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Research article

Co-pelletization of microalgae *Chlorella vulgaris* and pine sawdust to produce solid fuels

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ABSTRACT

Handling, storage, and transportation of dried microalgae is challenging due to its low density. In addition, using pure microalgae as fuel is currently not economically feasible. In the present research, the pelletization of microalgae *Chlorella vulgaris* blends and sawdust was studied. Pelletization of pure *Chlorella* occurred in two distinct regions of particles' rearrangement and particles' deformation. However, there was no clear separation between the two regions when sawdust was added to *Chlorella*. Adding microalgae *Chlorella* to sawdust resulted in a decrease in densification energy and improvement in pellets' properties, i.e. higher durability, density, and heating value, lower porosity, moisture absorption, and pellets' expansion.

Testing densification temperatures of 50, 75, and 100 °C revealed that by increasing the temperature from 50 to 75 °C, the pellets' quality was improved. However, further temperature increase to 100 °C enhanced properties of the pellets that had a higher fraction of sawdust. Similarly, increasing the compressive force from 2500 to 3500 N improved properties of the pellets having more sawdust. The results showed that adding microalgae to sawdust not only eliminates the need for elevated densification temperature and force, but also results in the production of pelleted fuels with improved quality.

1. Introduction

As the demand for oil and gas resources rises with the growth of population, viable alternative fuels are required [1–4]. Microalgae have recently received substantial attention as a renewable energy feedstock owing to their distinct characteristics [5]. Microalgae have high productivity and do not compete with terrestrial food crops since microalgae do not need arable land for their growth [6–8]. Microalgae's carbon dioxide fixation ability is one to two orders of magnitude higher than terrestrial plants, and their associated environmental problems are much lower than fossil fuels [1,7,9,10]. Microalgal fuel can undergo several conversion pathways for energy production like direct combustion, pyrolysis, gasification, hydrothermal liquefaction, transesterification, anaerobic digestion, and fermentation [7,10,11]. Microalgae can also be processed to animal feed and high-value products like cosmetics, supplements, and food colorants [5].

The production of algae-based fuels involves cultivation, harvesting, dewatering and thickening, storage, and conversion to biofuel [7,12]. Microalgae are produced as dilute suspensions of 0.06% (0.6 g/L) in growth media. Harvesting is applied to separate microalgae from culture media, followed by mechanical dewatering (e.g., centrifugation) to concentrate algal biomass to about 15–20% (200 g/L) of solids [13–15]. The remaining water in the biomass cannot be removed further by using mechanical methods [16]. It is difficult and costly to produce microalgae-based fuels from wet biomass since the efficiency of many conversion techniques in the presence of water is as low as 30–50% of maximum achievable yield [17–20]. Therefore, thermal drying is applied to decrease the moisture to 10%, which is regarded safe for storage and handling [21–23].

Algal biomass has a density around 600 kg/m^3 after drying and grinding, but the desired bulk density of the fuel is in the range of 650–750 kg/m^3 [24]. In addition, handling of fine microalgal particles is challenging, since significant electrostatic charges may build up when fine particles are fed into the equipment. Moreover, because of high surface per unit volume of fine particles, surface forces like Van der Waals' play an important role in creating bonds between particles. The formed bonds and charged particles lead to blockage of storage and handling equipment (e.g., hoppers). As a result, microalgae particles need to be agglomerated to larger particles before processing. Pelleting improves fuel quality by increasing the density and creating agglomerated structures [24,25]. The high density of pellets compared to the density of raw biomass and their homogenous structure [26] make pellets valuable fuel to be used in industrial and residential applications. Their elevated density will reduce handling, storage, and

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Fig. 1. Picture of pine sawdust particles (left) and microalgae particles (right) at 10% wet basis moisture content.

transportation costs [27–31]. Pelletization is carried out by forcing the particle toward each other via applying a mechanical force to produce a homogeneous pellet [31].

At the current stage of technology, combustion of pure pelleted microalgae might not be economical [11]. Co-pelletization of microalgae with woody biomass, a commonly used biomass for energy production, was proposed as a potential approach to making energy production from microalgae economically feasible. On the other hand, adding microalgae to woody biomass is a useful method to decrease the required energy for making wood pellets. When pure woody biomass is used for energy applications, it should be pelletized in order to increase the bulk density. Adding microalgae to wood not only improves pellets' properties (e.g., density and durability) but also decreases pelletization energy for woody biomass (will be further discussed in the Results and discussion section). This will, in turn, improve the economics of wood pelletization.

To best of our knowledge, there is no study in the open literature on pelletization of microalgae *Chlorella vulgaris*, which is a valuable potential fuel owing to its distinct characteristics [32]. In addition, there is a lack of knowledge on the co-pelletization mechanism of microalgae *Chlorella vulgaris* with woody biomass. Thapa et al.'s research [33] is the only published study on mechanical densification of algae. They used dried fine powder *Rhizodonium* spp. algae, a waste product obtained from wastewater treatment systems, as a natural binding agent for densification of *Miscanthus*. The results of compressing using a mounting press indicated that discs containing > 20% algae had better strength compared to pure *Miscanthus* discs. The algae used in Thapa et al.'s study was a low-value waste biomass, and its low calorific value (11 MJ/kg) reveals that it might have been combined with some impurities. In addition, the densification mechanism has not been addressed in Thapa et al.'s paper. The objective of this research was to understand the mechanism of co-pelletization of valuable pure microalgae *Chlorella vulgaris* and pine sawdust and to evaluate the properties of the pelleted fuel.

2. Materials and methods

2.1. Raw biomass preparation

Chlorella vulgaris was provided by Algae Testbed Public-Private Partnership (ATP^3) (Arizona, U.S.). The microalgae were cultivated in flat panel photobioreactors (PBR) in BG-11 culture media at their site. The harvested biomass was centrifuged and the resultant paste was kept frozen at −20 °C until shipped to the lab in Vancouver, BC for the experiments. When received, the algae mass was kept frozen at −4 °C until use, and when needed it was thawed at 4 °C.

Microalgae were dried in a convective air dryer at 80 °C in thin-layer drying mode to a final 10% moisture content (w.b.). The drying temperature of 80 °C was selected based on our previous study [16] that preserved microalgae quality the best. After cooling in lab air, the dried biomass was ground to fine powder, vacuum packed, and stored at 4 °C until pelletization.

Pine sawdust was supplied by Fiberco Inc. (North Vancouver, BC, Canada). The material was size reduced by a hammer mill (Glen Mills Inc., USA; Model 10HMBL) using the screen openings of 3.2 mm (1/8 in). The ground sawdust was remoistened to 10% by adding the required amount of distilled water. The prepared sample was stored in plastic bags at 4 °C until use [34].

Biomass particle size has an important effect on pelletization process and the quality of produced pellets. Generally, finer particles create more durable pellets. However, fine particles might cause blockage in the die during pelletization. In addition, in fibrous biomass (agricultural and woody biomass), fine particles need more energy for pelletization [35]. Based on the literature, it is desired to have a distribution of different particle size in the biomass. Vest reported that pellet mills that used hammer mill with a screen size of 3.2 mm produced the most durable pellets [35]. The mass-averaged diameter of pine sawdust particles in this study was 0.58 mm (based on Rezaei's research who used the same material [36]). Since grinding results in extremely fine microalgae particles and there is no control of the particle size, the microalgal particle size was not measured in this study. Fig. 1 shows sawdust and microalgae particles at 10% moisture content. The microalgae particles are much smaller and finer than sawdust particles.

The characteristics of the two raw materials are presented in Table 1. The chemical composition of microalgae *Chlorella vulgaris*, proximate and ultimate analysis and calorific values of both materials

Table 1
Properties of raw samples of *Chlorella vulgaris* and pine sawdust.

Analysis		*Chlorella vulgaris*	Pine sawdust
Elemental analysis (% dry basis)	C	59.17 ± 0.33	48.02 ± 0.03
	O	28.44 ± 0.31	45.85 ± 0.05
	H	8.20 ± 0.03	6.14 ± 0.07
	N	1.85 ± 0.01	–[a]
	S	0.26 ± 0.01	–[a]
Proximate analysis (% dry basis)	Moisture (% wet basis)	10.15 ± 0.58	9.85 ± 0.36
	Ash	2.19 ± 0.16	0.086 ± 0.01
	Volatile matter	83.08 ± 3.02	87.68 ± 0.25
	Fixed carbon	14.73 ± 1.84	11.93 ± 0.45
Chemical analysis (% dry basis)	Lipid	10.63 ± 0.36	–[b]
	Protein	11.56 ± 0.06	–[b]
	Carbohydrate	26.18 ± 0.24	–[b]
	Cellulose	–[b]	41.81 ± 0.43
	Hemicellulose	–[b]	27.48 ± 0.87
	Lignin	–[b]	25.12 ± 0.36
HHV (MJ/kg)		27.29 ± 0.69	19.46 ± 0.04
Bulk density (kg/m^3)		646.83 ± 12.34	180.78 ± 2.35

[a] Not detected.
[b] Not measured.