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3Improved solvent economy and rate of rice bran lipid extraction using hydrolyzed rice bran with hexane as solvent

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ARTICLE INFO ABSTRACT Keywords: This study provides kinetic and equilibrium information of the

2extraction of rice bran lipids using hexane **from**

Rice bran Dilute acid hydrolysis post-hydrolysis rice bran (PHRB).

2Rice bran (RB) is an agricultural **residue**

with promising valorization potential Equilibrium in biodiesel production. In this study, native RB was subjected to dilute acid hydrolysis (DAH) with an acid Kinetics solution 3 vol% using 95 wt% H₂SO₄ at 90 °C for 6 h, increasing the lipid density threefold. Batch extraction with Lipid extraction hexane

11was carried out at various **temperatures** (30, 45, and 60 °C) and

solvent to solid ratio (SSR, 4, 8, and 12 Post-hydrolysis residue mL g⁻¹). Improved extraction rates were observed at higher temperatures and lower SSRs. Regardless, ~

990% of – the extractable lipids were solubilized **in hexane in less than 10 min**

. Data obtained were fitted with 5 different models. The extraction of lipids from RB and PHRB involves at least 2 mechanisms, a rapid washing step, and a diffusion step. The extraction process was found to be exergonic, endothermic, and irreversible. An SSR of 4 mL g⁻¹ would require at least 5 ideal crossflow extraction stages for a lipid recovery of over 95%. Compared to RB, the extraction of lipids from PHRB provides potential solvent savings of ~80%. 1. Introduction Asia having a production share of up to ~90% of the world's paddy rice (~782 million tons) in 2018 [1], makes rice a staple cereal for the region. Milling and refining

3of paddy rice to produce white rice grains

entail the generation of residues like rice husk and bran. Rice bran, which comprises 8 to 10 wt% of dry paddy rice (13–14 wt% moisture content) [2] and is characterized by its significant lipid content of 15–23 wt% [3], is of interest in food, feed, and fuel applications. However, the lipid content of bran greatly varies depending not only on the rice variety but also on the milling technology employed. Although bran is technically the aleurone of the cereal along with the germ, where most of the lipids are initially contained, the technology adopted and the extent of milling and refining of paddy rice makes the resulting collected residue a heterogeneous mixture containing not only bran but also husk and broken rice [4,5]. Particles of over 0.710 mm generally had * Corresponding author. E-mail address: awgo@mail.ntust.edu.tw (A.W. Go). components that did not contain significant amounts of lipids whereby resulting in an average lipid content of ~10% or less [5]. Nevertheless, the intentional separation of the different components to have a fraction of the residue containing over 20 wt% lipid to make it comparable with other oleaginous biomass [6], would not be practical if there is no target application for the different fractions and with such physical separation resulting in at least 10% loss of the available lipids. Lipids in the bran are also found to be easily hydrolyzed, resulting in high free fatty acids (FFA) of the extracted lipids [3], making its recovery for food and feed limited and would require immediate stabilization of the bran [6]. Compared to applications in food and feed, bran oil with high FFA could still be practically employed as feedstock for biodiesel. Hydrothermal pretreatment like parboiling has been previously found not only to stabilize the bran or reduce the activity of indigenous lipases but also allows the extraction of 15–30% higher amounts of lipids [7]. However, the additional treatment does not result in apparent

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Received 24 June 2020; Received in revised form 29 August 2020; Accepted 8 September 2020 Available online 21 September 2020 0961-9534/© 2020 Elsevier Ltd. All rights reserved. value-added by-products. More recent developments on the maximized utilization of RB involved subjecting the collected RB with

2dilute acid hydrolysis, which results in the generation of

6sugar-rich hydrolysates and lipid-dense post-hydrolysis residue

[5]. The hydrolysates have been used as a substrate for fermentation [8], while the post-hydrolysis rice bran (PHRB) allowed the full recovery of the originally available lipids in RB while in the form of lipid dense biomass (41–52 wt% lipids) [5,8]. Although previous researches have been carried out on the hydrothermal treatment of related lipid-containing biomass like spent coffee grounds [9] and copra cake [10,11] and proved the potential recovery of the lipids, only post-hydrolysis copra cake [11] has so far been further studied on its lipid extraction kinetics. For the extraction of lipids from native RB, several prior works have been reported in the literature. Technologies for lipid extraction from RB ranged from extraction aided with the Soxhlet extractor [7,12], conventional batch solid-liquid extraction [13–17] supercritical fluid extraction [12], microwave-assisted extraction and even with pilot-scale solid-liquid extraction units [7]. Extraction using Soxhlet extractor remains a preferred choice when it comes to determining the total extractable lipid content as it is not limited by equilibrium. However, conventional batch solid-liquid extraction is still the preferred technique adopted as it is readily scalable for later industrial applications. Related works also investigated the use of various solvents including the use of ethanol [14], isopropanol [15,16] as alternatives for hexane. However, there are some contradicting conclusions drawn from the comparison of different

solvents. For instance, when Proctor and Bowen [15] compared the extraction efficiency of isopropanol and hexane at ambient conditions, both

2solvents were found to be comparable in terms of **extraction**

efficiency. A later report by Hu et al. [16] indicated that hexane performed significantly better

2than isopropanol with extractions carried out at 40 and 60 °C. These discrepancies may have resulted

since

4different solvent-to-solid ratios (SSR

) were

2employed with the prior **employing an SSR of 10 mL g⁻¹**

[15], while the latter employed 4.6 mL g⁻¹ [16]. The – use of polar solvents like those of alcohol tends to extract other components than lipids [18], where the use of isopropanol was observed to have tendencies of extracting more lipids than the control using hexane [15]. Making hexane a preferred solvent for selective extraction of the desired lipids and for gathering baseline data of lipid extraction. Extraction temperatures are often carried out from ambient temperatures to temperatures near the boiling point of the solvent employed [7, 14, 17]. Studies focusing on the lipid extraction kinetics and its mechanism of the process has been limited. Among the studies found available in published literature included the work of Amarasinghe and Gangodavilage [7], published in 2004, which

2looked into RB (pelleted) and hexane system, at a fixed temperature (60 °C) and using a Soxhlet extractor, where the process was found to follow a single-step first order extraction rate. Unfortunately, modeling a Soxhlet extractor as a strict batch process is not appropriate as the extraction process involved in a

Soxhlet extractor

2is a semi-batch process where **the products** are intermittently **separated after each extraction cycle**

2More recent works published in 2017 involving RB-hexane [17] and RB (pelleted)-ethanol [14] systems have concluded that the extraction process

involved more than a single mechanism and is primarily governed by a rapid washing step and slower diffusion steps. However

, discrepancies were still observed as

Zuniga-Diaz et al. [17] still opted to model the system according to a single step diffusion model, while Kamimura et al

claimed to have modeled the system adopting the So and Macdonald model [19] (3 mechanisms), which was Patricelli et al. model [20] (2 mechanisms). With the interest of valorizing RB and to have a better understanding of the lipid extraction mechanism involved in the extraction of lipids from PHRB, this research aimed to establish laboratory-scale data on the kinetics of lipid extraction from RB after it has been subjected to dilute acid hydrolysis. Specifically,

the effect of SSR and temperature on the extraction kinetics

was investigated. In addition, experimental kinetic data were fitted with different solid-liquid extraction models to determine the values of the model parameters, the dependence of such parameters to temperature, and the possible mechanisms involved in the extraction process. Also carried out were a preliminary assessment of the equilibrium limits of the extraction process and their thermodynamic implications. A preliminary evaluation was also carried out to assess the extractability of the lipid from PHRB as compared to native RB and while accounting for the solvent economy of the respective processes. Through pretreatment with via dilute acid hydrolysis, the obtained PHRB are not only dense in lipids, but could be extracted with ease while requiring less solvent. Moreover, lipid which were initially bound are also made extractable through such pretreatment process. In addition, the lipids obtained could potentially be used as feedstock for biodiesel production. The details of how these advantages came about is discussed in this study.

3.2. Materials and methods Rice bran samples (~10 kg) were collected from a local rice mill in Kaohsiung

1 Taiwan. The chemical reagents used in the experiment include analytical grade ethyl acetate 99.9 vol% from Echo Chemical Co., Ltd, Taiwan, sulfuric acid 98 wt% from Scharlau, Spain and sodium chloride 99

19 wt% from Showa, Japan; technical grade hexane (95 wt%) from Echo Chemical Co., Ltd, Taiwan

1potassium hydroxide 85 wt% from Acros organics, USA; FAME 37-mix and boron trifluoride methanol complex solution 13–15% (BF₃ basis) from Sigma, Aldrich, Germany. **2.1**. Dilute acid hydrolysis of

RB Dilute acid hydrolysis of RB samples was done referencing a previously optimized procedure, in (3 vol%) sulfuric acid (98 wt%) solution

6at a constant temperature of 90 °C and SSR of 8 mL/g

– 1 (

6dry lipid-free basis) for 6 h [5]. The

resultant liquid hydrolysate and post-hydrolysis solid residue, then after referred to as post-hydrolysis RB (PHRB), were separated by vacuum filtration

4using Advantec No. 2 filter paper as the filter medium. The collected PHRB was

transferred to a

4pre-dried and pre-weighed glass beaker and then dried to constant weight in

a convective oven at 50 ± 5 °C. The PHRB yield, YPHRB (g dry residue/g dry rice bran grounds), was calculated using Equation (1). $YPHRB = (m_{DR+GB} - m_{GB}) / (m_{RB}(1 - MRB))$ (1) where m_{DR+GB} is the mass of dry PHRB with the glass beaker (g) after oven drying at 50 °C, but not totally free of moisture, m_{GB} is the mass of the glass beaker (g), m_{RB} is the initial mass of the RB sample (g) subjected to hydrolysis,

6and M is the fractional moisture content of the collected RB sample

and the residue after drying at 50 °C. With a resulting solid yield of ~43%, a total of 4 kg of PHRB was accumulated. The PHRB tends to clump together and form cakes after drying, which were milled to an average particle diameter of ~0.59 mm and stored for further characterization and lipid extraction trials. **2.2**. Characterization and profile of lipids from RB and PHRB Moisture content via gravimetric determination was done by representative sampling (~5 g) of RB and PHRB. The samples were

1accurately weighed to the nearest 0.1 mg and placed in pre-dried and pre-weighed glass tubes

and then lyophilized using a freeze dryer (Labconco Free-Zone 2.5 L, Model 7,670,520, Kansas City, MO). The

1 mean particle size was determined by the ANSI (American National Standards Institute Method) S319.4 [21]. The crude lipid content

of RB and PHRB samples were determined following the AACC Method 30–25 [22]

1 using a Soxhlet extractor with hexane as a solvent

for an extraction period of 8 h. All samples, RB, PHRB, as well as those after solvent extraction, which were lyophilized, were also subjected to scanning electron microscope (SEM) imaging using field emission electron microscope (FE-SEM) (JSM-6500F, JOLE, Ltd. Tokyo, Japan) with the samples coated with platinum.

1 Lipid profile of the extracted crude lipids was determined via gas chromatographic analysis using Shimadzu GC-2010 Plus equipped with a split injector, ZB-5HT Inferno column (15 m × 0.32 mm

4x 0.1 µm), and using a flame ionization detector following the

program described previously [23],

1 to quantify the amount of free fatty acids, monoglycerides, diglycerides, and triglycerides. Lipid samples (20–25 mg) were dissolved in ethyl acetate (1 mL), and passed through 0.20-µm PTFE membrane filters (13-mm syringe filters) before subjecting to gas chromatography analysis. The identified peaks from the chromatograms were converted to mass percentages using the calibration curves established

. A 7 to 10-point calibration curve was established using lipid standards of with lipid standards of mono-, di- and triolein as well as oleic acid. Determination of unsaponifiable content and lipid profiling was conducted starting with total fatty acid content determination according to the principles outlined in the AOAC official methods (Method 993.08 and Method 972.28) [24] with modifications as

1 described in the work of Loyao et al. [18]. The

collected total fatty acids were converted fatty acid methyl esters by reaction with BF₃-methanol reagent for fatty acid profiling. The resulting fatty acid methyl ester composition from different samples was determined via gas chromatography using the same method mentioned previously for lipid profile determination, using FAME 37-mix as reference for peak identification. 2.3. Lipid extraction kinetic and thermodynamic evaluation To determine the effect on temperature and SSR to the lipid extraction kinetics, experiments for PHRB were carried out at various temperatures (30, 45, and 60 °C) and SSR (4, 8, 12 mL g⁻¹). For each of the extraction conditions investigated, 80 mL of hexane (~53 g, weighed to the nearest 0.1 mg) was poured into a Teflon-lined screw-capped 250 mL Erlenmeyer flask, and corresponding amounts of PHRB for the

different SSR's were weighed in screw-capped conical polypropylene centrifuge tubes. The flasks and the tubes were sealed and incubated at the extraction temperature for 30 min before mixing. Extraction was carried out in a shake-flask incubator at the investigated extraction temperature and constant shaking speed of 200 rpm. A minimum of ten (10) replicates of the setup were made for each run to represent the pre-determined extraction times (2.5, 5, 10, 15, 30, 60, 120, 240, 180, and 480 min). Duplicate runs per extraction time were terminated to determine the extraction as a function of time. The contents, hexane and lipid mixture and solids, of the flask removed at the pre-determined extraction time, was separated by filtration using Advantec No. 2 filter paper as the filter medium and collected into a round bottom flask. From the filtrate collected, two 5-mL aliquots were pipetted out and stored in a pre-dried and pre-weighed 7- mL screw-capped vials. The covered vials containing the aliquots were immediately weighed, and subjected to a rotary evaporator to evaporate hexane from the mixture until constant weight. Equation (2) to Equation (6) were used in calculating the response variables, concentration CL (g lipids per 100 g hexane), percent lipid extracted EL (wt.%), lipid yields relative to the PHRB mass, YLPHRB and relative to the original RB mass, YLRB (g lipids g⁻¹ dry biomass), and percent lipid recovery RL (wt.%) with respect to the post-hydrolysis residue extracted or equivalent native biomass, respectively. $CL = \frac{m_{ALVV} - m_{LVV}}{m_{LVV}} \times 100$ (2) $EL = \frac{LCRB}{0.1Cr0L0P(HmRBFH \times m_s(1 - M) m_F)} \times 100$ (3) $YLPHRB = \frac{m_s(1 - M - R)}{M}$ (4) $YLRB = YLPHRB \times YPHRB$ (5) $RL = \frac{YL}{RB \text{ or } PHRB} \times 100$ $LCRB \text{ or } PHRB$ (6) where mLV

10 is the mass of lipids and vial (g), mV is the mass of vial (g)

), mAV is the mass of aliquot and vial, mFH

10 is the mass of flask and hexane (g), mF is the mass of flask (g)

), LC is the crude lipid content of PHRB or RB expressed in dry basis, ms is the mass of solid sample subjected to lipid extraction (g), M is the fractional moisture content of PHRB or RB, and mR is the mass of total lipids recovered (lipids from the two aliquots and from the remaining filtrate) (g). 2.3.1. Fitting of kinetic models Selected theoretical and semi-empirical kinetics models found in Table 1 were fitted to the experimental data gathered to aid a better understanding of the possible mechanisms involved in the lipid extraction process. To assess the suitability of the kinetic models to represent the experimental data gathered, regression analysis was carried out adopting the least-square method, whereby

5 minimizing the sum of the squares of the residuals or error (SSE, Equation (7)) while the model coefficients are iteratively modified. The

analysis was

5 carried out using Microsoft Excel equipped with Solver data analysis tool pack with the regression results assessed through the resulting coefficient of

determination (R², Equation (8)), adjusted R-squared (R²adj, Equation (9)), standard error of the mean (SE, Equation (10)),

14 root mean square error (RMSE, Equation (11

)), and standard error of estimate (SEE, Equation (12)). $\sum_{i=1}^n (CL_i - \hat{CL}_i)^2$ (7) $R^2 = 1 - \frac{\sum_{i=1}^n (CL_i - \hat{CL}_i)^2}{\sum_{i=1}^n (CL_i - \bar{CL})^2}$ (8) Table 1 Theoretical and semi-empirical models for lipid extraction kinetics. Model Name Mathematical Expression Modified-Fick's Law $CL = C^\infty \left(1 - A e^{-\frac{4Dd}{\pi^2} t} \right)$ [32] Ae^{Bt} – Patricelli [20] $CL = C^\infty w(1 - e^{-kwct}) + Cd^\infty(1 - e^{-kdc t})$ So & Macdonald [19] $CL = C^\infty w(1 - e^{-kwct}) + Cd^\infty(1 - e^{-kdc t})$ Modified-Peleg [33] $CL = k_1 + k_2 t$; $R_0 = k_1$ and $C^\infty t = 1$ Linares [29] $k_2 CL = Tw1C/2^\infty w + t + Cd^\infty(1 - e^{-kdc t})$; $Tw1/2 = k_2 nd Cw^\infty$ and $Rw0 = 1$ $k_2 nd Cw^\infty$ at $t \rightarrow 0$ ACL is lipid concentration (g lipids per 100 g hexane) at any time t (min), C^∞ is lipid concentration after infinite time (g lipids per 100 g hexane), D is the diffusion coefficient ($m^2 \text{min}^{-1}$), d is diameter of the particle (m), A is pre-exponential coefficient (dimensionless), B is volumetric

13 mass transfer coefficient (min^{-1}), and t is extraction time (min)

C^∞ is lipid concentration after infinite time (g lipids per 100 g hexane), and k is kinetic coefficient(s) (min^{-1}) for the washing (w) and diffusion stages (d); k_1

15 is Peleg's rate constant ($\text{min} \cdot 100 \text{ g hexane g}^{-1}$ lipids), k_2 is Peleg's capacity constant (100 g hexane g)

C^∞ is lipid concentration after infinite time (g lipids per 100 g hexane); dCw^∞ is lipid concentration after infinite time due to the washing stage (g lipids per 100 g hexane), $C^\infty d$ is lipid concentration after infinite time due to diffusion stage (g lipid per 100 g hexane), $Tw1/2$ is half-life time in washing stage (min), kdc is kinetic coefficient for diffusion stage (min^{-1}), $R_0 w$ is initial extraction rate for washing stage (g lipids per 100 g hexane \cdot min), and $k_2 nd$ is second-order kinetic coefficient for washing stage ($100 \text{ g hexane per g lipids} \cdot \text{min}$). ($R^2_{adj} = 1 - \frac{1}{n} \sum_{i=1}^n (CL_i - \hat{CL}_i)^2$) $SE = \hat{CL}_i \sqrt{\frac{1}{n} \sum_{i=1}^n (CL_i - \hat{CL}_i)^2}$ $RMSE = \sqrt{\frac{SSE}{n}}$ $SEE = \sqrt{\frac{SSE}{n-k}}$ (9) (10) (11) (12) where CL is the measured lipid concentration (g lipids/100 g hexane), \hat{CL} is the predicted lipid concentration (g lipids per 100 g hexane), CL

5 is the average mean value of the

measured lipid concentrations (g lipids per 100 g hexane),

5n is the number of experimental data points, and k is the number of parameters in the model including the equilibrium concentrations predicted.

2.4. Thermodynamic parameters The

thermodynamic parameters determined from the experimental data gathered were activation energy, Gibbs free energy, entropy, and enthalpy. The activation energy (E_a , J mol^{-1}) for the extraction process was estimated by fitting the determined kinetic coefficient (k , min^{-1}) or initial extraction rate (g lipids per 100 g hexane \cdot min), to the linearized form of the Arrhenius model (Equation (13)). $\ln k = -\frac{E_a}{RT} + \ln k'$ (13)

7 where R is the universal gas constant ($8.31447 \text{ J mol}^{-1} \text{ K}^{-1}$), T is the absolute temperature (K), k' is the

pre-exponential factor (min^{-1} or $\text{g K lipids per 100 g hexane} \cdot \text{min}$, depending on the order of diffusion model). At equilibrium conditions,

10the Gibbs free energy G (J mol^{-1})

– 1) values for lipid extraction done at various temperatures (T) were calculated using Equation (14) and Equation (15), while the entropy S (J/mol) and enthalpy H (J mol^{-1}) were estimated by regression of Equation (16) with – the calculated G s at different temperatures,

7where R is the universal gas constant ($8.31447 \text{ J mol}^{-1} \text{ K}^{-1}$), T is the absolute temperature (K)

). $G = -RT \ln K_{eq}$ $K_{eq} \cong K_c = \frac{C_{CL} S_{CY} - L_{CY} L_e}{C_{LE} C_{SE}} = \frac{E_{LE}}{1 - E_{LE}}$ or $K_{eq} \cong K_d = \frac{C_{LE}}{C_{SE}}$ $G = H - TS$ (14) (15) (16) The equilibrium constant (K_{eq}), could be represented either as the equilibrium constant or the distribution coefficient. The equilibrium constant, K_c , expresses the concentrations of lipids in the liquid and solid phases relative to the total amount of solvent present in the system. The distribution coefficient, K_d , accounts for the concentration of lipids expressed relative to the non-solute material in the respective phases. At equilibrium, C_{LE} is the lipid concentration in the liquid phase ($\text{g lipids per 100 g hexane}$), and C_{SE} is the lipid concentration in the solid phase ($\text{g lipids per 100 g hexane}$), since the amount of solvent in the system does not change, the equilibrium yields (Y_{LE}) and lipid extracted (E_{LE}) were used to determine K_c , while C_{LE} is the lipid

17concentration in the liquid phase ($\text{g lipids per 100 g}$

hexane) and C_{SE} is the lipid

17concentration in the solid phase ($\text{g lipids per 100 g dry lipid-free solid}$

) are used to determine K_d . 3.

12Results and discussion Characteristics of RB

and PHRB as well as their extractable

12lipids are summarized in Table 2. Rice bran

, initially containing 17.4 wt% lipids, lost at least ~55 wt% of its initial biomass component, which resulted in

6lipid-dense PHRB with a lipid content of

48.55%. The

6increase in the lipid content is primarily owing to the removal of

non-lipid components during hydrolysis and the release of bound fatty acids [5], which is supported by obtained lipid yield (20.95 wt%) calculated with respect to the native biomass, translating to a lipid recovery of ~120%. The lipid recovery exceeding 100% is indicative that additional lipids have been extracted, with PHRB having up to 16.9 g of total fatty acid extractable per 100 g of native RB as compared to untreated RB which only allowed extraction of 13.99 g total fatty acid per 100 g RB. Hydrothermal treatment of rice bran is known to induce the extraction of additional lipids. An earlier study by Amarasinghe and Gangodavilage [7], RB from different rice varieties were subjected to parboiling resulted in 15–35% more lipids being extracted. The results obtained in this work are also consistent with earlier reports on direct dilute acid hydrolysis of RB [5,8, 25]. The advantage provided by DAH treatment compared to simple parboiling is the fact that lesser solids would need to be handled in the subsequent lipid extraction process. The increase in the extractable total fatty acids also translates to the increased amount of biodiesel that could be produced from the processing of RB, which would reach up to 17.8 g FAME per 100 g RB processed. The fatty acid profile of the lipids from PHRB was not significantly different from those recovered from native RB, with oleic (45%), linoleic (31%), and palmitic (19%) being the major fatty acids (Table 2). From the determined fatty acid profile, estimated biodiesel properties including density, kinematic viscosity, iodine value, cold filter plugging point, pour point, heating value, and cetane number could potentially meet standards set by ASTM and EN (Table S1). A potential advantage of subjecting lipid-biomass to hydrolysis prior lipid extraction is the breakdown of cellular components containing the lipids, exposing the lipids allowing ease of extraction [26]. Images obtained from scanning electron microscopy (Fig. 1) supports this idea as a shiny or goeey layer or texture on the surface of the sample, primarily the exposed lipids, is observed covering the biomass matrix of PHRB (Fig. 1c and e), which is not observed in the native RB (Fig. 1a). A comparison of SEM images PHRB before (Fig. 1c and e) and after (Fig. 1d

3Table 2 Characteristics of collected biomass and

lipid profile. Biomass

3Rice Bran (RB) Post-hydrolysis Rice Bran* (PHRB

) Composition (wt.%) Moisture Lipidsc Free fatty acid Monoglyceridee Diglyceridee Triglyceridee Unsaponifiable Mattere Total Fatty Acid Content Fatty Acid Distributionf Myristic

8acid (C14:0) Palmitic acid (C16:0) Linoleic acid (C18:2) Oleic acid (C18:1) Stearic acid (C18:0) Gondoic acid (C20:1) Arachidic acid (C20:0) Behenic acid (C22:0) Lignoceric acid (C24:0

) Others Particle size (µm) 9.49 ± 0.08a 17.44 ± 0.09 (17.44 ± 0.09)d 29.54 ± 0.83 Trace amounts Trace amounts 66.84 ± 0.41 4.95 ± 0.60 80.26 1.01e (13.99 ± ± 1.02)d 0.28 ± 0.03 17.17 ± 1.53 31.97 ± 1.87 43.70 ± 0.31 1.60 ± 0.04 0.44 ± 0.03 3.50 4.13 ± 0.28 ± 0.04 0.69 ± 0.11 0.57 ± 0.02 510.86 ± 3.05 4.16 ± 0.12b 48.55 ± 1.53 (20.95 ± 2.51)d 44.37 ± 0.07 1.68 ± 0.60 1.93 0.69 ± 48.25 ± 1.34 3.64 ± 0.22 80.78 1.56e (16.93 ± ± 2.95)d 0.32 ± 0.02 19.42 ± 0.57 30.61 ± 0.18 45.10 ± 0.89 1.67 ± 0.02 0.50 ± 0.04 0.72 0.07 ± 0.33 ± 0.01 0.83 ± 0.03 0.52 ± 0.06 592.39 ± 14.57 Fig. 1. SEM images of (a) lyophilized as received rice bran (RB), (b) solvent extracted as received RB, (c and e) lyophilized post-hydrolysis RB, and (d and f) solvent extracted post-hydrolysis RB. and f) extraction with hexane clearly shows the disappearance of the

shiny or gooey layer or texture from the surface of the sample, which further supports the presence of lipids on the surface of the biomass matrix and their subsequent removal. To compare the ease of lipid extraction from RB and PHRB, batch extractions were

4carried out at the same SSR of 12 mL g⁻¹ and

16at the same solvent-to-oil ratio (SOR) of ~23 mL g⁻¹ at 60 °C

. As could be observed from the

16extraction kinetics (Fig. 2), it is evident that the

initial extraction rate of lipids from PHRB and the equilibrium concentration reached is much faster and higher than RB at the same SSR. This is expected since PHRB has higher amounts of lipids than RB, whereby a larger

13concentration gradient exists between the solid and the solvent, which drives the

extraction process to proceed much faster. When comparisons are made using the same SOR to have similar oil loading in the system and achieve equilibrium comparable concentration, PHRB lipids were still extracted much more easily (Fig. 2a), owing to a significant portion of the lipids already exposed on the surface. In view of the fraction of lipids extracted (Fig. 2b), over 95% of the lipids were extracted and dissolved in hexane at equilibrium,

2which could be achieved in a short period of

1–2 h. These results are consistent with what has been previously reported by Zuniga-Diaz et al. [17], where lipid extraction from the bran of Morelos rice with hexane

4at an SSR of 10 mL g⁻¹ allowed the

extraction of over – 95% when the extraction was carried out at 60 °C. The advantage of ° PHRB is that, despite having higher lipid contents, the same extraction efficiency could be achieved within the same extraction period. This observation is consistent with the work reported by Te et al. [11] and Go et al. [27], on the lipid extraction from post-hydrolysis copra cake and spent coffee grounds, respectively. To have a better understanding of the lipid extraction process involving PHRB and hexane, sections that follow focuses on the influence of temperature and SSR on the extraction, modeling of the extraction kinetics, thermodynamic, and equilibrium information of the extraction process. 3.1. Effect of temperature and SSR on lipid extraction kinetics Changes in temperature for any physical or chemical reaction entails changes in the process rates and shifts in equilibrium conditions. This is also true for

2lipid extraction from PHRB with hexane as the solvent, where the

extraction proceeds much faster and a higher equilibrium concentration is achieved

1 as the extraction temperature is increased from 30 to 60 °C

(Fig. 3a). In terms of the fraction of lipids extracted at equilibrium, 89.6–96.3% could be achieved within 2 h (Fig. 3b), and Fig. 2. Comparison of lipid extraction kinetics for RB and PHRB at different SSR and 60 °C under constant shaking speed of 200 rpm in terms of (a) lipid concentration; (b) percent lipid extracted. Fig. 3. Lipid extraction kinetic profiles for PHRB at constant SSR of 4 mL g⁻¹ under different extraction temperature (30, 45, and 60 °C) in terms of (a) lipid concentration in the liquid phase, and (b) percent lipid extracted or solubilized in the liquid phase, and at constant temperature of 60 °C with different SSRs (4, 8, 12 mL g⁻¹) in terms of (c) lipid concentration, and (d) percent lipid extracted or solubilized in the liquid phase. higher temperatures of 60 °C favoring a higher fraction of available lipids being extracted. Similar observations were made previously in the

2 extraction of lipids from RB with different solvents

, like hexane [17] and ethanol [14], where both the extraction rate and efficiency increased as the temperature was increased. This is because at higher temperatures viscosities of both lipids and solvent are reduced, while the solubility of the lipids in the solvent is improved, which favors the diffusion of the lipids into the solvent phase [14]. The decrease

3 in SSR from 12 to 4 mL g⁻¹ resulted in

a marked increase in the initial rate of extraction and the equilibrium concentration (Fig. 3c). In terms of the fraction of the lipids extracted, the influence of SSR is less significant ($p = 0.00392$) as compared to temperature ($p = 0.0001$), with up to ~96% of the lipids extracted even at a low SSR of 4 mL g⁻¹ (Fig. 3d). Studies on the influence of SSR during solid-liquid extraction have been limited as most studies choose to focus on a single SSR while investigating the kinetics of the extraction process. One of the earlier works on lipid extraction from rapeseed with hexane as solvent suggested that factors influencing the mixing of the solid and liquid phases would affect the observed rate of extraction, while further suggesting that kinetic coefficients are expected to decrease with the increase in SSR for extraction systems carried out at the same mixing conditions [19]. In a separate work involving the lipid extraction from olive cake with ethanol as solvent, it was observed that higher solvent to solid ratios improved extraction rates, mass transfer coefficients, and yields, while further suggesting that higher SSR values increase the concentration gradient [28], which in certain aspects contradicts the earlier idea. Both ideas presented by So & Macdonald [19] and by Meziane & Kadi [28] have merits but should be put in proper perspectives to avoid erroneous generalization. Extraction rates and extraction coefficients have been directly associated without consideration of the equilibrium concentration that limits and dictates the rate of extraction, while the solubility of the solute in the solvent used was not also accounted for. In principle, considering that the solubility and mixing conditions are not limiting, solid-liquid extractions will always be limited and influenced by the equilibrium concentrations. Thus, lower SSRs would tend to result in systems with higher concentration gradients and resulting in higher extraction rates. Diffusion or extraction coefficients may have to be considered separately from the extraction rate itself as these may be influenced by other factors.

3 To better understand the influence of temperature and SSR

, as well as the mechanism involved in the lipid extraction process involving PHRB and hexane, kinetic

11 **models were fitted to the** obtained **experimental data and**

is discussed in the following section. 3.2. Kinetic models and model parameters Five prominent extraction kinetic models (Table 1) were adopted in this study and fitted to the experimental data. Representative curve fitting results of the different models are presented in Fig. 4. Single-step extraction models like modified Fick's Law model ($R^2 = 0.9957$ to Fig. 4. Comparison of different fitted models based on (a and c) single and multiple step first order diffusion mechanism and (b and d) first order, second order and combined diffusion mechanism. 0.9984) and modified Peleg's model ($R^2 = 0.9943$ to 0.9991), despite having adequately high coefficients of determination, these models tend to overestimate the concentrations (Fig. 4c and d) before the equilibrium is reached and underestimates the equilibrium concentrations (Fig. 4a and b) and have high SEE of 0.06–0.32 g lipid per 100 g hexane, which could translate to an error of over ~4% of the equilibrium concentration (Table S2) with a mean absolute error ranging from 1 to 1.4%. Also, no apparent logical trend could be observed from the extraction coefficients as the temperature and SSR were increased. A closer inspection of the kinetic data would suggest that multiple equilibrium steps are involved, with the most apparent one taking place at around 2.5–5 min, for both RB and PHRB. The same was observed by Kamimura et al. [14] when carrying out the extraction of RB lipids with ethanol as the solvent and is also confirmed by Zuniga-Diaz et al. [17], stating that the main extraction mechanisms involved washing and a diffusion step when lipids from RB were extracted with n-hexane. Kinetic model parameters and some measures for the goodness of fit for the different multiple-step models are summarized in Table 3. All regression carried out with multi-step models resulted in coefficients of determination of at least 0.999, to further distinguish the best models to represent the kinetic data adjusted

14 **coefficients of determination (R^2_{adj}), root mean square error (RMSE), and**
standard **error of the**

mean (SEM) were adopted to further validate and qualify the models while taking into consideration physical significance of the resulting model predictors or coefficients. For RB, 2-step models (Patricelli's model and Linares's model) are adequate in describing the extraction kinetics of the lipids. So and Macdonald's model would best describe the lipid extraction kinetics for both RB and PHRB systems, with R^2_{adj} over 0.999 and higher than the single-step models, which indicates that no over-fitting was incurred, while reducing the prediction errors (Table 3) and having a mean absolute error of less than 1.1%. The multiple-step or in most cases referred to as multi-stage extraction mechanism does not necessarily mean distinct separate stages along the extraction process could be observed, but rather these so-called steps are actually occurring in parallel [19]. The most rapid step referred to as the washing step [19,20,29], pertains to the extraction of lipids which are most easily solubilized into the solvent. In the case of PHRB, these are those lipids found on the surface. At least 90% of the extractable lipids were readily extractable and are removed from the solid matrix during the washing step which occurs within 2.5–5 min of extraction. As for RB, up to 87% of the available lipids are extracted during the washing step. These coincide with previous findings where as much as 85% of lipid material from oilseeds could be removed by simple washing [19]. For RB and hexane system, it was previously reported that the activation energy based on a single step extraction model was estimated to be about 20.86 kJ mol⁻¹ [17] which is higher in comparison with estimated activation energy (6.8–7.3 kJ mol⁻¹) based on the washing step of So and Macdonald's model for PHRB. This implies that the lipids in PHRB were relatively easier to extract. The extraction coefficient for the washing step increases as temperature and SSR increases. This observation is consistent with what was observed by Meziane Kadi [28] for olive cake and ethanol system, & however, the rates were higher at lower SSR in the case of PHRB. This is observed probably because lipids from PHRB are very much soluble in Table 3 Summary of kinetic model parameters for a multiple step extraction mechanism. Biomass Post-hydrolysis Rice Bran

(PHRB) RB Temp (°C) 30 45 60 30 45 60 30 45 60 60 60 SSR (mL g⁻¹) Patricelli's Model k_{wc} (min⁻¹) C_{∞w} (g lipids per 100 g hexane) k_{dc} (min⁻¹) C_{∞d} (g lipids per 100 g hexane) C_∞ (g lipids per 100 g hexane) SEE R² R_{2adj} RMSE SE So & Macdonald's Model k_{wc} (min⁻¹) C_{∞w} (g lipids per 100 g hexane) k_{dc1} (min⁻¹) C_{d∞1} (g lipids per 100 g hexane) k_{dc2} (min⁻¹) C_{d∞2} (g lipids per 100 g hexane) C_∞ (g lipids per 100 g hexane) SEE R² R_{2adj} RMSE SE Linares' Model k₁ (min · 100 g hexane per g lipids) k₂ (100 g hexane per g lipids) R_{0w} (g lipids per 100 g hexane · min) k_{2nd} (100 g hexane per g lipids · min) C_{∞w} (g lipids per 100 g hexane) k_{dc} (min⁻¹) C_{∞d} (g lipids per 100 g hexane) C_∞ (g lipids per 100 g hexane) SEE R² R_{2adj} RMSE SE

4 4 2.4297 1.6087 15.8068 16.8254 0.0481 0.0037 0.7117 0.3960 16.5185 17.2214 0.0999 0.2278 0.9996 0.9982 0.9996 0.9979 0.0903 0.2061 0.0383 0.1992 3.8762 15.7786 0.0516 0.7267 0.0118 0.0137 16.5191 0.1064 0.9996 0.9995 0.0907 0.0386 4.2640 15.9235 0.4083 0.9442 0.0015 0.5658 17.4335 0.2393 0.9982 0.9977 0.2041 0.1953 1 × 10⁻⁵ 0.0634 100,004 401.59 15.7804 0.0506 0.7372 16.5175 0.1002 0.9996 0.9996 0.0385 0.0906 0.0034 0.0591 297.60 1.0397 16.9183 0.0008 0.7843 17.7025 0.2255 0.9982 0.9980 0.2039 0.1951 4 8 1.4030 1.8438 17.2115 7.7001 0.0159 0.1344 0.07183 0.5281 17.9299 8.2282 0.1920 0.0638 0.9988 0.9994 0.9986 0.9993 0.1736 0.0577 0.1414 0.0156 4.9818 3.9299 16.1928 7.4612 0.2118 0.2328 1.3073 0.7061 0.0044 0.0096 0.5612 0.0823 18.0614 8.2496 0.1793 0.0642 0.9991 0.9995 0.9988 0.9993 0.1529 0.0547 0.1096 0.0140 0.0074 0.0178 0.0569 0.1217 134.96 56.1308 0.4372 0.8315 17.5708 8.2159 0.0038 0.0037 0.5139 0.0502 18.0847 8.2662 0.1718 0.0617 0.9991 0.9994 0.9989 0.9993 0.1555 0.0558 0.1134 0.0146 8 8 2.1593 5.3100 7.8145 8.2370 0.1148 0.1254 0.6283 0.5062 8.4429 8.7432 0.0568 0.0630 0.9995 0.9995 0.9995 0.9994 0.0514 0.0570 0.0124 0.0152 4.4108 5.0063 7.7554 8.1714 0.1292 0.2003 0.6767 0.4900 0.0116 0.0051 0.0128 0.01474 8.4449 8.8089 0.0605 0.0549 0.9995 0.9996 0.9994 0.9995 0.0516 0.0468 0.0125 0.0103 0.0036 0.0108 0.1268 0.1153 276.14 92.2550 4.4403 1.2261 7.8861 8.6744 0.1153 0.0056 0.5588 0.1307 8.4445 8.8051 0.0569 0.0585 0.9995 0.9995 0.9995 0.9995 0.0515 0.0529 0.0124 0.0131 12 12 2.5707 3.3401 5.1467 5.0413 0.1178 0.2045 0.2753 0.5823 5.4220 5.6238 0.0338 0.0443 0.9996 0.9994 0.9995 0.9993 0.0305 0.0401 0.0044 0.0075 4.0020 4.4099 5.1206 5.0237 0.1399 0.2177 0.2907 0.5909 0.0116 0.0115 0.0125 0.0126 5.4238 5.6271 0.0358 0.0467 0.9996 0.9994 0.9995 0.9992 0.0305 0.0398 0.0044 0.0074 0.0199 0.0313 0.1847 0.1774 50.2037 31.8984 1.7131 1.0039 5.4135 5.6369 0.0043 0.0043 0.0160 0.0000 5.4295 5.6369 0.0379 0.0462 0.9995 0.9993 0.9994 0.9992 0.0343 0.0418 0.0055 0.0082 12 4 1.5007 1.0874 5.6620 5.3719 0.0188 0.0225 0.2518 0.6067 5.9138 5.9787 0.0513 0.0901 0.9992 0.9976 0.9991 0.9972 0.0464 0.0815 0.0101 0.0312 5.1999 1.1341 5.4289 5.3082 0.1732 0.0704 0.3405 0.2451 0.0047 0.0156 0.1905 0.4329 5.9600 5.9863 0.0503 0.0947 0.9993 0.9976 0.9991 0.9969 0.0429 0.0807 0.0086 0.0306 0.0190 0.0472 0.1731 0.1787 52.5996 21.1994 1.5763 0.6772 5.7764 5.5951 0.0055 0.0151 0.1748 0.3969 5.9512 5.9920 0.04724 0.0931 0.9993 0.9974 0.9992 0.9970 0.0427 0.0842 0.0086 0.0332 12 1.5199 2.0223 0.02436 0.2174 2.2397 0.0231 0.9989 0.9987 0.0209 0.0021 1.9309 1.9737 0.0944 0.1330 0.0132 0.1384 2.2451 0.0225 0.9990 0.9988 0.0192 0.0017 0.0539 0.4835 18.5662 4.3404 2.0682 0.0188 0.1749 2.2431 0.0221 0.9990 0.9988 0.0200 0.0019 hexane compared to olive oil in ethanol system. For olive cake and ethanol system, there was an observed increase in the extractable lipids as SSR was increased [28], which was not the case for PHRB, making PHRB and hexane system not solubility limited. Contrary to what So and Macdonald [19] proposed, the kinetic constants or diffusivities increased with the increase in SSR. This observation is valid considering that a higher amount of solvent would also lower down the system viscosity and avoids agglomeration of the solids and would thus, result in better diffusivities. The observed increase in the extraction co- efficiencies or diffusivities would also indicate that the process was not hindered by the mixing dynamics of the system. Unlike the washing step, no clear trends could be observed for the extraction or diffusivity co- efficiencies for the slow diffusional steps. These complexities may have surfaced from the fact that the diffusion of the lipids on the biomass surface may occur in both directions and what is estimated by the exiting models are only the apparent extraction or diffusion coefficients, which could be functions of other system variables and that of the concentra- tion of the lipids in the solvent and in the solid itself. Nevertheless, what is evident from the existing models is that the lipid extraction process from PHRB with hexane occurs in a multi-step mechanism with most of the lipids dissolved and extracted into the solvent in less than 5 min regardless of temperature and SSR.

3.3. Equilibrium data and thermodynamic parameters

Apart from the kinetics, which provides a better understanding of the possible mechanism involved in the process, it is also important to

consider the equilibrium information to aid the assessment of the process. Summarized in Table 4 are the equilibrium information of the extraction system investigated and corresponding process yields and recoveries under different temperatures and SSRs. The experimentally obtained overall equilibrium concentrations are well below the theoretical maximum concentration, which is expected as the process is limited by equilibrium and would not result in complete transfer of the solute from the solid phase into the liquid phase. Both the equilibrium concentration and the fraction of lipid extracted increased with temperature. Unlike the equilibrium concentration, which remarkably decreased as SSR was increased, the influence of SSR of the amount of lipid extracted was not as significant. From these equilibrium information, the thermodynamic parameters were estimated and presented in Fig. 5. The average Gibbs free energy based on the average equilibrium constant is well below zero, indicating that the process is generally spontaneous (Fig. 5a) Gibbs free energy as determined based on the distribution constants or coefficients (Fig. 5b) indicates that lower SSRs are more thermodynamically favored over higher SSRs and increasing the extraction temperature improves the spontaneity of the process. It can be further inferred from Fig. 5 that the process is endothermic ($\Delta H > 0$) and irreversible ($\Delta S > 0$). Reprocessing of available literature data [17] on the lipid extraction of lipids from RB with hexane at the same temperature range elucidated that the enthalpy for extraction of lipids from PHRB (29.0–32.7 kJ mol⁻¹) is comparable to RB (~29.16 kJ mol⁻¹). In the later actual processing of PHRB, the concern would not only be on the amount of lipid extracted or dissolved into the solvent, but rather the actual quantity that could be recovered. Also presented in Table 4 are corresponding recoveries for the various conditions investigated. Unlike the fraction of lipid extracted which could reach as high as 90% or better, the actual amounts of lipids recovered were much lesser. Higher SSRs facilitated better recoveries, whereby the increase from 4 mL g⁻¹ to 12 mL g⁻¹ resulted in improved recoveries from about 54% to – as much as 72%. The same trend is observed for RB and PHRB. In view of changes in temperature, the increase in temperature did not facilitate better recoveries. During separation of the miscella from the solids, some of the miscella is still left behind or entrained in the solids and the later filter medium used in aid of separation. This resulted in lower actual recoveries obtained as compared to the determined amount of lipid extracted or dissolved into the solvent. Although higher temperatures resulted in higher fraction of the lipids extracted and equilibrium concentrations, this also meant that more lipids are left entrained along with the entrained miscella. To compare the recoveries for RB and PHRB, recoveries were expressed in relative to the native RB. Higher amounts of lipids could be recovered when extracting from PHRB as compared to RB regardless if comparisons are to be made at the same SSR or SOR. To preliminarily assess the process the overflow and underflow, concentrations of solute and inert (Table 4) were first determined by material balance, these were then used to estimate the ideal equilibrium stages required to achieve complete recovery of the lipids assuming that the overflow and underflow concentrations ratio were constant and that the solvent to inert ratio was also maintained at each crossflow stage. To achieve the same relative recoveries based on the available lipids in the system an SSR of 8 mL g⁻¹ would suffice for PHRB while 12 mL g⁻¹ is required for RB (Fig. 6a and c). Moreover, if the same quantity of lipids is could further be decreased to 4 mL g⁻¹ implying a solvent economy of to be recovered in a single extraction stage with the use of PHRB the SSR 10.09 kg hexane kg⁻¹ lipid recovered as compared to RB which would require 64.69 kg hexane kg⁻¹ lipid recovered (Fig. 6b and c). This translates to savings in the solvent of over 80%, even if recoveries of up to 95% are to be achieved which requires at least 5 to 6 ideal crossflow extraction stages. Better recoveries and solvent economy is owed to the fact that PHRB is more lipid-dense than RB, which also means that lesser inert solids are present to hinder the separation of miscella. The successful recovery of lipids from PHRB may require consideration for the disposal of the remaining residue. In conventional solvent extraction of oils from oilseeds, the generated residues are first removed of the residual solvents prior to disposal or use as animal feed. In the case of PHRB, its later use as feed may not anymore be possible, since the solids have undergone partial carbonization and sulfonation when dried after the hydrolysis step. However, it was previously found that the solid itself exhibited catalytic activity, owing to sulfonic sites attached [30]. Future works may have to consider the further use of the residue

or better yet, explore the possibility of employing in-situ transesterification of the lipids in the PHRB. In line with its potential application for biodiesel production, the recovery and use of rice bran in Taiwan would translate an estimated amount of about 17,000 m³ of biodiesel that could be produced annually, based on the paddy rice production in 2018 (1.95 Mt [31]).

4. Conclusions Lipids in RB could be densified by subjecting the native biomass to dilute acid hydrolysis, where by the resulting PHRB is 3 times as dense in terms of its lipid content. Further, slightly higher amounts of lipids of up to 0.21 kg could be recovered instead of 0.17 kg per kg of moisture-free bran processed. The lipids from PHSRB have similar fatty acid profile with the native RB and are found suitable as raw material for biodiesel production. In the extraction of lipids from PHRB, increase in temperature and lower SSR improves the rates of lipid extraction. Regardless of temperature or SSR, ~

990% of the extractable lipids are solubilized in hexane in less than 10 min. In

terms of recoveries, higher SSRs allows better actual recovery of the lipids but lower SSR results in extract with higher concentrations. The extraction of lipids from PHRB involves 3 mechanisms, a rapid washing step and 2 diffusion steps, which could be best described by So and Macdonald's model ($R^2 \geq 0.999$). The extraction process was found to be exergonic ($-8.9 \Delta G \leq -5.6 \text{ kJ} \leq \text{mol}^{-1}$), endothermic ($\Delta H 30.8 \text{ kJ mol}^{-1}$) and irreversible ($\Delta S 0.12 \text{ kJ mol}^{-1} \text{ K}^{-1}$), with lower SSRs found to be more thermodynamically favored. Under favorable conditions, employing an SSR of 4 mL g⁻¹ would require at least 5 crossflow extraction stages to achieve lipid recovery of over 95% or ~0.20 kg of lipids obtained per kg of moisture-free bran subjected to the hydrolysis process and subsequently extracted of its lipids. Extraction of lipids from PHRB provides potential

Table 4 Equilibrium data* of lipid-hexane-inerts for RB and PHRB at different temperature and

6solvent-to-solid ratio. T (K) SSR (mL g

– 1) Theoretical Maximum Concentration (g lipid per 100 g solvent) Kinetic Model Based Concentration# (g lipid per 100 g solvent) Actual Concentration (g lipid per 100 g solvent) Lipid Lipid Extracted Yield_PHRB (g lipid per g dry PHRB or RB) Lipid Yield_RB (g lipid per g Dry RB) Lipid Recovery_PHRB (%) Lipid Recovery_RB (%) Overflow, X (g solute per g solution)c Underflow, Y (g solute per g solution)d underflow, N (g inert per g solution)e Post-Hydrolysis Rice Bran (PHRB) 304.15 4 18.29 318.15 4 18.29 333.15 4 18.29 304.15 8 9.17 10 318.15 8 9.17 333.15 8 9.17 304.15 12 6.13 318.15 12 6.13 333.15 12 6.13 Rice Bran (RB) 333.15 4 6.04 333.15 12 2.26 16.52 (0.11)a 17.43 (0.24) 18.06 (0.18) 8.25 (0.06) 8.45 (0.06) 8.81 (0.05) 5.42 (0.04) 5.63 (0.04) 5.96 (0.05) 5.98 (0.09) 2.24 (0.02) 16.51 (0.02) 17.05 (0.20) 17.83 (0.17) 8.24 (0.02) 8.44 (0.01) 8.75 (0.06) 5.42 (0.01) 5.67 (0.04) 5.89 (0.01) 5.97 (0.04) 2.24 (0.01) 90.51 (0.51) 94.09 (0.96) 96.48 (0.69) 89.00 (1.21) 92.49 (0.33) 95.67 (0.46) 89.55 (0.37) 92.29 (0.98) 96.28 (0.01) 0.25 0.26 0.26 0.32 0.33 0.33 0.34 0.35 0.35 98.67 (0.31) 98.93 (0.21) 0.07 0.12 0.11 52.28 (0.34) 0.11 54.16 (0.42) 0.11 54.01 (0.33) 0.14 65.53 (0.30) 0.14 67.17 (0.33) 0.14 67.16 (0.61) 0.15 70.74 (0.37) 0.15 72.09 (0.67) 0.15 72.25 (0.00) 0.07 42.68 (0.70) 0.12 68.33 (0.29) 62.83 (0.41) 65.10 (0.50) 64.91 (0.40) 78.75 (0.36) 80.72 (0.40) 80.71 (0.74) 85.02 (0.45) 86.64 (0.80) 86.83 (0.00) 42.68 (0.70) 68.33 (0.29) 0.142 0.145 0.151 0.076 0.078 0.080 0.051 0.054 0.056 0.056 0.022 0.172 0.165 0.160 0.106 0.100 0.092 0.079 0.071 0.067 0.057 0.022 0.404 0.403 0.391 0.345 0.340 0.314 0.302 0.288 0.271 0.534 0.378 *Average of values observed from 120 min to 480 min; #based on So and Macdonald's Model; aStandard error of estimate; bStandard deviation; cCalculated based on the experimental lipid concentration; dSolute and solvent left behind determined by material balance based on lipids recovered and experimentally determined lipid concentration; eMoisture and solids are assumed to compose the inert fraction and is solely found in the underflow, while mass of solution is determined by material balance of lipid and solvent left in the extraction flask. A.W. Go et al. Biomass and Bioenergy 142 (2020) 105773 Fig. 5. Gibbs's free energy as a function of

temperature and thermodynamic parameters entropy ($-\Delta S$, slope) and enthalpy (ΔH , intercept) on the extraction of lipids from PHRB, based on (a) average equilibrium constants (K_c) and (b) distribution coefficient (K_d) at different solvent-to-solid ratio. Fig. 6. Mass balance of lipid extraction from PHRB at fixed SSR of (a) 8 mL g⁻¹ & (b) 4 mL g⁻¹, and (c) RB at fixed SSR of 12 mL g⁻¹ at 60 °C, for each crossflow extraction stage at constant underflow (N) and underflow (Y) to overflow (X) solute concentration ratio (constants from Table 4). solvent savings of over 80% compared to what is required for RB in the recovery of the same amount of lipids. Dilute acid hydrolysis as a pre- treatment step for lipid-containing residues like RB could potentially be adopted not only as an effective

1 means of maximizing the use of

biomass components but also as a means to improve productivity and reduce cost of subsequent processing steps. Declaration of competing interest None. *

3 Obtained after subjecting RB to dilute acid hydrolysis with 3 %v/v

H₂SO₄

3 at an SSR of 8 mL g⁻¹ (based on dry and lipid-free biomass) for 6 h – at 90 °C with intermittent shaking (30 min interval); aMoisture as ° received (expressed in wet basis

). bMoisture

3 after oven drying (expressed in wet basis); cExpressed in dry basis; dExpressed relative to the native dry biomass and in dry basis (dry matter yield after hydrolysis

= 43.16 ± 1.98%); eExpressed relative to the extracted lipids, fFatty

1 acid profile/distribution expressed as percent relative abundance (%w/w) based on chromatographic areas of detected fatty acid methyl esters

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4Appendix A. Supplementary data Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biombioe.2020.105773>. **References**

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