

Article

A Pilot Plant Study on the Autoclaving of Food Wastes for Resource Recovery and Reutilization

Chia-Chi Chang ¹, Yen-Hau Chen ¹, Yi-Shiou Lin ¹, Zang-Sei Hung ¹, Min-Hao Yuan ², Ching-Yuan Chang ^{1,3,*}, Yuan-Shen Li ⁴, Je-Lueng Shie ⁴ , Yi-Hung Chen ⁵, Yen-Chi Wang ¹, Chun-Han Ko ⁶, Far-Ching Lin ⁶, Chungfang Ho ⁷, Bo-Liang Liu ¹, Kuang-Wei Liu ⁸ and Shi-Guan Wang ⁸

¹ Graduate Institute of Environmental Engineering, National Taiwan University, Taipei 106, Taiwan; d92541005@ntu.edu.tw (C.-C.C.); p29681726@gmail.com (Y.-H.C.); r98541133@ntu.edu.tw (Y.-S.L.); p94541203@ntu.edu.tw (Z.-S.H.); r98541128@ntu.edu.tw (Y.-C.W.); r04541129@ntu.edu.tw (B.-L.L.)

² Department of Occupational Safety and Health, China Medical University, Taichung 404, Taiwan; mhyuan@mail.cmu.edu.tw

³ Department of Chemical Engineering, National Taiwan University, Taipei 106, Taiwan

⁴ Department of Environmental Engineering, National I-Lan University, Yi-Lan 260, Taiwan; ysli@niu.edu.tw (Y.-S.L.); jlshie@niu.edu.tw (J.-L.S.)

⁵ Department of Chemical Engineering and Biotechnology, National Taipei University of Technology, Taipei 106, Taiwan; yhchen1@ntut.edu.tw

⁶ School of Forestry and Resource Conservation, National Taiwan University, Taipei 106, Taiwan; chunhank@ntu.edu.tw (C.-H.K.); farching@ntu.edu.tw (F.-C.L.)

⁷ Department of International Business, Chung Yuan Christian University, Chung-Li 320, Taiwan; chungfangho@gmail.com

⁸ Environmental Analysis Laboratory, Environmental Protection Administration, Chung-Li 320, Taiwan; kwliu@mail.niea.gov.tw (K.-W.L.); skwang@mail.niea.gov.tw (S.-G.W.)

* Correspondence: cychang3@ntu.edu.tw; Tel.: +886-2-23638994

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Abstract: Autoclaving of food wastes (FW) for the resource recovery and reutilization was studied using the pilot plant scale. Experiments were conducted at various temperatures of 408, 428, and 438 K and times of 15 and 60 min. The in-filled steam to the autoclave was supplied by the incineration plant with a gauge pressure of 7 kg/cm² and a temperature of 443 K or above. The results obtained from the experiments show that the less energy- and time-consuming autoclaving conditions (408 K and 15 min, denoted as Case A408-15) are effective. Comparisons of the properties and characteristics of autoclaved FW (FW_A) of Case A408-15 with those of FW are made. The wet bulk volume and wet bulk density of FW_A are dramatically reduced to 15.64% and increased to 313.37% relative to those of FW, respectively. This makes the subsequent processing and reuse for FW_A more convenient than FW. The autoclaving results in an increase of carbon content and a decrease of nitrogen content, and thus an increase of the C/N ratio of FW_A. The contents of sulfur, hemi-cellulose, and cellulose of FW_A are also reduced. All these fluctuations are beneficial for making compost or other usages from FW_A than FW. The autoclaved liquid product (LA) separated from FW_A and liquid condensate (LC) from the released gas possess high COD and TOC. These two liquids can be mixed for use as liquid fertilizers with proper conditioning. Alternatively, further anaerobic digestion of the mixture of FW_A, LA, and LC can offer enhanced biogas production for power generation. All these thus match the appeal of sustainable materials management and circular economy. The emitted gas from autoclaving contains no CO and some hydrocarbons. Suitable air pollution control is needed. The results and information obtained are useful for the proper recovery and reuse of abundant food wastes from domestic households and food industries.

Keywords: autoclaving; food wastes; resource recovery; reutilization

1. Introduction

The autoclaving process is a mechanical heat treatment technique, which has been used to treat mixed industrial wastes, as well as municipal solid wastes (MSW), using saturated steam under high pressure. The autoclaving combined with the subsequent mechanical separation is known as mechanical heat treatment. The MSW, for example, were firstly autoclaved and hydrolyzed. Resource recycling takes advantage of the autoclaving process to reduce the volume of wastes and make them easy for sorting after solid-liquid separation. The valuable components of autoclaved solid products, such as the organic floc/fiber and inorganic recyclables (metal, plastics, and glass) can then be obtained separately from other in-organic discards or rejects [1–10]. In addition, the autoclaving pretreatment also sterilizes the wastes and decontaminates infectious and odor compounds, thereby enhancing the subsequent application of the recovered wastes. The floc/fiber can be used to manufacture (1) the refused derived fuel (RDF) or solid recovered fuel (SRF) via granulation with or without torrefaction [11,12], (2) the liquid fuel by hydrothermal liquefaction (HTL) [13], and (3) the compost [7]. The organic liquid can be handled by a wastewater treatment plant or recycled after detoxification and conditioning for fertilization application.

Autoclaving of bio-wastes can easily obtain solid organic floc/fiber without sorting the solid products, which contain little in-organics, if any; thus, they are better than those from autoclaving of mixed wastes such as MSW and are more appropriate for use as RDF, SRF, or compost. After heating the wastes with steam at proper detention time, this process can decompose the structure of the bio-wastes that are composed mostly of lignocellulose and enhance the efficiency of hydrolysis. Steam at high pressure will hydrolyze hemi-cellulose and cellulose, leading to lower density of cellulose crystal region while to higher porosity. The autoclaving helps to increase the carbon content and the carbon/nitrogen (C/N) ratio. Consequently, autoclaving pretreatment is promising to acquire better-quality organic floc/fiber for compost or other usages from a wide range of bio-wastes with a need to improve their C/N ratio, such as cooked and raw food wastes (FW), agricultural and livestock farming wastes, etc.

In the bio-wastes, FW from domestic households and food industries are abundant, while FW is defined by Food and Agriculture Organization as food appropriate for human consumption that is discarded. Previous studies estimated that FW comprises 40%–85% of the MSWs in developing countries, while it accounts for 6%–30% of the MSWs in developed countries [14]. In Taiwan, although about 60.22% of total 7,870,896 ton MSW in 2017 was recycled and reutilized, indicating the significant achievement of MSW management, a lot of FW are not recycled but go through wasted garbage. The un-recycled and un-reused MSW consists of 36.12% paper, 4.63% textiles, 1.55% garden trimmings, 38.14% FW, 16.00% plastics, 0.43% leather and rubber, 0.64% other combustibles (combustibles subtotal of 97.52%, on dry base), 0.21% iron, 0.28% non-iron metals, 0.80% glasses, and 1.19% debris (incombustibles subtotal of 2.48%, on dry base) [15]. Among them, FW must be handled properly due to their distinct properties. Some FW have been used for making compost via traditional composting method; however, most have been treated by incineration, and some by sanitary landfill. High carbohydrate content of FW often possesses high water content, which lowers their wet-basis heating value (H_{HWM}) [16]. On the other hand, higher fixed carbon contents result in a higher heating value. In general, water content of FW could be 50%–80% depending on their composition and types of cuisine [14]. FW with high water content would be inadvisable for the treatment of incineration or landfill. The acidic leachate resulting from FW may hinder the operation of landfill, while the low H_{HWM} of FW has low economic efficiency for combustion in incinerators. Although anaerobic digestion has been also applied for treating FW, improvement of the efficiency of biogas production for energy use and subsequent handling or treatment of waste sludge is needed. Moreover,

traditional composting is time consuming. This work thus applied the autoclaving method to treat FW, aiming at resource recovery of organic floc/fiber and liquid products for better reutilization. A pilot plant experiment was conducted to demonstrate the systematic performance of autoclaving of FW. The obtained data will be beneficial for the design and cost-effectiveness assessment of the recovery and reuse of abundant food wastes from domestic households and food industries.

2. Materials and Methods

2.1. Materials and Experiments

The raw materials consisted of FW composed of un-cooked raw vegetables and leafy and fruit wastes collected from a fruit and vegetable market in Yi-Lan, Taiwan. The FW was autoclaved in a pilot-scale rotary batch reactor (530 L) with 1 hp driving motor power. The autoclaving system is shown in Figure 1, which was manufactured by Chin Ying Fa Mechanical Ind. Co., Ltd. (Chang-Hua, Taiwan) and set up in Letzer Incineration Plant in Yi-Lan, Taiwan. The size of reactor is 680 mm in diameter and 1220 mm in length. The in-filled steam with the gauge pressure of 7 kg/cm² and temperature of above 443 K was supplied by the incineration plant. Operational conditions of autoclave were set at different temperatures (T) (408, 428, and 438 K) and times (t) (15, 60 min) while being maintained at the same rotation speed *r* (7 rpm). The actual steam pressures (P) for autoclaving at 408, 428, and 438 K were adjusted at 3, 6, and 7 kg/cm² gauge, respectively, which kept the temperatures at the corresponding setting values. 45.90 kg sample was charged per batch operation. The autoclaving was stopped at the end of setting time.

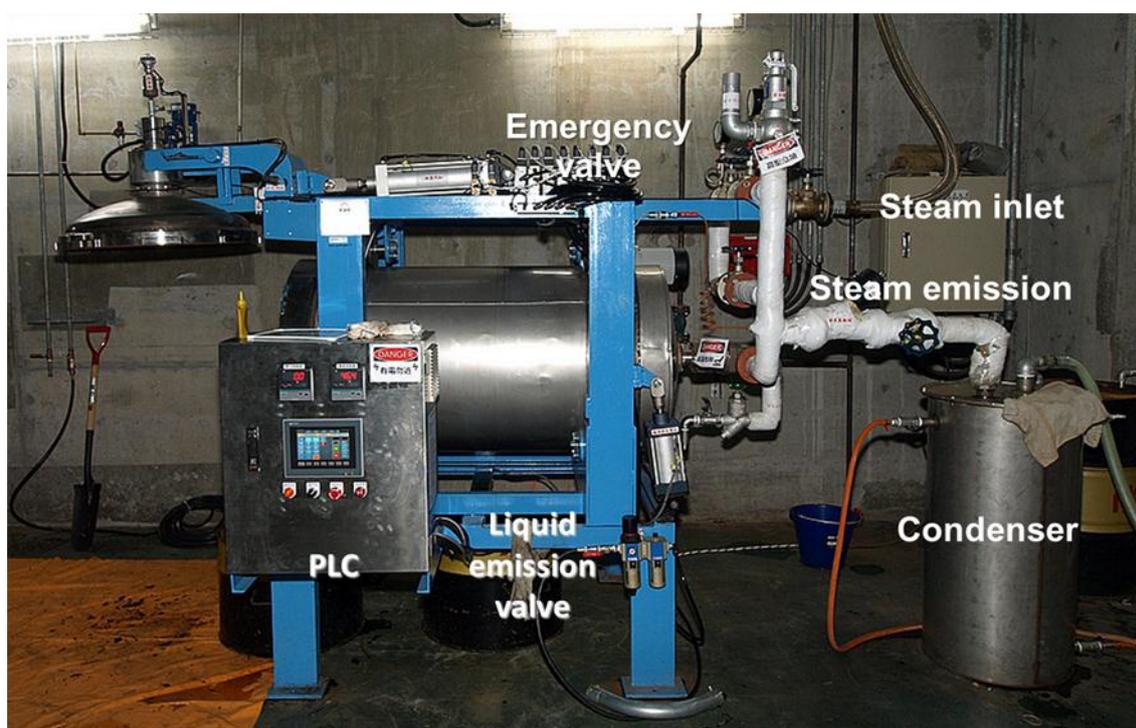


Figure 1. Diagram of autoclaving system.

The pressure in autoclave after finishing the autoclaving operation was then gradually reduced by releasing the gas. It was passed through a condenser to collect the condensed liquid product (LC) before discharging. The discharged (emitted) gases from relief valve after condenser were sampled as the pressures in autoclave were reduced to P1 and P2, for example, as P1 = 1.9–2.1 kg/cm² and P2 = 1.0–1.1 kg/cm² for cases A408-15 and A408-60, denoted as G1 and G2 gases, respectively. As the pressure in autoclave was reduced to ambient, the lid of autoclave was then opened. The gas sample

in the autoclave after opening the reactor lid was also collected and noted as GR gas. The products in autoclave for autoclaving of FW were subjected to solid-liquid separation to obtain the solid product of autoclaved FW (FW_A) and the autoclaved liquid product (LA).

The properties of these solid and liquid products, as well gases produced, were then analyzed. The concentrations of gases sampled at P1, P2 and in the autoclave were denoted CG1, CG2, and CGR, respectively. Multiplication of T and t, i.e., T-t, which is proportional to the energy consumed, was adapted as a parameter to elucidate the performance at various T-t values.

2.2. Analyses

2.2.1. Solid Analyses

The basic analyses including proximate analysis, metal analysis, heating value analysis, and fiber analysis of bio-fiber (i.e., FW_A) were conducted in accordance with the standard methods from American Society for Testing and Materials (ASTM), National Institute of Environmental Analysis (NIEA), Chinese National Standards (CNS), and Taiwan Bureau of Standards, Metrology, and Inspection (TBSMI). The detailed descriptions of the methods of analyses and the instruments employed can be found in the study of Chen et al. [12].

2.2.2. Liquid Analyses

Chemical oxygen demand (COD), total organic carbons (TOC), and pH values were examined in accordance with the standard methods NIEA W517.52B, W530.51C, and W424.52A from National Institute of Environmental Analysis (NIEA) in Taiwan.

2.2.3. Gas Analyses

As for identifying organic component of gas products from autoclaving, gas chromatography mass spectrophotometer also called GC-MS (Thermo Scientific FOCUS GC Gas Chromatograph 1255080, Thermo Fisher Scientific Inc., Waltham, MA, USA) was used, adapting column Trace TR-1701 with 30 m length, 0.25 mm ID, and 0.25 μm film thickness (Thermo Fisher Scientific Inc., Waltham, MA, USA). Helium was used as carrier gas in this system.

3. Results and Discussion

3.1. Properties of FW

On account of incoherent composition of FW, autoclaving was applied in this study to treat FW to seek the possibility for better utilizing the FW_A . The properties of raw FW are shown in Table 1. The FW are wet, containing about 92.73 wt.% water. Its wet bulk density (ρ_{BW}) is 359 kg/m^3 . With regard to dry basis, FW have high content of cellulose (47.96 wt.%), indicating that leafy vegetables are the primary raw materials in FW [17]. The higher heating value per mass in dry basis (H_{HDM}) of FW is 3954.66 kcal/kg, while high water content in FW causes the higher heating value per mass in wet basis (H_{HWM}) equivalent to only 287.45 kcal/kg. According to the buying standard of wood pellet of IWPB (Initiative Wood Pellet Buyers) [18], the qualified H_{HWM} of fuel should be above 3940.2 kcal/kg, but that of FW is far less than this standard. Thus, treatment of FW, such as dewatering and torrefaction, is needed in order to increase its heating value of H_{HWM} .

Table 1. Properties of raw food wastes (FW) and autoclaved FW (FW_A) at various autoclaving temperatures (T, K) and times (t, min).

		FW	A408-15 ^c	A408-60	A428-15	A428-60	A438-15	A438-60
Proximate analysis ^a (wt.%)	Combustibles, M _C	6.4347	9.1280	6.3803	8.3441	7.8499	7.9829	7.1092
	Fixed carbon, M _{FC}	0.1708	0.1871	0.2244	0.2531	0.2604	0.2569	0.2220
	Volatile matters, M _{VM}	6.2639	8.9409	6.1559	8.0910	7.5895	7.7260	6.8872
	Ash, M _A	0.8339	0.9056	0.8409	0.8668	1.0020	1.0351	0.9491
	Water content, M _W	92.7314	89.9664	92.7788	90.7891	91.1481	90.9820	91.9417
Ultimate analysis ^b (wt.%)	C	37.545 ± 0.136	39.917 ± 0.115	39.202 ± 0.066	39.887 ± 0.047	40.626 ± 0.085	36.936 ± 0.261	42.021 ± 0.748
	H	5.688 ± 0.086	5.903 ± 0.064	5.753 ± 0.056	5.863 ± 0.051	5.786 ± 0.001	5.635 ± 0.081	5.799 ± 0.081
	O	51.582	50.059	50.917	50.477	49.678	53.436	48.416
	N	3.514 ± 0.013	3.236 ± 0.029	3.283 ± 0.030	3.049 ± 0.083	3.103 ± 0.116	3.152 ± 0.033	3.024 ± 0.004
	S	1.673 ± 0.158	0.887 ± 0.056	0.846 ± 0.008	0.725 ± 0.037	0.808 ± 0.034	0.816 ± 0.040	0.742 ± 0.060
Fiber analysis ^b	Hemicellulose	3.3881	0.9686	0.0473	0.0589	3.8682	0.7695	1.9842
	Cellulose	47.9564	42.2591	40.6410	47.4245	44.1061	45.2092	38.7206
	Lignin	22.9077	14.7414	16.0123	17.1644	26.1972	16.2790	24.2762
Heating value	H _{HDM} (kcal/kg)	3954.66 ± 8.09	3761.81 ± 954.58	3351.37 ± 61.37	3449.80 ± 200.53	2976.66 ± 436.98	3065.04 ± 367.58	2800.27 ± 158.48
	H _{HDV} (kcal/m ³)	103194.33	424625.63	272987.43	352711.78	304895.82	284973.23	233261.01
	H _{HWM} (kcal/kg)	287.45	377.45	242.01	317.76	263.49	276.40	225.65

^a Wet basis. ^b Dry basis. ^c AT-t: Autoclaved at T K and t min.

3.2. Autoclaving of FW

3.2.1. Volume Reduction of FW_A

Autoclaving has an enormous effect on volume reduction. Originally, the wet bulk volumes of input wet samples were all set at about 127.86 L. After autoclaving at different temperatures and retention times, the wet bulk volumes of output wet products were all shrunk to 17.5–22.20 L (13.69%–17.36% relative to that of FW), as shown in Figure 2. The weight of wet FW also reduced because of the thermal decomposition of FW during autoclaving, decreasing to around 18.09–22.56 kg from 45.90 kg at these conditions. The dry weight dropped from 3.34 kg to about 1.46–2.26 kg. With the data of wet bulk volume and dry weight, the indicator “wet bulk density” can be computed to demonstrate more clearly the efficiency of autoclaving on volume reduction.

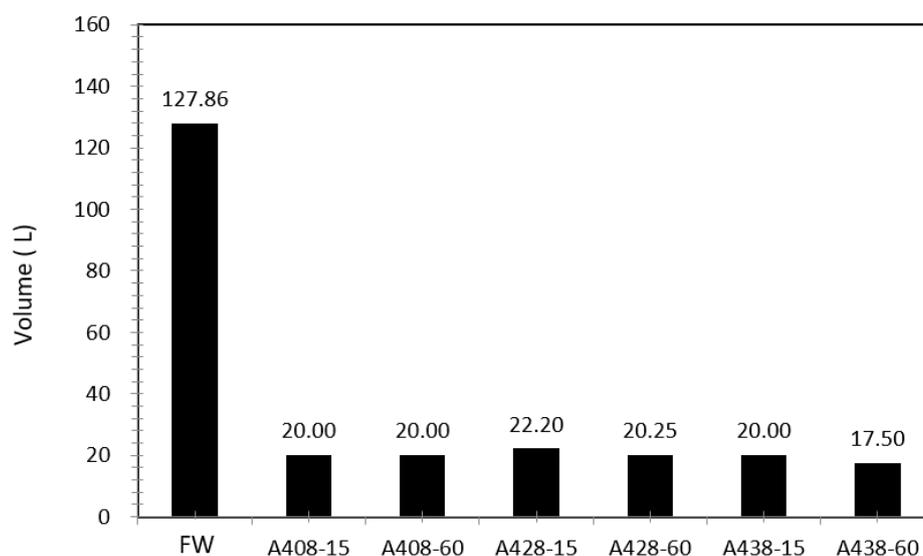


Figure 2. Change of wet bulk volume (V_{BW}) of food wastes (FW) after autoclaving.

Figure 3 indicates that the wet bulk density (ρ_{BW}) of FW increases drastically from 359 kg/m³ to 1125 kg/m³ after autoclaving at conditions of 408 K and 15 min (Case A408-15). The conditions of a higher temperature and longer retention time did not enhance the ρ_{BW} to a higher value, while ρ_{BW} was about 1031–1157 kg/m³ (287.19%–322.28% relative to that of FW).

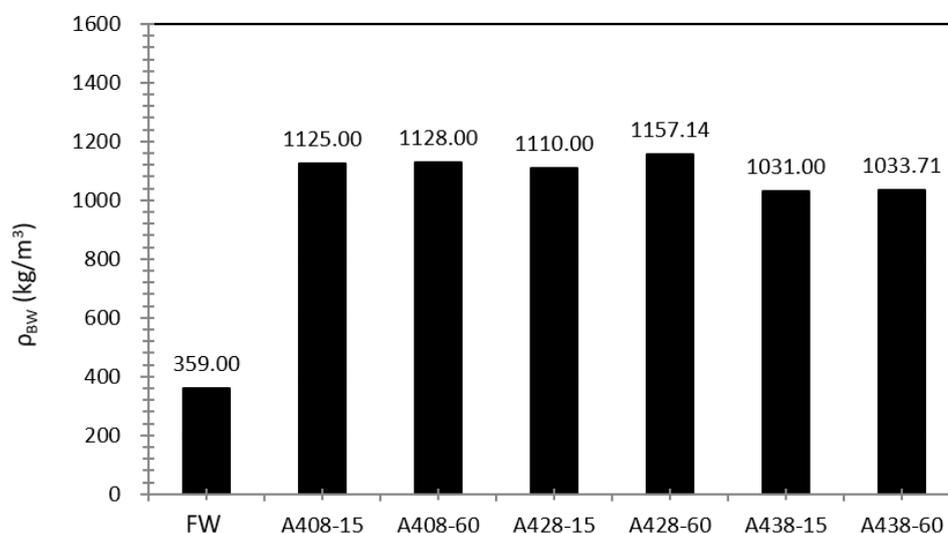


Figure 3. Change of wet bulk density (ρ_{BW}) of FW after autoclaving.

At the most energetic situation examined with 438 K and 60 min, the ρ_{BW} approaches 1034 kg/m³, which is lower than that of Case A408-15. By autoclaving performed in this research, the FW could be more concentrated, and the conditions of 408 K and 15 min are recommended in order to decrease energy consumption while achieving efficient volume reduction. Notice that the dry bulk density (ρ_{BD}) of FW also increases from 26.09 kg/m³ to 81.45–112.88 kg/m³. Thus, autoclaving process shows significantly pronounced effect on volume reduction and increase of mass intensity (mass per volume) of FW_A.

3.2.2. Change of Some Basic Properties of FW_A

Some basic properties of FW after autoclaving are presented in Table 1. The results indicated slight change of the properties of proximate analysis of FW_A in comparison with those of the raw FW. Water contents of FW_A remained high at around 89.97–92.78 wt.% among our experimental conditions. The high water-content may lead to a need for dehydration of FW_A for subsequent applications such as making solid fuel, which requires additional energy input. Fiber analysis showed that after autoclaving, the contents of hemi-cellulose, cellulose, and lignin generally decrease, except those for cases A428-60 and A438-60. This demonstrates that the construction of lignocellulose was destroyed during the heat treatment. Moreover, sulfur content of FW decreased remarkably after autoclaving. This may be attributed to the dissolution of sulfur compounds in liquid due to thermal reaction with steam. The sulfur content is reduced from 1.67 wt.% to around 0.73–0.89 wt.%, proving that autoclaving has ability to de-pollute the FW_A.

3.2.3. Energy Intensity of FW_A

The higher heating values per mass in dry basis (H_{HDM}) of FW_A were 2800.27–3761.81 kcal/kg, which were lower than those of original FW of 3954.66 kcal/kg. With higher temperature and longer retention time, H_{HDM} was decreased to the lowest value of 2800.27 kcal/kg at operation conditions of 438 K and 60 min. This was due to tense hydrolysis and oxidation of organic compounds in FW by autoclaving. As high water-content is still exhibited in all conditions of FW_A, the H_{HWM} of FW_A listed in Table 1 was as low as 225.65–377.45 kcal/kg. This would be a barrier for applying FW_A as a solid fuel. It is still worth noticing that evident volume reduction by autoclaving did raise the volume energy intensity of FW_A, although the decrease of H_{HDM} and the low H_{HWM} could not be avoided.

Regarding Table 1, the higher heating value per volume in dry basis (H_{HDV}) of FW_A reaches the highest value of 424,626 kcal/m³ at the conditions of 408 K and 15 min from the original value of 103,194 kcal/m³. With increasing retention time and increasing temperature, the H_{HDV} generally decreases due to the loss of hemi-cellulose, cellulose, and lignin, as noticed previously, and is much more easily decomposed in relatively high energetic environments. Hemi-cellulose, cellulose, and lignin are composed of organic compounds with high content of carbon and hydrogen, which have high heating values. As a result, loss of them results in decrease of energy intensity. From the prospect of recovery and reutilization of FW by autoclaving pretreatment, the findings suggest that mild operation temperature and short operation time (such as 408 K and 15 min) can conserve substantial energy needed in autoclaving of raw materials and effectively reduce the volume.

3.2.4. Comparison of Properties of FW_A with Compost Standards

The qualities of FW_A, along with those of FW, are compared with the standards for compost as listed in Table 2 to establish the possibility for utilizing FW_A as compost. Basically, FW_A obtained at different conditions have uniform heavy metal compositions. The water contents of FW_A of 89.97–92.78 wt.% exceed the standard of 40 wt.%. The contents of P₂O₅ of 8.82×10^{-3} to 1.32×10^{-2} wt.% and K₂O of 1.92×10^{-2} to 2.40×10^{-2} wt.% of FW_A in wet basis are lower than the regulated values of 0.3–6.0 wt.% and 0.3–4.0 wt.%, respectively. However, contents of the heavy metals in FW_A all are very low and meet the appropriate standards. The C/N ratios of FW_A are around 11.72 to 13.9 wt.%/wt.%, which are not only higher than those of FW of 10.68 wt.%/wt.% but also fit the

standard restricted from 10 to 20 wt.%/wt.% in wet basis. By adjusting the water content, nutrition, and C/N ratio properly, one can produce compost via rapid curing from FW_A. The FW_A obtained from autoclaving are more beneficial than raw FW with (1) higher wet bulk density requiring smaller reactor or working space and (2) shorter curing time for making the compost product, because FW_A was already significantly decomposed by autoclaving. Again, as a result of no significant distinction of composition of products obtained from the various conditions employed in this study, A408-15 at 408 K with 15 min would be the proper condition for autoclaving of FW with less energy consumption.

3.2.5. Properties of Autoclaved and Condensed Liquid Products

Table 3 presents the properties of autoclaved liquid product (LA) separated from FW_A and of condensed liquid product (LC) from the released gas from autoclave. The electrical conductivity (EC), COD, TOC, and ammonium nitrogen (NH₃-N) of LA are about 9.15×10^3 – 9.86×10^3 $\mu\text{S}/\text{cm}$, 1.04×10^4 – 2.25×10^4 mg/L, 9.38×10^2 – 1.21×10^3 mg/L and 2.70×10^2 – 3.10×10^2 mg/L, respectively. The corresponding values of LC are of 2.39×10^2 – 2.77×10^2 $\mu\text{S}/\text{cm}$, 3.06×10^2 – 8.67×10^2 mg/L, 1.33×10^2 – 2.79×10^2 mg/L, and 3.0–3.5 mg/L, respectively, which are lower than those of LA. Thus, most of the ionic, oxygen consuming, organic, and nitrogen-containing matters, which are dissolved or extracted from FW, are retained in LA, although some of them are emitted with the steam while being re-collected by condensation. The low pH values of 4.42–5.18 of LA are attributed to the formation of organic acids by the hydrolysis of hemi-cellulose and cellulose in the biomass of FW during autoclaving. Consequently, this thus also resulted in high COD and TOC concentrations as anticipated. Released waste steam also carried out some organic compounds, for which the condensable were condensed in condenser bucket. The pH values of LC were around 7.26–8.78. The LA and LC can be mixed and used as liquid fertilizer by conditioning their properties, such as increasing the pH value with alkaline additives while lowering the EC by dilution. It is noticed that the limiting values of EC for irrigate water and rice plantation are 750 and 1250 $\mu\text{S}/\text{cm}$, respectively, while pH value of irrigate water should be in 6.0–9.0 [19].

Moreover, all these COD and TOC are dissolved from the FW during autoclaving, indicating that the FW_A are more biodegradable than FW. The enhancement effect of thermal pre-treatment on the activated sludge solubilisation and thus the anaerobic digestion biodegradability was also noted by Bougrier et al. [20]. In a recent study, Le et al. [21] has also demonstrated that the biodegradability and thus the biogas production from anaerobic digestion increased with sludge solubilisation. Thus, the LA and LC can be mixed with FW_A as feed for anaerobic digestion to produce biogas for power generation.

3.2.6. Properties of Gases Formed

As described in Section 2.1 Materials and Experiments, three different gas samples, namely, G1, G2, and GR, were collected. The analyses of these gases included detection of total hydrocarbons (THCs) and identification of organic compounds. Figure 4 shows the concentrations of THCs of gases G1, G2, and GR, i.e., CG1, CG2, and CGR, at different autoclaving conditions. The concentrations at various conditions have no obvious tendency on account of the varied composition of different batches of FW. The emitted gas concentrations of CG1, CG2, and CGR are in the range of 143–3424 ppmv, 48–2424 ppmv, and 262–1407 ppmv, respectively. Among all the conditions, autoclaving at 408 K and 60 min has the highest THC concentrations of 3424, 2424, and 1407, respectively, for CG1, CG2, and CGR.

Table 2. Comparison of properties of FW and FW_A with compost standards.

Property in Wet Basis	Standard	FW	A408-15	A408-60	A428-15	A428-60	A438-15	A438-60
H ₂ O (wt.%)	<40	92.7314	89.9664	92.7788	90.7891	91.1481	90.9820	91.9417
C/N (wt.%/wt.%)	10–25	10.68	12.34	11.94	13.08	13.09	11.72	13.90
N* (wt.%)	0.6–5.0	3.514 ± 0.013	3.236 ± 0.029	3.283 ± 0.030	3.049 ± 0.083	3.103 ± 0.116	3.152 ± 0.033	3.024 ± 0.004
P (mg/kg)		3.91 × 10 ³	4.20 × 10 ³	4.54 × 10 ³	3.85 × 10 ³	5.03 × 10 ³	4.94 × 10 ³	5.76 × 10 ³
P ₂ O ₅ (wt.%)	0.3–6.0	8.96 × 10 ⁻³	9.62 × 10 ⁻³	1.04 × 10 ⁻²	8.82 × 10 ⁻³	1.15 × 10 ⁻²	1.13 × 10 ⁻²	1.32 × 10 ⁻²
K (mg/kg)		2.92 × 10 ⁴	1.80 × 10 ⁴	1.97 × 10 ⁴	1.60 × 10 ⁴	1.59 × 10 ⁴	1.99 × 10 ⁴	1.79 × 10 ⁴
K ₂ O (wt.%)	0.3–4.0	3.52 × 10 ⁻²	2.17 × 10 ⁻²	2.37 × 10 ⁻²	1.93 × 10 ⁻²	1.92 × 10 ⁻²	2.40 × 10 ⁻²	2.16 × 10 ⁻²
Cu (mg/kg)	<100	42.4	31.7	30.5	29.8	52.5	56.5	50.9
Cr (mg/kg)	<150	8.00	7.61	5.77	5.74	7.73	6.65	7.52
Pb (mg/kg)	<150	5.84	5.89	6.74	7.16	9.86	5.44	11.1
Cd (mg/kg)	<2.0	<0.70	<0.70	<0.70	<0.70	<0.70	<0.70	<0.70
Zn (mg/kg)	<250	41.3	75.7	94.0	77.2	139	79.0	369
Ni (mg/kg)	<25.0	14.3	12.2	18.0	12.6	20.3	22.1	19.5
As (mg/kg)	<25.0	<1.7	<1.7	<1.7	<1.7	<1.7	<1.7	ND
Hg (mg/kg)	<1.0	<0.015	<0.015	0.025	<0.015	0.021	0.015	<0.015

* Dry basis.

Table 3. Properties of autoclaved and condensed liquid products obtained from autoclaving of FW.

Autoclaved Liquid (LA)							
Condition				Item			
Temperature (K)	Time (min)	Rotation Speed (rpm)	pH	Electrical Conductivity (μS/cm)	COD (mg/L)	TOC (mg/L)	NH ₃ -N (mg/L)
408	15	7	4.94	9.84 × 10 ³	1.04 × 10 ⁴	1.21 × 10 ³	2.70 × 10 ²
408	60	7	4.73	9.15 × 10 ³	2.00 × 10 ⁴	9.38 × 10 ²	–
428	15	7	4.72	9.68 × 10 ³	2.16 × 10 ⁴	1.11 × 10 ³	3.10 × 10 ²
428	60	7	4.44	9.17 × 10 ³	1.96 × 10 ⁴	9.48 × 10 ²	–
438	15	7	5.18	9.86 × 10 ³	2.25 × 10 ⁴	1.04 × 10 ³	–
438	60	7	4.42	9.20 × 10 ³	2.12 × 10 ⁴	9.70 × 10 ²	–
Condensed Liquid (LC)							
Condition				Item			
Temperature (K)	Time (min)	Rotation Speed (rpm)	pH	Electrical Conductivity (μS/cm)	COD (mg/L)	TOC (mg/L)	NH ₃ -N (mg/L)
408	15	7	7.26	2.67 × 10 ²	3.06 × 10 ²	1.33 × 10 ²	3.00
408	60	7	6.68	2.65 × 10 ²	6.27 × 10 ²	2.24 × 10 ²	–
428	15	7	8.54	2.48 × 10 ²	3.90 × 10 ²	1.51 × 10 ²	3.50
428	60	7	8.29	2.39 × 10 ²	8.27 × 10 ²	2.57 × 10 ²	–
438	15	7	8.78	2.77 × 10 ²	5.07 × 10 ²	1.87 × 10 ²	–
438	60	7	8.19	2.44 × 10 ²	8.67 × 10 ²	2.79 × 10 ²	–

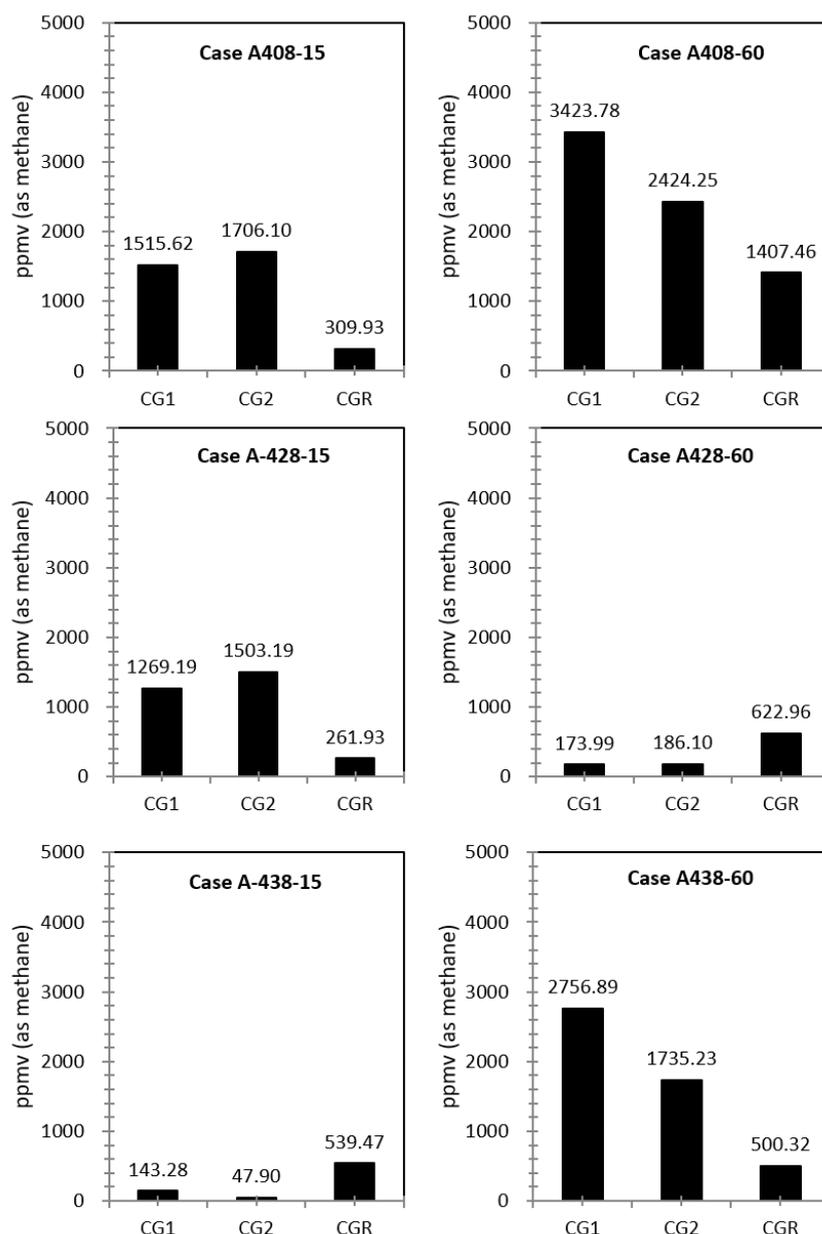


Figure 4. THCs of CG1, CG2, and CGR from autoclaving of FW. CG1 and CG2, and CGR: concentrations of released gases after condenser as pressures in autoclave were reduced to P1 and P2, and that of gas in autoclave after opening the reactor lid.

Table 4 elucidates the gas components in CG1, CG2, and CGR indicated by GC-MS. The THCs in CG1 and CG2 are mostly non-polar species, indicating that volatiles from FW were also pyrolyzed during autoclaving. This is consistent with the decreasing of dry weight of FW from 3.34 kg to about 1.46–2.26 kg after autoclaving, as pointed in previous section. Notice that GR was collected after the reactor lid was opened. Some components may be emitted to the ambient, thus resulting in fewer species in CGR, such as $C_{10}H_{16}$ being retained. There was no carbon monoxide formed, as autoclaving process was operated at oxygen-rich environment. Saturated steam also acted as an oxidant for decomposing the FW during autoclaving at high pressure; therefore, different aldehydes were produced. What should be noticed is that sulfur compounds were also formed from the sulfur-containing matters in FW during autoclaving. The sulfur element occupied 1.67 wt.% of FW in dry basis and was reduced to 0.725–0.887 wt.% after autoclaving, which led to the production of dimethyl sulfide, dimethyl disulfide, and other sulfides.

Table 4. Gaseous hydrocarbon products from autoclaving of FW.

Condition		408 K, 15 min			408 K, 60 min			428 K, 15 min			428 K, 60 min			438 K, 15 min			438 K, 60 min		
Rotation Speed		7 rpm			7 rpm			7 rpm			7 rpm			7 rpm			7 rpm		
Limonene	C ₁₀ H ₁₆	● ¹	● ²	● ³	● ¹	● ²	● ³	● ¹	● ²	● ³	● ¹	● ²	● ³	● ¹	● ²	● ³	● ¹	● ²	● ³
α-pinene	C ₁₀ H ₁₆	●	●	●	●	●		●	●	●		●	●	●	●	●	●	●	●
1R-α-pinene	C ₁₀ H ₁₆						●												●
1S-α-pinene	C ₁₀ H ₁₆										●								
β-pinene	C ₁₀ H ₁₆						●					●							●
2-methyl propanal	C ₄ H ₈ O	●	●		●	●		●	●		●	●		●	●	●	●	●	●
3-methyl butanal	C ₅ H ₁₀ O	●	●		●	●		●	●		●	●		●	●	●	●	●	●
2-methyl butanal	C ₅ H ₁₀ O									●	●		●	●		●	●		
Carbon dioxide	CO ₂		●		●			●	●		●	●		●	●		●	●	
Alcohol	C ₂ H ₆ O																	●	●
Dimethyl sulfide	C ₂ H ₆ S	●	●		●	●		●	●		●	●		●	●		●	●	
Dimethyl disulfide	C ₂ H ₆ S ₂	●	●		●	●	●	●	●		●	●	●	●		●	●	●	●
2,3-butanedione	C ₄ H ₆ O ₂									●				●					●
Nitrogen	N ₂	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Water	H ₂ O	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

1, 2: released gases of G1, G2 after condenser as pressures in autoclave were reduced to P1 and P2. P1 = 1.9–2.1 kg/cm², P2 = 1.0–1.1 kg/cm² for A408-15 and A408-60; = 3.9–4.0 kg/cm², 2.0–2.1 kg/cm² for A428-15 and A428-60; = 3.5–4.0 kg/cm², 2.0 kg/cm² for A438-15 and A438-60. 3: gas of GR in autoclave after opening the reactor lid at the end of autoclaving as the pressure in autoclave was reduced to ambient.

4. Conclusions

This study conducted the pilot-scale autoclaving experiments of food wastes (FW) at various temperatures of 408, 428, and 438 K and times of 15 and 60 min. The injected steam to the autoclave was supplied by the incineration plant with a gauge pressure of 7 kg/cm² and a temperature of 443 K or above. The results showed that the lower energy level and operation time by autoclaving were achieved at 408 K and 15 min (denoted as Case A408-15). The wet bulk density ρ_{BW} of FW_A drastically increased from 359 kg/m³ to 1031–1157 kg/m³ (287.19%–322.28% relative to that of FW) by autoclaving, while the volume reduction of FW decreased from 127.86 L down to 17.50–22.20 L. There was an increase of C/N ratio of FW_A, while the contents of sulfur, hemi-cellulose, and cellulose of FW_A decreased. These findings will be beneficial for subsequent processing and reutilization of FW_A and other agricultural and livestock farming wastes with low C/N ratios as compost.

The autoclaved liquid product (LA) separated from FW_A and liquid condensate (LC) from the exit gas containing high electrical conductivity, COD, and TOC can be mixed to produce liquid fertilizer with suitable procedure. Moreover, the mixture of FW_A, LA, and LC can be further treated by anaerobic digestion to provide biogas for power generation. These add to the appeal of sustainable materials management and the circular economy. The emitted gas from autoclaving contained non-detectable CO, while some hydrocarbons were identified by GC-MS. The results of this work will be useful for the design and cost-effectiveness assessment of the autoclaving pretreatment of food wastes from domestic households and food industries.

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Nomenclature

AT-t	Autoclaving at T K and t min (e.g., A408-15: at 408 K and 15 min)
CG1, CG2	concentrations of G1, G2 (ppmv)
CGR	Concentrations of GR (ppmv)
COD	Chemical oxygen demand (mg/L)
EC	Electrical conductivity (μ S/cm)
G1, G2	Released gases after condenser as pressures in autoclave were reduced to P1 and P2 after finishing the autoclaving at setting time
GR	Gas in autoclave after opening the reactor lid at the end of autoclaving as the pressure in autoclave was reduced to ambient
H _{HDM}	Higher heating value per mass in dry basis (kcal/kg)
H _{HDMV}	Higher heating value per volume in dry basis (kcal/kg)
H _{HWM}	Higher heating value per mass in wet basis (kcal/kg)
M _A	Ash (wt.%)
M _C	Combustibles (wt.%)
M _{FC}	Fixed carbon (wt.%)
M _{VM}	Volatile matters (wt.%)
M _W	Water content (wt.%)
NH ₃ -N	ammonium nitrogen (mg/L)
P	Steam pressure for autoclaving (kg/cm ² , gauge)

P1, P2	Two pressures in autoclave as gas were released after finishing the autoclaving at setting time (kg/cm ² , gauge)
r	Rotation speed of autoclave (rpm)
T	Autoclaving temperature (K or °C)
THCs	Total hydrocarbons (ppmv)
TOC	Total organic carbons (mg/L)
t	Autoclaving times (min)
V _{BW}	Wet bulk volume (L)
ρ _{BD}	Dry bulk density (kg/m ³)
ρ _{BW}	Wet bulk density (kg/m ³)

Abbreviations

ASTM	American Society for Testing and Materials
CNS	Chinese National Standards
FW	Food wastes
FW _A	Autoclaved food wastes
LC	Condensed liquid from the released gas from autoclave
LA	Autoclaved liquid product separated from FW _A
HTL	Hydrothermal liquefaction
IWPB	Initiative Wood Pellet Buyers
MSW	Municipal solid wastes
NIEA	National Institute of Environmental Analysis
RDF	Refused derived fuel
SRF	Solid recovered fuel
TBSMI	Taiwan Bureau of Standards, Metrology, and Inspection

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