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Chemical and Physicochemical Characterization of Agrowaste Fibrous Materials and Residues

YAU-HOONG KUAN AND MIN-TZE LIONG*

Food Technology Division, School of Industrial Technology, Universiti Sains Malaysia, 11800 Minden, Penang, Malaysia

The objective of this study was to evaluate the chemical, physicochemical, and functional properties of agrowastes derived from okara (*Glycine max*), corn cob (*Zea mays* sp.), wheat straw (*Triticum* sp.), and rice husk (*Oryza sativa*) for potential applications in foods. The fibrous materials (FM) were treated with alkali to yield fibrous residues (FR). Rice husk contained the highest ash content (FM, 8.56%; FR, 9.04%) and lowest lightness in color (FM, 67.63; FR, 63.46), possibly due to the abundance of mineral constituents. Corn cob contained the highest amount of soluble dietary fiber (SDF), whereas okara had the highest total dietary fiber (TDF). The high dietary fiber fractions of corn cob and okara also contributed to the highest water- and oil-holding capacities, emulsifying activities, and emulsion stabilities for both FM and FR samples. These results indicate that these agrowastes could be utilized as functional ingredients in foods.

KEYWORDS: Agrowaste; dietary fiber; water-holding capacity; oil-holding capacity; emulsifying activity; emulsion stability

INTRODUCTION

Agrowaste refers to waste generated from plants and animals such as plant fibers, leaves, hulls, and manures. Although not classified as hazardous waste, wastes produced from cereal crops make up a great volume of waste materials. Approximately 700,000 tons of okara are produced annually from the production of tofu in Japan, whereas 880 million tons of cereals are produced annually worldwide, of which 550 million tons are wheat straw (*1*). Traditionally, these waste materials are used as bedding for animals and livestock feeding, burned in the fields, or added into soil as green fertilizer. Recent studies have documented other uses of these agrowastes such as soil conditioners or fertilizers, biofuels, thermoplastics, activated charcoal, and components of other composite materials (*2*). However, the potential of these agrowastes as a source of food dietary fiber has not been fully examined.

Nondigestible carbohydrates and lignin are the main components of dietary fiber and are intrinsic and intact in plants, such as cellulose, hemicellulose, pectin, β-glucans, and gums, which have received much attention because of their health benefits. Dietary fiber is generally derived from plant cell walls and other substances such as resistant starch and protein that are not hydrolyzed by digestive enzymes. High dietary fiber intake has been shown to exert beneficial hypocholesterolemic effect, reduce the risks of cardiovascular diseases, improve hypertension, diabetes, obesity, and bowel cancers, and alleviate gastrointestinal disorders (*3*). Adequate amounts of dietary fiber in food have been found to increase bowel movements, whereas additional consumption of fruits and vegetables has been reported to decrease mortality and reduce heart attacks in infracted survivors (*4*).

The physiological functions of dietary fiber are likely to depend on its physicochemical properties such as absorption of organic molecules, water- and oil-holding capacities, and mineral binding and antioxidant activities (*5*). These properties are desired mostly by the food industries, which are often challenged to produce new functional ingredients derived from natural sources. Fiber is added to cooked meat and fried foods to increase cooking yield by increasing the moisture content and reducing the retention of lipids (*6*). Fiber-rich ingredients are also used for their textural and stabilizing effects. Additionally, the bulking ability of insoluble fibers has led to their incorporation into biscuits, confectionery products, drinks, sauces, desserts, and yogurt with a reduced calorie effect.

Residues from coconut, potato peel, cumin, legumes, and beans have been used as sources of dietary fiber. However, less information is available on the agrowaste fibrous residues from rice husk, wheat straw, corn cob, and okara. Therefore, the objective of the present study was to investigate the chemical composition as well as the functional and physicochemical properties of agrowaste materials and fibrous residues derived from rice husk, wheat straw, corn cob, and okara.

MATERIALS AND METHODS

Samples and Chemicals. Rice husk (*Oryza sativa*), wheat straw (*Triticum* sp.), corn cob (*Zea mays* sp.), and okara (*Glycine max*) were obtained from local small and medium industries and used as fiber sources.

* Corresponding author (telephone +604 653 2114; fax +604 657 3678; e-mail mintze.liong@usm.my).

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Fibrous Materials (FM). All agrowastes were chopped into smaller pieces (approximately 2 cm) and oven-dried at 60 °C. Dried samples were ground with an ultracentrifugal mill (Retsch ZM 100; F-Kurt Retsch GmbH & Co., Haan, Germany) and sieved through a no. 80 test sieve (Retsch) using a vibrator sieve shaker (Retsch AS 200).

Fibrous Residues (FR). The residues were prepared using the wet fractionation method with some modifications (*5*). Briefly, 200 g of fibrous material was suspended in distilled water at a ratio of 1:6 (w/v). The pH was adjusted to 11 with 1 N NaOH, and the dispersion was stirred for 1 h at 500 rpm with an overhead stirrer. The fibrous residue was washed five times, using a ratio of 1:3 solids to distilled water. The resulting fiber fraction was oven-dried at 60 °C and then ground with an ultracentrifugal mill (Retsch ZM 100) through a 250 μm mesh screen (Retsch).

Proximate Analysis. Nitrogen (method 954.01), fat (method 920.39), ash (method 923.03), crude fiber (method 962.09), and moisture (method 925.09) contents of the fibrous materials and fibrous residues were determined according to the official AOAC procedures (*7*). Protein content was determined using a conversion factor of 6.25. Fat content was obtained upon hexane extraction. Ash content was calculated from the weight of sample after burning at 550 °C for 2 h. Moisture content was measured on the basis of the sample weight loss upon oven-drying at 110 °C for 2 h. Carbohydrate content was estimated as nitrogen-free extract (NFE). The energy content was calculated from the proximate composition. The measured quantities (in grams) of the various fractions (protein, lipid, and carbohydrate) were multiplied by the known mean combustion equivalents of these compounds (23.9 kJ g^{-1} for protein, 39.5 kJ g^{-1} for lipid, and 17.5 kJ g^{-1} for carbohydrate) (*8*).

Color Measurement. Samples in triplicate were transferred to a glass Petri dish and measured with a colorimeter (Minolta CM-3500d; Minolta Co. Ltd., Osaka, Japan). The instrument was calibrated to standard black and white prior to use. A large size aperture was used, and Hunter color *L*, *a*, *b* values were reported through the computerized system using Spectra Magic software version 2.11 (Minolta Cyberchrom Inc., Osaka, Japan).

Total (TDF), Soluble (SDF), and Insoluble (IDF) Dietary Fibers. The dietary fiber fractions were determined as previously described (*9*) with modification. Briefly, 1 g of fiber was placed into each of four Erlenmeyer flasks (W_1) and weighed. Forty milliliters of phosphate buffer (0.08 M, pH 6.0) was added to each flask, and the pH was adjusted to 6.0 with 0.325 M HCl or 0.275 M NaOH. The mixtures were then placed in a water bath at 95−100 °C for 10 min. Then, 0.1 mL of α-amylase (Sigma A-3306) was added to each flask with constant stirring at low speed. All samples were incubated at 95−100 °C for 35 min with continuous agitation in the water bath. The flasks were then cooled to 60 °C, and the side wall of the flasks was rinsed with 10 mL of distilled water. The samples were placed in a water bath at 60 °C for 10 min prior to the addition of 0.1 mL of protease solution (Sigma P3910, 50 mg in 1 mL of phosphate buffer). The mixture was incubated for 30 min with constant agitation. All of the flasks were then cooled to 25 °C, and the samples were adjusted to pH 4.0 with 0.561 N HCl. After that, 0.1 mL of amyloglucosidase (Sigma A-9913) was added to the samples, and the mixtures were incubated in a shaking water bath at 60 °C for 30 min with constant agitation. Ethanol (95%) was added to the samples at a ratio of 1:4 (v/v), and the mixtures were left in the water bath for 1 h. The samples were filtered using a Büchner funnel lined with 1 g of Celite 503 and a filter paper (0.45 mm). The flasks were rinsed twice with 15 mL of 78% ethanol, twice with 15 mL of 95% ethanol, and twice with 15 mL of acetone. The samples were then oven-dried at 103 °C in crucibles and weighed (W_2). Two of the crucibles were placed in a furnace at 550 °C for 4 h for ash determination (W_3), and crude protein was determined using the contents of the remaining two (W_4) crucibles. Total dietary fiber was determined as

$$\text{total dietary fiber (\%)} = \frac{W_2 - W_3 - W_4 - W_5}{W_1} \times 100$$

where W_5 is the weight of the reagent (blank).

The above method was employed to quantify IDF. However, alcohol was not added to precipitate IDF. Calculation of IDF in the samples was the same as that used for TDF. The SDF was calculated by subtracting the amount of IDF from the amount of TDF.

Water- (WHC) and Oil-Holding Capacities (OHC). Water- and oil-holding capacities of fibrous materials and residues were determined as previously described (*10*). One gram of sample was weighed, added into 10 mL of distilled water or palm oil, and stirred for 1 min. The fibrous suspensions were then centrifuged at 2200*g* for 30 min, and the supernatant volume was measured. WHC was expressed as grams of water held per gram of sample, whereas OHC was expressed as grams of oil held per gram of sample.

Emulsifying Activity (EA) and Emulsion Stability (ES). The emulsifying activity and emulsion stability were determined as described by Chau, Cheung, and Wong (*10*) with modification. Briefly, 10 mL of 2% w/v fibrous suspension was homogenized using a MSI minishaker (Ika-Works, Wilminton, DE) at 2000 rpm for 2 min. Then, 10 mL of palm oil (Felda Iffco Sdn. Bhd., Selangor, Malaysia) was added to each sample and homogenized for 1 min. The emulsions were centrifuged (Hettich, Tuttlingen, Germany) at 1200*g* for 5 min, and the emulsion volume was measured. EA was expressed as percentage volume of the emulsified layer over the total volume used. To determine the ES, the prepared emulsions were heated at 80 °C for 30 min, cooled to room temperature (25 °C), and centrifuged at 1200*g* for 5 min. ES was expressed as percent volume of the remaining emulsified layer over the original emulsion volume.

Scanning Electron Microscopy (SEM). Samples were affixed to sample stubs using double-adhesive coated copper electrical tape and gold-coated using a Polaron SC515 SEM Coating System (Bio-Rad sputter coater, Bio-Rad Ltd., Hemel Hempstead, U.K.). The samples were then viewed and photographed in a Leo Supra 50VP Ultrahigh Field Emission scanning electron microscope (FESEM) (Carl Zeiss, Oberkochen, Germany).

Statistical Analysis. Experiments were conducted in triplicate. All analyses were performed using SPSS for Windows version 12.0 (SPSS, Chicago, IL). Differences between means were assessed using a one-way analysis of variance (ANOVA) with a posthoc determination by Tukey's test. α level was set at 0.05.

RESULTS AND DISCUSSION

Fibrous Residue Recovery. Fibrous residues (FR) were obtained from fibrous materials (FM) following alkaline treatment. The FR yields for rice husk, wheat straw, corn cob, and okara were 54.82, 8.09, 43.21, and 49.29%, respectively. Wheat straw illustrated the lowest yield for FR ($P < 0.05$), which can be attributed to the large portion of wheat starch derived from the spikelets of the free-threshing wheat (*11*). Treatments using NaOH had been reported to increase the swelling and rupturing of the starch granules (*12*), consequently leaching the carbohydrate from the treated wheat fibrous material. Rice husk had the highest yield for FR compared to all agrowastes studied. Rice husk fiber contains high amounts of cellulose, hemicellulose, and lignin, and these fiber-rich materials may have contributed to a high recovery of FR. One of the main nutritional constraints of rice husk as ruminant feed is the high content of silica, which causes a decreased digestibility and increased excretion of silicic acid in the urine. However, alkaline treatment of rice husk using a 3% (v/v) NaOH solution for 24 h at 25 °C has been found to leach 60% of silica (*13*). Although the content of silica was not determined in this study, we postulate that our alkaline treatment would have reduced the amount of silica in rice husk substantially. More studies are needed to further evaluate this.

Proximate Composition. The proximate composition of FM and FR are shown in **Table 1**. FM of rice husk and okara contained low moisture, whereas wheat straw contained the highest moisture content in both FM (7.62%) and FR (6.56%)

Table 1. Proximate Composition of Agrowaste Fibrous Materials and Fibrous Residues

material	constituents[a]						
	moisture (%)	ash (%)	protein (%)	carbohydrate (%)	lipids (%)	crude fiber (%)	energy (kJ g^{-1})
Fibrous Materials							
okara	4.38 ± 0.07c	3.45 ± 0.50c	18.37 ± 0.68a	8.72 ± 0.63c	9.65 ± 0.63a	55.44 ± 1.10a	9.73 ± 0.45b
corn cob	5.90 ± 0.04b	6.24 ± 0.14b	8.46 ± 0.37b	37.46 ± 0.59b	4.61 ± 0.45b	37.38 ± 0.53c	10.40 ± 0.20b
wheat straw	7.62 ± 0.07a	5.61 ± 0.16b	7.59 ± 0.18b	51.42 ± 0.67a	3.55 ± 0.30b	24.22 ± 0.46d	12.21 ± 0.04a
rice husk	4.27 ± 0.06c	8.56 ± 0.11a	4.34 ± 0.14c	38.40 ± 0.58b	1.55 ± 0.43c	42.89 ± 0.89b	8.73 ± 0.17c
Fibrous Residues							
okara	5.53 ± 0.28b	3.60 ± 0.21d	12.69 ± 0.42a	8.73 ± 0.83c	5.37 ± 0.47a	64.32 ± 0.68a	6.66 ± 0.20b
corn cob	4.38 ± 0.18c	6.43 ± 0.10b	6.40 ± 0.26b	23.74 ± 1.42b	3.22 ± 0.48b	55.82 ± 1.34b	6.95 ± 0.24ab
wheat straw	6.56 ± 0.13a	5.87 ± 0.19c	5.12 ± 0.14c	29.22 ± 0.65a	2.55 ± 0.27bc	50.68 ± 0.50c	7.34 ± 0.38a
rice husk	4.35 ± 0.11c	9.04 ± 0.17a	2.47 ± 0.20d	26.31 ± 0.97b	1.66 ± 0.21c	56.50 ± 0.93b	5.89 ± 0.17c

[a] Results are expressed as mean ± standard deviation; $n = 3$. Different letters in the same column of the same group are statistically different ($P < 0.05$).

samples ($P < 0.05$). Ash contents were significantly different among all samples studied. In general, the ash contents of FR were higher than that of FM and were notably highest in rice husk. Ash content had been reported to be associated with metallic constituents. Rice husk has been reported to contain metallic constituents such as Si, K, Ca, Na, Fe, Mg, Mn, Al, Zn, Co, Cu, and Ni (*14*). Additionally, silicon is made up of amorphous silica in rice husk ash (*13*). We postulate that this may have led to higher ash content. Although the level of silicon in rice husk was high, there was no vulnerable group, and data on the effects on children or toxicity have been identified (*15*).

Our results showed that protein, carbohydrate, and lipids for FR were lower than those of FM. This was possibly caused by the leaching of carbohydrate and decomposition of protein and lipids upon treatment with sodium hydroxide. The concentrations of protein and lipid were highest in okara for both FM and FR, followed by corn cob, wheat straw, and rice husk. This had led to the lowest amount of carbohydrate in okara, as the amount of carbohydrate was obtained from the deduction of the other components. Our results were consistent with the normal range of protein content in raw okara, which is between 18.2 and 32.2%. Okara FM and FR had the highest lipid content compared to corn cob, wheat straw, and rice husk. Oil recovery and extraction from okara were high, which was expected because of the high lipid content.

The amount of crude fiber from all FR samples was significantly higher than that of FM. Okara showed the highest concentration of crude fiber among all of the samples for FM (55.44%) and FR (64.32%), and this was consistent with the crude fiber content of raw okara, which is between 52.8 and 58.1%. The crude fiber value for okara FR was higher than that range, most probably due to the treatment used, where treatment by sodium hydroxide had eliminated the protein, carbohydrate, and lipids. The energy value did not differ much among all of the FR samples but was comparatively lower than that of FM samples. This could be attributed to the higher value of protein, carbohydrate, and lipid contents in FM samples. Both FM and FR of corn cob and wheat straw exhibited significantly ($P < 0.05$) higher energy value, indicating that these agrowastes could be incorporated into food products such as energy bars.

Color Measurement. The colors of FM and FR were measured using a colorimeter, and the results are shown in **Table 2**. The L^* value is the psychometric lightness (dark−light) and corresponds to black ($L^* = 0$) and white ($L^* = 100$), whereas the a^* and b^* values correspond to psychometric chromaticity. A positive a^* value represents red, and a negative value denotes green. A positive b^* value corresponds to yellow, whereas a negative value indicates blue. Okara on both FM and FR illustrated the highest L^* value, indicating highest lightness, whreas rice husk (FM and FR) showed the lowest L^* value, indicating the darkest color. L^* values are often negatively correlated with ash content. Results from our present study showed that okara contained the lowest ash content (**Table 1**), and this may have led to an increase in whiteness, leading to a high L^* value (**Table 2**). The highest ash content of rice husk samples also correlated with the lowest L^* value. A high value of ash content was due to the presence of silicon and metallic constituents (*13*). Thus, the higher concentration of silicon and traceable amount of metallic constituents in rice husk may have produced a darker color. The a^* and b^* values showed that all of the samples exhibited red and yellow tones. Corn cob showed the strongest yellow tone for both FM and FR. Corn cob contained major carotenoids such as zeaxanthin, lutein, polyoxy, cryotoxanthin, zeinoxanthin, and carotenes (*16*), which produce yellow tones. FR of both wheat straw and rice husk exhibited lower L^* values than that of FM, indicating changes induced by alkaline treatment.

Table 2. Hunter Color $L^*a^*b^*$ Values for Agrowaste Fibrous Materials and Fibrous Residues

material	color values[a]		
	L^*	a^*	b^*
Fibrous Materials			
okara	84.44 ± 0.10a	1.59 ± 0.02d	19.08 ± 0.03b
corn cob	74.97 ± 0.00c	5.23 ± 0.02a	22.65 ± 0.02a
wheat straw	78.17 ± 0.12b	2.50 ± 0.02a	16.82 ± 0.02d
rice husk	67.63 ± 0.10d	4.10 ± 0.01b	18.14 ± 0.01c
Fibrous Residues			
okara	84.22 ± 0.02a	0.77 ± 0.01d	15.68 ± 0.01d
corn cob	76.58 ± 0.02b	2.91 ± 0.01c	26.74 ± 0.01a
wheat straw	66.67 ± 0.01c	4.27 ± 0.02b	25.53 ± 0.01b
rice husk	63.46 ± 0.02d	4.40 ± 0.02a	22.48 ± 0.02c

[a] Results are expressed as mean ± standard deviation; $n = 3$. Different letters in the same column of the same group are statistically different ($P < 0.05$).

Total, Soluble, and Insoluble Dietary Fibers. All samples illustrated varying levels of TDF (**Table 3**) except for the FR of corn cob and rice husk. Okara contained the highest TDF content for both FM and FR samples. It was followed by rice husk, corn cob, and wheat husk. The major fiber components in okara contributing to TDF had been found to comprise cellulose and hemicelluloses including galactans, arabans, and pentosans (*17*).

The highest SDF content was obtained from corn cob, whereas the lowest was from rice husk. SDF is usually found around and inside plant cells. It either absorbs water or dissolves in water to form viscous solutions (*18*) and has hypocholesterolemic effects in controlled human studies (*19*). Physiologically,

Table 3. Dietary Fiber Fractions of Agrowaste Fibrous Materials and Fibrous Residues

material	dietary fiber fractions[a]		
	SDF (%)	IDF (%)	TDF (%)
Fibrous Materials			
okara	5.64 ± 0.97b	49.81 ± 1.01a	55.44 ± 1.10a
corn cob	8.75 ± 0.31a	28.63 ± 0.30c	37.25 ± 0.45c
wheat straw	1.57 ± 0.22c	22.65 ± 0.66d	24.22 ± 0.46d
rice husk	0.96 ± 0.10c	41.93 ± 0.98b	42.89 ± 0.88b
Fibrous Residues			
okara	9.17 ± 1.53a	55.15 ± 1.41a	64.32 ± 0.68a
corn cob	10.88 ± 0.15a	44.94 ± 1.19c	55.82 ± 1.34b
wheat straw	2.39 ± 0.24b	48.30 ± 0.58b	50.68 ± 0.50c
rice husk	1.30 ± 0.20b	55.21 ± 0.73a	56.50 ± 0.93b

[a] Results are expressed as mean ± standard deviation; $n = 3$. Different letters in the same column of the same group are statistically different ($P < 0.05$). SDF, soluble dietary fiber; IDF, insoluble dietary fiber; TDF, total dietary fiber.

Table 4. Functional and Physiological Properties of Agrowaste Fibrous Materials and Fibrous Residues

material	functional and physiological properties[a]			
	WHC (g/g)	OHC (g/g)	EA (%)	ES (%)
Fibrous Materials				
okara	5.17 ± 0.08b	2.67 ± 0.05b	58.79 ± 1.05a	58.79 ± 1.05a
corn cob	6.16 ± 0.12a	3.68 ± 0.07a	52.73 ± 0.00b	39.39 ± 1.05b
wheat straw	1.14 ± 0.03d	1.30 ± 0.03d	48.49 ± 1.06c	7.82 ± 0.96c
rice husk	2.10 ± 0.04c	1.52 ± 0.03c	47.02 ± 1.03c	45.83 ± 1.03d
Fibrous Residues				
okara	6.22 ± 0.14b	3.76 ± 0.08c	52.10 ± 0.54b	48.81 ± 1.03b
corn cob	8.98 ± 0.15a	7.56 ± 0.22a	59.02 ± 0.93a	54.76 ± 1.03a
wheat straw	6.38 ± 0.12b	4.13 ± 0.04b	43.25 ± 1.19c	43.77 ± 0.93c
rice husk	2.52 ± 0.08c	2.05 ± 0.07d	44.62 ± 0.93c	44.62 ± 0.93c

[a] Results are expressed as mean ± standard deviation; $n = 3$. Different letters in the same column of the same group are statistically different ($P < 0.05$). WHC, water-holding capacity; OHC, oil-holding capacity; EA, emulsifying activity; ES, emulsion stability.

SDF has been found to decrease lipid reabsorption in the ileum and to reduce postprandial glucose and insulin responses (*20*).

The dietary fiber analysis of FM showed that okara possessed the highest IDF content. As for FR samples, okara and corn cob showed significantly higher IDF contents than the other FR agrowastes studied. It can be observed that all samples from FR exhibited higher IDF content than that of FM. We suggest that the effect was attributed to the NaOH used, where soluble components from the fractions of carbohydrate, protein, and lipids were eliminated from FM (**Table 1**). IDFs are primarily those that are derived from the structural parts of plants, such as the cell walls. Cell walls include cellulose, hemicellulose, and lignin (*18*). IDF possesses passive water-attracting properties that serve to increase bulk, soften stool, and shorten transit time through the intestinal tract (*21*). Thus, because of the high TDF, IDF, and SDF contents in the agrowaste, FR obtained from okara and corn cob could be used to alleviate constipation, hemorrhoids, and diverticulosis. Our results indicate the possibility of FM obtained from okara and corn cob to be incorporated into foods to promote good health. More studies are needed to elucidate this.

Water-Holding Capacity. The WHCs of agrowaste FM and FR were performed to evaluate the functional and physiological properties of the samples. The WHC of dietary fiber has been proposed to be of value to predict the ability of fiber in the diet to alter stool weight (*22*). **Table 4** shows that the WHC of corn cob was highest in both FM and FR, whereas FM obtained from wheat straw and FR obtained from rice husk had the lowest WHCs. Our results showed that the WHC of FR was higher than that of FM. The alkaline treatment used had eliminated starch. Roberston and Eastwood (*23*) reported that the absence of starch granules led to an increased WHC, as more water was trapped by the cellulosic structures. In addition, our results showed that FR contained higher SDF than FM. SDF was associated with WHC due to its dispersible quality in water. Betancur-Ancona et al. (*5*) evaluated the physicochemical properties of several FM and reported that the higher WHC for jack bean (39.5%) was due to its higher SDF content (3.38%), whereas lima bean had a lower SDF content leading to a lower WHC (WHC, 26.5%; SDF, 0.77%). A high WHC has also been reported for cauliflower fiber (48.1%), which was associated with its high soluble fiber content (19.2%) (*24*). The WHC of corn cob FR was high, with an ability to retain about 9 times (8.89 g/g) its weight in water, which corresponds with its high content of SDF (**Table 3**).

Oil-Holding Capacity. The OHC has been found to depend on surface properties, overall charge density, thickness, and hydrophobic nature of the fiber particle, where those particles with the greatest surface area possess greater capacity of adsorbing and binding components of an oily nature (*24*). Sosulski and Cadden (*25*) evaluated different sources of dietary fiber and found that lignin-rich samples had higher OHC. Lignin and cellulose are the types of IDF that are commonly used as functional ingredients in food products. In our present study, FM obtained from okara and corn cob had the highest OHC (**Table 4**). This may be due to their high IDF content, which has been reported to be composed mainly of cellulose, hemicellulose, and lignin. OHC has been associated with oil, fat, and cholesterol absorption in the intestinal tract, and thus FM from okara and corn cob may exert such health benefits. More investigations are needed to elucidate this. However, the correlation between OHC and IDF was not observed in rice husk, where a low OHC was recorded despite a high concentration of IDF. We hypothesize that this may be attributed to the mechanical milling process that may have ruptured the oil-trapping cellulosic or honeycomb structure of the rice husk. Additionally, we also observed that an increase in OHC was evident in all of the FM samples upon alkali treatment. Native starches have been found to be poor oil absorbers as the granular structure remains intact (*26*), but this structure could be broken upon chemical treatments. Samples of FM contained a higher amount of starches (**Table 1**), leading to a lower OHC as compared to those of FR, which was low in carbohydrate but high in fiber.

Emulsifying Activity and Emulsion Stability. EA and ES of agrowaste FM and FR were determined to evaluate the functionality of agrowaste, which makes them suitable as emulsifiers. A thermodynamical balance between the emulsion phases is assured by an emulsifier, which decreases interfacial tension and keeps the emulsion stable (*27*). FM obtained from okara had the highest EA and ES (**Table 4**) compared to the other FM samples studied ($P < 0.05$). Okara possessed emulsion stability in milk beverages (*28*). The EA and ES of okara were attributed to the soluble polysaccharide fractions (SDF), containing a pectin-like structure composed of a galacturonan backbone of homogalacturonan (α-1,4-galacturonan) and rhamnogalaturonan (repeating units being composed of α-1,2-rhamnose and α-1,4-galacturonic acid) branched by β-1,4-galactan and α-1,3- or α-1,5-arabinan chains (*28*). The SDF of okara stabilizes the oil droplets by steric repulsion, whereas the long hydrophilic polysaccharide chains create a thick hydrated layer, which prevents the droplets from coming together and

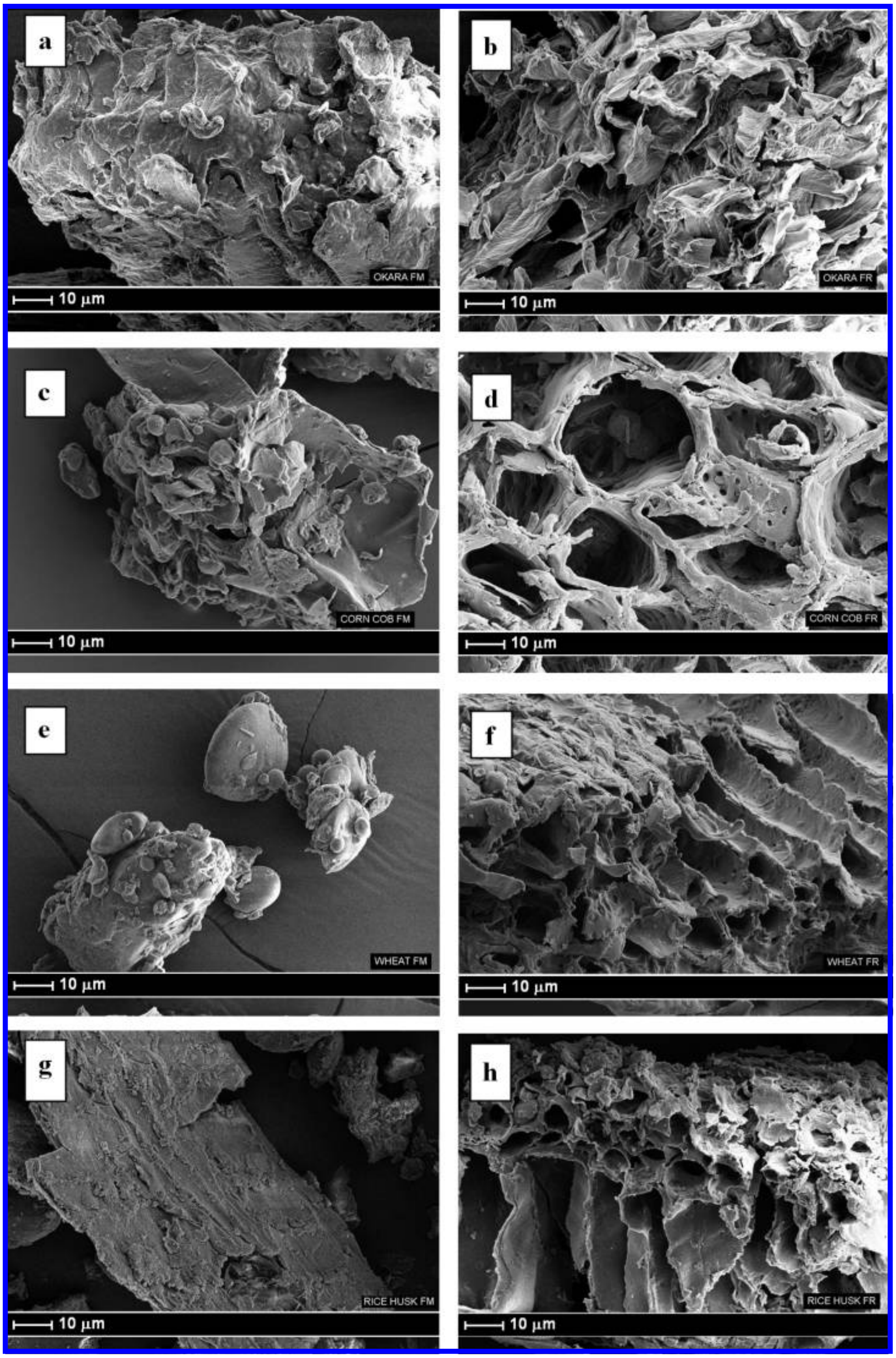

Figure 1. Scanning electron micrographs of fibrous materials (**a**, **c**, **e**, and **g**) and fibrous residues (**b**, **d**, **f**, and **h**): okara (**a** and **b**), corn cob (**c** and **d**), wheat straw (**e** and **f**), rice husk (**g** and **h**).

coalescing (*28*). The protein fraction associated with okara (**Table 1**) also plays an important role in anchoring the moiety of fiber to the oil or water interface (*28*). Our results show that the protein fraction (**Table 1**), SDF (**Table 3**), and WHC (**Table 4**) of okara were high, and we postulate that these led to an increase in EA and ES.

FR of corn cob showed the highest EA and ES among all of the FR samples evaluated ($P < 0.05$). The corn fiber gum has excellent emulsifying properties (*29*). Corn fiber gum is an arabinoxylan (a hemicellulose B), which is also a type of soluble fiber fraction. It is the major component of corn fiber and is generally composed of D-xylose, L-arabinose, galactose, and glucuronic acid. The emulsion-stabilizing capacity had also been reported to correlate well with their protein and lipid contents (*29*), which enable them to act as good oil absorbers. Our results showed that corn cob exhibited the highest SDF content (**Table 3**) and high protein and lipid contents (**Table 1**), which led to high EA and ES.

Scanning Electron Microscopy. The morphology of the all samples was observed under a scanning electron microscope. The scanning electron micrographs of all the samples are presented in **Figure 1**. Starch granules occur in corn cob, wheat straw, and rice husk FM, whereas no starch granules are evident in FR. We believe that the treatment with NaOH induced the rupture of the starch granules, which were subsequently leached. All of the FR samples depicted the typical "honeycomb" structure, almost devoid of starch granules. These typical structures were similar to those reported previously (*30*). A difference in microstructure of the cellulosic fibers could affect their WHC. It can be seen from **Figure 1d** that FR obtained from corn cob appeared to be more porous than the other samples, thus exhibiting higher WHC (**Table 4**). The honeycomb structure was more open in FR of okara (**Figure 1b**) and corn cob (**Figure 1d**) compared to the other agrowastes. We postulate that this opened structure of FR increased the surface area, trapping more oil molecules, therefore exhibiting higher OHC, EA, and ES.

FR obtained from okara and corn cob could be a good source of dietary fiber and could be used as functional ingredients due to their high WHC, OHC, EA, and ES. The excellent emulsifying properties illustrated by corn cob and okara have also exhibited their potentials as emulsifiers. Results from this study showed that agrowastes could be utilized as a source of dietary fiber with versatile physicochemical and functional characteristics.

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