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Degradation of Solid Wastes in Two Types of Bioreactors

Monchan Maketon and Kasinee Suttichart

Department of Zoology, Faculty of Science, Kasetsart University, Bangkok 10900, Thailand

Abstract: Two bioreactors were designed and tested for solid waste degradation. Reactor A, which was designed for the digestion food wastes, consisted of two cylindrical fermentation chambers placed horizontally, one above the other. Each fermenter contained an apparatus that mixed the wastes and also moved the degraded materials into the second fermenter and finally out of the fermenter. A chopper on top of the first fermenter broke waste into small pieces before it entered the first fermenter. Selected bacteria were added to increase the rate of degradation. Mixing and aeration (with a blower) was controlled by timers. The product obtained from reactor A after 4 days could be used as a soil conditioner because it contained substantial organic matter and a low C: N ratio. The C: N ratios of food waste/product from four trials with reactor A were 24.8/15.7, 19.1/15.7, 22.0/16.9 and 22.2/16.1. Reactor B was designed to handle fresh market refuse and resembled a conventional garbage receptacle; it lacked a mixer, but contained an air pump to increase aeration and nozzles to apply selected bacteria. The product obtained from reactor B after 7 days did not have an offensive smell and did not contain flies. Although the product from reactor B could be used for soil conditioning, it's C: N ratio varied substantially among trials. The C: N ratios of fresh market refuse/product from four trials with reactor B were 8.5/13.6, 11.9/9.0, 11.9/12.4 and 12.1/10.9.

Key words: Bioreactor · Enzymes producing bacteria · Carbon to nitrogen ratio · Soil conditioner

INTRODUCTION

Food waste disposal and fresh market refuse are rapidly becoming major unsolved problems in Thailand. Food wastes and fresh market refuse comprise approximately 40-60% of the total municipal solid wastes in different countries. Food wastes and fresh market refuse are considered to be semi-solid material because they usually contain more than 50% water [1]. Given that the population in Thailand and other countries is rapidly increasing, methods for disposing of food wastes and market refuses are increasing required [2, 3]. Various methods used for the treatment include landfill, incineration, recycling as compost or animal feed and complete decomposition. VanderGheynst *et al.* [4] used a 770 liter pilot scale reactor to measure temporal and spatial variations in temperature, oxygen and moisture content for aerobic decomposition of a synthetic food waste instead of an actual waste. Most of others researches were performed only in a lab scale size fermenter for instance Gingnara [5] studied a fed-batch composting of agricultural wastes with a 5 liter fermenter and found that sawdust with 60 mesh size, bargass with 40 mesh size and cassava refuse with 40 mesh size are good for using as a bulking agent in a compost fertilizer preparation. Park *et al.* [6] utilized a 80 liter stirred tank reactor (50 liter working volume) to study a long-term operation of slurry food wastes decomposition but no other types of refuses was reported. Yun *et al.* [7] studied a high-rate slurry-phase composition of food wastes using a 2 liter fermenter and reported indirect performance estimation from dissolved oxygen. Cekmecelioglu *et al.* [8] used a 55 liter fermenter to study for an optimum composting mixture among various combinations of food waste, manure and bulking agent, however, introducing manure into food waste and market refuse digestion is not amenable for urban area operation. Kim *et al.* [9] used a pilot-scale in-vessel of the total volume of 324 m^3 to evaluate the food wastes treatment efficiency, however, the process took no earlier than 30 days to decompose such wastes.

Recently, deposition of food wastes and fresh market refuses in landfills is the only solution. Landfills, however, pollute the local environment and leachate from landfills

Corresponding author: Monchan Maketon , Department of Zoology, Faculty of Science, Kasetsart University, Bangkok 10900, Thailand. E-mail: fscimcm@hotmail.com.

can contaminate the ground water [10]. Selvam *et al.* [11] had taken this problem into consideration by studied the neutralization effects of 0.1 M $NaHCO_3$, KPO_4-buffer (pH 7.0) and sodium acetate solutions on controlling the pH and leachate quality in an acidogenic reactor of food waste anaerobic digestion but only a 6.4 liter (4.6 liter working volume) was used.

In this research, two pilot-scale bioreactors were tested for the processing of food wastes and fresh market refuses. One bioreactor was designed by our laboratory in cooperation with Premier Products Co., Ltd., Bangkok, Thailand. The other was designed by Biobin Technologies Pty. Ltd., Willunga, Australia and Royal Motor Works Co., Ltd., Bangkok, Thailand. Both reactors used a mixture of local bacterial strains to digest waste and turn waste into useable compost within 4-7 days.

MATERIALS AND METHODS

The reactor designed by our group is designated as reactor A and the one designed by Biobin Technologies Pty. Ltd. and Royal Motor Works Co., Ltd. is designated as reactor B. The basic procedures described in the following sections were used for both reactors. In preliminary tests in which bacterium were not added to the reactors, degradation required a long time (3 weeks for reactor A and 6 weeks for reactor B) and the reactors produced an offensive odor (unpublished observations). In the following trials, therefore, selected microorganisms were added to the reactors to accelerate degradation and reduce production of offensive odors.

Selection of Microorganisms to Add to the Reactors: Microorganisms were isolated from the following sources: food wastes collected from the central canteen of Kasetsart University (KU), the canteen of the Faculty of Science KU and the Institute of Food Research and Products Development of KU; food wastes obtained from three food processing industries; four sludge samples (three from beer and one from wine fermentation industries); and waste vegetables, fruits peels, meat scraps, etc. collected from six fresh markets around the Bangkok metropolitan area. The microorganisms used were isolated in the slurry-phase condition [12]. Seventy-seven microorganisms including three yeasts, two fungi and 72 bacteria were isolated from these waste materials by using media designed to test for the production of enzymes involved in degradation of food wastes. The 77 isolates were stored by freeze drying (Heto FD3, Denmark). The 77 isolates were then tested for their capability to digest organic compounds (fats and oils, starch, protein, pectin and cellulose) as indicated by the production of clear zones on agar media (in 9-cm-diameter Petri dishes) containing the compounds. For each combination of microorganism and compound (see the following sections), three replicate Petri dishes were used. The Petri dishes were inoculated with each bacterium suspension using the disc diffusion method. Petri dishes were kept at 40°C.

Fat and Oil Digestion: Fat and oil digestion was measured with tributyrin agar [13]. After isolates had grown on this medium for 3 days, the diameters of the clear zone and of the colony were measured. The digestion capacity of each isolate on this substrate was calculated as: Digestion capacity = the clear zone diameter divided by the colony diameter.

Starch, Protein, Pectin and Cellulose Digestion: All procedures were similar to those used for fat and oil digestion except that starch agar medium, skimmed milk agar medium, pectin medium and CMC medium were used. Also, before the clear zone was measured on the pectin medium, a solution containing 1% w/v of hexadecyl-trimethyl-ammonium bromide was added to precipitate the pectin moiety. Similarly, 0.1% w/v congo red was added to the CMC medium, discarded after 15 min and replaced with a 1 M NaCl solution; clear zones appeared within 15 min.

Quantification of Enzyme Production by the Selected Microbes: Based on digestion of organic compounds in agar, six bacteria were selected for further study. The bacteria were identified by the Thailand Institute of Scientific and Technological Research (TISTR). Production of specific enzymes by these bacteria was quantified as described below. For each bacterium, the enzyme quantified was based on the organic compound that was degraded in the previous section.

Lipase Activity by *Bacillus vallismortis*: The medium used for lipase production contained (g/L) peptone 5, yeast extract 3, tributyrin (1%) 10 ml, pH 5.0. The shake cultures (150 rpm) were kept at 40°C in the dark. Samples were collected after 12, 24 and 48 h and analyzed for lipase activity according to the method of Ertugrul *et al.* [14].

Alpha-Amylase Activity by *Bacillus amyloliquefaciens*: The method of Liu and Xu [15] was used to culture *Bacillus amyloliquefaciens*. Samples were collected after 12, 24 and 48 h of incubation and analyzed for enzyme activity by the method of Bernfeld [16].

Protease Activity by *Bacillus thuringiensis*: The medium used for protease was described by Doddapaneni *et al.* [17]. Samples were collected after 12, 24 and 48 h of incubation and analyzed for enzyme activity by the method of Wang and Heseltine [18].

Cellulase Activity by *Bacillus subtilis*: The medium used for cellulose production culture contained (g/L) carboxymethylcellulose 10, yeast extract 2.5, K_2HPO_4 5, NaCl 1, $MgSO_4.7H_2O$ 0.2 and $(NH_4)_2SO_4$ 0.6, pH 5.0. The shake cultures (150 rpm) were kept at 40°C in the dark. Samples were collected after 12, 24 and 48 h and were analyzed for cellulose activity by the method of Kim *et al.* [19].

Chitinase Activity by *Bacillus chitinolyticus*: The method of Li *et al.* [20] was used for the production of chitinase. Chitinase activity was measured by the method of Wang *et al.* [21].

Pectinase Activity by *Bacillus circulan*: The method of Celestino *et al.* [22] was used for production of pectinase. Pectinase activity was measured with a modified method of Kobayashi *et al.* [23].

Reactors

Reactor A: A diagram of reactor A is presented in figure 1a. This reactor has a capacity of 300–500 kg per batch and uses 220 VAC. Reactor A consists mainly of a chopper and two cylindrical fermenters, which are located horizontally, one above the other (Fig. 1b and 1c). Food wastes are fed into the receiver, which is equipped with a chopper and are then forwarded to the first reactor. Each reactor is equipped with a blade-screw conveyer (Fig. 1d and 1e). The bacteria are introduced into the food wastes with continuous mixing by the screw conveyer and the temperature is increased to about 40°C with hot air produced by an electric heater and blower. After about 24 h in the first fermenter (or until most of the waste is digested and turned into a compost-like product), the material is driven into a second fermenter. The temperature in the second fermenter is increased to about 70°C and the material is slowly turned by the screw conveyer for about 24 h to ensure that the product is sufficiently dry for packing. In addition, waste water from the waste food is collected in the collection tank receiver (Fig. 1f) and then transferred to a waste water-treatment chamber (not shown) to reduce its biochemical oxygen demand (BOD) to $\leq$ 20 (ppm) before the water is discharged into the environment. Every step during the fermentation process is controlled with timers.

Reactor B: A diagram of reactor B is presented in figure 2a and 2b. Reactor B has a capacity of 500-1,000 kg per batch and uses 220 VAC. This reactor consists of a conventional garbage receptacle, but the inside is equipped with several features for accelerating fermentation (Fig. 2c). The container's bottom is lined with four polyvinyl chloride tubes (76 mm diameter) and each tube has about 12 holes (10 mm diameter) at 400 mm intervals (Fig. 2d). Woodchips were placed between these tubes, which were covered with a stainless steel sieve. The tubes allow air to be pumped into the waste material.

Fresh market wastes are fed into the reactor through the reactor's lid. If the waste contains some hard materials (coconut shells, durian shells, etc.), they should be shredded before they are loaded into the reactor. Fifty to sixty plastic balls (150 mm diameter) are mixed throughout the waste pile to increase air flow. Selected bacteria are prepared as a suspension, which is pumped through four lines with four nozzles per line. The nozzles are located on the top of the reactor (Fig. 2e) and provide thorough coverage of the waste pile because there is no mixing device. During fermentation, gases produced are circulated and trapped in the water tank; the cleaned air is then pumped back into the bottom of the reactor. The release of air with unpleasant odors is avoided by also passing the air through an air-filter tank filled with activated carbon. As with reactor A, every step during the fermentation process in reactor B is controlled with timers.

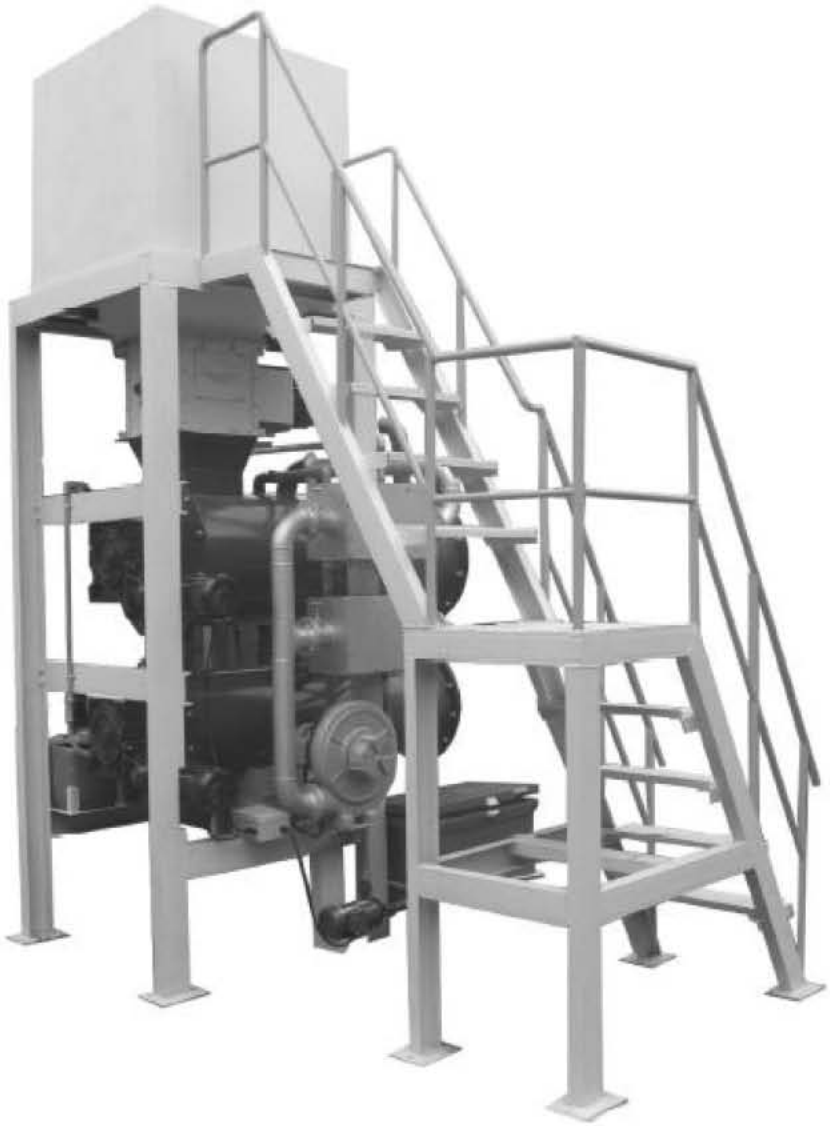
The garbage fermented in reactor B should become a compost-like product within 7 days and is discharged through the opened door. Like waste water in reactor A, waste water in reactor B is collected and transferred to a water treatment apparatus to reduce its BOD.

Trials with Reactors: Four different trials were conducted with each reactor. For trials with reactor A, four different batches of food waste were used. For trials with reactor B, four different batches of fresh market refuse were used.

The contents of food wastes and fresh market refuse samples were analyzed by the Institute of Food Research and Products Development, Kasetsart University. The average contents of food waste and fresh market refuse are listed in tables 1 and 2, respectively. The main component of the food waste was carbohydrate followed by fat and protein. Because the fresh market refuse mostly contained leafy vegetables, moisture was the main component.

Each of the six bacteria that were selected for additional study was formulated as a powder ($1x10^9$ cfu/g) using a freeze drier (Heto FD3, Denmark) and dextrose anhydrous (Fluka, Switzerland) as a filler. The relative proportion of each bacterium added to the reactor depended on the content of the food waste and fresh market refuse. For the food waste, the ratio of carbohydrate: fat: protein: pectin: cellulose was about 5:2:2:0.5:0.5 and so the bacteria (selected because of their abilities to degrade these substrates) were added at that ratio (Table 1). However, for reactor B, the ratio of bacteria used varied according to the content of fresh market refuse (Table 2).

Other conditions in these trials are listed in tables 3 and 4 .



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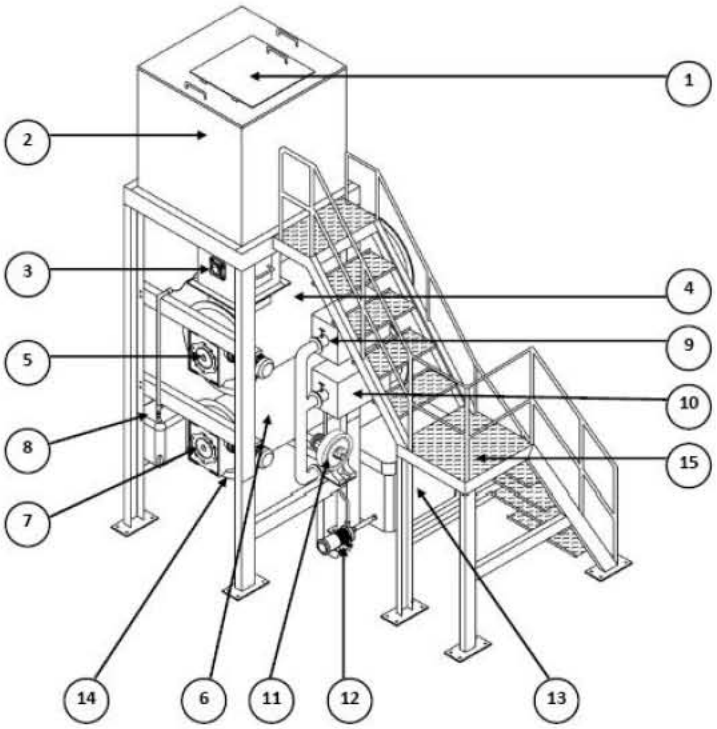

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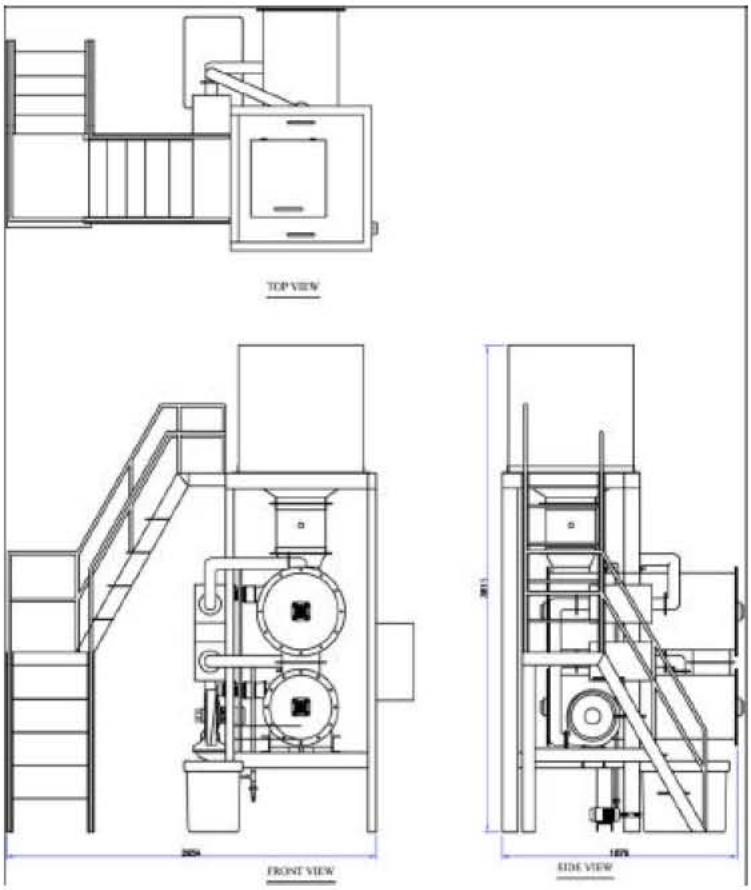

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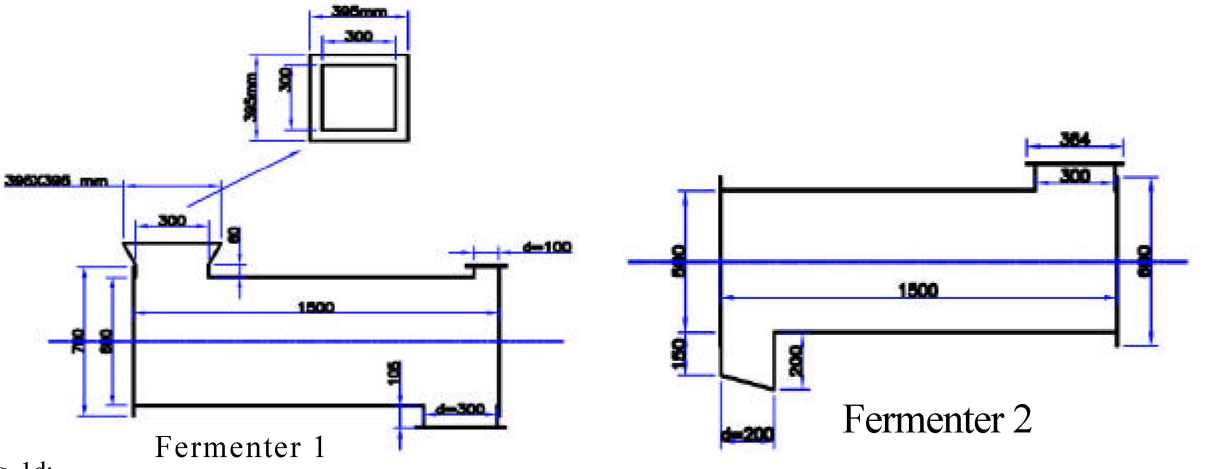

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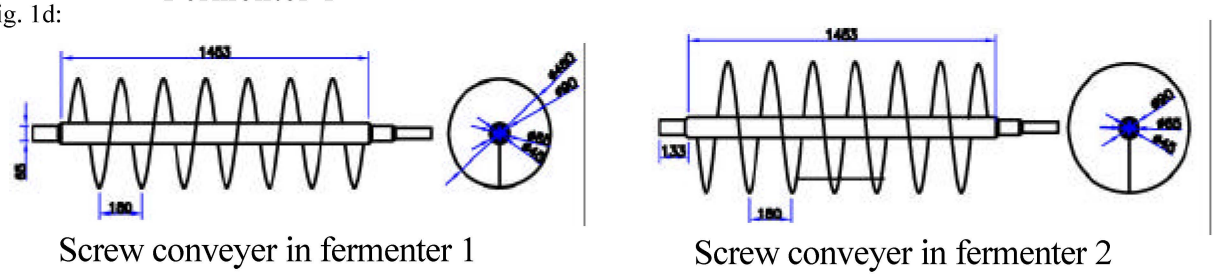

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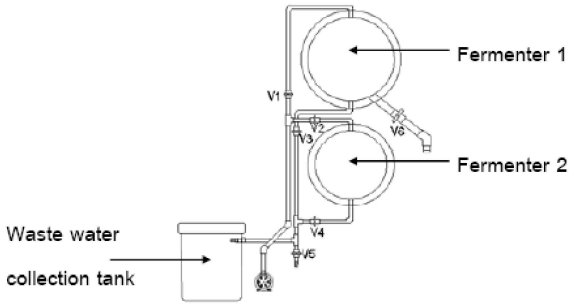

Fig. 1f:

Fig. 1a A general view of reactor A.

Fig. 1b Diagram of reactor A.

1. chamber lid 2. waste food loading chamber 3. chopper 4. fermenter 1
5. screw conveyer inside fermenter 1 6. fermenter 2 7. screw conveyer inside the fermenter 2
8. bacterial suspension tank 9. heater for fermenter 1 10. heater for fermenter 2
11. air blower 12. waste water pump 13. waste water collection tank 14. compost outlet
15. stair

Fig. 1c Dimensions of reactor A

Fig. 1d Dimensions of fermenter 1 and 2 of reactor A

Fig. 1e Mixing devices in fermenter 1 and 2

Fig. 1f

V1: valve for bacterial suspension and/or water pumped into fermenter 1

V2: valve for water flow into fermenter 2 V3: waste water from fermenter 1 flow into the collection tank

V4: waste water from fermenter 2 flow into the collection tank V5: waste water sampling outlet

V6: cleaning water from the chopper

Table 1: Composition of food wastes

Parameter	Result	Analytical method
Wet weight	5.0 kg	-
Dry weight	1.0 kg	-
Physical appearance	Brown mash powder	-
% Moisture (dry product)	8.53	T-CM-002, AOAC(2000) 925.45
% Protein (factor 6.25)	16.65	T-CM-003 Kjeldahl Method, AOAC(2000)991.20
% Fat	19.54	T-CM-075, AOAC(2000) 989.05
% Ash	6.38	T-CM-001, AOAC(2000) 938.08
% Crude fiber	4.40	T-CM-077, AOAC (2000) 978.10
% Total Carbohydrate	48.90	T-CM-078, AOAC(2000) by calculation

Table 2: Composition of fresh market wastes

Content	Result	Analytical method
Wet weight	10.0 kg	-
Dry weight	1.0 kg	-
Physical appearance	Brown lump	-
% Moisture (dry product)	20.0	TMC-02, AOAC (2008) 925.45
% Protein (factor 6.25)	2.10	TMC-03 Kjeldahl Method, AOAC (2005) 991.20
% Fat	0.26	TMC-75, AOAC (2005) 989.05
% Ash	0.61	TMC-01, AOAC (2005) 938.08
% Crude fiber	1.32	TMC-77, AOAC (2005) 978.10
% Total Carbohydrate	6.30	TMC-78, AOAC (2005) by calculation

Table 3: Working conditions of reactor A

Trial conditions	1	Trial2	3	4
1. Waste food blended before Loading	-	-	-	Yes
2. Concentration of bacteria Used	1%	1%	1%	5+5+5%
3. Sawdust added	-	-	-	2.5%
4. Time of waste food added	1	1	1	3
5. Length of bacterial spray (minute)	2	2	2	2+2+2
6. Fermenter # 1 working Condition	run 2 sec stop 30 min	run 2 sec stop 30 min	run 2 sec stop 30 min	run 2 sec stop 30 min
7. Fermenter # 2 working Condition	run 5 secondsstop 2 h	run 5 secondsstop 2 h	run 3 secondsstop 2 h	run 3 secondsstop 2 h
8. Air blower working Condition	run 4 hstop 2 min	run 4 hstop 2 min	run 4 hstop 2 min	run 4 hstop 2 min
9. Temperature of fermenter # 1 (oC)	35-40	35-40	35-40	35-40
10. Temperature of fermenter # 2 (oC)	65-70	65-70	65-70	65-70
11. Resident time of waste food in both fermenters (day)	4-7	4-7	4-7	4-7

Table 4: Working conditions of reactor B

Trial conditions	1	Trial2	3	4
1. Waste vegetable and fruit peels chopped before loading	1 times	2 times	2 times	2 times
2. Weight before loading (kg)	560	600	600	600
3. Ratio of vegetable: fruit Peel	5: 0	5: 0	5: 0	4: 1
4. Ratio of cellulolytic to pectinolytic bacteria (kg)	5.6: 0	6: 0	6: 0	4.8: 1.2
5. Sawdust added	-	-	5%	5%
6. Plastic balls added	-	100	100	100
7. Size of motor used for air	0.74 kW,	0.74 kW,	1.5 kW,	1.5 kW,
blower	1 phase	1 phase	3 phase	3 phase

Table 5: Degradation of organic substrates by bacteria on agar media. For each substrate, the bacterium listed caused the most degradation among 77 microbial isolates tested

Bacterium	Substrate	Diameter ofclear zone (cm)	Colonydiameter(cm)	Digestioncapacity
B. vallismortis	edible fat & oil	2.00	0.80	2.50
B. amyloliquefaciens	Starch	4.35	1.00	4.35
B. thuringiensis	Protein	3.00	1.00	3.00
B. subtilis	cellulose	2.70	0.60	4.50
B. chitinolyticus	chitin	1.90	0.50	3.80
B. circulan	pectin	1.30	0.60	2.17

Table 6: Enzyme production over time by six bacteria on six substrates. The bacteria and substrate were selected based on Table 1. The pH of the medium is also indicated

	α-Amylase from *B.amyloliquefaciens*		Protease from *B. thuringiensis*		Lipase from *B. vallismortis*		Cellulase from *B. subtilis*		Chitinase from *B. chitinolyticus*		Pectinase from *B. circulan*	
Hour	Activity (U)	pH	Activity (U)	pH	Activity (U)	pH	Activity (U)	pH	Activity (U)	pH	Activity (U)	pH
12	-	5.36	-	5.11	0.56	5.98	0.02	5.90	0.03	5.72	0.48	5.91
24	1.30	5.74	0.16	5.37	0.98	7.06	0.05	6.36	0.07	6.72	0.57	6.32
48	6.56	6.37	0.28	5.99	1.22	8.16	0.09	6.59	0.12	7.33	0.67	6.93

RESULTS AND DISCUSSION

Selection of Microorganisms: The organisms with the highest capability for digestion of organic compounds, as indicated by the production of a clear zone in agar, are listed in table 5. Lipid digestion was highest with *Bacillus vallismortis*. Carbohydrate digestion was highest with *B. amyloliquefaciens*. Protein, cellulose, chitin and pectin digestion were highest with *B. thuringiensis*, *B. subtilis*, *Bacillus chitinolyticus* and *B. circulan*, respectively. These six bacteria were selected for further study.

Enzyme Production by the Selected Bacteria: Table 6 indicates the quantity of specific enzymes produced in the six media by the six bacteria after 12, 24 and 48 h. Media pH values are also indicated.

Waste Digestion

Reactor A: Figure 3a and 3b illustrate the product resulting from the processing of food waste in trial 1 and 2 with reactor A. In these two trials, food wastes were loaded into the machine without prior blending, which resulted in some leafy products left undigested after 4 days. Like many other Asian foods, Thai food contains many spices and unmodified raw materials and these materials were not broken apart by the chopper. The food waste was therefore blended before it was loaded into reactor A in trials 3 and 4 (Table 3). Figure 3c and 3d illustrate the product when food wastes were first blended and then processed by reactor A for 4 days. Even though reactor A is equipped with a chopper, the chopper failed to break apart some of the larger pieces of waste and this slowed degradation in trials 1 and 2. Degradation was more uniform in trials 3 and 4 than in 1 and 2 because the waste was passed through a blender before it was chopped. Because the moisture content of the food waste was high (> than 50%), the degraded product had a high moisture content in trials 1 to 3. Therefore, sawdust was added in trial 4 along with food waste to prevent the waste from adhering to the fermenter's wall and to reduce

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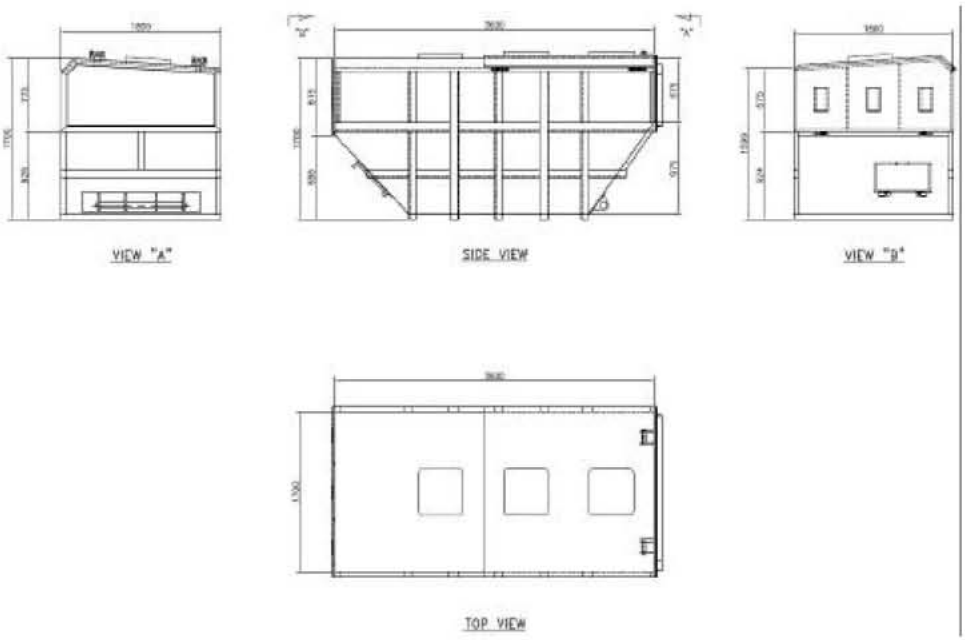

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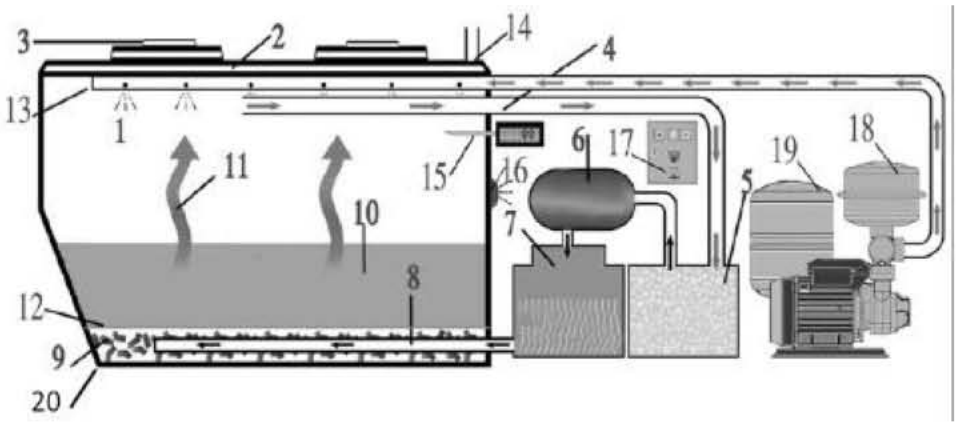

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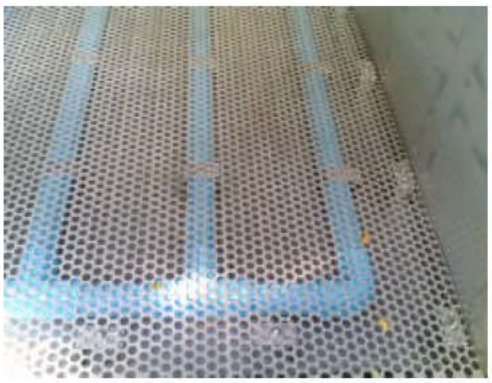

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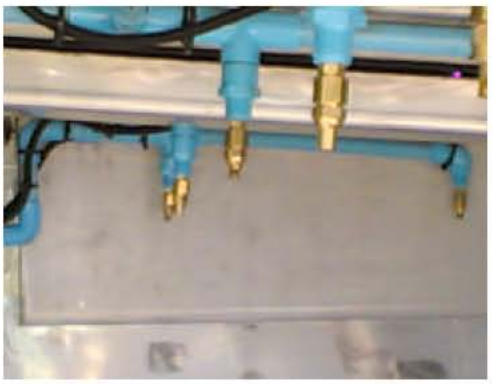

Fig. 2e:

Fig. 2a: A general view of reactor B

Fig. 2b: Dimensions of reactor B

Fig. 2c: Diagram of reactor B

1. inside the chamber 2. chamber lid 3. open lid for filling the garbage
4. suction hose for trapping fermented gases 5. water tank for absorption of waste gases
6. air pump for blowing air through garbage pile from below
7. air filter tank filled with activated carbon
8. air flow pipes with several small holes that allow air to flow upward
9. the area beneath the garbage is filled with small woodchips or sawdust to prevent air clogging
10. garbage pile 11. fermented gases 12. a stainless steel sieve lining
13. hose lined with nozzles for bacterial spray 14. vent valve for cleaned air
15. thermometer for inside temperature measurement 16. alarm indicating that lid is opened before operation
17. control panel 18. pump for bacterial suspension 19. air filter
20. waste water outlet

Fig. 2d Air tubes and stainless steel covering them

Fig. 2e Nozzles for bacterial spray

the moisture content of the final product. Although sawdust prevented the waste from adhering to the fermenter wall, the product still had an undesirably high moisture content. This problem might be solved by allowing the product to air-dry for 1 to 2 days and then by crushing it into a powder before packing. Products from all four trials with reactor A were free of undesirable odor. The carbon to nitrogen (C: N) ratio was reduced by processing in reactor A (Fig. 3e). The C: N ratios of the products indicated that there was no benefit from using a higher amount of bacteria (trial 4 vs. the other three trials) in the digestion process. The temperature in fermenter 1 (35-40°C) was only slightly higher than the ambient temperature, but the higher temperature in fermenter 2 (65-70°C) helped increase the rate of drying.

Reactor B: Because most of the material processed in reactor B consisted of leafy vegetables, the bacterium that produced cellulase was added in all four trials. The material added to the reactor in trial 4, however, also contained fruit peels and so the bacterium that produced pectinase was also added in trial 4 (Table 4).

The quantity of bacteria used was 1% by weight of the solid waste and the bacteria were prepared as a suspension that could be easily sprayed through the nozzles. Degradation of the waste material was poor in trial 1; it appeared that air flow through the waste pile was inadequate for aerobic degradation by bacteria (Fig 4a). Therefore, in trial 2 to 4 in reactor B, the waste material was chopped twice and 100 plastic balls were dispersed in the waste pile at the beginning of each trial.

Figure 4b illustrates the fermented product after 7 days in trial 2 with reactor B. The product was still poorly degraded, perhaps because the small motor (0.74 kW, 1 phase) did not generate enough air flow. In trial 3, a larger motor (1.5 kW, 3 phase) was used and sawdust was mixed with the vegetable waste to absorb moisture; the product was improved (Fig. 4c) and the product did not have a bad smell or flies. Because the fresh market waste in trial 4 contained some fruits peel (about 4:1 vegetables: fruit peels), a pectin-digesting bacterium was added with the cellulose-digesting bacterium at the ratio of 1:4 but the total concentration remained the same. Figure 4d shows the

(a)

(b)

(c)

(d)

(e)

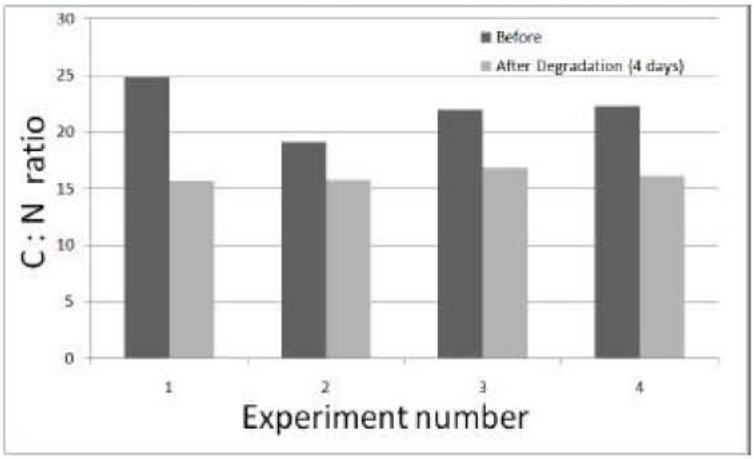

Fig. 3a: Product from waste food degradation from reactor A in trial 1
Fig. 3b: Product from waste food degradation from reactor A in trial 2
Fig. 3c: Product from waste food degradation from reactor A in trial 3
Fig. 3d: Product from waste food degradation from reactor A in trial 4
Fig. 3e: C: N ratios of each trial from reactor A

degraded product after 7 days. The product did not smell and did not have flies. In contrast to the C: N ratios obtained with reactor A, the pattern of C: N ratios of the starting materials and products were inconsistent in trials 1 to 4 with reactor B (Fig. 4e). We suspect that this inconsistency occurred because reactor B lacked a mixing apparatus. The inconsistency might also reflect differences in the C: N of the waste materials, which were lower with reactor B than with reactor A. Direct comparison of the two reactors will require the use of the same waste materials in future trials.

(a)

(b)

(c)

(d)

(e)

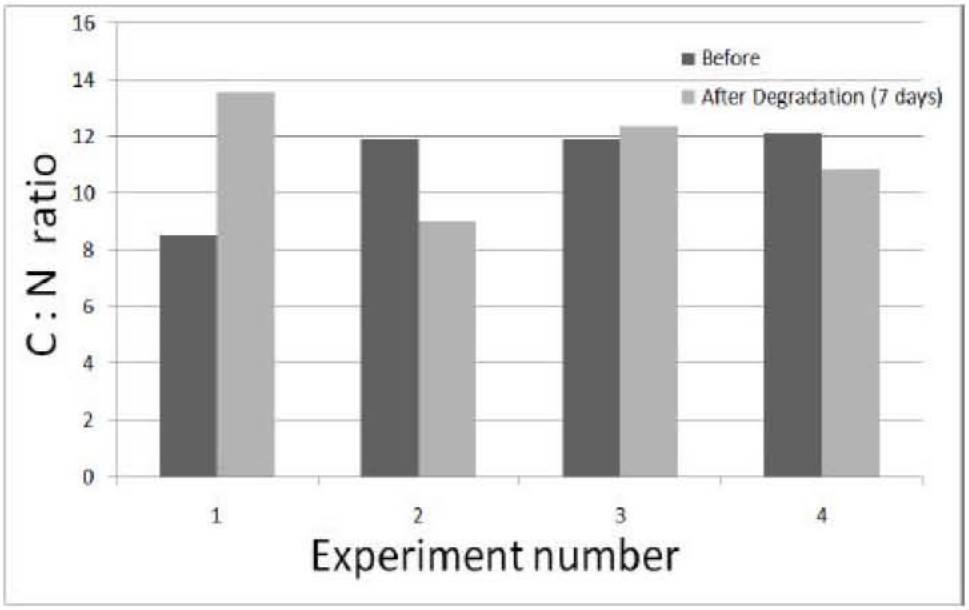

Fig. 4a: Product from waste market refuses degradation from reactor B in trial 1
Fig. 4b: Product from waste market refuses degradation from reactor B in trial 2
Fig. 4c: Product from waste market refuses degradation from reactor B in trial 3
Fig. 4d: Product from waste market refuses degradation from reactor B in trial 4
Fig. 4e: C: N ratios of each trial from reactor B

CONCLUSIONS

Because we wanted to limit the degradation time to 4–7 days, we inoculated with bacteria rather than fungi because bacteria generally grow faster than fungi when the environment is suitable. Even though some fungi effectively degrade cellulose [24], degradation is usually slower by fungi than by bacteria. In addition, temperature during the degradation process might not have been favorable for fungal growth and production of enzymes [25]. We suspect that the screening of more bacteria will reveal isolates that improve the efficiency of degradation in the reactors.

Genetically modified organisms might perform better than the bacteria selected in this study but genetically modified organisms cannot be used in Thailand. Mutagenesis of the natural occurring bacteria might also produce more effective organisms but our aim was to develop systems that did not require additional research and that could be easily developed and used by the general public and private institutions.

The performance of the two pilot reactors was satisfactory in that the products were obtained within the targeted time frame and their C: N ratios did not exceed 20:1, which corresponds to Thai Department of Agriculture's criterion for the material to be classified as organic fertilizer. Some engineering adjustments are needed such as the addition of a wastewater treatment apparatus, a dryer and a grinder. Given that the products contain substantial organic matter and have a relatively low C: N, they should be useful for crop production.

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