Biomass pellets from densification of tree leaf waste with algae

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Abstract: Fallen tree leaves in urban or public areas are usually discarded or accumulated and piled in open spaces where blockages of drainage or accidental fire can occur, causing damages to public properties and the environment. These tree leaves are seasonally available biomass residues that may potentially be substituted or mixed with wood to produce biomass pellets. In this work, densification of eucalyptus and teak leaf waste was carried out using a cylindrical die. Several influential operating factors (temperature of 30°C and 80°C, pressure of 100, 150 and 200 MPa, and addition of algae as binding agent at 10% to 20% w/w) were investigated with respect to mechanical properties of the biomass pellets such as mass and energy densities, and compressive strength. From the findings, the tree leaf waste was shown to have good pelletizing behavior under the conditions considered. Properties of the densified products appeared to be comparable to marketed wood pellets.

Keywords: biomass, pelletization, renewable energy, waste-to-energy

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1 Introduction

Urban trees provide shade, cool local air, remove some of air pollutants, absorb carbon dioxide, and help retain water. They are also important in providing recreational and aesthetic benefits (Gomez-Baggethun and Barton, 2013). It is estimated that a standing tree can produce more than 300 kg of dry biomass, including the stem, branches, twigs, and leaves (Tanhuanpää et al., 2017). Seasonally, trees lose their foliage, giving rise to substantial amount of biomass residues. Fallen leaves that shed from trees are usually transformed naturally into a nutrient source for the trees. However, in urban and public areas, most fallen leaves are on sealed surfaces, or collected to clear the spaces. They become in effect waste material to be disposed of. Furthermore, the accumulation of fallen tree leaves under hot, dry and windy condition risks accidental fire that can spread and do damages to human health and the atmospheric environment (Wongchai and Tachajapong, 2015; Pňakovič and Dzurenda, 2015; Tippayawong et al., 2006).

Alternatively, these biomass residues can be utilized for energy to ease these potential problems. Fuel derived from waste biomass can offer advantages in reducing greenhouse gas emissions and contribute to low carbon societies (Tippayawong et al., 2011; Jaroenkhasemmeesuk and Tippayawong, 2015; Tippayawong and Tippayawong, 2017). The use of urban tree leaf waste for energy production can be a win-win approach in dealing with burden of disposal and energy crisis (Li et al., 2017). The main challenge is how to exploit this tree leaf waste for energy production. Their energy value is high, but their use is limited by low density and varying characteristics. Densification is an obviously simple but effective practice to upgrade their characteristics by converting into pellets or briquettes (Wongsiriamnuay and Tippayawong, 2015; Kaliyan and Morey, 2009, 2010). Some of the examples are from those reported by Stegelmeier et al. (2011) and Wattana and Kittayaruksakul (2016). High quality pellets are usually obtained from densification at high temperature and high pressure conditions, possibly with costly binding agents. Pelletizing at moderate conditions may be effective with inexpensive binding agents from natural sources (Jiang et al., 2014). A proper binding agent may be acquired from algal biomass available from biological wastewater

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treatment and natural water resources. It is reported that algal biomass offers good alternative and acceptable binding property (Piboon et al., 2017; Thapa et al., 2014).

So far, reported work on densification of tree leaf waste is rather scarce. Information regarding the mechanical properties of the leaf pellets is hardly available in open literature. Utilization of algal biomass as binding agent for tree leaf waste remains non-existent. Thus, the objectives of this work were to affirm that tree leaves are generally pelletizable, and algal biomass may be effective in binding this biomass residue at relatively moderate conditions. In this work, densification of tree leaf waste was carried out with local algae as a binder. Effect on properties of the leaf pellets (length to diameter ratio, mass and energy densities, and compressive strength) was evaluated as a function of applied pressure (100-200 MPa), die temperature (30°C, 80°C), type of leaves (eucalyptus, teak, mixed), and algae to leaf mixture ratio (10%, 20% w/w).

2 Materials and methods

2.1 Raw materials

Fallen tree leaves were collected locally in Chiang Mai, Thailand from November to December 2016. Two different leaf species were considered, teak (*Tectona grandis*) and eucalyptus (*Eucalyptus globulus*). Impurities and particles were separated from the leaves manually. The leaves were later cleaned in water and dried naturally in sunlight. Clean and dried leaves were reduced in size using cutting mill and sieved into <1.7 mm. Algae (*Spirogyra sp.* and *Chara sp.*) were also collected locally. They were dried naturally under the sun by spreading on a plastic net for at least seven days. After which, they were milled into the size of <1.7 mm. Size reduction of dried leaves and algal biomass were observed to be rather simple. The similar sizes between the two were used to ensure good mixing. Moisture and ash content and bulk density of the materials were determined following the ASAE 358.2 and ASTM E 873-82 standards, respectively. Calorific value was measured using a bomb calorimeter following the BS EN 14918 standard. Lignin content was determined using a detergent method.

All samples were stored in plastic bags. Experiments were conducted for single leaf species and mixed leaves. Prior to densification, blending was performed by weight ratios into 100% leaf with no algae (L100A0), 90% leaf and 10% algae (L90A10) to 80% leaf and 20% algae (L80A20), and no leaf with 100% algae (L0A100) using digital balance. Mixing between leaves and algae was easily realized with no agglomeration or segregation observed.

2.2 Densification procedure

Each pellet mass loading was approximately 1.0± 0.05 g. A densifying apparatus used is shown in Figure 1, comprising a piston and a closed-end cylindrical die and a base. Internal diameter was 7 mm, indicating the resultant pellet size. The compacting apparatus was mounted with a 450 W heating blanket for obtaining 30 and 80°C conditions. A universal testing machine was employed to input known loads between 100, 150 and 200 MPa measured by a pressure gauge to the material. For each test condition, repetition for at least ten times was undertaken. The die temperature was monitored by a thermocouple and controlled by a digital controller. A holding time of 10 s was used for each pellet to restrain the spring-back effect.

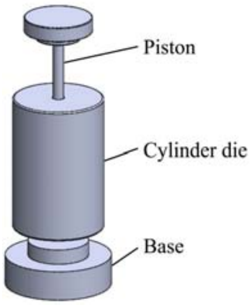


Figure 1 The compacting apparatus

2.3 Analysis

The resultant pellets were subsequently evaluated for various mechanical properties, including compact and relax densities, energy density, and compressive strength. The pellet density was determined based on the pellet mass per volume. In this work, the compact and relax densities were used and defined as that of the pellet determined immediately after compaction and that determined after storage for one week, respectively. The energy density (J m^{-3}) used in this work was defined as the product between heating value (J kg^{-1}) and density (kg m^{-3}) of the pellet. Durability of the pellets is an important property for solid fuels. It may be evaluated indirectly from compressive strength of the pellets. There is not yet a standardized procedure available to follow. Thus, in this work, the pellet compressive strength was determined by pressing the pellet along its axis until it breaks. The final force at breaking point was divided by the pellet cross section area to calculate its strength.

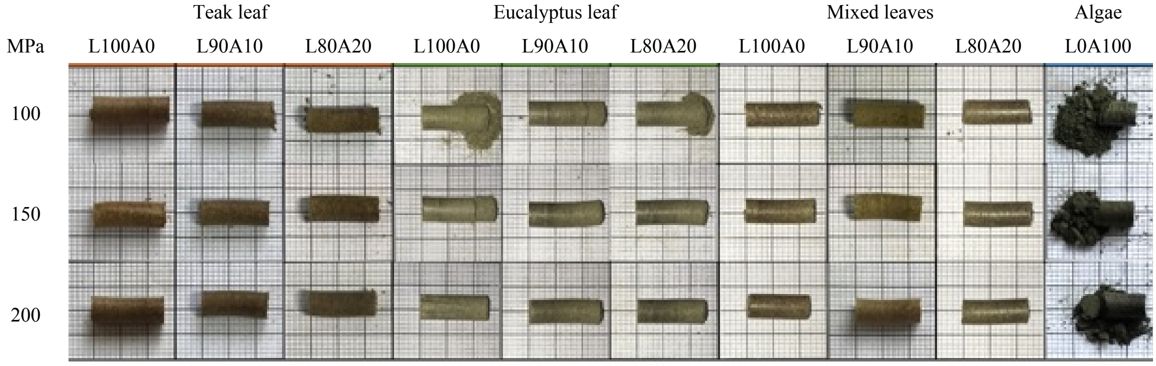
3 Results and Discussion

3.1 Biomass characteristics

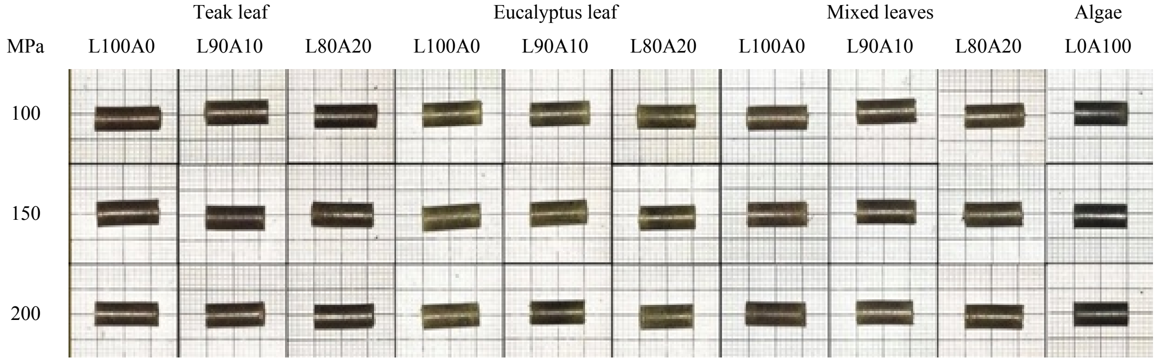
The fallen tree leaves were collected from pavement areas around Chiang Mai University campus. They were expected to be similar to those collected from the city. Impurities and dirt were marginal. The leaves could be cleaned very easily. Moisture contents on dry basis of the eucalyptus and teak leaves and algae were 7.9±0.6, 9.1±0.7 and 9.6±0.7%, and bulk densities of the leaves and algae were 528±10, 356±8 and 896±14 kg m^{-3}, respectively. Eucalyptus and teak eaves were found to have high lignin content at about 8.8% and 17.5%, respectively, whereas the algae was low in lignin (<2%). Ash content of the leaves was about 5.7%-9.1%, while that of the algae was about 15.9%. Teak and eucalyptus leaves were found to have similar heating value in the range between 18.1-18.5 MJ kg^{-1}, while the heating value of the algae was slightly lower, at about 15.1 MJ kg^{-1}.

3.2 Physical appearance of the pellets

Figure 2 shows pictorial views of the pellets after a week storage. It was evident that pure algal pellets (L0A100) processed at 30^{o}C at all pressure conditions could not retain the pellet form. They were found broken in bits and pieces. This also happened to eucalyptus leaf at lowest pressure considered, even with binder. They would need to be pelletized at higher pressures to form very tight pellets. All other cases appeared to be fairly tight at low pressure, and more tightened at higher pressures, with and without binder. For processing at high temperature of 80^{o}C, all cases were found to be successful in forming pellets. The tree leaf pellets comprised many small pieces of leaf packed together and shaped into solid cylinder, holding together by mechanical interlocking of solid bridges. They could preserve their shape because these tiny pieces were packed sufficiently close and had enough heat generated so that the glass transition temperature of lignin in the feedstock may have been reached. When the bonding was strong enough, the biomass left the die in a whole pellet form. When the bonding was weak, the biomass material tended to spring back after pressure was relieved. This may lead to expand further, causing cracks within the densified fuel.



(a) 30^{o}C



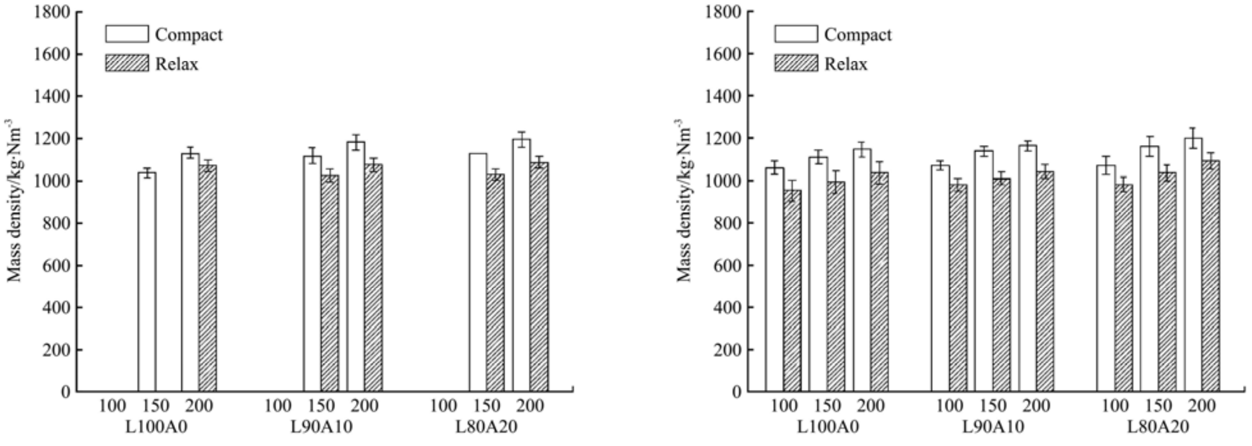
(b) 80^{o}C

Figure 2 Pellets after various compaction conditions and storage for 1 week

3.3 Compact and relax densities

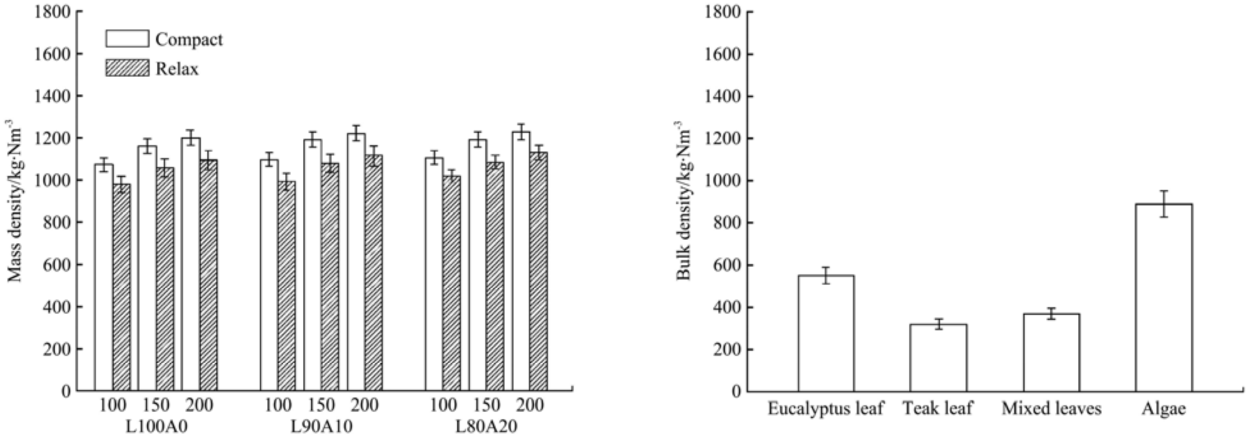
Measurement of change in length and diameter of the pellets between immediately after compression and after storage for one week was undertaken. This was used to calculate their corresponding volume, and density from a fixed mass input. It was observed that change in length of the pellets after storage was rather small (<2%) for those compressed at 80°C, whereas those processed at 30°C tended to expand more at about 3%-5%.

Resulting pellet densities processed at 30°C are shown in Figures 3(a) to (c) as a function of biomass type, applied pressure and mixture ratio. Bulk density of original materials was plotted in Figure 3(d) as reference. Error bars were given to represent corresponding standard deviations. Pressures were varied from 100, 150 to 200 MPa. Mixture ratios were varied from no algae to increasing amount of algae (0, 10%, and 20%). There are two thin columns for each condition, corresponding to compact density shown in white, and relax density after storage for 1 week shown in light grey. Some of eucalyptus leaf data were missing because they failed to retain a pellet form after processing or storage.



a. Eucalyptus leaf

b. Teak leaf



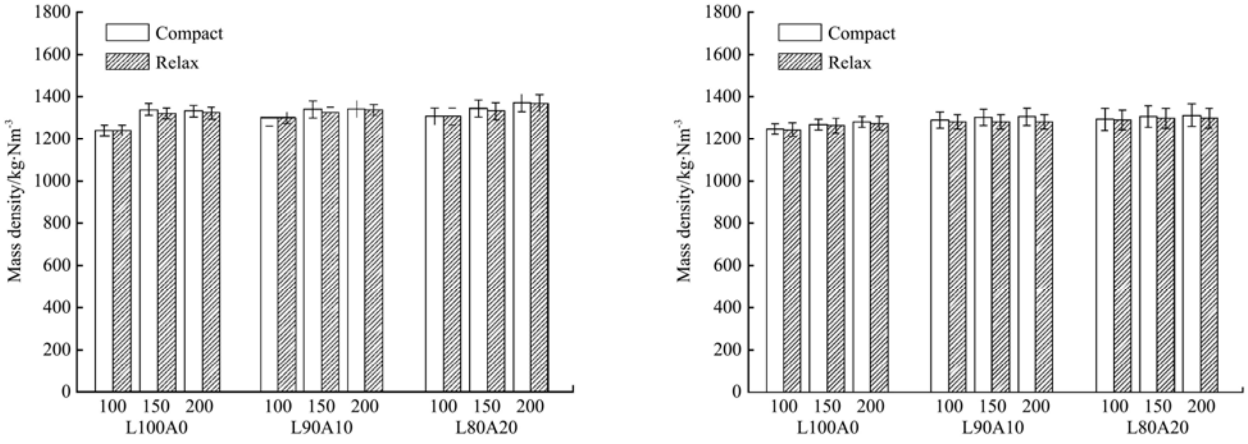
c. Mixed leaves

Figure 3 Variation in pellet densities with applied pressure, biomass type and mixture ratio at 30°C

From general observation, the biomass pieces appeared to be forced against each other and packed closely, forming attractive or interlocking bond, similar to those reported in Piboon et al. (2017), Wongsiriamnuay and Tippayawong (2015), and Thapa et al. (2014). The densified products were denser than original materials before compaction, around two- and three folds for eucalyptus and teak, respectively. Compact density was expected to be always higher than relax density, since expansion of the pellet dimension occurred during storage increased in the pellet volume. For a fixed pressure, both densities appeared to be in similar range (950-1190 kg m^{-3}), disregards to biomass type and mixture ratio. It was clear that pressure had positive impact on the pellet density. Increasing pressure resulted in increasing pellet densities, for fixed biomass type and mixture ratio. These differences were statistically significant, as the changes were larger than the spread of data for each condition.

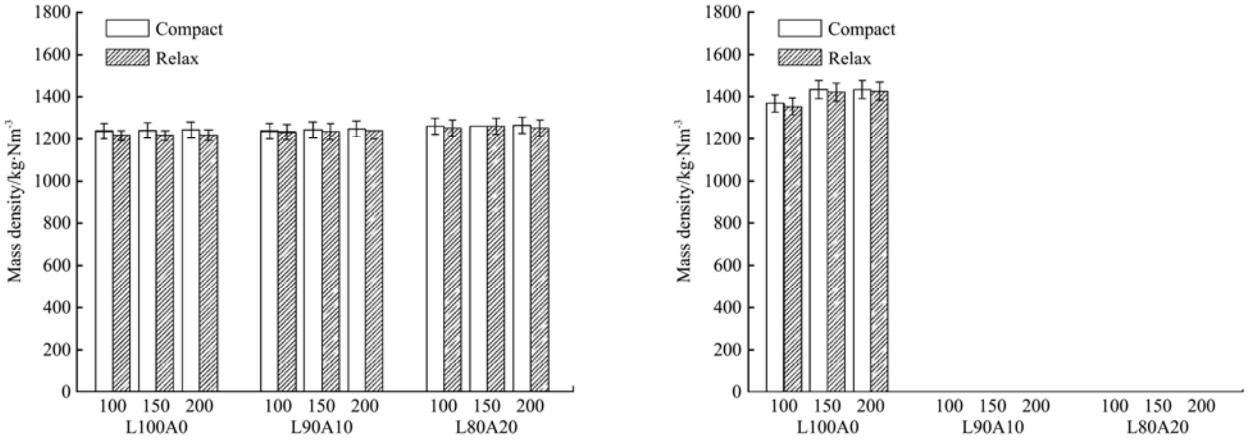
Figure 4 shows compact and relax densities of the pellets processed at 80°C. Changes in density were less pronounced with respect to those at lower temperature. Comparing against error bars, changes observed were not statistically significant. They remained relatively constant and high, at above 1200 kg m^{-3}. Varying biomass type, mixture ratio and pressure did not change the resultant densities much, except for pure eucalyptus leaf. Increase in applied pressure from 100 to 150 MPa led to significant improvement in density, but further increase to 200 MPa did not change markedly.

It should be noted the resultant pellet densities had a range of 950-1350 kg m^{-3}, far exceeding the minimum standard values of 600 kg m^{-3} by the US Pellet Fuel Institute (PFI). This was not a major issue since the pellet density could be regulated by applied compressing forces. Additionally, combustion characteristic of biomass pellet was reported to be dependent, only to a minor extent, on its density. Char combustion was found to increase slightly with an increase in biomass pellet density between 850 to 1200 kg m^{-3} (Rhén et al., 2007).



a. Eucalyptus leaf

b. Teak leaf



c. Mixed leaves

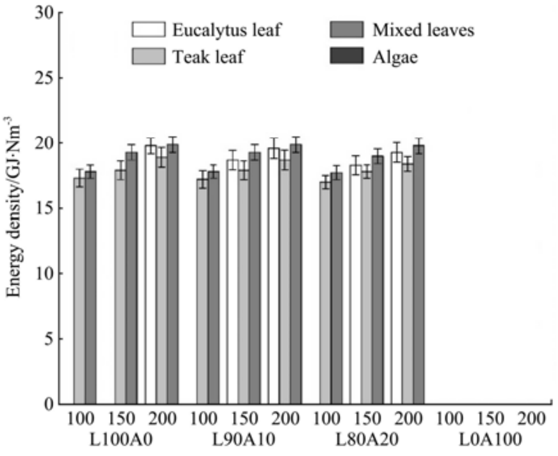
d. Algae

Figure 4 Variation in pellet densities with applied pressure, biomass type and mixture ratio at 80°C

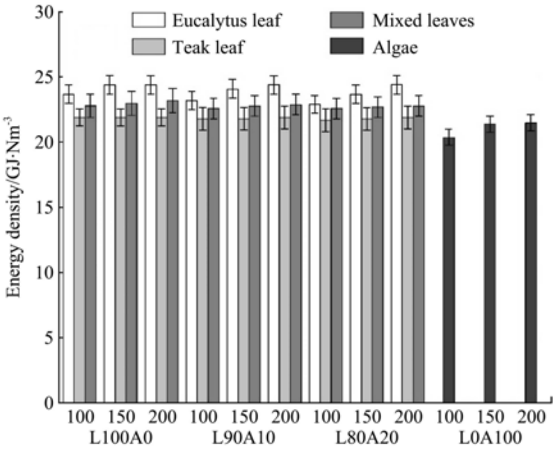
3.4 Energy density

Figures 5(a) and (b) show the variation of pellet energy density as a function of die temperature, applied pressure, biomass type and mixture ratio. Missing data were due to the unsuccessful preservation of pellet shape or damaged pellets, happening only to eucalyptus leaf at low pressures and algae at 30°C. Here, the energy density was defined as the product between heating value and relax density of the pellet. The unit was in energy per volume. This reflected the energy content of stored fuel pellets available to be used in downstream processes (Piboon et al., 2017; Wongsiriamnuay and Tippayawong, 2015). It should be noted that teak and eucalyptus leaves had similar heating value, but about 20% higher than the algae. From the findings, it can be seen that applied pressure and die temperature had positive influence on the energy density, whereas mixing with algae negatively affected the pellet heating value, hence energy density.

Increasing applied pressure and die temperature were found to enhance the energy density of the pellets. For sole teak pellets at low temperature, the energy density varied from 17 GJ m^{-3} when compressed at 100 MPa to about 19 GJ m^{-3} when compressed at 200 MPa, respectively. Similarly, for sole teak pellets at fixed applied pressure of 100 MPa, the energy density increased from 17 GJ m^{-3} when compressed at 30°C to about 22 GJ m^{-3} when compressed at 80°C, respectively. These values were slightly lower than those of eucalyptus and mixed leaves. Within the conditions considered, variation with mixture ratio was not statistically significant.



a. 30 °C



b. 80 °C

Figure 5 Variation in pellet energy density with die temperature, applied pressure, biomass type and mixture ratio

3.5 Compressive strength

Durability of a densified product is generally referred to its abrasive resistance. In this work, compressive strength was considered to indirectly represent durability of the pellets, as in Piboon et al. (2017). Figure 6 shows compressive strengths of the pellets from various compaction conditions. It can be seen that generally compressive strength increased with applied pressure. Eucalyptus leaf appeared to be the strongest pellets, whereas sole algae pellets were the weakest. This finding could also explain the fact that mixing more algae into the tree leaves resulted in less durable pellets. For a given temperature and pressure condition, compressive strength was found to decrease slightly with increasing portion of algae.

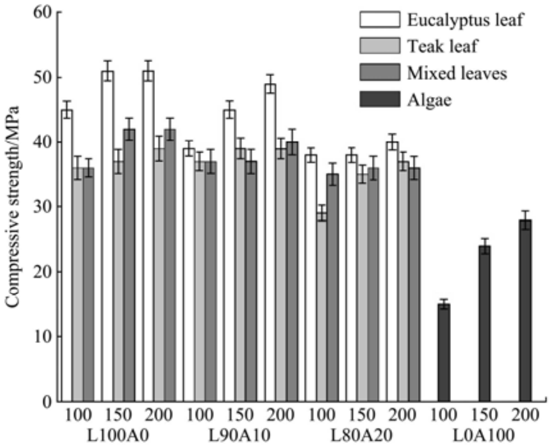


Figure 6 Variation in pellet compressive strength with applied pressure, biomass type and mixture ratio

3.6 Comparison with an international standard

Marketable wood and biomass pellets are currently graded by the US PFI. Pellet quality is a largely dependent on type of feedstock and process parameters. In this work, comparison of our densified products against the US PFI requirement was made for some indicators. Results are shown in Table 1. It can be seen that tree leaf pellets obtained from this work were in compliance with the US PFI requirements.

Table 1 Comparison of pellet properties against PFI fuel grade requirements

	This work	PFI utility	PFI standard	PFI premium
Bulk density, kg m^{-3}	950-1350	609-737	609-737	641-737
Diameter, mm	7.09-7.25	6.35-7.25	6.35-7.25	6.35-7.25
Durability index	-	≥95.0	≥95.0	≥97.5
Length, % >38 mm	0.7-1.0	≤1.0	≤1.0	≤1.0
Moisture, %	7.5-9.5	≤10.0	≤8.0	≤8.0
Heating value, MJ kg^{-1}	17.4-18.5	–	–	–

4 Conclusion

Fallen tree leaves in urban areas are seasonally available biomass residues that may potentially be utilized to produce biomass pellets. In this work, densification of eucalyptus, teak and mixed leaves with algae as binder was investigated, focusing on physical and mechanical properties of the leaf pellets. Die temperature, compression pressure, leaf type and leaf to algae mixture ratio were considered. They were also compared to requirements for wood pellets in the US in order to assess their potential for future use in pellet firing systems. It was conclusive that all tree leaves can be densified using a cylindrical closed end die at a relatively high temperature (80°C) for all applied pressures considered here. At room temperature, eucalyptus leaf was found to be difficult to retain shape after compaction and storage, possibly due to its relatively low lignin content. Use of algae as binder (10%-20% w/w) did not offer any marked improvement of the physical characteristics of the pellets. It was suggested that moderate applied pressure of 100 MPa and temperature of 80°C should be used, and use of algae as binding agent was not necessary. Overall, the urban tree leaves were shown to have good pelletizing behavior with the properties in compliance with the requirements of the US PFI standard for wood pellets.

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