

Influence of Supplementary Bioavailable Carbon on the Thermal and Biological Kinetic Parameters of the Composting Process of Tomato Plant Trimmings

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Abstract: Three laboratory-scale bioreactors were used to investigate the influence of bioavailable carbon addition on the composting process of tomato remains. Sugar, cheese whey and used cooking oil were used as bioavailable carbon sources. The amounts of materials added to the compost mixture had equal energy contents. The initial moisture contents and C: N ratios of the compost mixtures were maintained at 60 % and 30: 1, respectively. The average bioreactor temperature was strongly influenced by the type of bioavailable carbon. The maximum bioreactor temperature was 50.8, 56.9, 63.4 and 63.3 °C for the control and the mixtures receiving sugar, cheese whey and used cooking oil, respectively. Strong correlations were observed between the maximum temperature achieved (and its duration) and the reductions in fat and volatile solids contents. The total fat reductions were in the range of 64.6-88.8 %, whereas the total carbohydrates reductions were in the range of 21.5-31.7 %. Reductions of 12.4-25.3 % and 3.5-17.7 % were also achieved in protein content and TKN. Neither the nitrogen nor the moisture contents were limiting factors. The ammonium nitrogen remained unchanged at 0.33-0.35 % and the moisture content remained at 59.7 ±0.61 %.

Key words: Compost, bioavailable carbon, tomato remains, volatile solids, carbohydrate, protein, fat

INTRODUCTION

Green house tomato production represents 58% of the greenhouse total vegetable production in Canada in 2000, with a production area of 1550 hectares, yielding 182,736 tonnes^[1]. There is a considerable amount of plant residues as a result of trimming and after harvesting the crop that must be disposed off properly. A typical greenhouse operation produces 40-60 tonnes of organic residues per hectare per year which are usually piled near greenhouses or burned^[2]. These practices cause several undesirable agronomic and environmental problems, since these plants were subjected to intensive pesticide application to control insects and diseases. Therefore, management of these crop residues is necessary in order to minimize their adverse effects, especially recycling plant pathogens^[3].

According to NSDAFF^[4] and ODAF^[2], composting of greenhouse residues is considered the preferred organic waste management method. However, plant biomass is mainly composed of lignin, cellulose and hemicellulose^[5]. Lignin surrounds the cellulose and hemicellulose fibers protecting them from the microbial attack^[6]. Therefore, plant residues are usually lacking bioavailable carbon and are mostly considered as bulking agents when designing a composting mixture^[7]. While composting tomato plant residues, Alkoaik and Ghaly^[8] found that most of the carbon in the composting mixture was not readily available and the temperature never exceeded 50 °C. Therefore, readily

available type of carbon source is needed to start the composting process and maintain the duration of thermophilic temperature required to sanitize the composted mixture.

The main objective of this study was to investigate the suitability of different bioavailable carbon sources and their effects on the thermal (lag period, rate of temperature rise, maximum temperature and duration of the maximum temperature) and biological (moisture content, volatile solids, nitrogenous compounds, total carbohydrates, protein and fat and grease) parameters of the composting process of tomato plant residues.

MATERIALS AND METHODS

The experimental set up shown in Fig. 1 consisted of a frame, three bioreactors, mixing units, air supply units and data acquisition system.

The vertical part of the frame was made of three 3.2 mm thick aluminum sheets (the central one measured 330x1100 mm and the two side sheets measured 140x1100 mm each.) soldered together making a vertical channel (U-shaped) with a length of 1100 mm, a width of 330 mm and a depth of 140 mm. The U-shaped stand held the mixing motors, flow meters, air and exhaust gas manifolds, tubing and the thermocouple wires. The horizontal part of the frame was made of three 50x50 mm aluminum angles (3.2 mm thick and permanently soldered together), two of which measured 700 mm and were fixed to the vertical

part by means of four 6 mm diameter stainless steel bolts and nuts, whereas the third one measured 328 mm and kept the other two angles 330 mm apart.

Each bioreactor was constructed of polyvinyl chloride (PVC) tube having a length of 520 mm, an inside diameter of 20. mm and a wall thickness of 5 mm (Fig. 2). A removable circular Plexiglas plate (for cleaning purpose) of 203 mm diameter and 6 mm thickness was recessed and secured into the cylinder by means of six stainless steel screws (6 mm). A rubber gasket lining (O-ring, 2.5 mm thick) was added to the inner side of the removable circular plate to keep it tight. There was a small circular window (64 mm in diameter) on the removable circular plate, which was closed with a rubber stopper (No.13) and used as a sampling port. The other side of the tube was covered with a fixed circular PVC plate of 203 mm diameter and 6 mm thickness which was glued into the tube and secured by means of six stainless steel screws (6 mm). Each reactor was fitted into an aluminum ring, which was fastened into the frame by means of four bolts (6 mm) and nuts. Both the removable and fixed circular plates were insulated with 38.1 mm thick Styrofoam layer, while the tube was insulated with 38.1-mm thick Fibreglass. The three bioreactors were fixed into the frame.

There were three holes at the bottom and one at the top of the bioreactor, which were drilled and threaded to take a 12 mm nylon hose barb. The three holes at the bottom were connected to a manifold by 6.4 mm diameter tygon tubing and used for aeration, whereas the fourth one at the top was used for the exhaust gas. The air was supplied continuously to the bottom of the bioreactor from the laboratory air supply. It passed through a pressure regulator and a pressure gage to maintain the pressure around 5 kPa. The regulated air then passed through a water bath to humidify the inlet air to nearly 100% saturation and then passed through a flow meter (Model 32461-14, Cole-Parmer Instrument Company, Vernon Hills, Illinois, USA). The flow meter can measure a flow in the range of $0.0566\text{-}0.566\text{ m}^3\text{ h}^{-1}$.

Inside each bioreactor, a removable 10.5 mm diameter solid stainless steel shaft was mounted on two bearings. There were 5 stainless steel collars on the shaft in which five bolts of 69 mm in length and 6 mm diameter each were mounted. The shaft was rotated (5.76 rpm) by a thermally protected electric motor (Model No. 127P1486/B, D. C., Sigma Instruments Inc., Braintree, Mass, USA).

The data acquisition unit consisted of a master unit, a thermocouple scanning card, a software, temperature sensors, a personal computer and a printer. The master unit (Multiscan 1200, Omega, Stamford, CT) was connected to a computer via RS 232 interface. The Thermocouple/Volt Scanning Card (MTC/24, Omega, Stamford, CT) contained 24 isolated differential input channels. A window-based (Tempview) software, that featured a graphical

spreadsheet-style user interface, allowed easy configurations of hardware and the acquisition and displays parameters. Four type T (copper-constantan) thermocouples (Cole Parmer, Chicago, IL, USA) were used for each bioreactor for temperature measurements. Three thermocouples were located at the bottom of the bioreactor and were used to measure the temperature of the compost mass whereas the fourth was located at the top of the bioreactor, near the outlet air exit (21 mm away) and was used to measure the temperature of the exhaust gas. Thermocouple locations, on the bottom of all bioreactors, were chosen to be far enough from the inlet air (65 mm away). An IBM personal computer (Pentium IV) was used. The computer had a R232 C serial synchronous communications interface and centronics parallel printer interface. An hp (Hewlett Packard) laser jet4 printer was used.

Tomato plant residues: The tomato plant residues (leaves, stems and some fruits) were collected in polyethylene bags (13 kg each) from a large commercial greenhouse in Truro, Nova Scotia at an average moisture content (MC) of approximately 90 %. The bags were transported to the Waste Management Laboratory and the tomato plant residues were left over night at room temperature ($\approx 25\text{ }^\circ\text{C}$) to partially dry (MC 76 %) and then chopped into small pieces using a shredder (Model 242A645-515, SHP, Briggs and Stratton, Plainfield, NJ, USA). Some characteristics of the chopped tomato plant mixture (stems, leaves and fruits) are presented in Table 1.

Wood shavings: The wood shavings were collected in small polyethylene bags (~5 kg) from a commercial wood lumber mill in Sackville, Nova Scotia and transported to the Waste Management Laboratory. Some characteristics of the wood shavings are presented in Table 1.

Inoculum: A 15-day old municipal solid waste compost was obtained from a municipal solid waste composting (MSWC) facility operated by Miller Composting Corporation in Dartmouth, Nova Scotia. It was added to the mixture in order to introduce a wide range of active composting microorganisms. Some characteristics of the municipal solid waste compost are presented in Table 1.

Urea (nitrogen source): Urea [$\text{CO}(\text{NH}_2)_2$] was used in this study as a nitrogen source to adjust the C: N ratio to 30:1. The choice of Urea (46% nitrogen) was based on the recommendation of Manios and Balis^[9], an effective source of nitrogen for composting than $(\text{NH}_4)_2\text{SO}_4$ and KNO_3 in initiating and maintaining intense respiratory activity. It was purchased from Halifax Seed Co. Inc. in Halifax, Nova Scotia. The quantity of nitrogen required was calculated as follows^[10]:

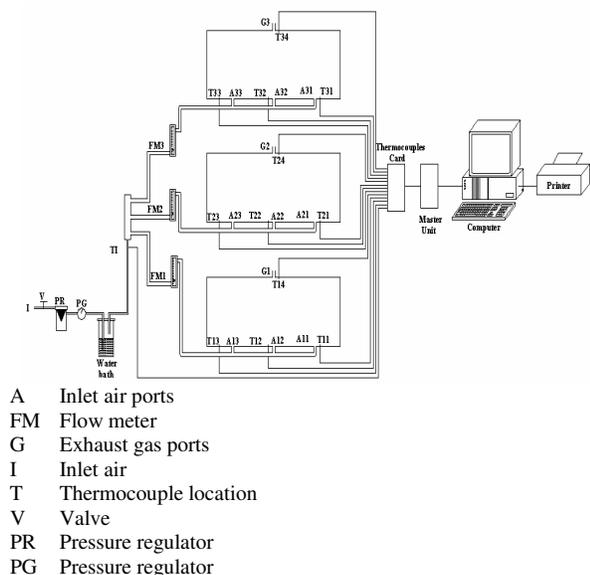


Fig. 1: Experimental setup

Table 1: Some characteristics of tomato residues, wood shaving and municipal solid waste compost

Characteristics	Tomato Plant Remains	Wood shavings	Municipal solid waste compost
Moisture Content (%)	76.0	8.0	58.6
Total solids (TS) (mg/g DM)			
Volatile solids (VS) ¹	693.0	997.4	854.6
Ash	307.0	2.6	145.4
Nitrogen (mg/g DM)			
Total Kjeldahl Nitrogen	27.0	1.0	18.0
Ammonium Nitrogen	2.2	0.2	5.2
Carbon (mg/g DM)			
Total	327.0	499.0	440.0
Organic	260.0	390.0	350.0
Elemental Composition (mg/g DM)			
Ca	51.0	0.8	20.0
Na	0.7	0.0	6.2
Fe	0.4	0.0	2.8
Mg	4.7	0.1	1.8
Zn	0.0	0.0	0.1
K	57.6	0.6	7.8
Cl	0.07	0.0	0.3
P	10.5	0.0	2.7
S	7.9	0.9	2.3
Others ¹	174.1	0.2	101.4

¹Volatile solids are the organic matter (largely carbon, oxygen and nitrogen) which are lost at 550°C, leaving only the ash.

²Others include mostly silica and other elements.

$$\text{Nitrogen required} = (\text{total carbon} / \text{desired C: N}) - \text{total available nitrogen} \quad (1)$$

Sugar: Commercial sugar was purchased from the Atlantic Super Store in Halifax, Nova Scotia. Sugar solution was prepared by dissolving 666.7 grams of sugar in 1 L distilled deionized water.

Cheese whey: The cheese whey was obtained from Farmer’s Cooperative Dairy Plant in Truro, Nova Scotia, in 60-L plastic containers. The container were sealed and transported to the Waste Management Laboratory and stored in a freezer at -10 °C until required. Some characteristics of the cheese whey are presented in Table 2.

Table 2: Some characteristics of cheese whey and used cooking oil

Characteristics	Cheese Whey	Used Oil
Moisture Content (%)	93.2	--
Total solids (TS) (mg/L)		
Volatile solids (VS) ¹	61550.0	999500.00
Ash	6750.0	500.00
Nitrogen (mg/L)		
Total Kjeldahl Nitrogen	1560.0	200.00
Ammonium Nitrogen	260.0	0.40
Elemental Composition (mg/L)		
Ca	429.0	52.00
Na	684.0	273.00
Fe	42.0	13.00
Mg	94.0	7.00
K	1670.0	9.00
Cl	--	674.00
P	154.0	<9.80
S	483.0	2110.00
Others ²	3677.0	146.00
Total Oil and Grease (mg/L)	4700.0	908,000.00
Carbohydrates (mg/L)	50,000.0	80255.00
Proteins (mg/L)	8125.0	1247.50
pH	5.0	6.00

¹Volatile solids are the organic matter (largely carbon, oxygen and nitrogen) which are lost at 550°C, leaving only the ash.

²Others include mostly silica and other elements.

Used cooking oil: The used cooking oil was obtained from a local fast food restaurant in Halifax, Nova Scotia. It was stored at room temperature in the Waste Management Laboratory until required. Some characteristics of the used cooking oil are presented in Table 2.

System preparation: The temperature sensors were calibrated using ice and boiling water baths. The thermocouples including the fittings were immersed into the ice bath and hooked up to the data acquisition system individually. The thermocouple readings were corrected to read zero °C (offset). They were then immersed into the boiling water bath to correct the upper limit. Before each run, temperature sensors were tested for 24 h in an empty bioreactor and the temperature readings were always within ± 0.5 °C of the reactor temperature (measured with thermometer), which is within the accuracy range of the thermocouple (Type T).

Mixtures preparation: The chopped tomato plant residues were mixed with wood shavings (1: 1.5 dry basis) and then ground in a hammer mill (Model C-H, Horvick Manufacturing, INC. Moorhead, Minnesota, USA). Particle size analysis was performed on the final mixture according to the procedure described by Kunii and Levenspiel^[11] and the average particle size was found to be 6.0 mm. The ground tomato plant residues-wood shavings mixture was tightly bagged and placed in a freezer until needed.

A mixture of tomato plant residues: wood shavings: municipal solid waste compost at a ratio of 2.5:0.28 (1: 1.5: 0.28, tomato plant residues: wood shavings: municipal solid waste compost) was prepared for the composting experiments.

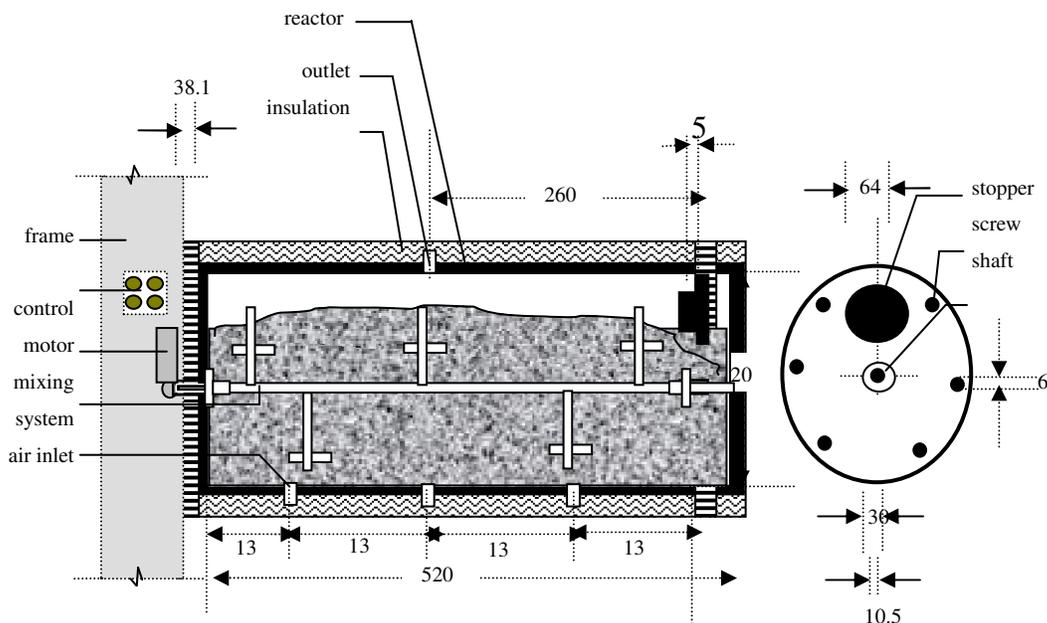


Fig. 2: Schematic of bioreactors

Table 3: The constituents of the mixture used in the study

Parameter	Control mixture ^A	Mixture with sugar	Mixture with cheese whey	Mixture with used oil
Tomato plant residues ^B (%)	36.0	36.0	36.0	36.0
Wood shavings (%)	54.0	54.0	54.0	54.0
Municipal Compost (%)	10.0	10.0	10.0	10.0
Moisture content (%)	60.0	60.0	60.0	60.0
Total dry weight ^C (g)	1400.0	1400.0	1400.0	1400.0
Initial C: N ratio	35.8:1	35.8:1 ^D	30.5:1	38.3:1
Urea required (g)	7.2	7.2	0.8	10.3
Final C: N ratio	30:1	30:1	30:1	30:1

A No whey or oil added.

B Tomato plant residues = tomato leaves, stems and fruits.

C Total mixture wet weight = 3.5 kg.

D The initial mixture is the same as that used in the control since sugar was added later.

The C: N ratio was determined for the mixture and corrected to 30:1 by the addition of Urea (46% nitrogen). The moisture content of each mixture was also adjusted to approximately 60%.

Experimental design: Two sets of experiments were performed in this study. The first set of experiments were conducted using sugar solution (6678 g L⁻¹) to determine whether the bioavailable carbon in the final tomato plant residues-wood shaving-MSWC mixture is limited as suggested by Alkokaik and Ghaly^[8]. The second set of experiments were dedicated to investigating the addition of other wastes, as bioavailable carbon sources on the performance of the composting process.

In the first set of experiments, the moisture content was adjusted to 60% using water. A volume of 150 ml of sugar solution was added to each of the first, second and third bioreactors before the temperatures started to decline (after 24 h). Another 150 ml of the sugar solution was added to each of the second and third bioreactors before the temperature started to decline

(after 36 h). Finally, a third sugar application of 150 ml was added to the third bioreactor before the temperature started to decline (after 48 h). The fourth reactor was used as a control (no sugar was added).

In the second set of experiments, cheese whey and used cooking oil were used as bioavailable carbon sources based on their availability in the local area. Preliminary analyses were first performed on these sources to determine their energy contents. The fat content was 908 and 5 g fat L⁻¹ for used cooking oil and cheese whey, respectively. Cheese whey had also 50 g Lactose L⁻¹. A volume of 1.92 L of cheese whey was added to 1.8 kg of the mixture of tomato plant residues: wood shavings: MSWC to bring the moisture content to 60%. This mixture had additional energy content (from the cheese whey) of 2243.5 kJ, which was determined from the following equation:

$$\text{Energy Content (kJ/100g)} = [\text{Carbohydrates} \times 16.8] + [\text{Proteins} \times 16.8] + [\text{Fats} \times 35] \quad (2)$$

Both whey and oil containing mixtures had identical energy contents. Since used cooking oil had energy content of 35 kJ mL⁻¹, about 64.1 mL of used

cooking oil was, therefore, added to 1.8 kg mixture of tomato plant residues: wood shavings: MSWC. Water was used to bring the moisture content to 60%. A mixture without whey or oil addition was used as a control.

Experimental protocol: The C: N ratio was adjusted to 30:1 by the addition of Urea (46% nitrogen). The compositions of the final mixtures used in the study are shown in Table 3. The final mixture used in each experiment was mixed well and then placed in the bioreactor which occupied 75% of the total volume of the bioreactor (or 0.012 m³). The side Plexiglas wall was put in place. The mixing unit was run continuously at 5 RPM and the air flow rate was maintained at 0.15 m³ h⁻¹ (2.5 L min⁻¹ or 0.17 volume per volume per minute) during all experiments.

Measurements and analyses: Temperature was continuously monitored during the study. Samples of approximately 150 grams were taken at the start and end of each run for moisture content, solids (total, volatile and fixed) and nitrogen (total kjeldahl nitrogen and ammonium nitrogen) analyses. The moisture content was performed using oven-drying method, following ASTM (D3173-73) procedure^[13]. The proximate analysis was performed to determine the weight fraction of volatiles and ash in the compost mixture according to the Standard Method for Proximate Analysis of Coal and Coke^[12]. Both the total kjeldahl nitrogen (TKN) and ammonium nitrogen (NH₄-N) were determined using a KjelTech Auto Analyzer (Tecator, Model 1030. Herndon, VA. USA). The organic nitrogen (ON) was calculated by subtraction (TKN-NH₄-N). Crude protein was calculated as the follows:

$$\text{Crude Protein} = \text{ON} \times 6.25 \quad (3)$$

Total fat and grease was analyzed following EPA method 1664 procedure^[13]. Total carbohydrates were calculated according to the following mass balance equation:

$$\text{Total Carbohydrate} = 100\% - (\text{Proteins \%} + \text{Fat \%} + \text{Mc \%} + \text{Ash \%}) \quad (4)$$

The composted materials pH was measured using Fisher Accumet pH meter (Model 805 MP. Fisher Scientific. Pittsburgh, PA, USA). A 50 to 100 cm³ sample of the composted material was diluted 1:10 (v:v) with distilled-deionized water and placed in a mechanical shaker at 230 rpm for 30 minutes prior to pH measurement.

RESULTS AND DISCUSSION

Addition of sugar: The profiles of the average bioreactors temperatures (T_{ave}) and the inlet air temperature (Ti) are presented in Fig. 3. The maximum temperatures, time of peak and duration are presented in Table 4. Maximum temperatures of 50.8, 56.9, 61.8

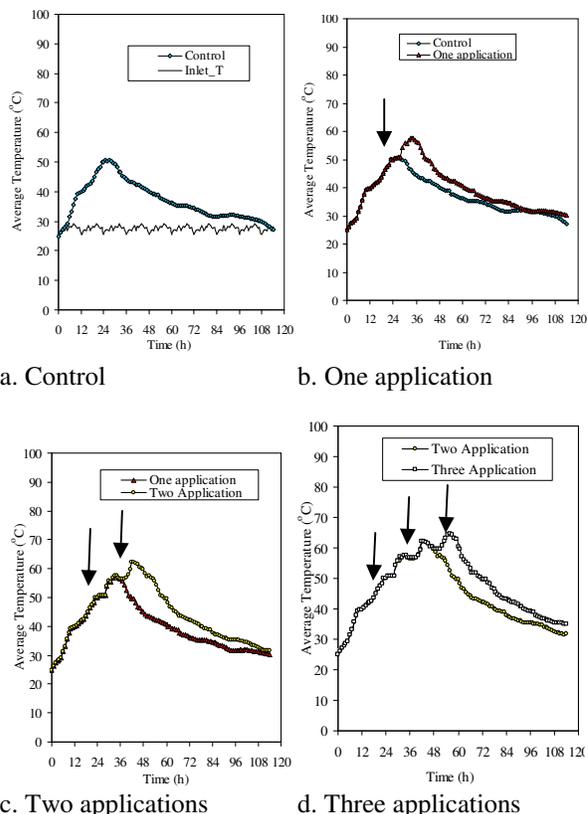


Fig. 3: The temperature profiles of the sugar experiments

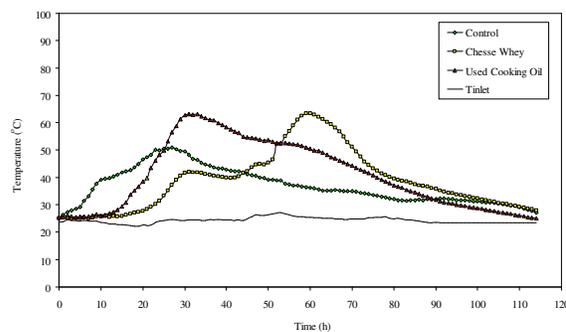


Fig. 4: Temperature profiles of the cheese whey and cooking oil experiments

and 64.3 °C were reached after 27, 35, 44 and 57 hours in the control bioreactor and the bioreactors with one, two and three sugar applications, respectively. Temperatures higher than or equal to 50 °C were maintained in the control bioreactor and the reactors with one, two and three sugar applications and lasted for 5, 20, 36 and 50 hours, respectively. Temperatures higher than 55 °C were observed in bioreactors with one, two and three sugar applications and lasted for 7, 24 and 35 hours, respectively. Only the bioreactors with two and three sugar applications had a temperature of 60 or higher which lasted 7 and 20 hours, respectively.

Microorganisms break down simple organic molecules (sugar) immediately and use them for growth

Table 4: Temperature ranges and duration observed during the sugar experiment

Treatment	Maximum Temperature (°C)	Time of Peak (h)	Duration of the Temperature ≥ (h)					
			35°C	40°C	45°C	50°C	55°C	60°C
Without Sugar	50.8	27	63	37	16	5	0	0
With Sugar								
One Application	56.9	35	78	51	32	20	7	0
Two Applications	61.8	44	94	68	46	36	24	7
Three Applications	64.3	57	106	81	61	50	35	20

Table 5: Temperatures and durations observed during the cheese whey and used cooking oil experiments

Treatment	Maximum Temperature (°C)	Time of Peak (h)	Duration of the Temperature ≥ (h)					
			35°C	40°C	45°C	50°C	55°C	60°C
Control	50.8	27	54	37	16	5	0	0
Cheese Whey	63.4	60.0	66	50	26	19	14	9
Used Oil	63.3	31.0	66	55	46	36	17	9

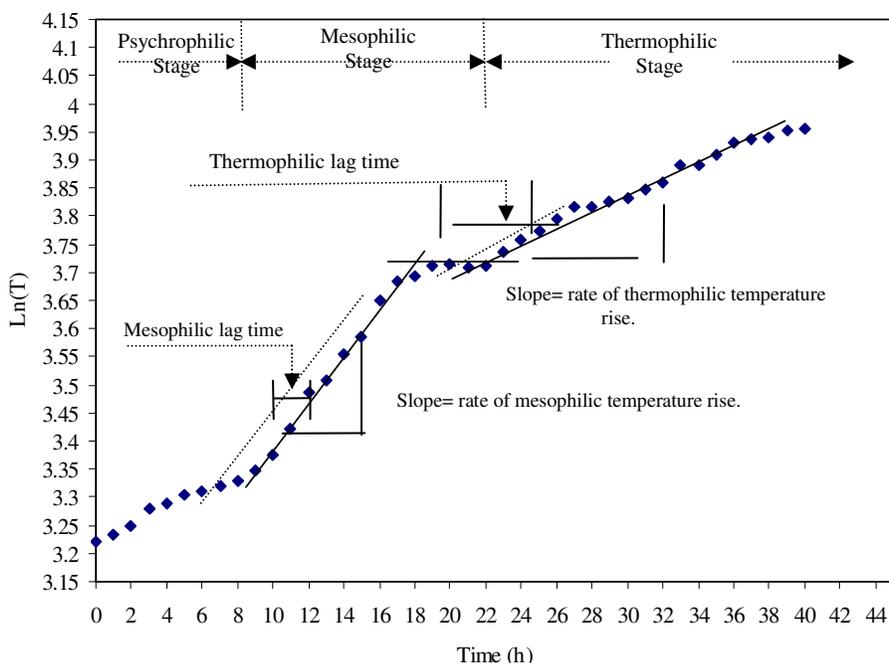
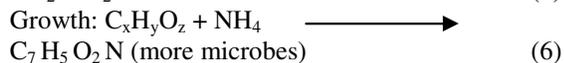
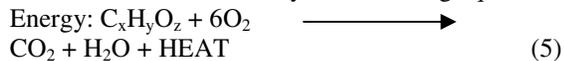


Fig. 5: Determination of the mesophilic and thermophilic lag periods and rates of temperature increase

and reproduction^[14,15]. As carbon compounds decompose under aerobic condition, part of the organic carbon is converted to microbial cell mass, while the other part is converted to energy with the release of CO₂ and water as shown by the following equations^[14]:



The average bioreactors temperatures (T_{ave}) gradually increased as a result of heat being produced (3.76 kcal g⁻¹ decomposed) due to microbial metabolism^[16].

It is clear from the results that the effect of the sugar as a source of readily available carbon on the average temperature in the bioreactor was positive. The maximum temperature in the control bioreactor (without sugar) was only 50.8°C and remained for very

short time (5 h) before starting to decline. The average temperature in the other bioreactors which had the similar mixtures but with sugar applications, continued to rise and temperatures higher than 50 °C were maintained for longer periods. The results indicated that the bioavailable carbon in the compost material was somewhat limited and the addition of readily bioavailable carbon source (sugar) increased the microbial activity and resulted in higher temperature. Rahn and Lillywhite^[17] studied the influence of the carbon source of 13 vegetable crop residues on the degradation rate and concluded that the decomposition rate correlated to the amount of bioavailable carbon and nitrogen contents of the material and that the organic matter remaining after the process correlated with the nonbioavailable carbon (lignin content) of the source material. The addition of sugar to the tomato plant

residue-wood shaving-MSWC mixture raised the bioreactor temperature to the thermophilic stage but the duration of that stage depended on the amount of sugar added.

Addition of cheese whey and used cooking oil

Temperature: The profiles of the average temperatures (T_{ave}) of the bioreactors are presented in Fig. 4. The maximum temperatures and their peak times are presented in Table 5. The average maximum temperature in the control bioreactor and the bioreactors containing cheese whey and used cooking oil reached 50.8, 63.4 and 63.3 °C after 27, 60 and 31 hours, respectively. Temperatures higher than 55 °C were observed only in the bioreactors containing cheese whey and used cooking oil and were maintained for 14 and 17 hours in the bioreactor receiving cheese whey and used cooking oil, respectively. Temperatures higher than 60 °C were also observed in the bioreactors receiving cheese whey and used cooking oil and were maintained for 9 hours.

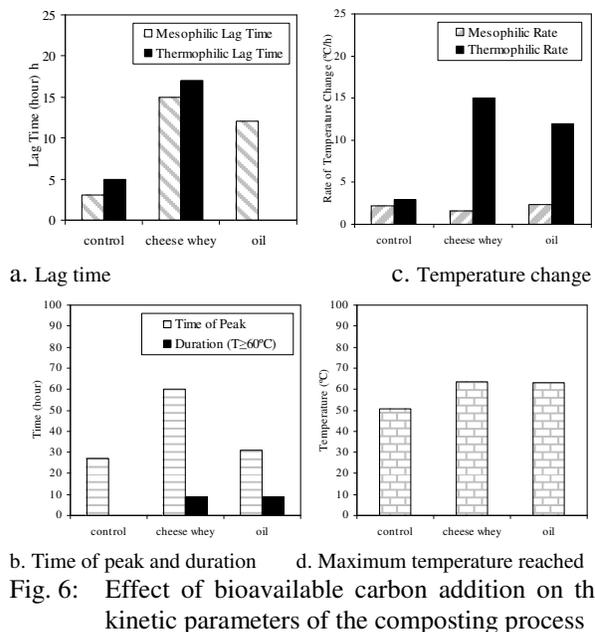
Heat was generated as a result of the degradation of organic matter which raised the temperature inside the bioreactor first to the mesophilic stage (25-45 °C) and then to the thermophilic stage (40-63 °C). The lag period of the mesophilic (first lag) and thermophilic (second lag) phases as well as the rates of temperature increase during the two phases were determined graphically according to the procedure described by Ghaly *et al* (1989) as shown in Fig. 5. The results are also illustrated in Table 6. Figure 6 shows the various kinetic parameters of these experiments. The mesophilic lag period was 3, 15 and 12 h and the rate of mesophilic temperature increase was 2.17, 1.63 and 2.28 °C h⁻¹ for the control and the mixtures receiving cheese whey and used cooking oil, respectively. The thermophilic lag period was 50, 17 and 0 h and the rate of thermophilic temperature increase was 0.85, 2.24 and 2.28 °C h⁻¹ for the control and the mixtures receiving cheese whey and used cooking oil, respectively.

Composting microorganisms adjusted much faster to oil as a nutrient compared to cheese whey. This could be due to the availability of only one source of carbon (fat) in used cooking oil compared to fat and lactose in the cheese whey^[18-20]. Although, both mixtures had the same energy content, the carbon in the used cooking oil seems to be more accessible to microbes than that in the cheese whey lactose. Shuler and Kargi,^[19] stated that different microorganisms have different favorable carbon sources and when the favorable carbon sources is available, microbes will not expend energy to create a pathway for utilization of a less favorable one unless the favorable sources is low or depleted. The phenomenon of diauxic growth, which refers to the sequential use of different carbon sources or sequential population growth, was observed in this study. Monod^[18] observed diauxic growth on two carbon sources: glucose and lactose. In his study,

Table 6: Composting kinetic parameters

Treatment	Mesophilic Range		Thermophilic Range	
	Lag Time	Rate	Time	Rate
	(h)	(°C/h)	(h)	(°C/h)
Control	3	2.17	5	0.85
Cheese Whey	15	1.63	17	2.24
Used Cooking Oil	12	2.28	0	2.28

40 °C was considered to be the end of mesophilic stage and the beginning of the thermophilic stage.



microbes grew first exponentially on glucose as the preferred carbon source, a lag period was noticed after glucose was depleted during which the enzymes necessary for growth on lactose was synthesized, then microbes grow again exponentially on lactose until it was depleted. The phenomenon was also reported by Ghaly *et al.*^[21] for a mixed culture grown in liquid swine manure and by Alkoik and Ghaly^[8] during composting of plant residues.

The pH value of the mixture receiving cheese whey was about 5.0 - 5.5. Sundberg *et al.*^[22] reported very small carbon dioxide production in samples with an initial pH lower than 6.0. Thus, the longer mesophilic lag period observed with the mixture receiving cheese whey could be the result of low pH. Several researchers^[22-24] reported decline in microbial activity during the transition from mesophilic stage to thermophilic stage when composting acidic material (pH ~ 4.5-5.5).

The time of peak was affected by the type of carbon added to the mixture. The maximum temperature was achieved after 31 h of composting the mixture with used cooking oil, while it took double the time (60 h) for the temperature to peak during the composting process of the mixture with cheese whey due to the long lag periods (the initial lag period caused

by lower pH and the thermophilic lag period caused by the shift from fat to lactose as a source of carbon). VanderGheynst *et al.*^[25] reported that a maximum temperature of 60 °C was obtained after 56 h and was maintained for 344 h during the composting process of a synthetic food waste and digested biosolids in a pilot-scale (0.77 m³) bioreactor (5 and 12.5 h for mesophilic and thermophilic lag periods, respectively). The maximum temperature and lag period reported by the authors were similar to the calculated values in the current study for the control and the oil experiments. However, the maximum temperature was maintained for a shorter time in this study due to the smaller compost mass utilized (3.5 kg wb).

Thermophilic composting is preferred when dealing with material infected with pathogens^[26-29] or contaminated with pesticides^[30-35]. These authors indicated that the temperature and time relation is considered to be the most reliable parameter for prediction of pathogens inactivation and pesticide destruction. The maximum temperature obtained with the used cooking oil (63.3 °C), combined with the uniform temperature distribution provided by the continuous mixing, suggests that current composting process will be effective in destroying the pathogens and pesticides. However, the duration of high temperature should be extended by continuous addition of used cooking oil as a bioavailable carbon source.

Moisture: The initial moisture contents of all mixtures were adjusted to approximately 60% ± 0.70 %. The final moisture content was approximately 59.7 ± 0.61 % as shown in Table 7. Even though continuous aeration was supplied, little changes were observed in the moisture content of the material during composting. The final moisture content was within the optimum range of 50 - 60 % reported by Liang *et al.*^[36] and Richard *et al.*^[37] and was not, therefore, a limiting factor in this study.

Drying potential of the composting material is considered a serious problem challenging researchers^[36-39]. Significant moisture content reduction (45 %) was reported by Walker *et al.*^[38] after 13 to 20 days of composting. Although high temperature was reached during this study, the moisture content stayed relatively unchanged. This could be due to the short composting time (< 5 days) and the compensation of water lost with the exhaust by the water produced as a by-product of degradation process during the initial active stage of composting according to equation 5.

Volatile solids: The initial and final volatile solids concentrations were 872.0, 872.0 and 871.9 g kg⁻¹ and 710.0, 678.4 and 618.2 g kg⁻¹ giving reductions of 18.5, 22.2 and 29.1% for the control and the mixtures receiving cheese whey and used cooking oil, respectively (Table 7). The results showed that the addition of cheese whey and used cooking oil has

Table 7: Changes in the biological parameters of the composting process

Parameter	Control	Cheese Whey	Used Cooking Oil
MC			
Initial (%)	61.7	60.3	61.0
Final (%)	59.9	58.9	59.0
Reduction (%)	2.9	2.3	3.3
Volatile Solids⁺			
Initial (g/kg)	872.0	872.0	871.9
Final (g/kg)	710.6	678.4	618.2
Reduction (%)	18.5	22.2	29.1
Total Carbohydrates			
Initial (g/kg)	775.0	738.6	735.0
Final (g/kg)	608.7	560.0	502.1
Reduction (%)	21.5	24.2	31.7
Total Fat and Grease⁺			
Initial (g/kg)	14.7	23.7	56.3
Final (g/kg)	5.2	5.6	6.3
Reduction (%)	64.6	76.4	88.8
TKN-N⁺			
Initial (g/kg)	14.3	18.7	14.5
Final (g/kg)	13.8	15.4	12.9
Reduction (%)	3.50	17.70	11.04
NH₄-N⁺			
Initial (g/kg)	3.3	3.5	3.4
Final (g/kg)	3.3	3.4	3.5
Reduction (%)	0	0	-2.9
Crude Proteins			
Initial (g/kg)	82.3	109.0	80.6
Final (g/kg)	72.1	82.1	66.3
Reduction (%)	12.4	25.3	17.8

+ Calculated based on the dry matter basis.

increased the volatile solid reduction over that of the control. The rates of volatile solids reductions were 0.12, 0.14 and 0.19 kg VS day⁻¹ for the control and the mixtures receiving cheese whey and used cooking oil, respectively.

Temperatures in the range of 52 - 60 °C have been reported to be the optimum for biological degradation during the composting process^[40-42]. Both cheese whey and used cooking oil experiments reached temperatures ≥ 55 °C. However, a longer higher temperature period (thermophilic stage) was observed with used cooking oil than that observed with the cheese whey and as a result a higher reduction rate of volatile solids was achieved. The biodegradable portion of volatile solids (bioavailable carbon in the form of carbohydrates, proteins and fats) is utilized by microorganisms for energy (equation 5) which results in increased temperature of the compost material^[10,36]. The duration of temperature ≥ 55° C correlated (R²= 0.74) with the reduction in the volatile solids as shown by the following equation:

$$D = 17.98 + 0.51 (VSR) \quad (7)$$

Where:

D Duration of temperature ≥ 55 °C (h).

VSR Reduction in volatile solids (%).

Total carbohydrate: The initial and final total carbohydrate concentrations were 775.0, 738.6 and 735.0 g kg⁻¹ and 608.7, 560.0 and 502.1 g kg⁻¹ giving reductions of 21.5, 24.2 and 31.7% for the control and

the mixtures with cheese whey and used cooking oil, respectively. Higher reductions in soluble forms of carbohydrates (60-86 %) were reported by Sanchez-Monedero *et al.*^[43], Hsu and Lo^[44] and Mishra *et al.*^[45] Wood shavings and tomato remains are mostly lignocellulosic materials that have initial high non-bioavailable carbohydrates. Therefore, the reductions in total carbohydrates were relatively smaller in the present study. However, it appears that the used cooking oil experiment achieved higher temperature for a longer period of time which resulted in more non-bioavailable carbon becoming available through biodegradation. Similar findings were reported by Palm and Sanchez^[46] who stated that the breakdown of complex carbohydrates is accelerated under higher temperature. A strong correlation ($R^2 = 0.99$) was found between the total carbohydrates reduction and the maximum temperature reached as shown by the following equation:

$$T_m = 43.44 + 0.62 (\text{TCR}) \quad (8)$$

Where:

T_m Maximum temperature ($^{\circ}\text{C}$).

TCR Total carbohydrates reduction (%).

Total fat and grease: The initial and final fat and grease concentrations were 14.7 and 23.7 and 56.3 g kg^{-1} and 5.2, 5.6 and 6.3 g kg^{-1} giving reductions of 64.6, 76.4 and 88.8% for the control and the mixtures with cheese whey and used cooking oil, respectively. The results indicated that the carbon in the oil was readily available to indigenous microorganisms.

The results obtained from the used cooking oil experiment are in agreement with those of Fernandes *et al.*^[47] and Veil *et al.*^[48] who reported 85-95% reduction in lipids. Viel *et al.*^[48] reported that most of the thermal energy released was due to the degradation of fats. Higher fats reduction (97 %) was also reported by Baddi *et al.*^[49] after composting a mixture of olive-mill wastes and wheat straw for one year. Sasaki *et al.*^[50] reported a reduction of up to 80 % of used soybean oil and 85 % of expired mayonnaise fat were achieved by the end of the composting experiment. A strong correlation ($R^2 = 0.93$) was found between the total fat and grease reduction and the duration of high temperature ($\geq 55^{\circ}\text{C}$) of the compost as shown in equation (9). Similar finding was reported by Fernando *et al.*^[47].

$$D = -25.82 + 0.49 (\text{TFGR}) \quad (9)$$

Where:

D Duration of temperature $\geq 55^{\circ}\text{C}$ (h).

TFGR Reduction in total fat and grease (%).

Total Kjeldahl and ammonium nitrogen: The initial and final TKN in the mixture were 14.3, 18.7 and 14.5 g kg^{-1} and 13.8, 15.4 and 12.9 g kg^{-1} giving reductions of 3.50, 17.70 and 11.04% for the control and the mixtures with the cheese whey and used cooking oil,

respectively (Table 7). The TKN reduction in cheese whey and used cooking oil experiments were higher than that of the control experiment. de Bertoldi *et al.*^[51], Diaz *et al.*^[52], Hamoda *et al.*^[53] and Martins and Dewes^[54] reported that nitrogen loss during in-vessel composting process is influenced by many factors including carbon bioavailability (or C: N ratio). The initial and final $\text{NH}_4\text{-N}$ concentrations were 3.3, 3.5 and 3.4 g kg^{-1} and 3.4, 3.5 and 3.5 g kg^{-1} for the control and the mixtures with the cheese whey and used cooking oil, respectively. There was no change in the $\text{NH}_4\text{-N}$ concentration as the rate of conversion of organic nitrogen was equivalent to the rate of conversion of $\text{NH}_4\text{-N}$ to organic nitrogen (microbial cells). However, the degradation of organic nitrogen was faster than the microbial growth in the case of the mixture with used cooking oil due to the higher temperature achieved in this bioreactor.

Crude protein: The initial and final protein concentrations were 82.3, 109.0 and 80.6 g kg^{-1} and 72.1, 82.1 and 66.3 g kg^{-1} giving reductions of 12.4, 25.3 and 17.8% for the control and the mixtures with cheese whey and used cooking oil, respectively. A decrease in protein content was also reported by Hsu and Lo^[44]. Proteins undergo enzymatic oxidation to form complex amino compounds, which can then be synthesized into microorganisms or undergo additional decomposition into simpler products^[55]. The products of the digestion of the proteins and complex amino acids can only be used in the synthesis of new cellular material if sufficient carbon is available^[56]. Otherwise, unstable nitrogen forms (NH_3 and NH_4^+) will accumulate and become susceptible to volatilization.

CONCLUSION

The result of this study indicated that the addition of bioavailable source of carbon (sugar, cheese whey or used cooking oil) to the tomato residues-wood shavings-compost mixture elevated the average bioreactor temperature into the thermophilic zone. The maximum temperatures achieved in all bioreactors (and their durations) were influenced by the type of bioavailable carbons. The maximum temperatures were 50.8, 56.9, 63.4 and 63.3 $^{\circ}\text{C}$ which lasted 5, 7, 9 and 9h for control and mixtures receiving sugar, cheese whey and used cooking oil, respectively. Strong correlations were observed between the maximum temperature achieved and its duration and the reductions in fat and volatile solids. The total carbohydrates reductions were in the range of 21.5-31.7 %, the protein reductions were in the range of 12.4-25.3 %, the fat reductions were in the range of 64.6-88.8 % and the TKN reductions were in the range of 3.5-17.7 %. The NH_4 remained unchanged (0.33-0.35 %) and the moisture content remained at $59.7 \pm 0.61\%$. Neither the nitrogen nor the moisture contents were limiting factors. The maximum

temperature obtained in this study, combined with the uniform temperature distribution provided by continuous mixing, suggests that the composting process will be effective in destroying the pathogens and pesticides. However, the duration of the high temperature should be extended by continuous addition of a bioavailable carbon source (used cooking oil).

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