

The use of the analysis of variance to assess the influence of mixing during composting

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Abstract

One of the problems encountered in assessing the process dynamics of composting is the considerable variation observed between experimental replicates. The major objective of this study was to use ANOVA to assess the statistical differences between mixing treatments in bench-scale reactors. Two sets of mixing experiments were performed with 30-litre reactors using intervals between mixing of 0, 24, 96, and 192 h. Using ANOVA, mixing was found to increase the time required to achieve maximum temperatures, to prolong the time spent at elevated temperatures and to extend the period of high rates of O₂ uptake. ANOVA for spatial gradients indicated a significant influence of mixing on the formation of moisture gradients; however it had little influence on temperature gradients. This study underscores the importance of improving experimental reproducibility in order to reach quantitative conclusions. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Composting is a naturally occurring aerobic decomposition process for reducing the volume of an organic waste. Over the years there have been numerous engineering research studies focused on making this process more predictable and controllable. The basic objective of these studies is the engineering of the process to maximize the extent of degradation, minimize the release of odours, and create a stable product. Research has focused upon aeration algorithms in aerated static piles as a means of process control [1–4] and mixing to minimize gradients in temperature, moisture content, and oxygen concentration [5,6].

One of the problems encountered in assessing the behaviour of this process is the considerable variation that has been observed between replicates and the

limited statistical analysis of the data [6–14]. Statistical methods that have been used include analysis of variance (ANOVA) to describe variation between treatments [8–13]; the coefficient of variation (CV), or ratio of the S.D. to the mean to demonstrate reproducibility [6–8]; and linear regression analysis has been used to show differences between treatments for different biochemical properties with time as the independent variable [14]. Linear regression is a poor choice for composting experiments since temporal and spatial changes in temperature, moisture content, and oxygen are highly non-linear. CV is a poor choice since it only takes into account the variation between treatments and does not consider the variation of data within each treatment, while ANOVA is attractive since it is possible to partition the variance of a given data set according to possible sources of variation [15].

The major objective of this study was to use ANOVA to assess statistical differences between mixing treatments in bench-scale reactors. Pilot-scale reactors are known to be difficult to operate for mixing experiments [6]. Large experimental variability is intro-

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duced in field-scale studies by changes in the surrounding environment as well as in the heterogeneity of the composting pile. Bench-scale reactors were used in this study because of the ability to reduce the time and effort required for mixing the substrate and to control experimental variability. The study focused specifically on the effects of mixing on the time profiles of temperature, moisture content, and effluent oxygen concentration. Also, the effects of mixing on spatial gradients at specific times for temperature and moisture content were investigated in this study using ANOVA.

2. Experimental methods and materials

2.1. Substrate preparation

Big Red Puppy Food (Pro-Pet Inc., Syracuse, NY) was chosen as a model substrate. Dog food was chosen because of its nutritional similarity to cafeteria wastes, its long shelf life, and consistency between bags [16]. Air dried maple wood chips obtained from Coastal Lumber (Cayuta, NY) were used to increase the porosity of the organic matrix and to increase the carbon content of the substrate to the desired carbon

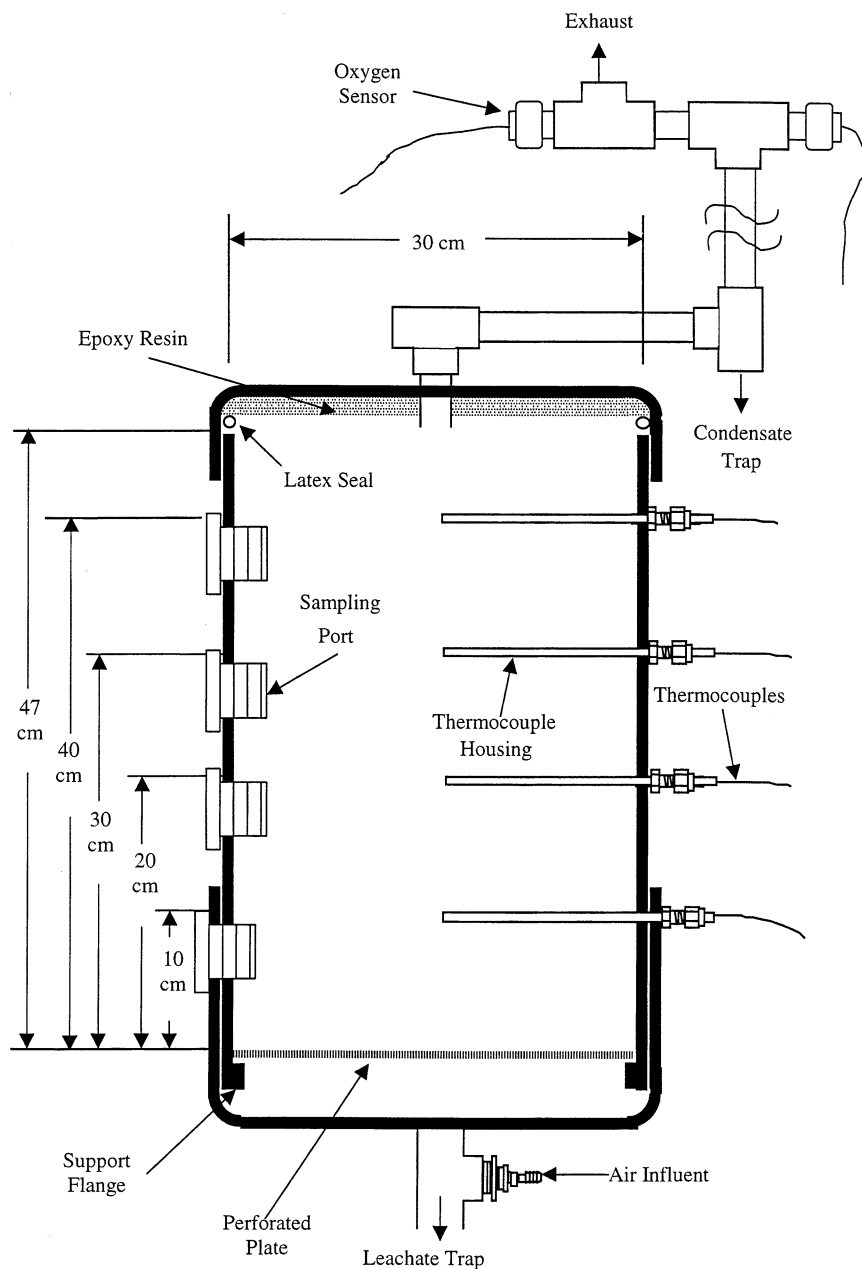


Fig. 1. Bench-scale aerated mixed bed reactor.

to nitrogen ratio (C/N) of 18 [17]. Water was added to all trials to establish an initial moisture content of 55% wet basis (w.b.). The dry bulk density of the mixture was 290 kg/m³.

2.2. Reactor configuration

Eight 30-litre bench-scale reactors were constructed with a 49-cm section of 30-cm inner diameter (i.d.), schedule 40 PVC pipe (Fig. 1). A support flange for the perforated plate was made from a 2-cm section of 30-cm i.d., SCH 40 PVC pipe. The flange was cemented into the 49-cm section flush with the bottom. Lids and bottoms were made of 30-cm i.d., SCH 40 PVC end caps. The bottoms were cemented onto the reactors. Air influent and effluent were transported through 2.54-cm diameter holes drilled into the top and bottom of each reactor. Silicon was used to bind 6.35-mm latex tubing to the top edge of the reactor to provide a gasket. Reactor lids were partially filled with acrylic to form a seal between the latex tubing and the lid. Before the experiment, the inside lip of the lid was coated with vacuum grease. A 30-cm diameter perforated plate was made from a 6.35-mm thick PVC plate. Enough 6.35-mm diameter holes were drilled throughout the plate to provide 20% open area.

Holes were drilled (31.75 mm) into the reactor wall at 10, 20, 30, and 40 cm from the upper surface of the plenum to serve as solids sampling ports. Thermocouples (copper-constantan thermocouple wire, PP-T-24, Omega Engineering, Stamford, CT) with the tips spot-welded and coated in epoxy were inserted to holes 10, 20, 30, and 40 cm above the upper surface of the plenum through 6.35-mm diameter stainless-steel tubes. To minimize radial temperature gradients caused by conductive heat loss, the reactors were insulated using R 18 K/W fibreglass insulation. Preliminary investigations showed that when insulated in this manner, temperature differences between the reactor centre and wall are less than 2°C. An insulated room (5.08-cm thick foam insulation with an *R*-value of 10 K/W, Dow Chemical, Midland, MI) measuring 3.5 × 3.7 × 2.4 m housed the eight reactors used in this investigation to maintain a constant temperature of 30°C.

2.3. Air treatment

Water saturated air was used to aerate the reactors. Compressed air was bubbled through the bottom of 20-litre tanks using fish tank diffusers and fed to each reactor through Nalgene tubing. Continuous monitoring of the saturated air showed an average temperature of 18.4°C ($\sigma = 2.6$). Precision-valve flow meters (Gilmont Instruments, Barrington, IL) were used to regulate the airflow into each reactor. A continuous aeration rate of 0.6 l/min per kg dm (dry matter) or

5.25 l/min was used in all experiments. The oxygen mol fraction of the effluent air stream was measured using two oxygen sensors located in the reactor exhaust system described in detail elsewhere [18].

2.4. Mixing

The contents were removed by hand into a bucket, weighed, and loaded into an insulated (12.7-mm thick sheets of foam insulation with an *R*-value of 10.5 K/W, Armaflex AP, Armstrong, Lancaster, PA) RLX3 Grossman Cement Mixer (United Supply, Braintree, MA). A lid was made from 5.08-cm thick foam insulation with an *R*-value of 10 K/W. Mixing of the substrate lasted for at least 30 s. A few substrate balls formed early in the experiment, but these were broken up by hand and the substrate re-mixed. The substrate was removed from the mixer, weighed and then reloaded into the reactor.

2.5. Data acquisition system

Every 30 min, a computerized data acquisition system measured temperature and O₂ concentration. Thermocouples and O₂ sensors were connected to an analog to digital converter computer board (Computer Boards, Mansfield, MA) and an IBM 286 computer. A Pascal computer program was developed to record data [19].

2.6. Measurement of moisture content

Each day, two samples between 5 and 10 g were removed from the 10-, 20- and 30-cm reactor ports. Representative samples were drawn using a core sampler. It was not possible to remove samples at the 40-cm level from many of the reactors because the reactor bed height decreased with time due to compaction. Two composite samples were removed after each mixing, and at the conclusion of each experiment. These samples were dried in a drying oven (655G, Fisher Scientific, Pittsburgh, PA) at 101°C for 24 h.

2.7. Experimental design

The intervals between mixing used in this study were 0, 24, 96, and 192 h. Mixing occurred 1 h after solids sampling and within 15 min of the scheduled time of mixing. Experiments were performed in two groups. The first began in January 1998 and the second began in March 1998, both used two reactors subjected to each interval between mixing. The group begun in January will be referred to as Experiment 1 while the group begun in March will be called Experiment 2. Two reactors were run for each treatment during each experiment so that the total number of reactors used for each treatment was four.

Table 1
Generic ANOVA table for data to be analyzed using Eqs. (1)–(4)

Source of variation	df	Sum squared (SS)	Mean SS (MS)	F_s
Among treatments	$a-1$	SS_{Treat}	$SS_{\text{Treat}}/(a-1)$	$MS_{\text{Treat}}/MS_{\text{Exper}}$
Among experiments	$a(b-1)$	SS_{Exper}	$SS_{\text{Exper}}/(a(b-1))$	$MS_{\text{Exper}}/MS_{\text{within}}$
Within experiments	$ab(n-1)$	SS_{within}	$SS_{\text{within}}/(ab(n-1))$	
Total	$abn-1$	SS_{total}	$SS_{\text{total}}/(abn-1)$	

3. Data analysis methods

3.1. Description of analysis

The method used to analyze differences among intervals between mixing and position in the reactor for these data was a balanced mixed design using a two-tiered nested ANOVA [15]. A balanced design refers to the collection of an equal number of observations for each experimental group and treatment. This study was balanced since an equal number of observations were recorded for each treatment and experimental grouping. There are two possible models encountered in statistical analysis. Model I refers to data with fixed effects, such as interval between mixing length or position in the reactor. Model II refers to data with random effects not directly controlled by the experiment, such as when the experiment group was started. Since the experimental design used in this investigation produces data with both of these effects, it is a mixed design. ANOVA is effective because it allows for the partitioning of the total variance of a data set into categories that represent either Model I or II.

Although debated by statisticians, ANOVA is only applicable when several assumptions are satisfied [15,20]. The first assumption states that all observations must be independent. Second, the variance of each treatment must be homogeneous or homoscedastic. Finally, observations for each experiment should be parametric, or follow a normal distribution. The statistical test for significance using ANOVA is the F distribution, which is very robust to minor violations of these assumptions [20]. These assumptions will be addressed later in this paper.

In order to complete the ANOVA for this nested design it is necessary to calculate the sum-squared values between treatments, between experiments, and within the experiments. Once calculated, the results obtained from Eqs. (1)–(4) can be used to generate the parameters in Table 1 and allows the significance of the calculated F -value to be tested with the associated degrees of freedom [15]

$$SS_{\text{total}} = \sum \sum \sum (Y - \bar{Y})^2 \quad (1)$$

$$SS_{\text{treat}} = nb \sum (\bar{Y}_A - \bar{Y})^2 \quad (2)$$

$$SS_{\text{exper}} = n \sum \sum (\bar{Y}_A - \bar{Y}_B)^2 \quad (3)$$

$$SS_{\text{within}} = \sum \sum \sum (Y - \bar{Y}_B)^2 \quad (4)$$

where, Y is temperature of observation; \bar{Y}_A is mean temperature for observations within experiment; \bar{Y}_B is mean temperature for observations within treatment; \bar{Y} is mean temperature for entire data set; a is number of treatments; b is number of experiments; n is number of observations per experiment.

Significance of the overall F -test does not indicate which specific contrasts are significant. Therefore, Tukey's method of honestly significant differences (HSD) was used to detect differences between treatments [15]. HSD can be used to determine the minimum significant difference when comparisons are not planned before the experiment is initiated. The HSD is the product of the Studentized range, $Q_{\alpha[k, n]}$, and the S.E. as shown in Eq. (5)

$$HSD = Q_{\alpha[k, df]} \sqrt{\frac{MS_{\text{within}}}{bn}} \quad (5)$$

where, k is number of treatments; df is degrees of freedom for MS_{within} ; α is level of testing; b is number of experiments; n is number of observations per experiment.

The effect of mixing on temporal and spatial variation was measured using ANOVA. In order to compare the effect of mixing on the state variables, ANOVAs were performed at various times throughout the 384-h process. In order to remove the effects of spatial variation, the ANOVAs were performed at constant heights. This yields data showing the effect of mixing on the state variables for a given time and height. The second method of analysis performed ANOVAs using the height in the reactor as the primary treatment and the interval between mixing length was held constant.

In order to divide the data into meaningful blocks of time and reduce the amount of analysis, ANOVAs were performed every 12 h throughout the entire 384 h. The data were partitioned such that analysis could be conducted the hour before the mixing event. By analyzing data at these intervals, it was possible to determine the

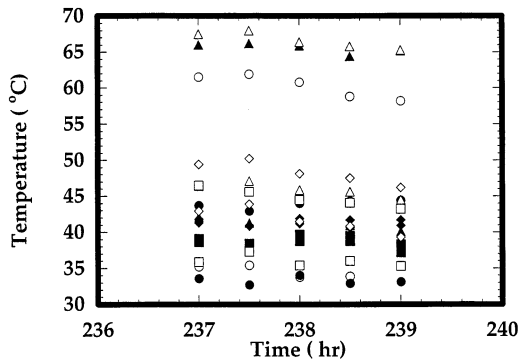


Fig. 2. Temperature data collected between 237 and 239 h at 30 cm for all intervals between mixing. The reactors mixed every 24 h were significantly different from the other mixing frequencies using Tukey's HSD method ($P < 0.001$). ● represent static reactors. ▲ represent reactors mixed every 24 h. ■ represent reactors mixed every 96 h. ◆ represent reactors mixed every 192 h. Closed symbols represent experiment one while open symbols represent experiment two.

effect of mixing on temporal and spatial effects using each variable throughout the entire process without including data from the mixing period. All statistical tests were performed using SPSS (SPSS Inc., Chicago, IL).

4. Results and discussion

4.1. Example of ANOVA and pair-wise comparison

In order to increase the number of observations and total degrees of freedom, temperature and oxygen data were analyzed in 2-h clusters prior to the actual point

of interest. For example, if analysis were to be conducted on data at 239 h, data from 237, 237.5, 238, 238.5 and 239 were used in the analysis. Fig. 2 shows a typical cluster of data. Clustering of data was not possible for moisture content since only two samples were analyzed every 24 h. For sake of brevity, discussion of differences between treatments will be referred to by the last time point of a cluster for the remainder of the paper. It is also clear from this figure that large variations existed within each experimental grouping.

Temperature data in Table 2 were collected between 237 and 239 h at 30 cm above the reactor floor for both experimental groupings and is presented because the variations in this data set are representative of the data collected. Based on a qualitative comparison of the treatment means in Table 2, it appears the reactors mixed every 24 h had higher temperatures than the other reactors and the reactors mixed every 96 h were cooler than the other treatments. Listed in Table 2 are the values required to calculate Eqs. (1)–(4) for the ANOVA table template in Table 1.

It is difficult to test the assumptions of ANOVA for small data sets, such as the data provided in Table 2, created in this study. Sokal and Rohlf describe a 'run-test' to test for independence. According to this test, for five data points, the observations are statistically independent if there are at least two runs in the data. A run is defined by a trend in the data that is either increasing or decreasing [15]. This test shows that all of the data in each cluster from each reactor throughout the study are statistically independent. Inspection of the data in Table 2 shows that for each interval between mixing and experimental group there are at least two runs in the data. The results for the other data sets used in this

Table 2
Description of experimental design and example data used to show calculations for nested ANOVA^a

Treatment ($a = 4$)	Static reactor		Reactor mixed every 24 h		Reactor mixed every 96 h		Reactor mixed every 192 h	
	1	2	1	2	1	2	1	2
Temperature (Y) ($n = 5$); Trial 1	43.7	61.5	42.1	46.4	39.1	46.5	41.3	49.4
	42.9	61.9	41.3	47.1	38.4	45.6	40.8	50.2
	44.0	60.8	41.8	45.9	39.7	44.5	41.2	48.1
	44.3	58.8	40.9	45.6	39.5	44.1	40.6	47.5
	44.4	58.2	40.1	44.5	38.3	43.2	40.9	46.2
Temperature (Y) ($n = 5$); Trial 2	33.6	35.2	66.0	67.5	38.6	35.9	41.8	42.9
	32.7	35.4	66.2	68.0	38.1	37.3	40.9	43.9
	34.0	33.8	65.9	66.4	38.8	35.4	41.9	41.5
	32.9	33.9	64.4	65.8	38.8	36.0	41.7	40.8
	33.1	33.1	65.2	65.3	37.2	35.3	41.7	39.3
Mean temperature for experiment (\bar{Y}_A)	38.6	47.3	53.4	56.3	38.7	40.4	41.2	45.0
Mean temperature for treatment (\bar{Y}_B)	43.0		54.9		39.6		43.1	
Mean temperature for all treatments (\bar{Y})	45.2							

^a Data are temperatures recorded at 30 cm above the bottom of the reactor, between 237 and 239 h into each experiment. Temperatures are listed in the order they were recorded.

Table 3
Completed ANOVA table following template used in Table 2 and using data described in Table 1

Source of variation	df	Sum squared (SS)	Mean SS (MS)	F_s
Among treatments	3	2686.9488	895.6496	7.1258*
Among experiments	4	502.7625	125.6906	1.8525 ^a
Within experiments	72	4885.2150	67.8502	
Total	79	8056.8889	101.9859	

^a Variation between means is not significant at the 0.05 level.

* Variation between means is significant at the 0.05 level.

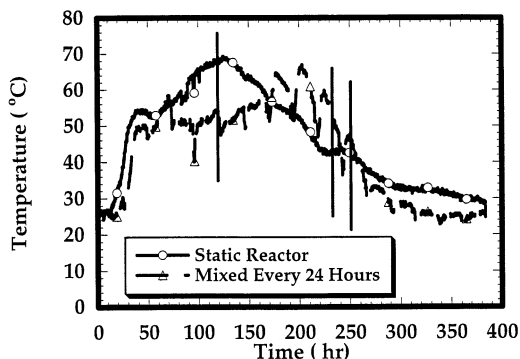


Fig. 3. Temperature profiles representing average values for each trial and experiment of static reactors and those mixed every 24 h at 30 cm. Vertical lines show where Tukey's method detected significant differences between the two curves.

study are not shown but they all yielded similar results. It is difficult to test for normality with the small number of data points available; however if the data does violate the assumptions of normality and homoscedasticity the result is a loss of power and would not result in errors of the first kind [20]. Since multiple data points are drawn from each reactor for each time point, it would be possible to partition the within experiment source of error further for each reactor to variation due to the reactor and within reactor variation. However, further partitioning the data does not improve the ability to detect differences between treatments and only increases the complexity of analysis.

Table 3 is the completed ANOVA table for the data set in Table 2. The calculated F -value for the comparison of variation between experiments and within experiments was 1.85, which is less than the tabulated value $F_{0.05[4,72]}$ of 2.51. Based on the comparison of these tabulated and calculated F -values, the initial time of each experiment had no significant effect at 237 h. However, the calculated F -value for comparison of the variance between treatments with the variance between

experiments was 7.13, which is greater than the $F_{0.05[3,4]}$ of 6.59. Since the tabulated value is less than the calculated value, a significant difference exists at the 0.05 testing level. The ANOVA table has shown that despite the large variations within the data set, a significant difference exists between treatments at 237 h and 30 cm above the perforated plate of the reactor.

In order to determine how many of the treatments are significantly different from the others or how beneficial mixing is, Tukey's HSD was used with an α of 0.05, k equal to 4, and df equal to 10. Using Eq. (5), with $Q_{0.05[4,72]}$ equal to 3.72 and the b , n , and MS_{within} values from Tables 1 and 2, the HSD is 6.85. This shows that in order for a treatment mean to be significantly different than the others, it must differ by at least 6.85°C. This value is relatively large considering the error of the thermocouple is approximately 1°C. This demonstrates the large amount of variability found in this study. This example has shown that reactors mixed every 24 h are significantly warmer than the other conditions at 237 h and 30 cm above the reactor floor, and that the difference between the reactors mixed every 96 h and the other reactors was not significant.

4.2. Effect of mixing on temperature profile

Fig. 3 presents average temperature profiles at 30 cm for static reactors and those mixed every 24 h. These are examples of the shortest and longest intervals between mixing at the position in the reactor that experienced the highest temperatures. The vertical lines in this figure show where Tukey's method detected significant differences between the two curves.

During the rise through thermophilic temperatures, (15–130 h) significant differences existed among intervals between mixing at each of the three depths in the reactor. Temperatures at 10 cm and 107 h into the process, were significantly different among intervals between mixing ($P=0.025$) while temperatures at 20 ($P=0.022$) and 30 cm ($P=0.031$) showed differences among intervals between mixing 131 h into the process.

There were significant differences before 192 h between the static reactors and those mixed every 192 h at all three depths into the reactor. This was unexpected since the reactors received the same treatment up to this time. Other than pure chance, it is not clear what caused this result.

Between static reactors and those mixed every 24 h there were significant differences in temperature at 131 h. At 10 cm, reactors mixed every 24 h were an average of 15.8°C ($P<0.001$) cooler than the static reactors, while at 20 and 30 cm the differences were 17.5°C ($P<0.001$) and 14.4°C ($P<0.001$), respectively. It is clear that mixing every 24 h maintains cooler temperatures than the other intervals between mixing during

the rise to peak temperatures. Once the reactors began to cool (210–384 h), differences between treatments became more apparent. However, the significant differences determined by pair-wise comparisons between treatments did not follow a logical order. At 20 cm and 239 h, the static reactors as well as those mixed every 24 and 192 h were between 7.2 and 14.0°C warmer than the reactors mixed every 96 h (all $P < 0.05$).

Despite these difficulties, comparisons of all pair-wise analyses showed that the reactors mixed every 24 h retained elevated temperatures longer than the other intervals between mixing for most time periods. The reactors mixed every 24 h were an average of 14.0°C warmer than the other treatments at 20 cm at 251 h ($P < 0.001$). Similarly, at 30 cm and 239 h, the reactors mixed every 24 h were between 11.7 and 15.3°C warmer than the other treatments ($P < 0.001$), at 251 h the same reactors were between 12.7 and 19.8°C warmer than the other treatments ($P < 0.001$). From this analysis, it is clear that mixing the reactor contents every 24 h maintains elevated temperatures for a longer period

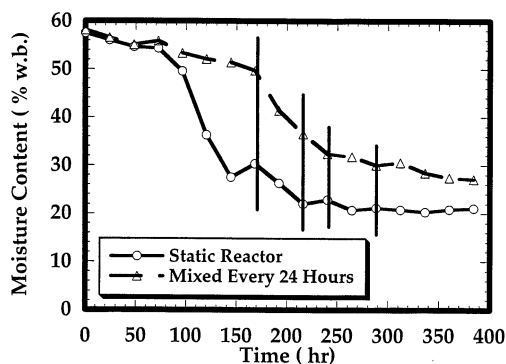


Fig. 4. Average moisture content data collected from reactors mixed every 24 h and those that were static for the entire process at 10 cm. Vertical lines show where Tukey's method detected significant differences between the two curves.

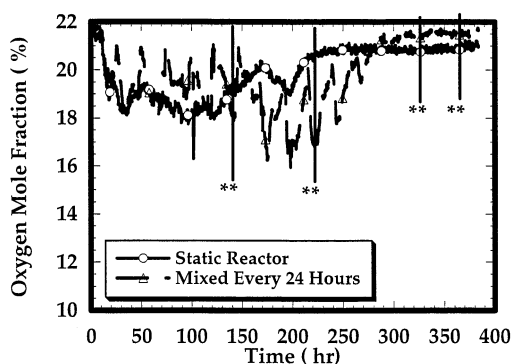


Fig. 5. Profiles of effluent oxygen concentration data averaged across both experiments for reactors mixed every 24 h and those that remained unmixed throughout the investigation. Vertical lines with '**' denote significant differences between means according to Tukey's method.

than the other intervals between mixing tested under this experimental design.

4.3. Effect of mixing on moisture content profiles

There are three phases of the moisture content profile. In the first phase, the amount of moisture lost by advection is comparable to the amount of moisture created due to degradation. Rapid drying occurs in the second phase, where elevated temperatures and aeration force a decrease in the moisture content. The moisture content profile levels off in the last phase after the reactor contents return to ambient temperature and the air stream cannot remove any more moisture from the substrate. Presented in Fig. 4 are average moisture content data measured 10 cm for the static reactors and those mixed every 24 h. Similar to the presentation of data for the temperature profiles, these treatments demonstrate the largest differences in moisture content detected by Tukey's method, as shown with vertical lines. Comparison of intervals between mixing at all time points shows no significant differences in moisture content at 20 and 30 cm.

Between 167 and 287 h, significant differences in moisture content were detected among intervals between mixing at 10 cm. Reactors mixed every 24 h retained moisture better than the static reactors. After 167 h into the process, the reactors mixed every 24 h averaged 19.4 percentage points more moisture than the static reactors ($P < 0.015$). The moisture content of the static reactors at 167 h was 30.3%, while it was 49.7% in the reactors mixed every 24 h. At 167 h, there were no significant differences between reactors mixed every 96 and 192 h and the static reactors. The reactors mixed every 24 h maintained higher moisture contents than the static reactors by 14.6 percentage points at 215 h ($P < 0.029$), 9.6 at 239 h ($P < 0.014$), and 8.8 at 287 h ($P < 0.001$). At 215 and 287 h there were no detected differences between any of the mixed reactors ($P > 0.778$). The moisture content of the static reactors at 287 h was 21.2%, and it was 30.0% in the reactors mixed every 24 h. After 287 h it was not possible to detect differences between those reactors mixed every 96 and 192 h and the other two intervals between mixing. In summary, longer intervals between mixing resulted in lower moisture content relative to the shorter intervals between mixing.

4.4. Effect of mixing on effluent oxygen concentration

Presented in Fig. 5 are effluent O_2 concentration data averaged across both experiments for reactors mixed every 24 h and static bed reactors. Vertical lines show where the curves are significantly different according to Tukey's method. Significant differences between treatments were found at 119 ($P = 0.036$) and 143 h ($P =$

Table 4
Total cumulative oxygen uptake computed using Eq. (6)^a

	Unmixed reactor	Mixed every 24 h	Mixed every 96 h	Mixed every 192 h
Experiment 1	326.13	343.30	352.76	333.13
Experiment 2	241.85	343.24	270.04	253.17

^a All numbers expressed as g O₂/kg dry solids.

0.007). The reactors mixed every 96 h developed significant differences in effluent O₂ concentration compared to the other intervals between mixing ($P < 0.001$). The effluent O₂ concentrations from the reactors mixed every 96 h averaged 2.01 percentage points lower than the other reactors (all tests $P < 0.023$). Also, at 119 h there were no significant differences in O₂ concentration between the reactors mixed every 24 h and the static reactors ($P = 0.992$). Significant differences between all of the treatments developed at 143 h. The effluent concentrations from the reactors mixed every 96 h were lower than those of the reactors mixed every 24 h followed by the static reactors. The differences between the static reactors and those mixed every 24 and 96 h were 1.19 ($P < 0.001$) and 1.63 percentage points ($P < 0.001$), respectively. The average O₂ concentration at 167 h in the static reactors is 19.23%, while in the reactors mixed every 24 h the average O₂ concentration was 18.04 and 17.60% in the reactors mixed every 96 h.

The effluent oxygen concentrations analyzed during the time frame in which reactor temperatures decreased to initial temperatures gives interesting insight. Reactors mixed every 24 h had more consistent and longer lasting biological activity than any other interval between mixing. Data analyzed at 227 h showed significant differences between treatments ($P = 0.006$). At 227 h the concentrations in the reactors mixed every 24 h averaged 2.91 percentage points lower than the static reactors, while the reactors mixed every 192 h were 0.96 percentage points lower than the static reactors, and the reactors mixed every 96 h were 0.59 percentage points higher than the static reactors (all tests $P < 0.001$). The average concentration in the static reactors was 20.65, and 17.73% in the reactors mixed every 24 h, 21.24% in those mixed every 96 h, and 19.70% in those mixed every 192 h. Reactors mixed every 24 h sustained biological activity longer than the other mixing frequencies did.

Cumulative O₂ uptake relates the total mass of oxygen consumed to the initial dry mass of the substrate to describe total biological activity. Eq. (6) gives the cumulative oxygen uptake value.

$$Y = \int_0^{384} \frac{F\rho M_{\text{air}}}{m_{\text{solids}}M_{\text{O}_2}} (X_{\text{O}_2,\text{influent}} - X_{\text{O}_2,\text{effluent}}) dt \quad (6)$$

where Y is cumulative oxygen uptake; F is volumetric flow rate; ρ is dry air density; M_{air} is molecular weight

of dry air; m_{solids} is dry mass of solids; M_{O_2} is molecular weight of oxygen; X_{O_2} is mol fraction of influent and effluent air stream.

Table 4 presents Y values at 384 h for each interval between mixing and experiment. The lack of any significant difference between treatments shows mixing has no effect on cumulative O₂ uptake ($P > 0.05$). The inability to detect differences in cumulative oxygen uptake while being able to detect differences between oxygen uptake rates is most likely due to the effect of integration. When integrating, the errors between replicates for the rates of uptake are averaged over the entire process. Based on the above results the variability between replicates is high for most of the process, which would also cause the average error for the entire process to be higher than the differences between treatments. A previous study showed that the coefficient of variation for cumulative oxygen uptake for a similar system to be between 25 and 30% which would be much larger than the differences seen in Table 4 [6].

4.5. Effects of mixing on spatial gradients in temperature

Fig. 6 shows the largest significant differences detected between 10 and 30 cm using Tukey's method for each interval between mixing. ANOVA testing of significance between positions in the matrix for each interval between mixing demonstrated large temperature gradients. Significant differences were found for all intervals between mixing throughout the period between 117 and 311 h into the process (all tests $P <$

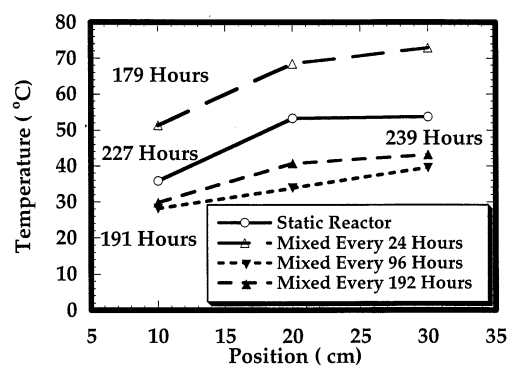


Fig. 6. The largest significant temperature differences detected between 10 and 30 cm using Tukey's method for each interval between mixing. The time of gradient formation is next to each curve.

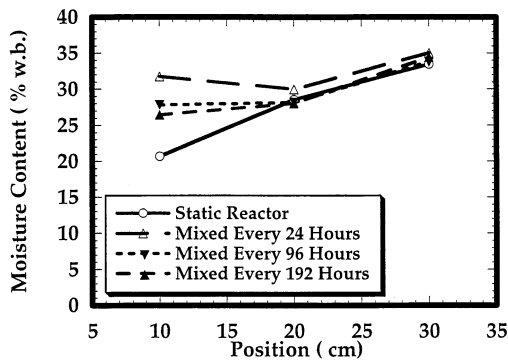


Fig. 7. Spatial moisture content gradients for all treatments at 263 h. The gradients in the static reactors are significant, while the differences between heights for the other intervals between mixing presented are not significant.

0.05). Since it was previously shown that mixing had no effect on cumulative O_2 uptake, the temperature gradients that did form had little effect on the overall degradation process. Furthermore, the occurrence of gradients in all reactors for nearly 200 h shows mixing had no significant effect on the formation of temperature gradients.

4.6. Effects of mixing on spatial gradients in moisture content

Spatial gradients in moisture content form because of the combined effect of aeration and spatial gradients in temperature. Mixing is effective at reducing the magnitude of these gradients. This is shown in Fig. 7 where spatial gradients are shown for all treatments at 263 h. This time was selected because a gradient was detected in the static reactors at 263 h.

The ANOVA performed between depths in the reactor for each interval between mixing clearly showed that mixing had an effect on the magnitude of these gradients. During the first 384 h of the process, the reactors mixed every 24 and 96 h showed no significant differences in moisture content across the reactor bed. The static reactors as well as those mixed every 192 h developed significant gradients between 191 and 287 h (all tests $P < 0.037$).

While mixing had an impact on the formation of moisture gradients, its relevance to the degradation process is minimal. Previous studies [6] have suggested that once the moisture content of a reactor bed falls below 35%, the loss of activity from optimal conditions is about 70%. Since the gradients formed in the static reactors and those mixed every 192 h occurred once moisture contents had dropped below 35%, these gradients had little effect on the process.

5. Conclusions

Mixing has statistically significant effects on three important variables: temperature, moisture content, and effluent oxygen concentration. First, mixing the reactor matrix every 24 h decreases maximum temperature observed because mixing liberates heat. Also, temperatures remained elevated longer in reactors mixed every 24 h than in static reactors. Second, mixing the substrate slows the rate of moisture loss. Third, mixing facilitates constant and prolonged O_2 utilization by microbial populations in the matrix although mixing does not affect the total amount of oxygen consumed. Finally, mixing appears to have no effect on the time course for the formation of temperature or moisture gradients.

The large variations found between and within experiments are important. It is possible that the large variability introduced by performing this investigation as two experiments obscures other effects of mixing causing a reduction in statistical power. While it is desirable to have multiple replications, particular differences between treatments could be determined using only one experimental grouping. This would increase the statistical power to determine differences between treatments. However, use of only one experimental grouping eliminates the ability to understand the universality of the results. It is unfortunate that while much attention has been paid to methods of process control described in the introduction, little attention has been given to the fundamental requirement of an engineered system, reproducibility. The field of composting desperately needs to develop methods for reducing variability between reactors since these methods would benefit both researchers and practitioners. Future studies will evaluate methods for improving reproducibility between reactors.

Analysis of the data from this study has demonstrated the need for a combination of statistical testing and practical interpretation. As shown in the example calculation, differences between treatments are not always statistically significant when one considers the variation between reactors and experimental groupings. While the variation within each experiment is large, the experimental variation suggests that studies comparing trails that are not performed simultaneously may not be subjected to the same conditions. Future composting studies will be of more value if methods are developed that reduce experimental variability. This will allow experiments performed separately to be compared statistically.

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