BioEnergy Research (2020) 13:618–629
https://doi.org/10.1007/s12155-019-10061-2

Co-pelletization of Microalgae-Sewage Sludge Blend with Sub-bituminous Coal as Solid Fuel Feedstock

Nazia Hossain [1] · Nurul Afiqah Haji Morni [2]

Published online: 25 October 2019

Abstract

Microalgae have been appeared as excellent source of bioenergy recently in Brunei Darussalam due to the favorable growth conditions, while sewage sludge emerged as major threat to the environment. Therefore, the challenge of sewage sludge management and microalgae utilization has spurred the demand of developing an innovative approach to utilize these sources for commercial applications. Hence, the main objective of this study was to characterize the bioenergy properties of microalgae, sewage sludge, and different blending ratios of microalgae-sewage sludge incorporated with sub-bituminous coal. Among three different blended samples, sample mixture 1 (SM-1) combined with 25% microalgae, 25% sewage sludge, and 50% coal presented the highest calorific value of 16.57 MJ/kg and lowest ash content of 45.61%. Along with this, SM-1 also manifested the highest values for pellet density (1.23 g/cm^3) and energy density (20.41 GJ/m^3) that can be referred as the most favorable values among all co-pelletized samples for transportation and logistics. Besides the characterization of raw samples, this study also emphasized on elemental analysis of ash content to determine the possibility of fouling and slugging. Ash analysis of all blends represented the major inorganic components aluminum (Al) and silicon (Si). Thermogravimetric analysis of all samples demonstrated the different phases of pyrolysis and combustion within 50 to 900 °C at heating rate of 10 °C/min. It can be concluded that this study recommended SM-1 as a potential feedstock for solid fuel purpose.

Keywords Co-pelletization · Sub-bituminous coal · Microalgae · Sewage sludge · Thermogravimetric analysis · SEM-EDX

Introduction

In the eve of this modern era, the demand of fossil fuel (petroleum oil, gas, and coal) is increasing day by day worldwide due to the excessive use of energy that results in fossil fuel depletion as well as tremendous environmental pollution. Therefore, energy sector and environmentalists are striving to look for renewable energy sources to minimize the environmental pollution and mono-dependency on fossil fuel [1–4]. In this scenario, microalgae caught substantial attention due to its distinct characteristics such as high biomass productivity, large amount of cellulosic oil content, fast growth rate, and favorable growth conditions in weather divergence. Nowadays many studies are being conducted all over the world on liquid fuel such as biodiesel, bioethanol, biobutanol, and biomethanol besides biomethane and biohydrogen production from microalgae since liquid fuels can easily be blended with diesel and gasoline for transportation purpose [5–9]. Compared with liquid fuel, very limited experimental studies were performed for solid fuel purpose. However, liquid fuel production is beneficial while energy content (calorific value) of microalgae is high. In the case of low amount of calorific value, solid fuel can be the best option in terms of pre-treatment and purification cost [10–12]. According to the previous studies, naturally grown microalgae from wastewater contained low energy content (8–11 MJ/kg) and the liquid biofuel production from them is economically unfavorable [13, 14]. Hence, studies were carried out on wastewater-borne microalgae for direct combustion to produce heat and energy [13, 15]. On the other hand, recently wastewater

We undertake and agree that the manuscripts submitted to your journal have not been published elsewhere and have not been simultaneously submitted to other journals.

✉ Nazia Hossain
bristy808.nh@gmail.com

Nurul Afiqah Haji Morni
afiqah.91n@gmail.com

[1] Department of Civil and Infrastructure Engineering, School of Engineering, RMIT University, Melbourne, VIC 3001, Australia

[2] Faculty of Integrated Technologies, Universiti Brunei Darussalam, Jalan Tungku Link, Gadong BE1410, Brunei Darussalam

treatment plants are facing a major issue concerning the increased volume of urban wastewater, particularly the production of sewage sludge. Sewage sludge is the solid, semi-solid, or liquid products produced from wastewater treatment plants, and disposal of sewage sludge to the open environment causes severe environmental hazards and that plays negative impact on environment. In consequences, sludge is being experimented to convert into energy everywhere as a suitable waste management approach. Owing to high inorganic compounds and low energy content, sewage sludge is mostly used for solid fuel feedstock. Hence, it is deemed as another potential waste for energy production all over the world as a form of waste management [16–18]. However, application of sewage sludge contains several drawbacks such as high moisture content in raw sample and large ash content after combustion which causes complications for combustion process such as adverse impact on thermal behavior of fuel and the combustor's design. High sewage sludge moisture content can significantly reduce the energy content and eventually lead to incomplete oxidation [16]. Therefore, sewage sludge must be properly dried prior to combustion. The high ash content allows the ash to slag and agglomerate at the combustor reactor wall. This would reduce the thermal efficiency of the combustion process and increase the operating costs of the reactor [17]. Recent studies are gaining interest on co-blending of sewage sludge with other solid fuels. Blending sludge with other solid fuels such as coal and other biomass has been observed to increase reactivity and reduce the reaction time of fuel mixtures during combustion due to high sludge volatility [19, 20]. It was also observed that slagging of sewage sludge ash was reduced due to co-blending with agricultural waste, rice husk, and decrease in heavy metal emissions [21, 22].

This study focused on the wastewater microalgae combined with sewage sludge combustion for heat production in Brunei Darussalam since sewage sludge disposal is a major environmental concern in the country and microalgae is overgrown in the drain water. Another significant issue behind experimenting the biofuel properties of drain water microalgae is that the drainage system in Brunei Darussalam is well organized and it rains there throughout whole year. Therefore, continuous microalgae growth has been projected from drain ways [23, 24]. Brunei Darussalam, located in Southeast Asia, is a country blessed with petroleum oil and gas. In line with that, immense application of fossil fuels in the country tended the highest carbon dioxide emission to the environment among Southeast Asian countries. To reduce fossil fuel monopolization as well as environmental pollution, the country has emphasized on potential renewable energy sources such as rice husk, *Acacia* sp., microalgae, and others biomass for biochar and bio-oil [25–27]. Besides microalgae from wastewater, sewage sludge is also projected as a new feedstock recently since several sources in the country are generating sludge in quite large amount, although no potential planning has been done for sludge management [24]. A previous microalgae study in Brunei Darussalam delineated adequate biofuel potential blended with sub-bituminous coal that encouraged this study to be performed further with sewage sludge addition [15].

The aim of this study was to determine the potential of the sewage sludge and microalgae mixture as solid fuel feedstock. Different blending ratios of microalgae sewage sludge blend incorporated with sub-bituminous can project the most favorable combination for better combustion output. To the author's best knowledge, there was no research study in the literature performed on sewage sludge-microalgae-coal mixture as solid fuel material. Moreover, lack of knowledge and information is another barrier for co-pelletization owing to very less research experiments on co-pelletization so far. The most related experimental study performed was the combustion characteristics of sewage sludge and algae in India where merely bulk density, moisture content, calorific value, and ash content were determined [28]. Some other studies presented co-pelletization of microalgae with woody biomass and microalgae with coal only [1, 15]. Previous co-pelletization study was confined to the identification of the major elemental composition: carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S), and proximate analysis [1]. In comparison with that, this study included proximate analysis, major and minor elemental composition analysis, and thermogravimetric analysis which are considered as significant analyses to demonstrate the combustion characteristics. Besides, this study simultaneously emphasized on the ash analysis after combustion process. Ash analysis can project the slugging and fouling profile of the biomass blend that leads the possibility of environmental pollution and corrosion in furnace during combustion. In line with proximate and thermogravimetric analysis, this research also determined bulk density, pellet density, and energy density, and all these factors are regarded as the fundamental factors for transportation and logistics analysis.

Materials and Methods

Materials

Three different materials were investigated in this research: sewage sludge, microalgae, and sub-bituminous coal. Dried activated sewage sludge (SS) was collected from Gadong wastewater treatment plant, Brunei Darussalam, after secondary treatment by activated sludge system. Figure 1 presented the schematic diagram of sewage sludge generation from wastewater treatment plant. Mixed microalgae species, *Stigonematales* sp., were obtained from the rainwater drain ways at the Universiti Brunei Darussalam (UBD) campus,

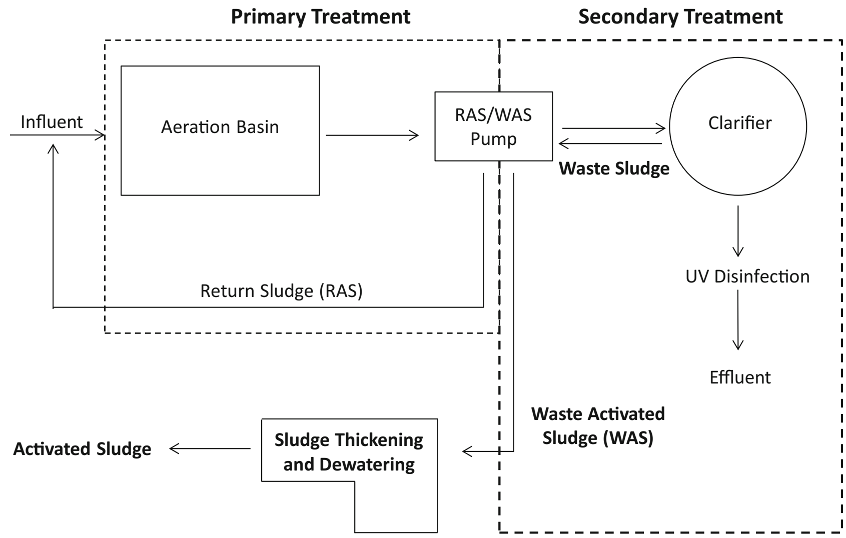

Fig. 1 Schematic diagram of sewage sludge generation from wastewater treatment plant

and sub-bituminous coal was purchased from local market of Indonesia.

Characterization of Bioenergy Properties

Three different samples were pre-treated separately. Microalgae were sun-dried for 2 weeks and sewage sludge was oven-dried at 103 °C for 24 h. All samples were crushed separately by mortar and pestle and sieved through 45–50-μm (diameter) test mesh sieve for fine powder. Then, samples were blended into 3 different ratios stated at Table 1.

One gram of each pure sample and blended sample was pelletized and characterized. The characterization parameters, ASTM (American Society for Testing and Materials) methods, determining formulae, operating machines, and conditions are tabulated in Table 2. Analyses for physical properties (bulk density and energy density) were determined through laboratory experiments. Proximate analysis (moisture content, calorific value, and ash content) was conducted by laboratory tests. Physical property (energy density) was calculated from energy density and calorific value. Morphological and elemental analysis of all pure, blended and ash samples as well as thermal behaviors of pure samples during pyrolysis (by the presence of nitrogen) and combustion (by the presence of air) was performed by laboratory experiments. All experiments were repeated several times, and average value was counted as the final data.

Results and Discussion

Physical Analysis

Bulk density, pellet density, and energy density of pelletized biomass are referred as significant parameters for transportation and logistics purposes. In this study, pellets were manufactured by using a manual hand pelletizer in laboratory scale. Though the pellet sizing was uniform for all samples, the pressure for pelletization was indefinite which might be considered as non-standardized size for commercial approach. Moreover, it implies a process which is very different from industrial ones. Therefore, further research can be carried out to implement various types of pelletization methods (e.g., hydraulic press, extrusion, kiln, pellet mill) for different scales such as laboratory, pilot, and plant scale according to the characteristics of the manufactured pellets.

The mass and volume of pellets to determine the pellet, the bulk, and energy density of all pure and blended samples have been presented in Table 3. The results revealed that microalgae biomass is lighter than sewage sludge where fossil fuel sub-bituminous coal is much heavier than both biomass samples. Pure coal contained the maximum energy density while microalgae contained the minimum value. Therefore, microalgae and sewage sludge samples will require more space during transportation and storage with either powder or pellet form and that leads to higher expense for this purpose. A previous

Table 1 Samples mixture with different ratios

Mixed sample name	Mixture (%)
Sample mixture 1 (SM-1)	Microalgae (25%) + sewage sludge (25%) + bituminous coal (50%)
Sample mixture 2 (SM-2)	Microalgae (50%) + sewage sludge (25%) + bituminous coal (25%)
Sample mixture 3 (SM-3)	Microalgae (25%) + sewage sludge (50%) + bituminous coal (25%)

Table 2 Characterizing parameters, ASTM methods, determining formulae, operating machines, and conditions

Characterization parameters	ASTM methods	Determining formulae	Operating machines and conditions
Bulk density	ASTM D1895-96 [42]	$Bulk\ Density = \frac{m}{V}$ where m = mass of the sample (g) and V= volume of the sample (m^3).	0.1 L volume beaker, analytical balance
Pellet density	-	$PD = \frac{m}{V}$ where m = mass of the sample (kg) and V = volume of the sample (m^3).	Hand pelletizer (C-200 by P.A. Hilton, UK), digital vernier calipers
Energy density	-	$ED = NCV \times BD$ where ED = energy density (J/m^3), NCV = net calorific value (J/kg), and BD = bulk density (kg/m^3).	-
Moisture content	ASTM D 2974-87 [43]	$\%MC = \frac{Original\ weight - Oven\text{-}dry\ weight}{Original\ weight} \times 100\%$	Analytical balance, oven; temperature: 100 ± 5 °C
Calorific value	ASTM E711-87 [44, 45]	$LHV = \frac{\varepsilon\theta - m_c q_c - m_w q_w}{m_f}$ where LHV = net calorific value (J/kg), ε = heat equivalent to bomb (MJ/K), θ = effective temperature rise (K), m_c = mass of cotton thread (g), m_w = mass of wire (g), m_f = mass of fuel, q_c = calorific value of cotton thread (J/g), and q_w = calorific value of wire (J/g).	Digital bomb calorimeter (C-200 by P.A. Hilton, UK); oxygen pressure: 25 psi
Ash content	ASTM E1534-93 [46]	$AC\% = \frac{Final\ mass\ of\ residue\ (g)}{Original\ mass\ of\ the\ sample\ (g)} \times 100\%$	Tubular furnace; temperature: 600 °C ± 3 °C for 3 h
Scanning electron microscopy (SEM), energy dispersive X-ray (EDX) analysis	-	-	Schottky Field Emission Scanning Electron Microscope, JSM-7610F (Japan Electron Optics Laboratory Co. Ltd., Japan); pressure: 3Mpa, vacuum environment
Thermogravimetric analysis	ASTM E1131 [47]	-	Thermogravimetric analyzer (TGA7, Perkin Elmer, USA); temperature: 50 °C to 900 °C at 10 °C/min

experimental study on sewage sludge-microalgae powdered samples collected from different locations in India showcased that sewage sludge sustained bulk density of 830–1080 kg/m^3 which is higher than that of the experimented sample of this study. Besides sewage sludge, green algae species, e.g., *Hydrodictyon* sp., *Lyngbya* sp., *Microcystis* sp., and *Pithophora* sp., grown in several reservoirs presented bulk density of 910–1070 kg/m^3 that is also higher than that of the experimented sample of this study [28]. Another study of microalgae-pine sawdust co-pelletization presented that *Chlorella vulgaris* grown in freshwater in a photobioreactor has bulk density of 646.83 ± 12.34 kg/m^3 which is in similar range with that of the experimented microalgae [1]. On the other hand, SM-2 containing the highest microalgae proportion (50%) presented the largest amount of bulk density and pellet density due to the fluffy characteristics of microalgae while energy density was the highest for SM-1 due to 50% coal content.

Proximate Analysis

Proximate analysis containing moisture content, calorific value, and ash content plays a pivotal role for fuel processing technologies of biomass due to its energy content and combustion characteristics. Based on the outcomes of Table 3, all pure and blended samples contained moisture content in the range of 3.21–5.95% which is very low and suitable for combustion purpose. Sewage sludge and sub-bituminous coal were collected as dry sample, although microalgae were wet sample. After microalgae collection, this biomass was sun-dried unless it turned into crispy formation. Therefore, no additional energy and expense was required for the drying purpose in laboratory scale. Due to the geographical location, Brunei Darussalam contains direct sunlight with high temperature and no cold weather exists throughout the whole year which may even save a significant amount of the drying cost/energy for pre-treatment purpose in pilot or large-scale scenario, although sun-drying has not been encouraged for

Table 3 Physical properties and proximate analysis of the experimented samples

Physical properties	Pure microalgae	Pure sewage sludge	Pure coal	Sample mixture 1	Sample mixture 2	Sample mixture 3
Bulk density (kg/m^3)	673.07	691.33	922	517	684.06	505
Mass of pellet (g)	0.5	1.07	0.2	1.03	1.02	1.01
Volume of pellets (cm^3) (length × width × height)	0.57 × 1.0 × 1.0	1.18 × 1.02 × 1.02	0.214 × 1.306 × 1.0	1.04 × 1.01 × 1.01	0.95 × 1.01 × 1.01	0.97 × 1.01 × 1.01
Pellet density (g/cm^3)	1.18	1.10	0.71	1.23	1.5	1.34
Energy density (GJ/m^3)	5.76	8.90	21.31	20.41	13.84	14.21
Moisture content (%)	5.13	3.12	3.21	5.95	5.84	5.28
Calorific value (MJ/kg)	8.57	8.04	29.78	16.57	10.46	10.56
Ash content (%)	72.4	62.60	11.25	45.61	54.66	53.21

commercial applications to produce bioethanol from microalgae in Brunei Darussalam since this source of heat cannot be controlled [29, 30]. A life cycle assessment of bioethanol production from microalgae in this country presented that the total required heat and electricity for drying wet microalgae for bioethanol production were 16.48 MJ/kg and 1.23 MJ/kg, respectively [30]. However, in the case of solid fuel, moisture content does not need to be removed 100% from biomass for good quality pellet formation, though very high moisture content of the biomass affects strongly the combustion process (e.g., lowering flame temperature and boiler efficiency) which consequences incomplete combustion as well as other operational complications [31, 32]. An experimental study on wood pellet quality by Idaho National Laboratory of the US Department of Energy presented that moisture content of the pellets is one of the most crucial factors for safe storage, efficient transportation, and combustion. This study also mentioned that higher moisture content (> 15%) in the pellets can lead to spoilage during storage due to microbial decomposition, while very low moisture (< 3%) can result in low durability, lead to produce more crumbles, and generate more fine particles during storage and transportation which can be considered as loss of biomass. This study demonstrated good pellet quality for biofuel can be achieved within 10–15% moisture content [31]. This study emphasized on pellet formation instead of biological conversion processes, and the laboratory scale obtained crispy microalgae biomass within 2 weeks of continuous sun-drying and 3.21–5.95% moisture content for all the samples. Hence, sun-drying process still can be projected for primary drying purpose for large-scale application, and later, sun-dried biomass can be fully dried through some additional heat which is more sustainable for economical perspective.

Calorific value of pure microalgae and sewage sludge was truncated that leads unelevated outcome for blended samples SM-2 and SM-3 as well. SM-1 delineated moderate range of energy content due to the higher proportion of coal. Besides energy content, SM-1 also maintained lower ash content compared with the pure biomass samples as well as SM-2 and SM-3. It is worth to note that large amount of ash content causes technical impediments during combustion as well as corrosion in furnace, fouling, and environmental pollution, although sometimes chemical leaching enhances combustion intermediaries for biofuels [13, 15]. Previous studies mentioned that sewage sludge and microalgae from wastewater showed calorific values of 7.5–16 MJ/kg [1, 28] and microalgae-sewage sludge blends presented 16.53–20.02 MJ/kg with high energy content (23.52 MJ/kg) of microalgae [33]. With 50% coal, SM-1 sample can accumulate the microalgae and sewage sludge with medium amount of energy production that leads to waste management and greener environment simultaneously. Since calorific values of microalgae and sewage sludge in this study are quite low, the energy profile of these waste biomass do not look attractive to be implemented solely for industrial applications, although both feedstocks can be obtained free of cost. However, proximate analysis of the samples also presented high ash content which can be considered as major obstacle for environment as well as industrial applications. To get rid of this issue, ash could be used for wastewater treatment as activated carbon or tool for soil amendment [34, 35]. A previous study in Poland demonstrated that biomass ash integrated with sewage sludge was applied in agricultural practices especially in fertilizing perennial plant plantations, and this inexpensive natural fertilizer reduced the total bacterial in soil by 83–89% in laboratory scale and 40–53% in technical scale [34]. Another experimental study presented that waste biomass ash was employed as low-cost alternative to commercial activated carbon in wastewater treatment for leather dye and heavy metals removal [35]. Waste biomass especially sewage sludge is a crucial environmental challenge all over the world, and environmentalists are striving to identify new approaches to utilize sewage sludge in large scale instead of dumping into environment [14]. Therefore, to meet the better environment and waste management goals, this study experimented coal blend with the waste samples since coal has been established as the finest combustion material in various industries from decades ago due to its high energy and low ash profile. Since coal is a fossil fuel and non-renewable source, mixture of waste biomass with coal will provide better sustainable outlook for industrial approach [23].

According to the experimental outcomes, microalgae from drain water and sewage sludge contained almost similar range of calorific values, moisture content, ash content, and elemental composition as well as thermogravimetric characteristics. Hence, they can be combined and utilized together as the general source of waste materials. However, both waste samples contained high ash content which is the major limitation to implement these samples for co-combustion. Therefore, it is recommended to combine sewage sludge and microalgae separately with coal as well as the waste sample mixture possibilities in terms of percentages should be much lower (approximately 3–10%) for further research so that the resulting fuel have a more feasible ash percentage. Since the waste management is a major concern in the country, after application of microalgae and sewage sludge for biofuel purpose, the ash is recommended further either for wastewater treatment to accumulate heavy metals or soil amendment purpose.

Morphological Analysis

The three different combinations of microalgae pellets and their ash samples were analyzed through scanning electron microscope while SEM images were represented at Fig. 2 as (a) SM-1 raw sample, (b) SM-2 ash sample, (c) SM-2 raw sample, (d) SM-2 ash sample, (e) SM-3 raw sample, and (f) SM-3 ash sample.

SEM experiments for all samples were on similar conditions with carbon-coated specimens, secondary electron image (SEI) detector at low voltage, 5.0 kV, 8.3-mm working distance (WD), 10-m scale bar, and × 1000 magnification. In Fig. 2, SM-1 raw sample images presented quite dusty with scattered fine powder on the top while SM-2 raw sample was comparatively more congested and SM-1 showed the most robust and non-porous solid form. SM-2 and SM-3 both raw pellets did not represent dusty layer on top. According to the previous study, microalgae were transformed into pellets easily during pelletization while coal pellets were very brittle to be pelletized [15]. Therefore, SM-1 pellets seemed most dusty due to the highest coal (50%) presence. However, no binder has been applied for this pelletization technique. Binder application may improve the pellet's robustness. For the ash samples, SM-1 did not change much; only dustiness has disappeared but SM-2 ash samples showed that all particles over raw pellets have been combusted well and turned to solid ash with some cracks on the surface. SM-3 ash samples seemed more solidified and biochar type with much lighter color. It is evident that SM-3 contained the highest (50%) amount of sewage sludge and presented the best formation of pellet and ash.

Elemental Analysis

Elemental analysis was carried out to determine the presence of elements present in the specimens since elemental analysis by EDX provides both semi-qualitative and semi-quantitative information of the samples [36]. The purpose of elemental analysis of pure samples, blended samples, and ash samples of this study was to determine the elemental composition for all sets of samples as well as compare the elemental variations between raw and ash samples. Elemental compositions of solid components in pure and blended samples have been tabulated in Table 4. Table 4 presented the highest carbon content in bituminous coal and lowest in sewage sludge among pure samples. But among the blended sample, SM-3 presented the highest carbon content, though SM-3 contained 50% sewage sludge. In contrast, SM-3 presented the largest amount of oxygen (O) content, while SM-2 contained the lowest O content among all pure and blended samples. To be noted, coal presented minor oxygen presence which is one of the characteristics of perfect fuel [13]. Consequently, O/C was almost negligible for coal. O/C for sewage sludge was too high compared with experimented microalgae in this study as well as other biomass for fuel purpose [13, 15]. O/C for SM-2 and SM-3 are in similar range, while SM-1 contained little lower O/C than other blended samples. A previous study presented that most of potential biomass for biofuel such as bamboo, wood, miscanthus, straw, husk, and diverse type of microalgae carried O/C less than 1 [15]. Table 5 has presented the elemental weight (%) and atomic weight (%) of pure biomass ash samples performed by tube furnace, while Table 6 presented elemental composition of mixed biomass ash samples performed by tube furnace and bomb calorimeter. The results from Table 5 demonstrated that carbon (C) and silicon (Si) are common ash elements of pure biomass ash samples. Since the silicon content is quite high in ash elements, the ash is recommended to be utilized for wastewater treatment before disposal. Nowadays experiments are ongoing to treat wastewater with biomass ash enriched with silica [35, 37]. For microalgae sample, carbon content reduced from 30.30 to 6.91% after combustion while carbon content for sewage sludge dropped down from 8.71 to 6.74% after combustion which presented low combustion quality for sewage sludge. This may occur due to less volatility and presence of higher amount of ceramide solids in the raw sewage sludge [38]. A previous experimental study of sewage sludge combustion also presented that dried sewage sludge that contained 28.7% volatile matters and large amount of ceramic solids resulted in low carbon combustion and 67.8% ash content [38].

In contrast, coal does not contain any oxygen (O) content after combustion while microalgae and sewage sludge still

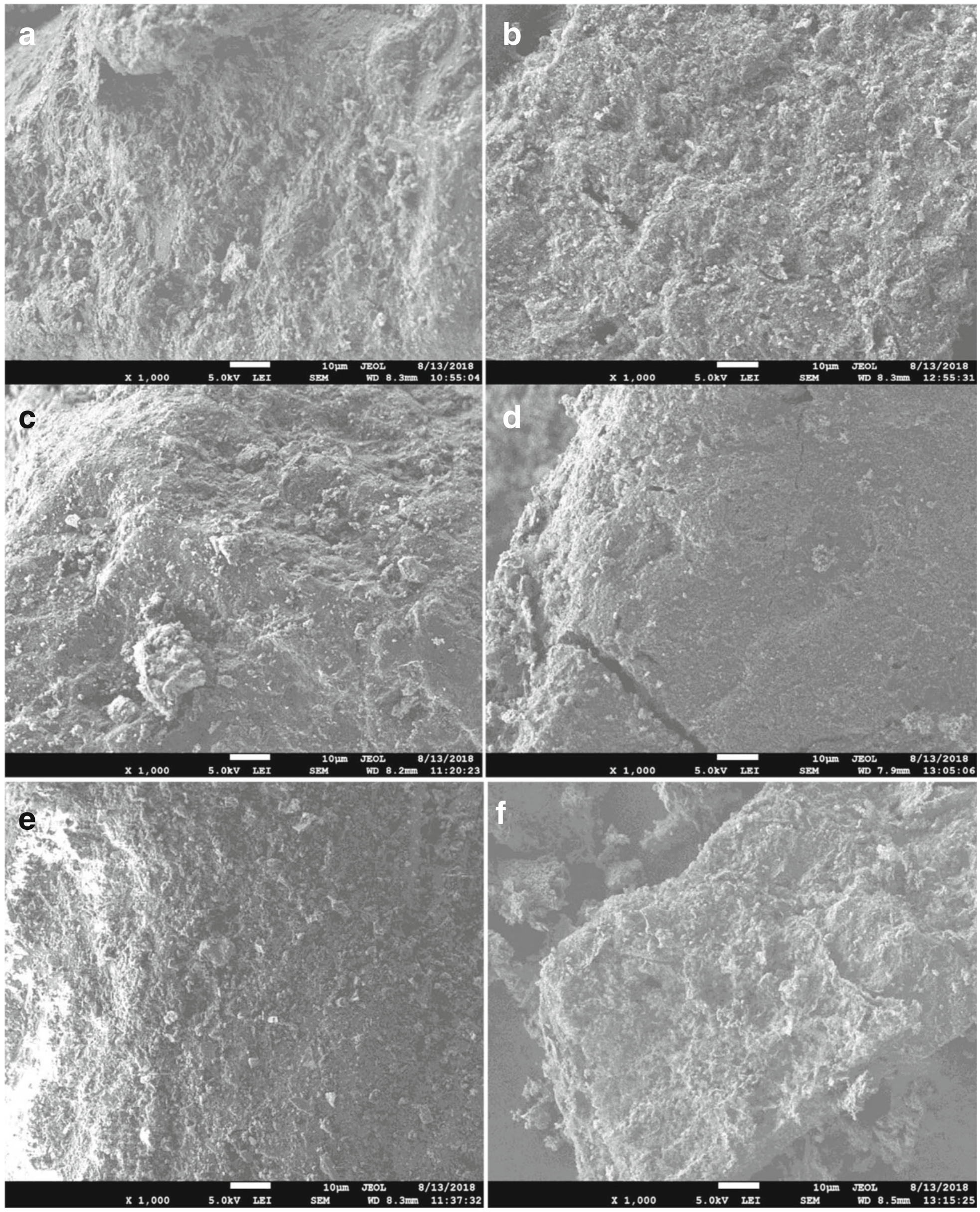

Fig. 2 Scanning electron microscopy of blended raw and ash samples. **a** SM-1 raw sample. **b** SM-2 ash sample. **c** SM-2 raw sample. **d** SM-2 ash sample. **e** SM-3 raw sample. **f** SM-3 ash sample

have oxygen content. Apart from that, aluminum (Al), sulfur (S), potassium (K), iron (Fe), phosphorus (K), calcium (Ca), magnesium (Mg), and titanium (Ti) remained for these samples. Based on Table 5, for the mixed biomass ash samples, presence of C, O, Si, and Al was noticed as common elements while potassium (K), calcium (Ca), zinc (Zn), copper (Cu), titanium (Ti), telenium (Te), sulfur (S), and phosphorus (P) appeared as minor elements. A previous experimental study of sewage sludge-biomass ash analysis presented inorganic minerals, e.g., Al_2O_3, Fe_2O_3, CaO, MgO, SiO_2, Na_2O, K_2O, P_2O_5, in ash content. This study also mentioned higher amount of these metal oxides could form slag melt (liquid phase) during combustion that may lead to condensation on the cooler regions of the boiler and cause temperature falling. Another consensus was that chlorine (Cl) presence in ash content accelerates the evaporation rate and acts as high-temperature transport medium for potassium and sodium which leads severe ash-related hassles for combustion system [39]. Ash compositions of this study presented low amount of inorganic minerals and zero content of Cl that projects less alkali-induced slagging formation which is very favorable for combustion process.

Thermogravimetric Analysis

Figures 3 and 4 presented the thermogravimetric and derivative thermogravimetric curve of microalgae, sewage sludge, and coal, respectively. This TG-DTG profile of these samples revealed an initial weight loss at 100 °C for coal, between ambient temperature and 160 °C for microalgae, and between

Table 4 Elemental composition of biomass raw samples

Elements	Sample type	Weight (%)	Atomic weight (%)
Carbon (C)	Microalgae	30.30	41.28
	Sewage sludge	8.70	16.53
	Coal	61.92	63.60
	SM-1	9.80	32.44
	SM-2	12.30	16.38
	SM-3	15.89	26.04
Oxygen (O)	Microalgae	40.87	41.80
	Sewage sludge	49.00	63.67
	Coal	17.24	21.33
	SM-1	26.79	61.58
	SM-2	38.06	63.91
	SM-3	53.65	65.99
Nitrogen (N)	Microalgae	6.36	0.96
	Sewage sludge	-	-
	Coal	-	-
	SM-1	-	-
	SM-2	-	-
	SM-3	-	-
Aluminum (Al)	Microalgae	1.00	0.06
	Sewage sludge	0.69	1.38
	Coal	7.28	16.23
	SM-1	0.21	0.30
	SM-2	0.90	4.21
	SM-3	2.87	2.10
Silicon (Si)	Microalgae	3.62	2.11
	Sewage sludge	0.50	0.95
	Coal	8.90	19.06
	SM-1	0.29	0.41
	SM-2	5.69	25.71
	SM-3	2.89	2.03
Phosphorus (P)	Microalgae	-	-
	Sewage sludge	2.71	4.69
	Coal	-	-
	SM-1	-	-
	SM-2	-	-
	SM-3	1.96	1.24
Sulfur (S)	Microalgae	0.32	0.16
	Sewage sludge	0.50	0.84
	Coal	-	-
	SM-1	0.05	0.06
	SM-2	-	-
	SM-3	0.84	0.52
Potassium (K)	Microalgae	-	-
	Sewage sludge	0.18	0.25
	Coal	0.15	0.24
	SM-1	-	-
	SM-2	-	-
	SM-3	0.36	0.18
Calcium (Ca)	Microalgae	13.22	5.40
	Sewage sludge	0.70	0.93
	Coal	0.08	0.12
	SM-1	0.12	0.12
	SM-2	1.79	5.66
	SM-3	0.96	0.47
Iron (Fe)	Microalgae	0.86	0.25
	Sewage sludge	10.61	10.18
	Coal	0.57	0.62
	SM-1	0.09	0.07
	SM-2	0.23	0.52
	SM-3	3.96	1.40
Zirconium (Zr)	Microalgae	-	-
	Sewage sludge	0.97	0.57
	Coal	-	-
	SM-1	-	-
	SM-2	-	-
	SM-3	-	-
Titanium (Ti)	Microalgae	-	-
	Sewage sludge	-	-
	Coal	0.11	0.14
	SM-1	0.09	0.02
	SM-2	-	-
	SM-3	0.11	0.05
Nickel (Ni)	Microalgae	3.46	0.96
	Sewage Sludge	-	-
	Coal	-	-
	SM-1	-	-
	SM-2	-	-
	SM-3	-	-
O/C	Microalgae	1.34	1.01
	Sewage sludge	5.13	3.85
	Coal	0.27	0.33
	SM-1	2.73	2.05
	SM-2	3.09	3.90
	SM-3	3.37	2.53

ambient temperature and 110 °C for sewage sludge at 10 °C/min. This weight loss could possibly take place due to the moisture absorption from the environment during handling process or superficial water bounded by surface tension. A large degradation of sample weight has been continued until 400–420 °C for coal. For microalgae and sewage sludge samples, this main degradation took place between 260 and 320 °C and this can be considered as the peak region for sample weight degradation. A scientific consensus demonstrated that the low molecular compounds of the samples are decomposed with this range of temperature during combustion [15]. Roughly from 160 to 500 °C for biomass samples, the fast

Table 5 Elemental composition of pure biomass ash samples performed by tube furnace

Elements	Sample type	Weight (%)	Atomic weight (%)
Carbon (C)	Microalgae	6.91	14.16
	Sewage Sludge	6.74	16.12
	Coal	10.92	11.60
Oxygen (O)	Microalgae	43.18	66.43
	Sewage Sludge	36.49	65.51
	Coal	-	-
Aluminum (Al)	Microalgae	-	-
	Sewage sludge	5.56	5.92
	Coal	7.28	16.23
Silicon (Si)	Microalgae	21.40	18.76
	Sewage sludge	1.77	1.81
	Coal	8.90	19.06
Phosphorus (P)	Microalgae	-	-
	Sewage sludge	6.43	5.96
	Coal	-	-
Sulfur (S)	Microalgae	-	-
	Sewage sludge	0.72	0.65
	Coal	-	-
Potassium (K)	Microalgae	-	-
	Sewage sludge	0.30	0.22
	Coal	0.15	0.24
Calcium (Ca)	Microalgae	0.13	0.02
	Sewage sludge	0.83	0.59
	Coal	0.08	0.12
Iron (Fe)	Microalgae	0.26	0.03
	Sewage sludge	5.70	2.93
	Coal	0.57	0.62
Magnesium (Mg)	Microalgae	-	-
	Sewage sludge	0.25	0.29
	Coal	-	-
Titanium (Ti)	Microalgae	-	-
	Sewage sludge	-	-
	Coal	0.11	0.14

weight loss has appeared with the presence of nitrogen gas and this is referred as the active pyrolysis zone. From 500 to 800 °C, the biomass sample lost weight steadily with the presence of air and this stage is referred as the combustion zone. On the other hand, the coal sample was continuously decomposed until 800 °C that presented well pyrolysis and clean combustion. A previous study of thermogravimetric analysis of *Chlorella* sp. mentioned that one strong peak during the main pyrolysis process indicated only one degradation process of crude protein decomposition [40]. Accordingly, this study also presented a strong peak between 260 to 320 °C shown in Fig. 4 which demonstrated the protein decomposition. For sewage sludge sample, several strong peaks were shown while

Table 6 Elemental composition of mixed biomass ash samples performed by tube furnace and bomb calorimeter

Elements	Sample type	Weight (%) (ash from tube furnace)	Atomic weight (%) (ash from tube furnace)	Weight (%) (bomb calorimeter)	Atomic weight (%) (bomb calorimeter)
Carbon (C)	SM-1	53.68	32.29	2.40	15.14
	SM-2	2.79	8.43	3.69	13.75
	SM-3	7.57	17.94	6.29	15.87
Oxygen (O)	SM-1	14.39	66.57	2.15	60.51
	SM-2	28.34	64.17	22.91	64.00
	SM-3	36.39	64.74	33.96	64.35
Aluminum (Al)	SM-1	1.75	0.47	0.13	2.16
	SM-2	9.54	12.82	0.64	1.06
	SM-3	2.53	2.67	2.75	3.09
Silicon (Si)	SM-1	2.32	0.60	0.25	4.08
	SM-2	10.51	13.55	5.46	8.69
	SM-3	2.09	2.12	5.90	6.37
Phosphorus (P)	SM-1	-	-	-	-
	SM-2	-	-	-	-
	SM-3	5.23	4.80	0.83	0.81
Sulfur (S)	SM-1	-	-	0.02	0.27
	SM-2	-	-	1.94	2.70
	SM-3	0.57	0.50	1.86	1.76
Potassium (K)	SM-1	-	-	-	-
	SM-2	0.33	0.31	0.66	0.75
	SM-3	0.36	0.26	0.16	0.12
Calcium (Ca)	SM-1	-	-	-	-
	SM-2	0.16	0.14	7.04	7.85
	SM-3	1.20	0.85	3.07	2.32
Iron (Fe)	SM-1	-	-	1.80	14.56
	SM-2	0.71	0.46	1.41	1.13
	SM-3	11.96	6.10	8.92	4.84
Titanium (Ti)	SM-1	-	-	0.02	0.18
	SM-2	0.15	0.12	-	-
	SM-3	-	-	-	-
Copper (Cu)	SM-1	-	-	0.01	0.10
	SM-2	0.01	0.00	0.02	0.01
	SM-3	-	-	-	-
Magnesium (Mg)	SM-1	-	-	0.01	0.17
	SM-2	-	-	-	-
	SM-3	-	-	-	-
Zinc (Zn)	SM-1	-	-	0.01	0.08
	SM-2	-	-	0.07	0.05
	SM-3	-	-	-	-
Telenium (Te)	SM-1	-	-	0.04	0.15
	SM-2	-	-	-	-
	SM-3	-	-	0.48	0.11

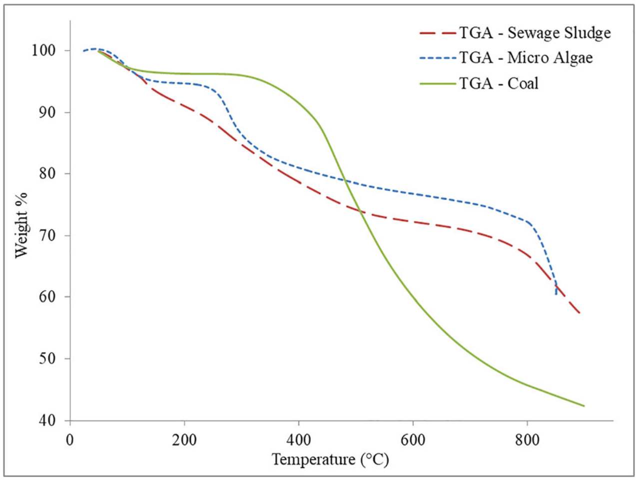

Fig. 3 Thermogravimetric (TG) curve for sewage sludge, microalgae, and coal

for coal, only strongest peak was seen between 410 to 610 °C. Overall thermogravimetric study presented that microalgae and sludge degraded weight and released energy component at much lower temperature than coal. The shorter thermal degradation profile of the microalgae can be potential feedstock for thermo-chemical conversion processes while the degradation profile of sludge is quite broader. Another significant point of this study is that this experimented coal presented outstanding thermal profile and co-pelletization of these samples with coal will boost the thermal profile of the biomass samples more.

According to DTG curves at Fig. 4, coal presented sharp peak and no fluctuations for weight (%) in terms of temperature that manifested high stability for pyrolysis modelling for large-scale application. In comparison with that, microalgae and sewage sludge presented quite higher fluctuations that proved lesser stability for pyrolysis [41]. A previous comparative TGA study between microalgae and sewage sludge presented high fluctuations for both microalgae (*Chlorella vulgaris*) and sewage sludge DTG curve. In comparison with this study, experimented sewage sludge sample in this study presented less fluctuations while DTG curve fluctuations were almost in similar range for *Stigonematales* sp. and *C. vulgaris*. DTG curve analyses of both studies indicated that microalgae can be considered as reference values in numerical studies of the pyrolysis of biofuel due to the homogeneity of chemical and biological element composition while sewage sludge can only be employed for pyrolysis modeling for similar composition sludge [41].

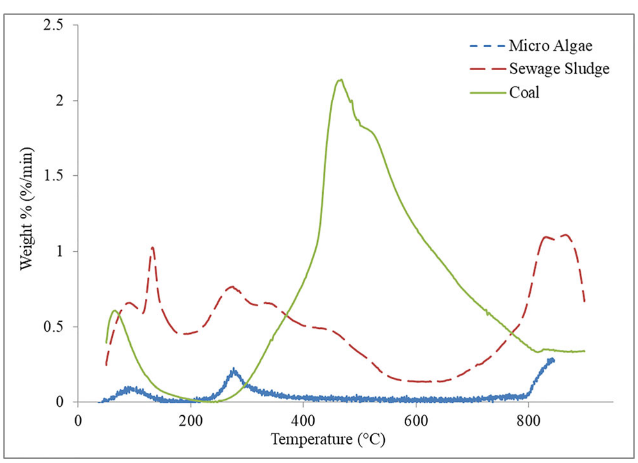

Fig. 4 Derivative thermogravimetric (DTG) curve of microalgae, sewage sludge, and coal

Conclusions

Microalgae (25%) and sewage sludge (25%) combination integrated with sub-bituminous coal (50%) presented the best energy profile with comparatively lower ash content than other blends. Though this blend showed comparatively better output, still large amount of residual ash was left after combustion which can be impediment for industrial applications. Lower percentages of microalgae and sewage sludge (approximately 3–10%) in addition with coal is recommended for further research to make the waste sample utilization more feasible for commercial applications of fuel purpose. Furthermore, current study is the first initiation to conduct experiments on microalgae (collected from wastewater) as well as combination with sewage sludge throughout the country. The drainage system in Brunei Darussalam is very well organized; it rains there throughout the whole year, and algae overgrowth causes the drain blockage often. Therefore, the concept of drain water microalgae utilization for value-added product generation has been considered for research. Though the study outcome presented some potential for the co-combustion fuel purpose, monitoring of the growth rate and production stability of microalgae in drainage system is recommended for further research. Besides the microalgae collected from wastewater, cultivation of microalgae in controlled environment of laboratory is recommended to achieve more stable outcome for continuous batches.

The elemental analysis of blended ash samples demonstrated low inorganic disposals to the environment. Thermogravimetric analysis determined the phases of pyrolysis and combustion for the samples. Overall, this study has performed comprehensive characterization of co-pelleted microalgae, sewage sludge, and coal blend. To conclude, the outcomes not only can contribute for sludge management in Brunei Darussalam but also initiate an alternative source energy generation. The plant scale heat production from microalgae-sludge-coal pellet can be recommended for future applications. This study also recommends microalgae cultivation in raw sewage sludge plants in Brunei Darussalam to accumulate organic and inorganic component to reduce environmental pollution as well as produce green energy.

Acknowledgment This research was supported by laboratories of The Faculty of Integrated Technologies and SEM Laboratory of Geology Department, Universiti Brunei Darussalam. The authors would like to thank Dr. Muhammad Saifullah Abu Bakar and Dr. Rahayu Sukmaria Sukri for providing The Brunei Research Council Grant (UBD/BRC/11) as well as Dr. Neeranuch Phusunti from Prince of Songkla University for her assistance in conducting the TGA analysis.

Compliance with ethical standards

Competing interests The authors declare that they have no conflict of interest.

Disclaimer The facts and views in the manuscript are ours and we are totally responsible for authenticity, validity, and originality. We also declare that manuscripts are our original work, and we have not copied from anywhere else. There is no plagiarism in our manuscripts.

References

1. Hosseinizand H, Sokhansanj S, Lim CJ (2018) Co-pelletization of microalgae *Chlorella vulgaris* and pine sawdust to produce solid fuels. Fuel Process Technol **177**:129–139. https://doi.org/10.1016/j.fuproc.2018.04.015
2. Hossain N, Jalil R (2015) Analyses of bio-energy properties from Malaysian local plants: sentang and sesendok. Asia Pac J Energy Environ **2**(6):141–144
3. Hossain N, Haji Zaini J, Mahlia TMI (2017) A review of bioethanol production from plant-based waste biomass by yeast fermentation. Int J Technol **8**(1). https://doi.org/10.14716/ijtech.v8i1.3948
4. Mahlia TMI, Ismail N, Hossain N, Silitonga AS, Shamsuddin AH (2019) Palm oil and its wastes as bioenergy sources: a comprehensive review. Environ Sci Pollut Res Int 26:14849–14866. https://doi.org/10.1007/s11356-019-04563-x
5. Cheng HH, Whang LM, Chan KC, Chung MC, Wu SH, Liu CP, Tien SY, Chen SY, Chang JS, Lee WJ (2015) Biological butanol production from microalgae-based biodiesel residues by Clostridium acetobutylicum. Bioresour Technol **184**:379–385. https://doi.org/10.1016/j.biortech.2014.11.017
6. Han SF, Jin WB, Tu RJ, Wu WM (2015) Biofuel production from microalgae as feedstock: current status and potential. Crit Rev Biotechnol **35**(2):255–268. https://doi.org/10.3109/07388551.2013.835301
7. Hossain N, Jalil R (2015) Sugar and bioethanol production from oil palm trunk (OPT). Asia Pac J Energy Environ **2**(5):89–92
8. Hossain N, Mahlia TMI (2019) Progress in physicochemical parameters of microalgae cultivation for biofuel production. Crit Rev Biotechnol **39**(6):835–859. https://doi.org/10.1080/07388551.2019.1624945
9. Hossain N, Zaini J, Jalil R, Mahlia TMI (2018) The efficacy of the period of saccharification on oil palm (Elaeis guineensis) trunk sap hydrolysis. Int J Technol **9**(4). https://doi.org/10.14716/ijtech.v9i4.1808
10. Thangalazhy-Gopakumar S, Al-Nadheri WMA, Jegarajan D, Sahu JN, Mubarak NM, Nizamuddin S (2015) Utilization of palm oil sludge through pyrolysis for bio-oil and bio-char production. Bioresour Technol **178**:65–69. https://doi.org/10.1016/j.biortech.2014.09.068
11. Ahmed A, Hidayat S, Abu Bakar MS, Azad AK, Sukri RS, Phusunti N (2018) Thermochemical characterisation of Acacia auriculiformis tree parts via proximate, ultimate, TGA, DTG, calorific value and FTIR spectroscopy analyses to evaluate their potential as a biofuel resource. Biofuels:1–12. https://doi.org/10.1080/17597269.2018.1442663
12. Nizamuddin S, Baloch HA, Griffin GJ, Mubarak NM, Bhutto AW, Abro R, Mazari SA, Ali BS (2017) An overview of effect of process parameters on hydrothermal carbonization of biomass. Renew Sust Energ Rev **73**:1289–1299. https://doi.org/10.1016/j.rser.2016.12.122
13. Jones, J.M., Lea-Langton, A.R., Ma, L., Pourkashanian, M., Williams, A.: Combustion of solid biomass: classification of fuels. 9-24 (2014). doi:https://doi.org/10.1007/978-1-4471-6437-1_2
14. Greinert A, Mrówczyńska M, Szefner W (2019) The use of waste biomass from the wood industry and municipal sources for energy production. Sustainability **11**:3083. https://doi.org/10.3390/su11113083
15. Hossain N, Mahlia TMI, Saidur R (2019) Latest development in microalgae-biofuel production with nano-additives. Biotechnol Biofuels **12**(1):125. https://doi.org/10.1186/s13068-019-1465-0
16. Han X, Niu M, Jiang X, Liu J (2012) Combustion characteristics of sewage sludge in a fluidized bed. Ind Eng Chem Res **51**(32):10565–10570. https://doi.org/10.1021/ie3014988
17. Oladejo J, Shi K, Luo X, Yang G, Wu T (2019) A review of sludge-to-energy recovery methods. Energies **12**(1):1–38. https://doi.org/10.3390/en12010060
18. Hossain N, Mahmud L (2019) Experimental investigation of water quality and inorganic solids in Malaysian urban lake, Taman Tasik Medan Idaman. Lakes Reserv Res Manag **24**:107–114. https://doi.org/10.1111/lre.12259
19. Lin Y, Liao Y, Yu Z, Fang S, Ma X (2017) The investigation of co-combustion of sewage sludge and oil shale using thermogravimetric analysis. Thermochim Acta **653**. https://doi.org/10.1016/j.tca.2017.04.003
20. Huang L, Liu J, He Y, Sun S, Chen J, Sun J, Chang K, Kuo J, Ning X (2016) Thermodynamics and kinetics parameters of co-combustion between sewage sludge and water hyacinth in CO2/O2 atmosphere as biomass to solid biofuel. Bioresour Technol **218**:631–642. https://doi.org/10.1016/j.biortech.2016.06.133
21. Rong H, Wang T, Zhou M, Wang H, Hou H, Xue Y (2017) Combustion characteristics and slagging during co-combustion of rice husk and sewage sludge blends. Energies **10**:438. https://doi.org/10.3390/en10040438
22. Chen G-B, Chatelier S, Lin H-T, Wu F-H, Lin T-H (2018) A study of sewage sludge co-combustion with Australian black coal and shiitake substrate. Energies **11**:3436. https://doi.org/10.3390/en11123436
23. Hossain N, Zaini J, Mahlia TMI, Azad AK (2019) Elemental, morphological and thermal analysis of mixed microalgae species from drain water. Renew Energy **131**:617–624. https://doi.org/10.1016/j.renene.2018.07.082
24. Morni NAH, Radenahmad N, Bakar MSA, Sukri RS, Phusunti N, Azad AK (2018) Potential of sewage sludge as energy recovery via gasification process. IET Conference Proceedings. 7th Brunei International Conference on Engineering and Technology 2018 (BICET 2018). Bandar Seri Begawan, Brunei Darussalam, p 4. https://doi.org/10.1049/cp.2018.1528
25. AL Hinai M, Azad AK, Abu Bakar MS, Phusunti N (2018) Characterisation and thermochemical conversion of rice husk for biochar production. Int J Renew Energy Res **8**(3):1648–1656
26. Hossain N, Zaini J, Mahlia TMI (2018) Experimental investigation of energy properties for Stigonematales sp. microalgae as potential biofuel feedstock. Int J Sustain Eng:1–8. https://doi.org/10.1080/19397038.2018.1521882
27. Ahmed A, Abu Bakar MS, Azad AK, Sukri RS, Phusunti N (2018) Intermediate pyrolysis of Acacia cincinnata and Acacia holosericea species for bio-oil and biochar production. Energy Convers Manag **176**:393–408. https://doi.org/10.1016/j.enconman.2018.09.041

28. Sahu Y, Sahu P, Chakradhari S, Patel KS (2016) Combustion characteristics of sewage sludge and algae. Nat Resour 7(4):205–213. https://doi.org/10.4236/nr.2016.74019
29. Hossain N, Mahlia TMI, Zaini J, Saidur R (2019) Techno-economics and sensitivity analysis of microalgae as commercial feedstock for bioethanol production. Environ Prog Sustain Energy. https://doi.org/10.1002/ep.13157
30. Hossain N, Zaini J, Indra Mahlia TM (2019) Life cycle assessment, energy balance and sensitivity analysis of bioethanol production from microalgae in a tropical country. Renew Sust Energ Rev **115**:109371. https://doi.org/10.1016/j.rser.2019.109371
31. Tumuluru JS (2016) Specific energy consumption and quality of wood pellets produced using high-moisture lodgepole pine grind in a flat die pellet mill. Chem Eng Res Des **110**:82–97. https://doi.org/10.1016/j.cherd.2016.04.007
32. Gebgeegziabher T, Oyedun AO, Zhang Y, Hui CW (2013) Effective optimization model for biomass drying. In: Kraslawski A, Turunen I (eds) Computer aided chemical engineering. 23rd European Symposium on Computer Aided Process Engineering 32:97–102. https://doi.org/10.1016/B978-0-444-63234-0.50017-8
33. Wang X, Zhao B, Yang X (2016) Co-pyrolysis of microalgae and sewage sludge: biocrude assessment and char yield prediction. Energy Convers Manag **117**:326–334. https://doi.org/10.1016/j.enconman.2016.03.013
34. Wójcik M, Stachowicz F, Masłoń A (2018) The use of wood biomass ash in sewage sludge treatment in terms of its agricultural utilization. Waste Biomass Valori:1–16. https://doi.org/10.1007/s12649-018-0518-0
35. Purai A, Rattan VK (2010) Removal of basic green 4 from wastewater by adsorption on biomass ash and activated carbon. Indian Chem Eng **51**(4):287–299. https://doi.org/10.1080/00194500903430689
36. Scimeca M, Bischetti S, Lamsira HK, Bonfiglio R, Bonanno E (2018) Energy dispersive X-ray (EDX) microanalysis: a powerful tool in biomedical research and diagnosis. Eur J Histochem **62**(1):2841–2841. https://doi.org/10.4081/ejh.2018.2841
37. Hasan R, Chong CC, Bukhari SN, Jusoh R, Setiabudi HD (2019) Effective removal of Pb(II) by low-cost fibrous silica KCC-1 synthesized from silica-rich rice husk ash. J Ind Eng Chem **75**:262–270. https://doi.org/10.1016/j.jiec.2019.03.034
38. Hartman M, Svoboda K, Pohořelý M, Trnka O (2005) Combustion of dried sewage sludge in a fluidized-bed reactor. Ind Eng Chem Res **44**(10):3432–3441. https://doi.org/10.1021/ie040248n
39. Jiang L-B, Yuan X-Z, Li H, Chen X-H, Xiao Z-H, Liang J, Leng L-J, Guo Z, Zeng G-M (2016) Co-pelletization of sewage sludge and biomass: thermogravimetric analysis and ash deposits. Fuel Process Technol **145**:109–115. https://doi.org/10.1016/j.fuproc.2016.01.027
40. Phukan MM, Chutia RS, Konwar BK, Kataki R (2011) Microalgae Chlorella as a potential bio-energy feedstock. Appl Energy **88**(10):3307–3312. https://doi.org/10.1016/j.apenergy.2010.11.026
41. Soria-Verdugo A, Goos E, Morato-Godino A, García-Hernando N, Riedel U (2017) Pyrolysis of biofuels of the future: sewage sludge and microalgae – thermogravimetric analysis and modelling of the pyrolysis under different temperature conditions. Energy Convers Manag **138**:261–272. https://doi.org/10.1016/j.enconman.2017.01.059
42. International, A.: ASTM D1895 – 96 (2010) Standard test methods for apparent density, bulk factor, and pourability of plastic materials. In: ISO Standards: R60 Determination of apparent density of molding materials that can be poured from a specified funnel, vol. 60. ASTM International, West Conshohocken, PA
43. Materials, A.: A5TM D 2974-87 (1987) Standard test methods for moisture, ash, and organic matter of peat and other organic soils. In: Moisture content. Annual Book of ASTM Standards, 1916 Race St., Philadelphia, PA 19103
44. International, A.: ASTM E711-87(2004) (1987) Standard test method for gross calorific value of refuse-derived fuel by the bomb calorimeter. ASTM International, West Conshohocken, PA
45. Hossain N, Jalil R, Mahlia TMI, Zaini J (2017) Calorific value analysis of azadirachta excelsa and endospermum malaccense as potential solid fuels feedstock. Int J Technol 8(4):634–643. https://doi.org/10.14716/ijtech.v8i4.9482
46. International, A.: ASTM E1534-93(2013) (2013) Standard test method for determination of ash content of particulate wood fuels, vol. ASTM E1534-93(2013). ASTM International, West Conshohocken, PA
47. Laboratories, I.P.T Compositional analysis by thermogravimetric analysis (TGA). In: ASTM E1131, ISO 11358. Intertek Plastics Technology Laboratories, 50 Pearl Street, Pittsfield, MA 01201