base. However, the single tube

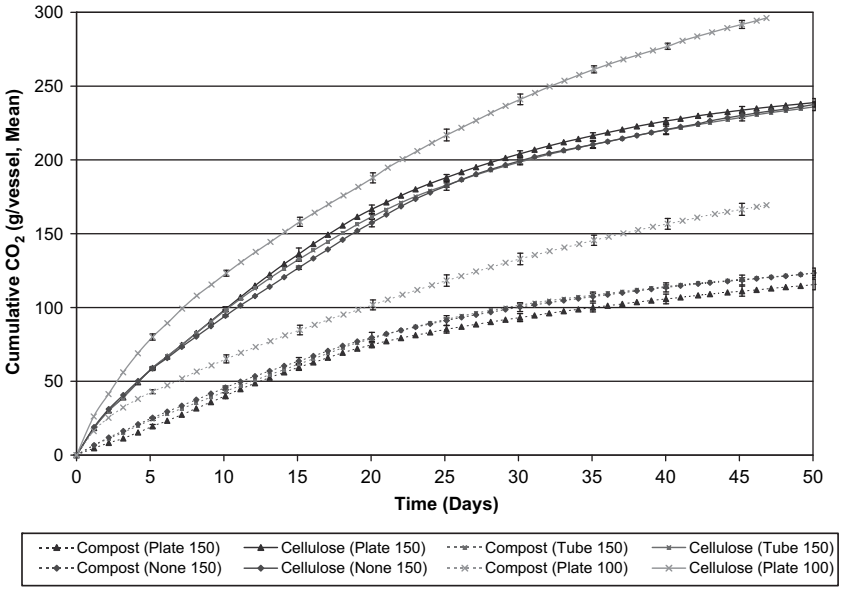

Fig. 11. Cumulative CO_2 traces for compost and cellulose samples in each of the three bioreactor designs.

outlet leads to localised channeling of the air upward and localised convective drying of the compost.

3.7. Respirometric activity

The composition of the respired air exiting the bioreactors can be seen in Table 5. It was observed that the air flow through the bioreactor was higher than 16% v/v and, thus, maintained a highly aerobic condition in both the compost and cellulose samples. The carbon dioxide evolved from the bioreactors remained below 6%, also ensuring that the aerobic limits described in ISO 14855 were maintained. The amount of carbon dioxide evolved from the cellulose sample was approximately double as compared to that of the blank compost sample due to increased carbon content for microbial respiration.

The cumulative carbon dioxide traces for compost and cellulose samples can be seen in Fig. 11. This figure shows that the bioreactor design did not have any significant influence on the cumulative carbon dioxide evolved during the test on the cellulose sample. The compost samples did reveal a slightly lower carbon dioxide evolution for the bioreactor that included the diffusion plate ('Plate') as compared to the other two bioreactor designs.

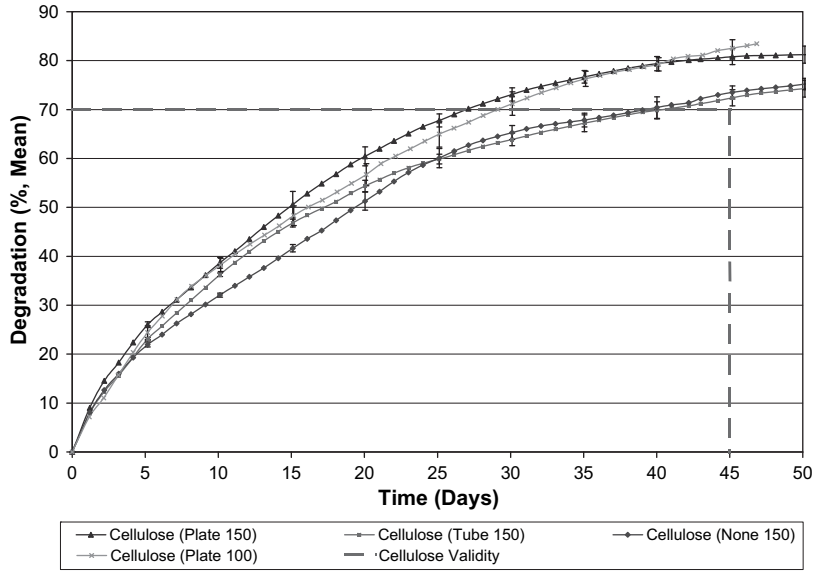

Fig. 12. Degradation profile for the cellulose powder with respect to the bioreactor design. NB: the dashed-line represents the 70% degradation threshold required for cellulose at 45 days defined in ISO 14855.

Table 6
Degree of cellulose degradation at 45 days with respect to bioreactor design.

Bioreactor design	None 150	Tube-150	Plate-150	Plate-100
Degree of cellulose degradation at 45 days	73.5 ± 1.3%	72.4 ± 1.6%	80.8 ± 1.6%	82.5 ± 1.8%

The compost and cellulose cumulative carbon dioxide traces using the 'Plate-100' design were higher than those with any of the designs at 150 mL/min. However, the lower CO_2 trace obtained for the 'Plate-100' results are not directly comparable to the 150 mL/min results as it was collected in a subsequent trial that used different compost.

The resulting degradation profiles for cellulose can be seen in Fig. 12 and the degree of degradation at 45 days are summarised in Table 6. The figure shows that the 'Tube-150' and 'Nil-150' designs only just met the 70% degradation threshold at 45 days set by ISO 14855 (represented by the dashed-line). The 'Plate-150' and 'Plate-100' both showed higher percentage degradation profiles than those of the other two and passed the 70% degradation threshold by day 30. The higher degradation rate of the plate design could be attributed to a more stable moisture content and air flow throughout the compost. The respiration rates for the 'Tube-150' and 'Nil-150' could have been substantially inferior had the contents not been thoroughly homogenised twice a week to correct for the moisture and aeration imbalances.

4. Conclusions

As interest in field biodegradable plastics grows, so too must the methods to accurately assess their biodegradable properties. The use of respirometric units to control and monitor in-situ degradation is one popular method to achieve this, however little is understood about the consequences of their design when applied to high-temperature large-scale replications of bioreactors. This study shows that the choice of internal bioreactor design as well as the bioreactor inlet conditions of air flow rate and rehydration method can directly affect the health of the compost medium and the resultant respiration rates. It was found that the 150 mL/min air flow rate dehydrated the compost more rapidly than the 100 mL/min flow rate and required rehydration every 4 days to maintain the 50–55% compost dry weight threshold. The internal design of the bioreactor can lead to different air and moisture circulation patterns within the bioreactor compost-sample mix. Of all the designs evaluated, the 'Plate' design achieved the best overall aeration of the compost, the least moisture imbalance within the compost and was the easiest method for rehydration. The overall effect of this was a slightly higher respiration rate than the 'Tube' standard design; 81% compared to 72% degradation respectively.

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