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Overview of Pelletisation Technology and Pellet Characteristics from Maize Residues

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Maize is a popular field crop in Thailand for animal feed production. The country dedicates more than six million hectares to maize cultivation, and its total output amounts to about five million tons. The harvest of maize results in three primary residues: roots, stalks, and leaves. Over 80 % of these residues are disposed of in the cultivated area itself, usually by open burning. This practice releases large amounts of pollutants (such as the hazardous particulate matter known as PM2.5) into the atmosphere. Pelletisation represents one promising alternative to such strategies as open burning. The main objective of this study is to provide an overview of the pelletisation process in order to guide future attempts to increase efficiency and sustainability in maize pellet production. Thai standards for the production of pellets are compared with international standards, and the effects of differences in pellet composition on combustion efficiency are discussed. The results of this study can serve as a guideline for spearheading zero-waste agriculture initiatives and promoting the use of renewable resources like pellets for utilisation in biomass power plants, per the recommendations in the Alternative Energy Development Plan (AEDP 2012-2021).

1. Introduction

Due to the sheer severity of their consequences, the various forms of waste produced by the everyday functions of the global economy pose a global problem. These wastes, which include municipal solid waste (MSW), industrial wastes, and agricultural wastes, can have serious impacts on local environments. Cumulatively, human-produced wastes represent an issue of global environmental concern. For these reasons, several promising waste management practices have been developed (Fan et al., 2019).

One form of waste especially relevant to Thailand is the agricultural residue produced by maize farming. Maize is a very popular crop in Thailand for its use in animal feed production (Tippayawong et al., 2018). The total area dedicated to its cultivation in Thailand amounts to more than six million hectares, and the country's total annual output is about five million tons (Office of Agricultural Economics, 2019). However, while maize thus plays a crucial role in Thailand's agricultural economy, the waste resulting from maize cultivation is substantial. Residues that remain in maize fields after harvesting include roots, stalks, and leaves, over 80 % of which are disposed of in the cultivated area via burning. This causes local air pollution, and contributes specifically to the prevalence of hazardous particulates like PM2.5 in Thailand (Moran et al., 2019).

However, burning is not the only option for eliminating maize residues. Residues can also be utilised for energy and fuels via densification (Wongsiriamnuay and Tippayawong, 2015), densification with binder (Piboon et al., 2017), torrefaction (Onsree et al., 2019), gasification (Homdoung et al., 2019), slow pyrolysis (Tippayawong et al., 2017), fast pyrolysis (Jaroenkhasemmeesuk and Tippayawong, 2015), and combustion (Sittisun et al., 2015). The physical and chemical characteristics of maize residue (specifically residue left in fields following harvesting) are shown in Table 1. The use of maize residue as a fuel portends economic and political benefits in addition to ecological ones. The prevalence of biomass power generation is likely to grow under the Ministry of Energy's Alternative Energy Development Plan (AEDP 2012-2021), which provides a framework for increasing the country's capacity for alternative energy production by 25 % before 2021.

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Table 1: Maize residue characteristics

Researchers	Proximate analysis (%)				Ultimate analysis (wt%)							HHV (MJ/kg)
	MC	VM	Ash	FC	C	H	N	O	S	Cl	Others	
Machado et al. (2018)	NA	78.1	10.5	11.2	44.5	5.4	0.8	39.5	NA	NA	NA	13.6
Križan et al. (2018)	NA	NA	1.0-1.1	NA	NA	NA	NA	NA	NA	NA	NA	17.0-17.8
Poudel and Oh (2014)	13.2	84.7	2.1	NA	44.8	5.5	0.3	44.3	0.04	0.06	5	18.5
Migailovic et al. (2014)	NA	NA	6.49	NA	44.8	5.8	1.3	41.8	0.05	NA	NA	17.9
Costa et al. (2014)	6.1	76	4.7	13.2	49.3	6	0.7	43.9	0.11	NA	NA	NA

Thailand has agreed to the United Nation's Intended Nationally Determined Contributions for reducing greenhouse gas emissions 20% by 2030 (Lee et al, 2018). The target set for power generated from biomass in the AEDP is 3,630 MW. This will be promoted through biomass pellet production and co-generation (i.e., the use of pellets for both electricity and heat) (Sutabutr, 2012). Under the AEDP, biomass pellets will become an important solid fuel for heat and power production. The advantages of pelletisation (Garcia-Maraver and Perez-Jimenez, 2015) include the facts that (i) the bulk density of biomass can be increased from an initial bulk density of 40-200 kg/m^3 to a final bulk density of 600-800 kg/m^3, (ii) the uniform size and shape of the pellets make them easy to handle using existing handling and storage equipment, (iii) a high energetic density (16.5-19 MJ/kg) and low moisture content (6-8 %) can be achieved, and (iv) the versatility of biomass pellets, which can be produced from a wide range of raw materials.

The European Union is the largest international market for biomass pellets, with a 94 % growth in pellet purchasing over the last decade and average prices of around 200–250 €/t (Hernández-Solorzano et al., 2017). However, demand for pellets is high globally. Thrän et al. (2017) report that the global wood pellet market has increased dramatically since 2011, with an average increase of 14 %/y. New regions have entered the market both as producers (e.g., Southeast Europe) and buyers (e.g., East Asia).

A search for recent research on the production of biomass pellets from maize residues revealed that various aspects of the biomass pellet production process have attracted scholarly attention, including pre-processing, pelletisation, and utilisation. Tumuluru et al. (2016) evaluated the effects of binder addition on the quality and energy consumption of the high-moisture pelleting process. The flat die pellet mill (10 Hp) was used to produce corn stove pellets. Increasing the binder (pure corn starch) percentage to 4 % improved pellet durability (over 98 %) and reduced specific energy consumption 20 – 40 %. The bulk density of pellets was over 510 kg/m^3, and the percentage of fine particles generated was reduced to less than 3 %. This process is a part of the biomass pellet supply chain. The test used high-moisture raw materials. No tests consider emissions, deposit formation, and corrosion of combustion. Whittaker and Shield (2017) examined two factors (feedstock dualities and pelleting conditions) affecting the durability of biomass pellets made from wood, grasses, and straw. The factors influencing durability are the moisture content of material, size reduction during pre-processing, the use of binders, feedstock mixes, die pressures and temperatures, storage conditions, and handling frequency. This research relates to the biomass pellet supply chain. Only durability was studied. Hamzah et al. (2018) compared fuel properties for wood pellets and torrefied wood pellets. The study considered chemical and physical properties, moisture analysis results, TGA (thermo gravimetric analyser) data, bomb calorimeter readings, and elemental analysis and SEM (scanning electron microscope) data. Torrefaction improved the wood pellets' properties, making them nearer to those of coal. This work emphasized only pre-treatment for upgrading pellets. Malik et al. (2015) offered a review of biomass processing in terms of the available pelletisation technology, biomass pellet energy efficiency, and opportunities for the biomass pellet market. There are two types of conventional pelletisers: flat die and ring die pelletisers. In a flat die pelletiser, the rollers rotate and compress the biomass feedstock while the die remains stationary. This way, when the biomass is forced through the die holes, friction will cause the temperature of the die to increase to 75–85 °C. This review focused on pelletisation process technology with no regard paid to the harvesting process. Pradhan et al. (2018) reviewed the production and consumption of fuel pellets made from non-woody biomass. The study considered pre-processing for pelletisation, the influence of process parameters on pellet quality, and the economic feasibility of fuel pellets for energy utilisation. Non-woody biomass (e.g., agricultural residues, energy crops, and other organic wastes) may provide an effective sustainable energy source. Pelletisation process parameters such as moisture content, particle size, and biomass composition have significant effect on fuel pellet quality. Pellet quality has implications for storage, transport, and international trade. This review focused on pelletisation process technology with no regard paid to the harvesting process. There was also no specific focus on maize residues. However, harvesting practices and the transport of raw materials did not receive significant attention, even though these are important components of the pellet supply chain.

To meet the goals outlined in the AEDP, Thailand should develop its ability to participate in biomass pellet markets. Both the government and the private sector should encourage the production and consumption of high-quality biomass pellets so that these can be sold domestically and exported to foreign countries. As this occurs, the AEDP can provide guidelines for achieving zero waste in the agricultural sector, which would include promoting the use of renewable energy from agricultural by-products like maize residue.

The main objective of this study was to provide an overview of the production of pellets from abundant non-woody raw materials such as maize residues. Additionally, we focus on the processes involved in the harvesting and transportation of raw materials. A comprehensive review of the characteristics of the biomass pellets, with a special focus on their combustion efficiency, is also presented. Both Thai and International standards for efficiency are included in this review.

2. Pelletisation of maize residues

This study considers the harvesting and transportation of maize residue to locations where the pelletisation process occurs. The databases used for the literature search are Google Scholar, Web of Science, and Scopus. The supply chain of the maize residue pelletisation process is shown in Figure 1. Harvesting is the first process. Pradhan et al. (2018) describe the pre-processing that follows (size reduction, torrefaction, steam explosion, hydrothermal carbonization, and biological treatment), using up-to-date pelletisation technology, theory, and process parameters for their review.

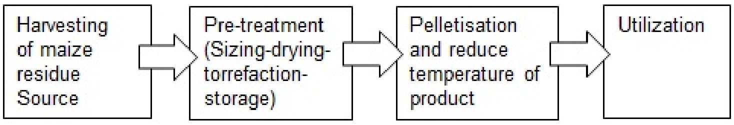

Figure 1: *Biomass pellet supply chain*

For Thailand to meet the goals laid out in the AEDP 2012-2021, the Ministry of Energy must support the development of the technologies used in the biomass pellet supply chain.

Crop maturity and maize residue quality are critical for biochemical conversion to energy during the harvesting process (Kole et al., 2012). Kludze et al. (2010) found two major obstacles to the efficient use of maize residues for heat and electricity generation. These are that maize residues have a relatively high moisture content during the harvest and that there are high levels of potassium (K) and chlorine (Cl) contained in the maize residues that make combustion difficult. Spring harvesting of maize residues is one possibility for overcoming these obstacles.

On flat ground or slopes of less than 35°, harvesting of maize residues has traditionally been accomplished by using tractor (Balaman, 2019) mounted with disc mowers, raking, and baling equipment (Kole et al., 2012). By contrast, manual labour is used to harvest crops in mountainous areas like Thailand’s highland fields. However, Pual et al. (2019) demonstrate that the harvesting methods for the field operations of maize residues include 1) shredding, raking into windrows, wilting, baling, gathering, bale loading, and transport 2) shredding, sun drying, ranking into windrows, baling, gathering, bale loading, and transport and 3) shredding and merging, wilting, chopping, windrowing, dumping into a wagon, truck filling, and transport. The 2nd method is the best process for producing high yields.

Maize residues are classified as non-woody biomass. Accordingly, the processes and equipment used for biomass pellet production are different from those used for wood biomass materials. González et al. (2011) finds that upon drying, the pellet’s quality increases and it combusts more efficiently. Multiple methods for drying biomass, such as exposure to hot air, desiccation, and the use of hot-air driers, can be implemented at industrial scales (Obernberger and Thek, 2004). The hot-air dryer is particularly suitable for pellet production in Thailand because it is easy to operate and relatively inexpensive. Size reduction is a critical step in pelleting, affecting not only compaction, but also particle contact area, friction in the die, and the feeding of biomass (Whittaker and Shield, 2017). Highly fibrous raw material was found to produce a more durable pellet. A shredding method may also be necessary (Nielsen et al., 2009). The machines that are popular for shredding or crushing are the ball mill (Hamzah et al., 2018), hammer mill (Whittaker and Shield, 2017), and grind mill (Kyauta et al., 2015). For maize residues, the hammer mill is most suitable because it can work with fibrous materials. Whittaker and Shield (2017) focus on lignin in the biomass, which they show to produce biomass pellets with improved strength. Lignin exhibits a transition behaviour at a temperature range of 135–165 °C, where it melts, acting as a binding agent during the densification process (Kambo, 2014). As a result, maize residue that includes lignin can produce high quality pellets with no additives (or only small quantities of additives). Whittaker and Shield (2017) investigate the pelleting process when undertaken at temperatures of between 100 and 130 °C and with high pressures between 115 and 300 MPa. Commercially, the densification of biomass is performed using pellet mills other than extrusion processes, briquetting presses or roller presses. The pelleting process is typically carried out in a pelletiser. The densification process is divided into three steps. First, a roller compresses the feedstock into a thin layer. Second, the compressed layer flows into the die channels and is partly compressed further from the sides in the cone. Last, the compressed feedstock is moved to the die channel (Frodeson et al., 2019). The machine is usually equipped with blades for cutting the pellets to the desired length. There are two types of conventional pelletisers: flat die and ring die. Both types may be suitable, depending on the size of the particular pelletiser and the capacity of its motor.

3. Combustion characteristics of the pellets

The characteristics of pellets (including their physical properties and composition) affect their combustion. Table 3 shows ENPlus standards, Initiative of Wood Pellet Buyers (IWPB) standards, and international standards for wood pellets. Non-industrial qualities are labelled A1, A2 and B, while industrial qualities are labelled I1, I2 and I3 (Thrän et al., 2017).

Table 3: Standards for maize residue pellets

Specifications	EnPlus Standards (Whittaker and Shield, 2017)			IWPB Standards (Whittaker and Shield, 2017)			ISO (Arti-Khalsa et al., 2016)
	A1	A2	EN-B	I1	I2	I3	(unit, Dry matter)
Total density (kg/m^3)	≥ 600			≥ 600			ISO 17828
Average diameter (mm)	6-8			6 ≤ D ≤ 8	6 ≤ D ≤ 10	6 ≤ D ≤ 12	NA
Durability (%)	≥ 97.6		≥ 96.5	≥ 97.5	≥ 97	≥ 96.5	ISO 17831-1
Random length	3.15 ≤ L ≤ 40 mm			≤ 40 mm			NA
Moisture (%)	≤ 10			≤ 10			ISO 18134-1
Net calorific value (MJ/kg)	16.5 ≤ CV ≤ 19	16.3 ≤ CV ≤ 19.	16.0 ≤ CV ≤ 19	≥ 16.5			ISO 18125
Ash (%)	≤ 0.7	≤ 1.5	≤ 3	≤ 1	≤ 1.5	≤ 3	ISO 18122
Chlorine content (%)	≤ 0.02		≤ 0.03	≤ 0.03	≤ 0.05	≤ 0.1	ISO 16994 (g/kg)
Sulphur content (%)	≤ 0.03		≤ 0.04	≤ 0.05	≤ 0.2	≤ 0.4	ISO 16994 (g/kg)
Nitrogen content (%)	≤ 0.3	≤ 0.5	≤ 1.0	≤ 0.3	≤ 0.5	≤ 1.5	ISO 16948 (g/kg)

The effects of pellet characteristics on combustion efficiency (for Thailand standards) are presented the difference of the class 1 and 2 in Table 4 (class 1 refers to class B: ISO 17225-6). The values of total density, usually diameter, durability, minimum length, maximum length, length over 40 mm, moisture, net calorific value, chlorine, sulphur, and nitrogen are ≥ 600 kg/m^3, 6 to 25 mm, ≥ 96.0 wt%, ≥ 3.15 mm, < 45.0 mm, < 1 wt%, < 15 wt%, ≥ 14.5 MJ/kg, < 0.30 wt%, < 0.30 wt%, and < 2.0 wt%, respectively. A number of the Thai standards are lower than the international standards. This will make pellets produced according to the Thai standards challenging to export abroad and will affect their use in power plants that are designed according to international fuel standards. The amount of ash is especially problematic. Furthermore, deposit formation and corrosion due to combustion should also be considered, as these can pose major problems during power plant operation, including both decreased performance and increased incidence of difficulties. This is demonstrated both in theoretical (Pintana and Tippayawong, 2015) and experimental (Gilbe et al., 2008) study.

Nevertheless, TISI specifies the use of non-woody pellets. Maize residues are included in this class. Non-woody pellets tend to be cheaper than wood pellets. For this reason, efforts to develop Thailand's production of non-woody biomass pellets should increase the standards for their quality and should also focus on previously-neglected aspects of the supply chain such as transportation and storage. The cost of the entire production process should be consistent with future demand and supply. These recommendations can be used as a guide for achieving zero-waste agriculture and promoting the use of renewable energy for sustainable development.

Table 4: The difference of class1 and 2 for non-woody pellets in Thai industrial standards (TISI, 2017)

Specifications	Class 1	Class 2
Amount of dust (wt%)	< 3.0	< 6
Random length (mm)	3.15 to 40 (Diameter 6 to 10), 3.15 to 50 (Diameter 12 to 25)	3.15 to 40
Ash (wt%)	< 10	< 18
Additive (wt%)	< 5	Not determined

4. Conclusions

This study presented an overview of the utilisation of maize residues for pellet production. The technology used in the supply chain of pellet processing (which includes harvesting, pre-treating, binding, and pelletising phases) was described. Special focus was given to technology that is commercially available and can be used especially for maize residues. The study presented a comparison of the Thai industrial standards for non-woody pellets and international standards for biomass pellets. The effects of various characteristics of maize residues and pelletised maize on combustion efficiency were described. This information can be used to direct efforts to expand biomass production capacity in Thailand to improve production efficiency and sustainability.

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