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Enhancing the potential of sugarcane bagasse for the production of EN*plus* quality fuel pellets by torrefaction: an economic feasibility study

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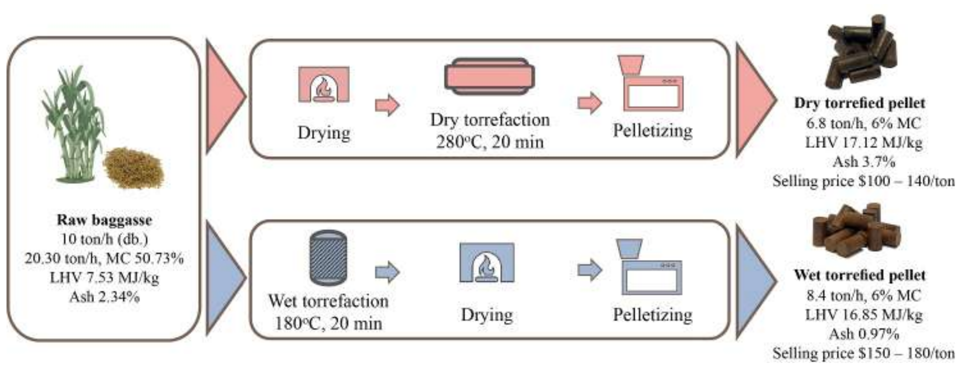
HIGHLIGHTS

- Production of sugarcane bagasse fuel by dry and wet torrefaction was investigated.
- Both wet and dry torrefaction could increase the calorific value of sugarcane bagasse.
- Wet torrefaction could reduce the ash content of the fuel to the standard level.
- Wet and dry torrefaction was both economically viable for fuel pellet production.

GRAPHICAL ABSTRACT



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ABSTRACT

When fossil fuel substitution with biomass is viewed as a potential solution to global warming caused by greenhouse gas emissions, the demand for biomass fuel pellets has increased worldwide. Although agricultural waste is an attractive potential feedstock for fuel pellet production due to its relatively high calorific value and low cost, its excessive ash content is a major drawback. This research investigates the properties of sugarcane bagasse fuel pellets treated by dry and wet torrefaction and evaluates the economic value of selling the fuel pellets, which were priced based on their quality. It was found that the wet torrefaction could significantly reduce the ash content in the product (1% ash content at a torrefaction temperature of above 180°C), resulting in higher quality and more marketable fuel pellets. Consequently, the yield and the net present value of the production of wet torrefied fuel pellets were greater than those of dry torrefied pellets. Nevertheless, the production of fuel pellets from sugarcane bagasse treated by either process is shown to be economically viable.

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Abbreviations and Nomenclatures

A	Capacity of present equipment	m_{ab}	Sample weight
A_0	Capacity of the base equipment	m_d	Initial dry weight
C	Cost of equipment	MI	Mechanical installation
C_0	Cost of the base equipment	*n* (Eq.2)	Values vary between 0.4 – 0.6 (**Table S2**)
CEPCI	Chemical Engineering Plant Cost Index	*n* (Eq.4)	Project life
D	Depreciation	NER	Net energy ratio
DT	Dry torrefaction	NPV	Net present value
DTB	Dry torrefied bagasse	SBG	Sugarcane bagasse
DTP	Dry torrefied pellet	TCI	Total capital investment
EI	Electrical installation	TDEC	Total direct equipment cost
F	Freight	TIC	Total indirect cost
FCI	Fixed capital investment	TOC	Total operating costs
GHG	Greenhouse gas	TPEC	Total purchase equipment cost
H	Hydrogen content	TR	Total revenue
HHV	Higher heating value	WT	Wet torrefaction
i	Internal rate	WTB	Wet torrefied bagasse
LHV	Lower heating value	WTP	Wet torrefied pellet

1. Introduction

Today, the rapid change in the climate has made the world more aware of the need to intensively cut back on greenhouse gas (GHG) emissions. At the COP26 conference in Glasgow, Scotland, at the end of 2021, leaders from the United States and China, the countries with the highest carbon dioxide emissions, pledged to increase cooperation on climate protection by reducing methane emissions, switching to clean energy, and reducing carbon emissions to zero within the next 10 years. Furthermore, over 40 countries agreed to phase out coal as a fuel, as it is the most significant contributor to climate change. In this regard, biomass pellets, which provide the amount of heat as one ton of coal for every 1.12 tons, have attracted considerable interest and emerged as a prominent fuel alternative (Wiloso et al., 2020). In particular, according to their life cycle assessment, the use of biomass pellets as a fuel can reduce GHG emissions by 65 to 100% compared to fossil fuels (Wiloso et al., 2020; Unnasch and Buchan, 2021). Furthermore, when combusted, solid biomass formed into fuel pellets, emits less particulate matter than raw biomass, is more convenient to use due to its uniform size and composition, and is cost-saving in terms of storage and transportation (Ghafghazi et al., 2011).

In response to the increasing demand for biomass pellets, almost all pellets traded internationally are made from wood or a byproduct of wood processing, such as sawdust. In fact, many types of biomasses, including agricultural waste, can be utilized to produce fuel pellets with comparable efficiency. Using agricultural waste to produce fuel pellets is beneficial not only for reducing GHG emissions but also for lowering the cost of raw materials and waste disposal. However, agricultural waste has not been accepted for use in the production of fuel pellets for international export as the standards used to determine the quality of fuel pellets, such as the net calorific value (≥16.5 MJ/kg), durability (≥97.5%w), moisture content (≤10%w), ash content (≤2%w), nitrogen (≤1%w), sulfur (≤0.05%w),

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chlorine (≤0.03%w), arsenic (≤1%w), cadmium (≤ 0.5%w), etc. (refer to EN*plus* B, the European pellet standard) are defined primarily from wood-based raw materials. Compared to woody biomass, agricultural waste has a low calorific value and density, a high moisture content, and a wide variety of compositions, making its quality difficult to control. Yang et al. (2016) reported that fuel pellets made from rice straws and husks contained an excessive amount of chlorine. Similarly, chlorine and ash levels in the rice husk pellets, in a study by Ríos-Badrán et al. (2020), were found to exceed the standard limits, whereas the calorific value and durability were even lower than the minimum criteria. This is consistent with studies on the production of fuel pellets from other types of agricultural waste with similar issues, including the exceeding of chlorine in pellets made from wheat straw (Agar et al., 2018), microalgae, and corn residues (Miranda et al., 2018), and the presence of excessive ash content in pellets made from garden waste (Pradhan et al., 2018), soybean, and sugarcane bagasse (SBG) (Scatolino et al., 2018). Moreover, nearly all agricultural waste materials have a relatively low net calorific value compared to conventional wood and fossil fuels, which could be a critical problem. Even worse, agricultural waste absorbs a great deal of moisture during storage, further reducing its net calorific value.

Torrefaction is a popular thermal treatment used to eliminate the flaws in waste biomass to convert it to a more efficient solid fuel. Typically, there are two approaches to this process: dry torrefaction (DT) and wet torrefaction (WT). During the DT process, biomass is slowly heated in either an oxygen-depleted or oxygen-restricted environment. Dehydration and decarboxylation reactions occur early in the process. At temperatures between 50 and 150°C, the moisture in the biomass evaporates, and the lignin begins to loosen. As the temperature increases further, the hydrogen and carbon bonds begin to break down. By the end of the process, hemicellulose is completely decomposed while cellulose and lignin are partially degraded at the degradation temperatures of hemicellulose, cellulose, and lignin ranging from 220–315°C, 315–400°C, and 150–900°C, respectively (Yang et al., 2007; Shankar Tumuluru et al., 2011). This process yields three types of products with different phases: a liquid fraction composed primarily of volatile organic compounds such as acetic acid, aldehydes, alcohols, and ketones; a gas product (sometimes referred to as torr gas) composed primarily of CO_2, CO, and trace amounts of methane; and a solid product known as torrefied biomass, which is used for energy purposes. Due to the darkish colors, torrefied fuel pellets are sometimes referred to as black pellets. These solid fuels have a lower percentage of moisture, greater energy density, hydrophobicity, grindability, and stability. On top of that, modifying biomass by torrefaction is also more energy-efficient than other thermal processes, such as pyrolysis or carbonization, as it is conducted at a low-temperature range (200–300°C) and in a short period of time, typically lasting less than 30 min in the absence of oxygen (Barskov et al., 2019; Cahyanti et al., 2020). However, DT does not solve the problem of the exceeding ash and chlorine content in waste biomass, unlike WT (also known as hydrothermal carbonization), which reacts at lower temperatures of around 180-260°C for approximately 2 h. As the reaction takes place in water, the water plays a significant role in removing unwanted inorganic compounds such as potassium and sodium, sulfur, and chloride, as well as reducing ash content. Gong et al. (2019) reported that WT could reduce ash, potassium, and chloride contents in palm empty fruit bunches by up to 67.99, 98.62, and 99.27%, respectively.

Past studies on applying torrefaction processes to improve the energy quality of waste biomass have focused mainly on the effect of reaction conditions on product properties. Those include, for example, a comparative study of the effects of DT and WT on the pyrolysis behavior of corncobs (Zheng et al., 2015), a study on the effect of torrefaction conditions on the calorific value of sorghums (Yue et al., 2017), ponkan peel (da Silva et al., 2020), spent coffee grounds and microalga residues (Zhang et al., 2018), rice husks (Chen et al., 2020), fruit peels (Lin et al., 2021), and cassava rhizome (Nakason et al., 2021). All the studies above indicate that torrefied waste biomass has great potential as an alternative to fossil fuels as it could be used to replace coal in coal power plants without needing mechanical upgrades (Koppejan et al., 2012). Furthermore, Devaraja et al. (2022) compiled and reviewed the torrefaction of various biomass of varying interest in several aspects, including the effect of various factors on the torrefied product, torrefaction kinetics, torrefaction mechanism, reactor type, applications, and environmental aspects. However, the economic feasibility of torrefaction biomass was not included. Despite this, the use of waste biomass to produce pellet fuels for commercial purposes is constrained by the profitability of production, which is a key factor in investors' decisions. The cost-effectiveness analysis of torrefied waste biomass production is therefore critical to pushing excellent research at the lab scale into industrial production and is thus a focus of this research.

SBG was chosen to represent waste biomass in this study due to the abundance of this biomass worldwide. In 2019, 526 million tons of SBG were produced from 1,900 million tons of sugarcane, with Thailand ranked third in the world as the top sugarcane grower, with approximately 35 million tons of SBG left over from sugar production each year (Miranda et al., 2021). This agricultural waste biomass is a rich carbon source that can be utilized for energy production. It is composed primarily of 39–43% cellulose, 25–32% hemicellulose, and 21–23% lignin (Mandegari et al., 2017). This SBG is mostly combusted as fuel to produce electricity and heat to be used in the manufacturing process. As previously stated, however, using SBG as fuel by direct incineration has many disadvantages, including a high moisture content resulting in a low calorific value, a high inorganic content resulting in slag in the furnace, and the emission of toxic gases into the atmosphere. In addition, sugarcane production is seasonal, necessitating bagasse be stored for year-round availability at a high cost and requires a large amount of storage space. Therefore, producing fuel pellets for value-added sales could be an attractive alternative.

This study's encompassing goal is to determine how feasible it is to produce high-quality fuel pellets out of SBG at a competitive price on a global scale. Herein, two torrefaction approaches were investigated, including DT and WT, with the optimal conditions (determined by laboratory experiments) contributing to international standard-compliant fuel pellets. Finally, the cost-effectiveness of producing fuel pellets from SBG was analyzed, considering the revenue earned by the pellets' quality.

2. Material and Methods

2.1. Preparation of sugarcane bagasse

The SBG samples used in the study were byproducts of the sugar production process at Thai Rung Ruang Industry Co., Ltd. (Thailand). After 5-7 d of natural drying, the samples were ground with a grinder and sorted by size. The 0.5–1 mm biomass was collected and stored in a desiccant chamber for further use.

2.2. Torrefaction process

2.2.1. Dry torrefaction

The DT process in this study was performed under inert gas conditions with nitrogen flow at 100 mL/min in a laboratory fixed bed reactor. As a 5 g bagasse sample was introduced in a quartz tube of 25 mm in diameter and 600 mm long, the study was conducted at a constant heating rate of 30°C/min and a retention time of 20 min. To study the effect of torrefaction temperature on the properties of biomass, various reaction temperatures were tested, i.e., 240, 260, 280, and 300°C. As soon as the specified retention time elapsed, the sample was allowed to cool under nitrogen flow conditions until the temperature fell below 100°C. The resulting dry torrefied bagasse (DTB) was weighed and stored in a desiccant chamber for further analysis.

2.2.2. Wet torrefaction

Using a 100 mL Parr reactor, the DT procedure was carried out at a constant pressure of 50 bar. Five g of bagasse samples were combined with DI water at a ratio of 12:1 and allowed to saturate in the reactor for approximately 30 min. The reactions were conducted at 160, 180, 200, and 220°C while stirring at a constant rate of 300 rpm. To cease the reaction after proceeding for 40 min, the vessel containing the samples was removed from the reactor and immediately immersed in cold water until the temperature decreased to 100°C. The resulting wet torrefied bagasse (WTB) was subsequently filtered and dried in an oven at 105°C for 3 h before being stored in a desiccator until further analyses.

2.2.3. Analysis of torrefied bagasse properties

Samples of raw SBG, DTB, and WTB were analyzed for their basic properties in order to select the torrefaction conditions used as a reference

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for the cost-effectiveness assessment. The analyses include determining moisture and ash content by a thermogravimetric analyzer (TGA) (Q50, TA Instruments, USA), in which samples were thermally decomposed under a nitrogen atmosphere at 40-800°C. The higher heating value (HHV) was analyzed using an oxygen bomb calorimeter (1341 Calorimeter, Parr Instrument, USA) and was converted to the net calorific value utilizing **Equation 1** (Scatolino et al., 2018):

$$Net\ calorific\ value = HHV - \left(600 \times \frac{9H}{100}\right) \quad \text{Eq. 1}$$

where H is a hydrogen content (%).

To determine the percentage of water uptake, bagasse samples (SBG, DTB, and WTB) were formed into pellets in a single pellet machine and dried at 105°C overnight to remove moisture. Before recording their initial dry weights, the samples were chilled in a desiccator until they reached room temperature. Following this, they were kept in a simulated desiccator at 25°C, with 75% relative humidity, obtained by a saturated NaCl solution. At the designated times, samples were weighed until stabilized, which took a minimum of 72 h. The percentages of moisture uptake were then calculated from **Equation 2**:

$$Moisture\ uptake\ (\%) = \frac{m_{ab} - m_d}{m_d} \times 100 \quad \text{Eq. 2}$$

where m_{ab} is the sample weight that absorbs moisture at different times, and m_d is the initial dry weight.

All trials of bagasse pretreatment by torrefaction and sample quality analysis were conducted in triplicate.

2.3. Cost-effectiveness analysis

2.3.1. Scenario description

Analyses of the cost-effectiveness of torrefied bagasse were conducted employing energy consumption and product yield data from the optimal conditions obtained from previous experiments. Herein, two scenarios with details as follows were evaluated.

Scenario DT: Raw SBG is dried to a moisture content of approximately 7% w/w, then crushed to a size of 0.5–1 mm, pretreated by the DT process, and finally pressed into fuel pellets.

Scenario WT: Raw SBG is subjected to WT without any reduction in water content. After undergoing WT, the biomass is separated from the liquid by filtration. The bagasse is then dried in an oven to a moisture content of approximately 6% w/w, crushed to a smaller size, and pelletized.

The results and experimental conditions that contributed to pellets of standard quality at the highest product yield were employed in assessing material and energy consumption. In this study, a production capacity of 10 tons of raw SBG/h was assumed (dry basis). The bagasse obtained from the milling process possessed an approximate moisture content of 50.73%w/w and a lower heating value (LHV) of 7.53 MJ/kg. The energy required for drying in the pretreatment, for both the DT and WT processes, was estimated from the sensible heat of bagasse, approximately 1.12 kJ/kg K (Ndagi et al., 2021), and the latent heat of the water.

2.3.2. Total capital investment

Total capital investment (TCI) includes all the costs required to operate the project. Applying an approach derived from research by Manouchehrinejad et al. (2021) and Doddapaneni et al. (2018), the investments assessed in this research consist of total purchase equipment cost (TPEC), installation cost, freight (F), construction expenses, engineering and supervision, legal expenses, etc., as shown in **Table 1**.

TPEC serves as the primary basis for all other cost estimates. It includes the cost of the principal production machinery, such as grinding, torrefaction reactor, dryer, pelletizer, filter, and pellet cooler, as well as the cost of site preparation, plant buildings and offices, receiving station, and storage (Supplementary Material, **Table S1**). These were estimated based on prior research prices, then modified to meet the production capacity indicated in this study by capacity factors (**Eq. 3**), and then updated to 2019 costs using the Chemical Engineering Plant Cost Index (CEPCI) factor (**Eq. 4**).

$$C = C_0 \times \left(\frac{A}{A_0}\right)^n \quad \text{Eq. 3}$$

where C is the cost of equipment, C_0 is the cost of the base equipment, A is the capacity of present equipment, A_0 is the capacity of the base equipment, and n values vary between 0.4 – 0.6 (Supplementary Material, **Table S2**).

$$Cost_{year\ X} = Cost_{year\ Y} \times \frac{CEPCI_X}{CEPCI_Y} \quad \text{Eq. 4}$$

Table 1.
Economic parameters considered in the present study.*

Parameter	Value
Year of analysis	2019
Plant life	20 yr
Plant capacity	10 tons of bagasse/h (d.b.)
Plant operating time	8,000 h/yr
Discount rate	10%
Income tax rate	30%
Financing	100% equity
Depreciation	10 yr (Straight line)
Capital and Operating cost estimation	
Capital cost estimation	
Direct cost	
• Total purchase equipment cost (TPEC)	100%
• Mechanical installation (MI)	32% of TPEC
• Electrical installation (EI)	20% of TPEC
• Freight (F)	4% of TPEC
Total direct equipment cost (TDEC)	Summation of 1.1.1 to 1.1.4
Indirect cost	
• Construction expenses	20% of TDEC
• Engineering and supervision	6% of TDEC
• Legal expenses	4% of TDEC
• Contractor's fee	10% of TDEC
• Contingency fee	20% of TDEC
Total indirect cost (TIC)	Summation of 1.2.1 to 1.2.5
Fixed capital investment (FCI)	TDEC + TIC
Working capital	15% of FCI
Total capital investment (TCI)	FCI + working capital
Operating cost estimation	
• Maintenance cost	3% of FCI
• Insurance and tax	1% of FCI
• Labor and supervision	375USD/month for labor, 950USD/month for supervisor (estimated based on Thai wages)
• Overhead	0.9 of salaries
Total operating cost	Summation of 2.1 to 2.4 + materials cost + utilities cost + wastewater treatment cost
Electricity price	0.1USD/kWh (Nakason et al., 2021)
Natural gas price	0.27 USD/m^3 (EIA, 2022)
Water price	0.85 USD/m^3 (Provincial Waterworks Authority, Thailand)
Wastewater treatment cost	1.3 USD/m^3 (Doddapaneni et al., 2018)

* Source: Doddapaneni et al. (2018); Akbari et al. (2020); Manouchehrinejad et al. (2021)

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2.3.3. Total operating cost

Total operating costs (TOC) include fuel, utilities, water treatment costs (for WT), labor and supervision, overhead, maintenance, insurance, and taxes. The utility cost is approximated at 0.1 USD/kWh and 0.85 USD/m^3, based on Thailand's electricity and water tariffs, respectively (Nakason et al., 2021; Provincial Waterworks Authority, Thailand), as shown in **Table 1**.

2.3.4. Profitability

One of the most prominent metrics used to assess the cost-effectiveness of a project in investment decisions is the net present value (NPV). As described by **Equations 5** and **6**, NPV is calculated by subtracting the initial investment from the net cash flow over the project's lifetime.

$$NPV = \left(\frac{(1+i)^n - 1}{i \times (1+i)^n} \times net\ cash\ flow\right) - TCI \qquad \text{Eq. 5}$$

$$Net\ cash\ flow = \left((TR - TOC) \times (1 - tax\ rate)\right) + D \qquad \text{Eq. 6}$$

Denoted in **Equation 6**, total revenue (*TR*) is the revenue earned from the sale of torrefied pellets, *TOC* is the total production cost, and *D* is the depreciation. In this study, project lifetime (*n*) was defined as 20 yr, the internal rate (*i*) was 10%, and the income tax rate was 30%.

3. Results and Discussion

3.1. Selection of torrefaction conditions

Net calorific value and ash content are the two main criteria used in international standards to determine the quality of fuel pellets, which affect their market prices. Particularly, these two elements play a key role in rendering the use of agricultural waste as a raw material for fuel pellet production unacceptable. The first part of this study examined the effect of torrefaction temperature on the net calorific value and ash content of the produced pellets. Here, the optimal conditions under which the produced solid fuel meets international standards were selected for further economic evaluation.

Figure 1a depicts the calorific values of raw SBG, DBG, DTB, and WTB. Obviously, compared to raw SBG (7.53 MJ/kg) and DBG (15.04 MJ/kg), torrefied bagasse has a greater calorific value, ranging from 15.84 to 17.46 MJ/kg and 15.80 to 17.73 MJ/kg for DTB and WTB, respectively. The amount of water in the sample substantially affects the calorific value, as indicated by the 2-fold difference in that between raw SBG with 50.73% moisture and DBG with 7% moisture. Accordingly, to evaluate how torrefaction alone impacts the calorific value, the properties of DTB and WTB were compared to those of DBG. Here, torrefaction was found to enhance the calorific value by roughly 5.0–17.9%, with both DTB and WTB trending in the same direction, i.e., the higher the reaction

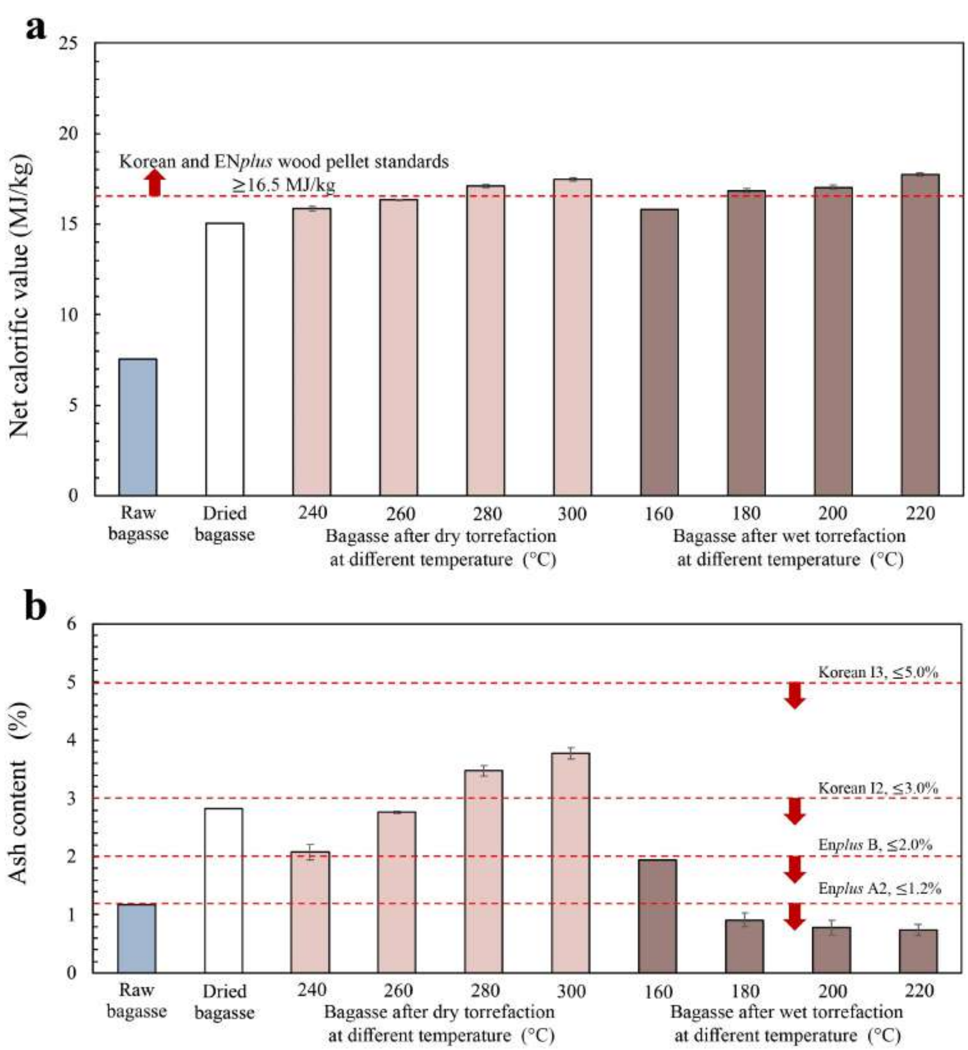

Fig. 1. Properties of bagasse and torrefied bagasse: **(a)** net calorific value, and **(b)** ash content

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temperature, the greater the calorific product. As shown in **Figure 1a**, the calorific value of DTB increased from 15.84 to 17.46 MJ/kg as the torrefaction temperature increased from 240 to 300ºC, similar to that of WTB, enhancing from 15.80 to 17.73 MJ/kg as torrefied at 160 and 220ºC, respectively. This is because the increase in temperature causes the reduction of the H/C and O/C ratios in the product, resulting in an increase in the fixed carbon in the sample (Doddapaneni et al., 2018; Perera et al., 2021). The results indicate that torrefaction has the potential to be an effective technique for improving the thermal quality of agricultural waste biomass like SBG. This finding is consistent with previous research studies in which torrefaction increased the calorific value by 11–45.25% for bagasse (Anukam et al., 2017; Kanwal et al., 2019), 63.40% for sorghum (Yue et al., 2017), 18.13% for corn cobs (Medic et al., 2012), 14 ~ 29% for rice husk (Chen et al., 2015; Zhang et al., 2017), 15–25% for grape pomace (Pala et al., 2014) after undergoing dry torrefaction at 250–300ºC, and 12.2-28.4% for daily sludge after wet torrefaction at 180-240ºC (Al Ramahi et al., 2021).

The contrast between DT and WT was emphasized by the ash content. Compared to WTB, DTB had a much greater ash content, ranging from 2.08 to 3.78% *vs.* 0.74 to 1.94% (**Fig. 1b**). This is because the water in the WT increased the accessibility of the reactants, promoting the leaching of inorganics contained in the sample to dissolve with water (Bach et al., 2017; Chen et al., 2021). The capability of WT to reduce the ash content of biomass has been established in several previous research investigations as one of its noteworthy characteristics. For instance, Zheng et al. (2015) discovered that the ash content in corncobs was reduced by up to 59% after 175ºC WT. However, considering the ash content in DTB, it was found to be higher at more elevated torrefaction temperatures. This is because the thermal decomposition of organic matter in the sample varies with process temperature. As a result, at higher temperatures, the mass yield gradually decreased while the ash content remained constant, increasing the proportion of ash in the product accordingly (Chen et al., 2021; Lin et al., 2021).

Compared with the European Wood Pellet Standards (European Pellet Council-EPC, 2015) and the Quality Specification of Industrial Wood Pellets in South Korea (DiPasquale, 2020), it was found in this study that high temperatures of over 280ºC for DT and above 180ºC for WT were required to torrefy bagasse into a fuel with a calorific value that meets both standard criteria (≥16.5 MJ/kg). Regarding ash content, the restriction defined by both standards is more stringent than the calorific value, as residual ash in the fuel pellets may generate slag in the furnace during combustion (Lin et al., 2021). According to the EU pellet standard, which classifies pellet quality into three grades with varying ash percentages (0.7% for EN*plus* A1, 1.2% for EN*plus* A2, and 2.0% for EN*plus* B, as determined by ISO 18122 testing), only WTB met these rigorous criteria. The Korean standard also categorizes pellet fuel quality into three tiers, with ash content restrictions of 1.5% for I1, 3.0% for I2, and 5% for Grade I3. Consequently, DTB samples torrefied at 280ºC and 300ºC met the criteria for both heat value and ash content according to the Korean standard for Grade I3.

To verify that the torrefied bagasse obtained from this study meets the fuel pellet standard, it was formed into pellets and tested for durability and bulk density. **Table 2** shows the key properties of fuel pellets made from raw and torrefied bagasse. Compared to previously published research and European and Korean fuel pellet benchmarks, it was found that the fuel pelletized from DT (280ºC, 20 min) possessed durability and bulk density of 96.76±0.51%w/w and 620±5.52 kg/m^3, respectively, which passed the Korean, I3 criteria. However, it can be seen that both the durability and bulk density of the fuel pellets derived from DT were lower than those from raw bagasse. This is because lignin, which acts as a binder in pelletization, was partially degraded during the DT process. In contrast, fuel pellets obtained from WT at 280ºC, 20 min, met all grades of all standards for durability and bulk density of 99.92±0.40%w/w and 637.40±0.4 kg/m^3, respectively. Furthermore, bagasse torrefaction pellets had a lower moisture uptake of around 10-11.6% compared to the 16.45% of raw bagasse pellets. Clearly, this indicates that the torrefaction process results in fuel pellets with a greater degree of hydrophobicity, a property that has a direct impact on the pellets' storage and calorific value.

The key factor influencing cost-effectiveness is the cost and revenue from the sale of fuel pellets. The temperatures of 280ºC and 180ºC were the least severe conditions for DT and WT, respectively, which resulted in the lowest energy costs while yielding products of standard quality and thus have the potential to be sold at a profit. For this reason, such conditions are chosen for the cost-effectiveness analysis.

3.2. Cost-effectiveness analysis

3.2.1. Mass balance and energy consumption

Figure 2 shows the configuration of the bagasse pellet production process (**Fig. 2a**) by DT at 280ºC for 20 min and (**Fig. 2b**) by WT at 20 min at 180ºC. These are the lowest temperatures and retention times that produced fuels with an international standard-compliant calorific value and ash content, contributing to the lowest production costs. By DT at 280°C for 20 min, I3-level (the Korean fuel pellet standard) DTB with a calorific value of 17.12±0.09 MJ/kg and an ash content of 3.5% w/w was obtained. As for WT at 180°C for 20 min, WTB with a calorific value of 16.85±0.12 MJ/kg and an ash content of 0.97%w/w, passing the EU fuel pellet standard, EN*plus* A2, was yielded. Based on these benchmarks, the quality of the fuel pellets determines their selling price, which, in this study, was used to estimate the project's revenue.

In this assessment, both processes were assigned a production rate of 10 tons of raw SBG /h (dry basis). The moisture content of raw SBG and torrefied bagasse pellet was 50.73% (Department of Alternative Energy Development and Efficiency, Ministry of Energy, Thailand, 2012) and 6.00% (assumed for this study), respectively. Additionally, it was assumed that there was no loss from processes other than the torrefaction. The fuel product's yield depends on the conditions' severity. By pretreatment under the higher temperatures of the DT process, a lower mass yield of 63.83% resulted in the production of 6.8 tons of DTB/h. With milder conditions, WT pretreatment contributed to a mass yield of 78.99%, resulting in a fuel pellet product of 8.4 tons/h. The mass yield obtained from DT in this study fell within the same range as the study by Abelha and Kiel (2020), which reported mass yields of 56, 68, and 76% for roadside grass, wheat straw, and miscanthus after DT pretreatment, respectively. However, the mass yields obtained in this study were lower than those from some of the previous research works. According to Manouchehrinejad et al. (2021), the mass yields of DT-treated wood logs were 75%, while Akbari et al. (2020) reported that DT and WT resulted in 83% and 80% of mass yields, respectively. These differences in mass yield are dependent not only on temperature and retention time but also on variables such as the type of raw material, the inert gas flow rate in the DT process, and the water-to-biomass ratio in the WT process, etc.

The assessment of the energy demand of both processes revealed that the majority of the energy consumed in the process is for drying and torrefaction. In Scenario DT, drying is performed before the torrefaction stage, while it is carried out after torrefaction in Scenario WT. Depending on the amount of moisture to be removed from the sample, the energy required for drying for both scenarios varies in the range of 2,170–3,578 kJ/kg of the pellet (898–1,198 kJ/kg of raw SBG). This is consistent with previous research reporting that approximately 1,328–1,372 kJ of energy is required for drying to reduce wood moisture before torrefaction (Ghiasi et al., 2014; Doddapaneni et al., 2018). Notably, the energy used in the torrefaction stage for WT (8,755 kJ/kg pellet) was 8 times higher than that for DT (1,050 kJ/kg pellet). This is due to the excess amount of water added in WT, particularly at a water-to-SBG ratio of 12:1, which results in extra energy required to heat a large amount of water. However, varying torrefaction energy requirements have been reported in recent studies, such as -630 to 350 kJ/kg of dry biomass for DT at 200–300°C (Bates et al., 2013) and 124±400 kJ/kg for DT at 300°C for 10 min (Prins et al., 2006). The reason for the wide range of energy consumption for DT, some of which are even negative, is that the total reaction of cellulose degradation is exothermic. However, energy is still required to drive the reaction, with varying amounts depending on the type of reactor. According to Kohl et al. (2015), the 280°C DT of 1 kg of biomass requires roughly 714 kJ of energy. The energy used in other processes, including grinding, screening, and pelletizing, was approximated using previous study data and was assigned as a whole at 400 MJ/ton of pellet (Manouchehrinejad et al., 2021).

When the entire process is taken into account, the specific energy consumption for the production of the wet torrefied pellet (WTP) is relatively high (11,358 kJ/kg of the pellet) compared to that of the dry torrefied pellet (DTP) (5,155 kJ/kg of the pellet), which is primarily due to the energy used in the different torrefaction stages.

The net energy ratio (NER) is another parameter indicating how energy efficient the torrefaction process is in fuel production. It is the ratio between

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Table 2.
Properties of biomass pellets.

Raw material	Treatment	Calorific value [MJ/kg]	Ash [%w/w]	Durability [%w/w]	Bulk density [kg/m³]	Moisture uptake [%]	Reference
Sugarcane bagasse	Untreated (dried)	15.04	3.14	97.36 + 0.45	627.51 + 7.23	16.45 + 0.15[b]	This study
Sugarcane bagasse	DT, 280°C, 20 min	17.12 + 0.09	3.5	96.76 + 0.51	620.34 + 5.52	10.03 + 0.05[b]	This study
Sugarcane bagasse	WT, 180°C, 20 min	16.85 + 0.12	0.97	99.92 + 0.40	637.40 + 0.40	11.56 + 0.11[b]	This study
Oat hull: mustard meal (50: 50)	DT, 350W, 20 min (microwave)	26.0 + 0.5[a]	n.d.	99.9 + 0.1	809.0 + 7.4	13.8 [d]	Sarker et al. (2022)
Canola hull: mustard meal (50: 50)	DT, 350W, 20 min (microwave)	25.5 + 0.4[a]	n.d.	97.8 + 2.02	822.0 + 7.8	16.5 [d]	Sarker et al. (2022)
Wood sawdust	DT, 230°C, 45 min	17.36[a]	0.22	n.d.	161.95	13.72 [d]	Alizadeh et al. (2021)
Rice straw	Untreated	14.80	10.14	~86	525.67	n.d.	Kizuka et al. (2021)
Spent coffee grounds	Untreated	23.15	1.5	89.2	563	n.d.	Park et al. (2021)
Pepper stem	Untreated	16.67	6.2	98.9	640	n.d.	Park et al. (2021)
Rice straw	DT, 250°C, 45 min	16.09	10.52	~92	716.50	n.d.	Kizuka et al. (2021)
Soybean straw	DT, 250°C, 45 min	18.1[a]	< 5.0	92.78	n.d.	7.4[e]	Zhang et al. (2020)
Pinewood	DT, 300°C, 45 min	21.3[a]	< 5.0	87.53	n.d.	4.3[e]	Zhang et al. (2020)
Canola meal	DT, 500W, 20 min (microwave)	23.2 - 23.50[a]	7.8	> 99.0	747	8.3 – 10.5[d]	Azargohar et al. (2019)
Microalgae	Untreated	27.80[a]	2.47	83.21	n.d.	n.d.	Hosseinizand et al. (2018)
Sawdust	Untreated	19.42[a]	0.08	28.64	n.d.	n.d.	Hosseinizand et al. (2018)
Oat hull	Untreated	17.0 + 0.1[a]	5.8 + 0.1	98 + 4	n.d.	20 + 1.5[d]	Abedi and Dalai, (2017)
Oat hull	DT, 550W, 30 min (microwave)	21.8 + 0.4[a]	n.d.	60 + 17	n.d.	8.5 + 0.1[d]	Abedi and Dalai, (2017)
Giant cane	Untreated	15.93	10.5	92 - 93	456	9.7[c]	Tenorio et al. (2015)
Wild cane	Untreated	18.75	4.9	76 - 88	542	5.7[c]	Tenorio et al. (2015)
Sugarcane	Untreated	12.15	6.6	90 - 91	500	5.7[c]	Tenorio et al. (2015)
Olive leaves	Untreated	18.01	14.17	88.6	< 600	n.d.	Garcia-Maraver et al. (2015)
Rice straw	Untreated	15.40[a]	15.94	n.d.	635	n.d.	Liu et al. (2013)
Standards							
European	EN*plus* A1	≥ 16.5	≤ 0.7	≥ 98.0	600 ≤ BD ≤ 750	n.d.	
	EN*plus* A2	≥ 16.5	≤ 1.2	≥ 97.5	600 ≤ BD ≤ 750	n.d.	
	EN*plus* B	≥ 16.5	≤ 2.0	≥ 97.5	600 ≤ BD ≤ 750	n.d.	
Korean	I1	≥ 16.5	≤ 1.5	≥ 97.5	≥ 600	n.d.	
	I2	≥ 16.5	≤ 3.0	≥ 96.5	≥ 550	n.d.	
	I3	≥ 16.5	≤ 5.0	≥ 95.0	≥ 500	n.d.	

DT = Dry torrefaction
WT = Wet torrefaction
[a] HHV [MJ/kg]
[b] Relative humidity 75% for 72 h.
[c] Equilibrium moisture content 21% for a week
[d] Relative humidity 90% for more than 48 h.
[e] Relative humidity 48 - 52% for more than 18 h.

the net energy output from the fuel produced and the net energy input from non-renewable energy sources. According to Shahrukh et al. (2015), the NER for conventional pellet production was approximately 5.0 and about 1.29 for steam-treated pellets, with the NER decreasing with increasing steam consumption. Due to the energy demand for heating, the water in the torrefaction stage, and the evaporation of the water in the drying, the NER value of the DTP in this study was higher than that of the WTP at 3.32 *vs.* 1.48. In past research, it was reported in the same direction that the drying process had the highest energy demand. In particular, in the production of conventional pellets, the moisture content of raw material is the main factor affecting the amount of energy used in the process (Pirraglia et al., 2010). Improving the NER value of the torrefied pellet is important to alleviate doubts regarding the necessity of incorporating a torrefaction step into conventional pellet production. Certainly, this can be achieved by increasing the calorific value of the fuel pellets and the mass yield or by reducing the energy demand in the production process to a lesser extent.

In particular, torrefaction was found to decrease the need for energy in the grinding process (Cahyanti et al., 2020). For instance, wood chips torrefied at 250°C required up to 90% less energy in grinding than un-torrefied (Manouchehrinejad et al., 2021). In addition, the sequence of torrefaction and pelletization also has an impact on energy demand quite a great deal (Yun et al., 2020).

3.2.2. Total capital investment and operating cost

The TCI cost of the project is estimated based on previous research, which comprises two major expenses:

(1) Direct cost: the cost of the primary machinery used in the manufacturing process, the site, plant buildings and offices, raw material and product storage space, installation, and transportation costs.

(2) Indirect costs: construction expenses, engineering and supervisory wages, legal charges, contractor's fee, and contingency fee.

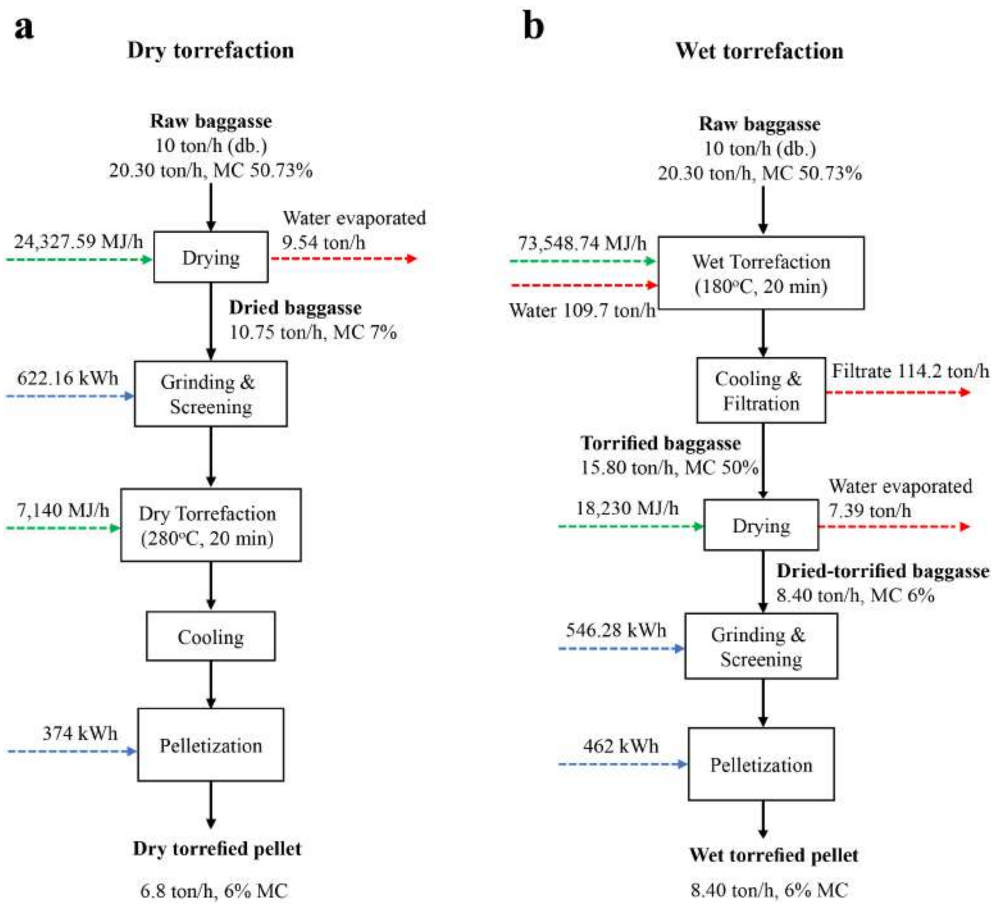

Fig. 2. Configuration of the bagasse pellet production process by **(a)** DT at 280ºC for 20 min, and by **(b)** WT at 20 min at 180ºC.

It was found that the TCI for a 6.8 tons/h (54,400 tons/yr) DTP plant in this study was determined to be greater than that for an 8.4 tons/h (67,200 tons/yr) WTP plant (18.55 MUSD *vs.* 13.98 MUSD) as a result of the differences in reactor costs (details in Supplementary Material, **Table S3**). In particular, the TCI for the DTP plant in this study lies in the range of that for a demonstration (1–4 tons/h) and a pilot biomass DTP plant (5–9 tons/h) investment costs reported by Batidzirai et al. (2013) at MUSD 5–14 and MUSD 16–23, respectively. However, previous research has shown that the TCI is quite variable, depending not only on capacity determination but also on the assessment of other factors. Specifically, 25–34% of the TCI was attributed to the pricing of torrefaction reactors, and this could be up to 60% in some studies (Pirraglia et al., 2013). Thus, it is then considered the core cost (Manouchehrinejad et al., 2021). In a study by Kumar et al. (2017), a 60,000 tons/yr DTP production plant was found to entail capital costs of MUSD 18.6–30.1, while Peng et al. (2010) reported TCIs of a 126,000 tons/yr plant, varying in the range of MUSD 22.1–31.0. Notably, incorporating the torrefaction into fuel pellet production inevitably increases project costs by 55 to 75% (Koppejan et al., 2012; Batidzirai et al., 2013); torrefied wood pellets have at least 20% higher calorific values and contribute to about 22% less shipping cost compared to white wood pellets (non-torrefied fuel pellets) (Radics et al., 2017).

The difference in production costs for the two processes is more apparent when considering the project's TOC, which includes utilities, labor costs, maintenance, insurance, and tax, accounting for 3.20 and 8.31 MUSD/yr, or 58.8 and 123.59 USD/ton of DTP and WTP, respectively (details in **Table S4**). In both processes, approximately 50-60% of TOC comes from natural gas, which is used as fuel for heating in both drying and torrefaction (**Fig. 3**). Compared to DTP, WTP has a TOC that is roughly 2.5 times higher due to the energy needed to heat the massive quantities of water used in WTP production.

Moreover, this is also due to the high cost of wastewater treatment generated by WTP production, which accounts for up to 23.3% of total TOC. This is consistent with a techno-economic assessment by Akbari et al. (2020) in which WT was found to be more costly than DT for all types of biomass. However, the TOCs obtained from this study are relatively low compared to the previous relevant research. At a similar production capacity of 80,000 tons/yr, TOCs for the production of dry torrefied woodchip pellets were estimated at 192 USD/ton (Pirraglia et al., 2012) and 205 USD/ton (Doddapaneni et al., 2018). With larger capacities of 100,000 and 120,000 tons/yr, TOCs of 197–207 USD/ton (Manouchehrinejad et al., 2021) and 174–229 USD/ton (Abelha and Kiel, 2020) were estimated, respectively. This is partly due to the fact that the raw material used in this study is a byproduct of sugar production that is already on the production site and therefore is not included in the cost of feedstock. Furthermore, the costs for the collection and transportation of feedstock are negligible. In other studies, on the other hand, the value of raw materials comprised between 40 and 60% of the TOC. Another factor contributing to the low TOC in this study is that wages are calculated using Thailand's employment rate, which is merely a quarter of those in European countries (Abelha and Kiel, 2020). In addition, unit production costs normally decrease as production capacity increases. For instance, as the production capacity increased from 50 to 500 ktons/yr, the production cost was reduced by 50% (Batidzirai et al., 2013).

3.2.3. Profitability

In assessing the profitability of each project, only fuel pellet sales revenues are considered. It is noted that the market price of fuel pellets is dependent on the heat, humidity, and ash content. According to the

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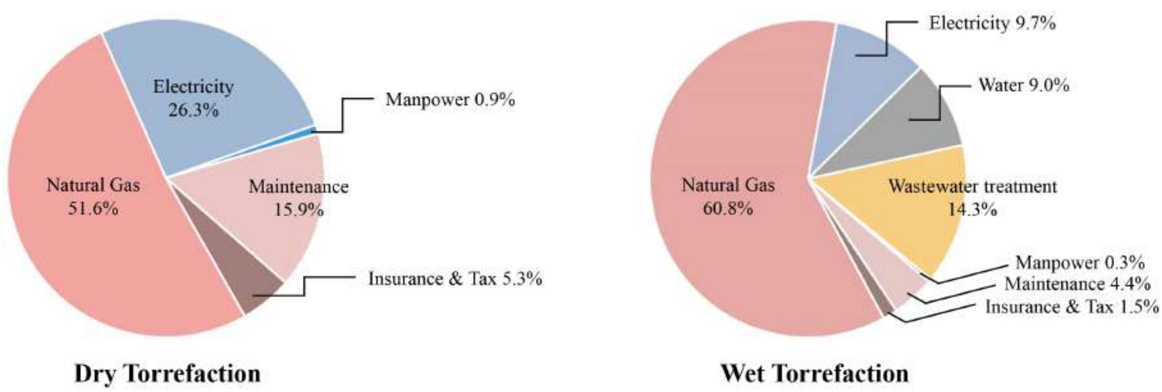

Fig. 3. Total operating cost for DTP and WTP production.

experiment, the calorific value of both DTP and WTP was within the standard ranges, i.e., the calorific value was greater than 16.5 MJ/kg, and the moisture content was less than 10%w/w, while the ash content varied. Therefore, in this study, the amount of ash was used to determine the selling price of fuel pellets. According to biomass market price data, fuel pellets are priced in a fairly wide range of 100-250 USD/ton (Visser et al., 2020; Manouchehrinejad et al., 2021), depending on a variety of factors such as fuel pellet quality, types of raw material used for production, demand, season, and location. In this study, the selling prices of DTP with a relatively high ash content of approximately 3.5%w/w and that of WTP with a low ash content of around 0.97%w/w were assigned at 100 and 163 USD/ton, respectively. This difference in selling price contributes to a greater return on investment for WTP than for DTP. In particular, the revenue from the sale of torrefied pellets produced by WT is 10.95 MUSD/yr, while that by DT is 5.44 MUSD/yr. Furthermore, at the project life of 20 yr (i=10%), the NPV analysis revealed that both the production of DTP and WTP resulted in a positive NPV of MUSD 6.2 and MUSD 10.4, respectively.

As evaluating the NPV of the two projects with pellet selling prices varying between 80 and 200 USD/ton (**Fig. 4**), the NPV of the DTP project was determined to be positive at a pellet selling price of USD 100 or higher. This corresponds to the range of prices for biomass pellets with the same quality as EN*plus* B, which is between 100 and 150 USD/ton. Therefore, it can be concluded that product quality is the main factor determining the cost-effectiveness of DTP production. It should be noted that the quality of DTP in terms of calorific value, ash content, and other contaminants is dependent on the quality of biomass used as a raw material. One of the major barriers to using agricultural waste as a raw material for fuel pellet production is its high ash content, which ranges from 5.9-7.3% in empty fruit bunches, 7.0-18.3% in wheat straw, and 18.8-22.0% in rice husk (Lo et al., 2021). It can also be stated that WTP production could be an interesting option for raw materials with high ash contents. Considering WTP production at varying pellet selling prices, in the cases where a selling price of less than 120 USD/ton was assigned for the pellet with the EN*plus* B quality, the NPV analysis for such projects is not even necessary as the annual production cost alone is already higher than the revenue. As shown in **Figure 4**, once the pellet selling price reaches 140 USD/ton, the project begins to generate a profit. In line with the findings of Doddapaneni et al. (2018) and Pirraglia et al. (2013), the NPV of a standalone torrefied biomass pellet project is negative when the pellet selling price is below 217 and 261 USD/ton, respectively. **Table 3** compares the results obtained from this research and past studies on the economic assessment of torrefied biomass pellets.

3.2.4. Sensitivity analysis

Figure 5 depicts the effect of varying input parameters on the NPV of a project. The NPV of DTP and WTP production is found to be susceptible to different factors in the same direction. The most noticeable difference between DTP and WTP production is based on the sensitivity of natural gas prices. Specifically, when the gas price changes by 20%, the NPV of the DTP project changes by approximately 33% (**Fig. 5a**), while that of the WTP changes more greatly by 85% (**Fig. 5b**). Additionally, in the case where gas prices increase by 40% or more, the NPV of the WTP project would be negative, and the project would be unfeasible due to the process's high energy demand.

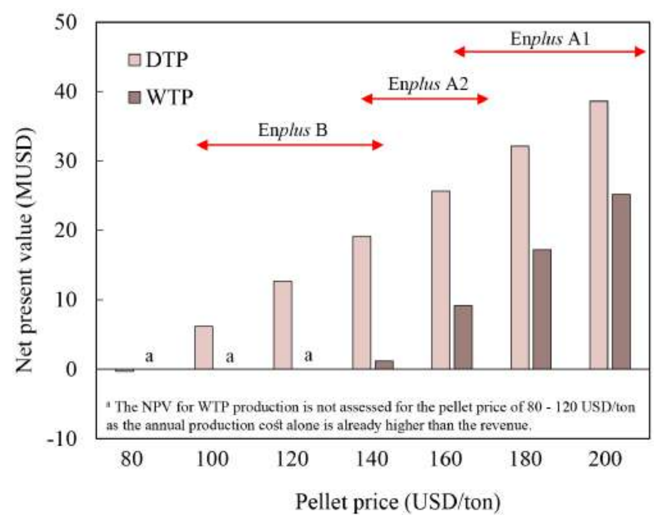

Fig. 4. NPV for production of DTP and WTP at different selling prices.

On the other hand, this sensitivity analysis demonstrates that if energy costs could be reduced, a substantial amount of value would be added to the project. Optionally, the energy required for the process in this study can be reduced by employing recovery heat, i.e., using residual heat from torrefaction in drying, generating electricity to be used in the system, and producing electricity from alternative energy sources. Furthermore, producing other products from process waste, such as biomethane from torrefaction condensate, could also increase the project's revenue and thus lower the pellet minimum selling price by 7% (Doddapaneni et al., 2018).

Sensitivity analysis of previous research results most frequently reported that the price of raw materials is the most important contributing factor to the project's economic feasibility. Abelha and Kiel (2020) reported that the project's annual revenue of torrefied roadside grass pellets reduced from MEUR 3.8 to 1.8, and the internal rate of return dropped from 15.6 to 8.5% when raw material prices rose 20%. This conforms to a study by Doddapaneni et al. (2018), reporting that the main factor affecting the NPV of a wood-torrefied pellet is the price of a wood chip. In particular, if the wood chip price increases by 25%, the project NPV decreases from MEUR 6.2 to 12.5. The results of this sensitivity analysis highlight the importance of using low-cost processed industrial or agricultural waste as a raw material for biomass pellet production.

Table 3.
Economic assessment of biomass pellet.

Raw material and treatment	Assumption	Economic results	Findings	Reference
Sugarcane bagasse - DTP, 280°C, 20 min	Capacity: 54,400 ton pellet/yr Plant life: 20 yr Discount rate: 10%	TCI: 18.55 MUSD TOC: 58.8 USD/ton NPV: 6.2 MUSD	- The TOC of WTP is significantly higher than that of DTP as a result of its high energy consumption during torrefaction and drying processes.	This study
Sugarcane bagasse - WTP, 180°C, 20 min	Capacity: 67,200 ton pellet/yr Plant life: 20 yr Discount rate: 10%	TCI: 13.98 MUSD TOC: 123.59 USD/ton NPV: 10.4 MUSD	- Although the TOC is higher, the NPV of WTP is higher than that of DTP because wet torrefaction pellets are of higher quality than dry torrefaction pellets and thus sell for a higher price.	
Sawdust - Torrefaction before pelletization with DT, 270°C, 30 min	Capacity: 100,000 ton pellet/yr Plant life: 15 yr Discount rate: 10%	TCI: 33.7 MUSD TOC: 191 USD/ton MSP: 207 USD/ton	- When biomass is pelletized, its volume is greatly reduced, allowing a smaller torrefaction reactor to be used. TCI and TOC were thus lower in torrefaction after pelletization than in torrefaction before pelletization. - Doubling the plant capacity decreases the MSP by 10%.	Manouchehrinejad et al. (2021)
Sawdust - Torrefaction before pelletization with DT, 270°C, 30 min		TCI: 29.6 MUSD TOC: 183 USD/ton MSP[a]: 197 USD/ton		
Wheat straw - DT	Capacity: 120,000 ton pellet/yr Plant life: 20 yr Discount rate: 6%	TCI: 35.25 MUSD TOC: 229.42 USD/ton	- The location of the plant has a significant impact on the production cost. The TOC will be approximately 64% lower in Asia than Europe due to lower wages, utility bills, and raw material costs.	Abelha and Keil, (2020)
Roadside grass - DT	Capacity: 20,000 ton pellet/yr Plant life: 20 yr Discount rate: 6%	TCI: 10.79 MUSD TOC: 111.73 USD/ton	- The capacity of the plant has a major impact on the selling price. The optimal production capacity should be between 100,000 and 150,000 tons per year for the pellet selling price to be competitive with the market price.	
Wood chips - DT, 300°C	Capacity: 79,200 ton pellet/yr Plant life: 20 yr Discount rate: 8%	TCI: 36.53 MUSD TOC: 205.30 USD/ton MSP[a:] 217 USD/ton	- The MSP can be reduced from 217 to 200.95 USD/ton by incorporating an anaerobic digestion system to generate electricity and heat for process use.	Doddapaneni et al. (2018)

Abbreviations: DT: dry torrefaction, DTP: dry torrefied pellet, MSP: minimum selling price, NPV: net present value, TCI: total capital investment, TOC: total operating costs, WTP: wet torrefied pellet.

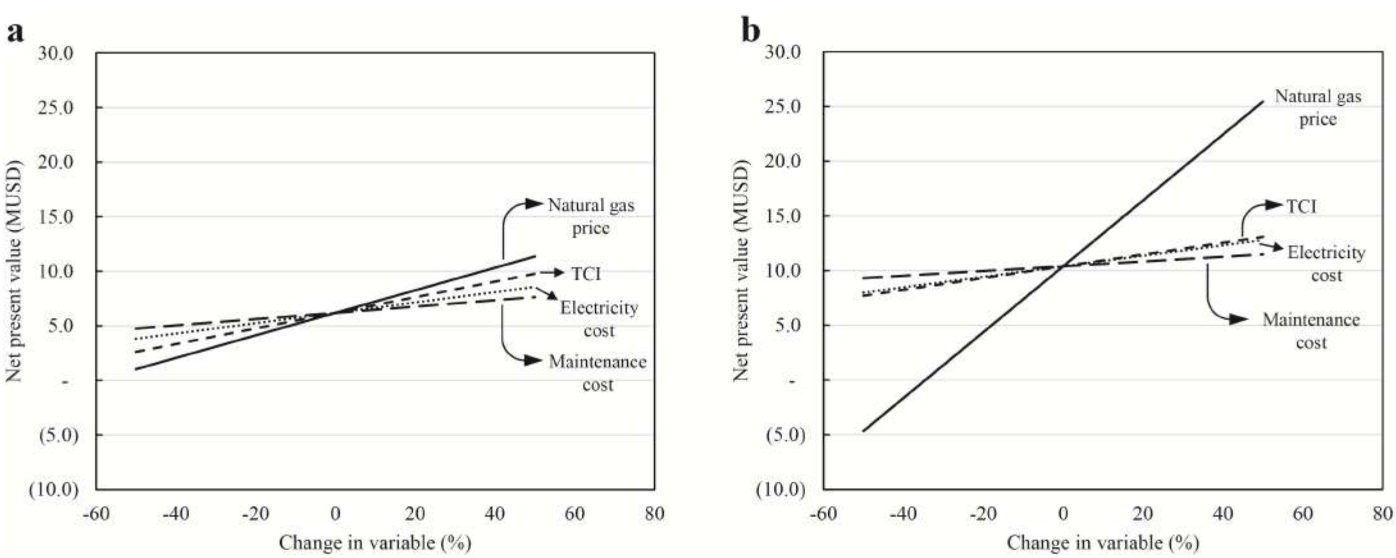

Fig. 5. Sensitivity analysis of NPV for production of **(a)** DTP and **(b)** WTP.

3.2.5. Environmental aspects

Lowering carbon dioxide emissions was the key reason for the switch from coal to biomass pellets. In any case, the original goals cannot be achieved if the torrefied pellets' life cycle results in more GHG emissions than the untreated pellets or even raw biomass. Therefore, in addition to technical and economic feasibility, the environmental impact of torrefied pellets throughout their life cycle cannot be disregarded.

Considering densified biomass, SBG, when pelletized, has a relatively low global warming potential of around 0.125 kgCO_2-eq compared to those that require a considerably higher amount of energy in collection and transportation from fields such as wheat straw, corn stover, and sweet sorghum stalk (Muazu et al., 2022). This indicated that SBG could be a promising agricultural byproduct for producing fuel pellets, not only from a technical and economic standpoint but also from an environmental aspect.

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Considering the environmental impact of the production of torrefied pellets, although the process contributes to higher TOC due to the high energy consumption, its GHG emissions per MJ were lower than that of producing white wood pellets. Due to the higher energy density of torrefied pellets, which in turn reduces the GHG emissions derived from transport, the GHG emissions of torrefied pellets were approximately 9 *vs.* 11.5 g/MJ caused by white wood pellets (Thrän et al., 2016). In particular, compared to coal, the use of torrefied biomass as a fuel for power generation can reduce CO_2 emissions by more than 90% (Lin et al., 2021).

Comparing DT and WT, Akbari et al. (2021) conducted a life-cycle assessment of power production using various types of biomasses treated with DT and WT as fuels, including wheat straw, pine, grape pomace, and manure. It was found that the water content of the samples was a key factor in determining which processes emit more or less GHG. For those with lower water contents like wheat straw and pine, treatment with DT caused less global warming potential, unlike water-rich ones like grape pomace and manure, which emitted less CO_2 when treated with WT. This is because, in the DT process, the sample contains a large amount of water, and high energy is required to evaporate the water before torrefaction. However, all samples caused less CO_2 emission per kWh of electricity than coal except for DT-manure. It should be noted that the amount of GHG emissions is largely determined by the amount of energy used. This means using green energy sources like biomass, wind, solar, and so on instead of fossil fuels to power the process could greatly reduce GHG emissions (Muazu et al., 2022).

3.2.6. Future outlook and practical implications

In this transition era, when "carbon neutral" is an issue of intense interest, every nation is intensively looking inward to find ways to lessen their GHG emissions. With coal being the most significant fuel contributing to the issue, the decrease in their reliance on it has been a top priority. In this regard, for many countries, the solution lies in biomass fuel. For example, supported by a long-term feed-in tariff, the demand for woody biomass to generate electricity in Japan has increased dramatically over the past decade and shows no signs of abating. With this sharply increasing demand, it is speculated that the supply may not be able to keep up, leading to a shortfall in 2023 onwards (Canadian Biomass, 2022). Before that occurs, market competition is expected to drive up the price of wood pellets. Accordingly, the production of biomass pellets from agricultural residue will be on the rise and is projected to expand by 7.1% between 2022 and 2032. Agro-pellet production is more likely to take off in agriculture-dependent counties like Brazil, India, and countries in Asia, according to the abundance of agricultural waste in these regions (Future Market Insights, 2022).

In terms of the adoption of torrefied pellets for electricity production, although many nations recognize its importance and are committed to carbon neutrality, it may be challenging to switch to biomass fuel with the existing coal power engines. This may initially be implemented by co-firing coal with biomass pellets at various percentages. Yun et al. (2020) discovered that compared with 100% coal, co-firing with 10% and 20% torrefied pellets reduced GHG emissions by 9% and 17%, respectively, and that using torrefied pellets up to 100% could reduce GHG emissions by up to 85%.

In India, for instance, the government has implemented a policy to combat pollution caused by burning post-harvest agro-waste. The Indian government has mandated thermal power plants to use a 5% blend of biomass pellets along with coal as fuel to generate electricity and later aims to increase the proportion to 7% by the end of 2022. However, despite the abundance of agro-waste, this policy faces difficulties in terms of supply, which may fall short of meeting demands. This is due to the fact that power plants purchase agro-pellets at a lower price than other industrial facilities, such as textile, food processing, etc. Thus, pellet suppliers favor selling their products to those offering greater incentives (Aggarwal, 2022).

From the researchers' point of view, as an alternative to coal, countries with agro-waste should promote its domestic use a priori, and they can be exported if surpluses. In this instance, torrefaction and pelletization will facilitate efficient transport and storage.

3.2.7. Limitations of the study

This study does not include a study on using biomass pellets as a fuel alternative to coal. Future works should include such content in terms of the appropriate proportions of biomass pellets blended with traditional coal and the consequences of switching to 100% biomass pellets. This should also include the analysis of off-gas and slag of combustion.

The effects on the environment come at a cost, which ought to be accounted for in the price. However, life cycle assessment was not included in the framework of this study and should be incorporated into future works.

4. Conclusions and Prospects

Most agricultural waste has high thermal potential and can be used as a substitute for fossil fuels, which are in high demand globally due to the global warming crisis. However, the main barrier preventing the production of fuel pellets from these agricultural waste materials relates to whether their quality, such as calorific values and ash content, falls within an acceptable range compared to wood pellets. To our knowledge, this research is the first to study the cost-effectiveness of adding value to agricultural waste by turning it into fuel pellets. Here, the WT and DT processes were found to improve the calorific value and lower the ash content of the fuel pellets. A comparison of the properties of SBG-derived fuel pellets produced by WT and DT was conducted. Consequently, the least severe conditions that produced fuel pellets of international standard quality were chosen for economic evaluation, where the projects' revenues were estimated based on the selling price of the pellets, which is dependent on their quality.

Both WT and DT were found to increase the heating value of SBG by approximately 5.0–17.9%, depending on the torrefaction conditions. In particular, higher temperatures increased products' heating values while mass yields were found to be lower. The ash content of the final products produced by WT and DT differed, with the former producing a higher ash concentration under severe conditions than the latter. This indicates that WT pretreatment is a promising option for high-ash raw materials to reduce the ash content to the standard level. However, according to the energy consumption assessment of the process, the specific energy demand of WTP production is almost double that of DTP.

Although WT produced a higher quality product than DT, resulting in a higher overall return and NPV, the energy requirements for producing WTP were so high that the project would only be feasible if the pellet's selling price fell below 140 USD/ton. However, the production of WTP is an interesting option for adding value to agricultural waste as there are rooms for improvement, including the addition of heat recovery systems to reduce production costs, the production of secondary products, and the parallel use of alternative energy.

Demand for biomass as an alternative to fossil fuels has increased in response to rising awareness of the need to mitigate climate change. This, along with the controversy over whether or not burning wood pellets for energy would actually benefit the environment, are the major driver of the emerging market for alternative fuels derived from agro-waste and other materials. Consequently, research into the feasibility of increasing production scale, improving fuel pellet quality, and introducing new production techniques are all essential in getting ahead of future demands. This study was predicated on using SBG, a byproduct of the sugar industry, as a raw material for fuel pellet production. As a result, there is no cost for the primary raw material or transportation, making the production of both DTP and WTP economically feasible. This approach could also apply to other industries that produce agro-residue in the same manner, such as rice and corn production, fruit production with high residual fiber fruit rinds, and so on. The difficulty of collecting and transporting agricultural waste is a major barrier to its use as a raw material in solid fuel production. Because of this, researchers may find it interesting and challenging to investigate further the viability of developing standalone torrefaction and pelletization systems for the on-site production of agro-pellets. Additionally, transport and storage expenses will decrease as this biomass is transformed into denser and more hydrophobic fuel pellets.

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Supplementary Material

Table S1.
Capacity and cost of major equipment.

Equipment	Reference-based year	Capacity (ton/h)	Cost (USD)	Reference
Dryer	2017	34.5	725,612	Manouchehrinejad et al. (2021)
Grinding	2017	8.0	102,509	Doddapaneni et al. (2018)
Dry torrefaction reactor	2017	34.5	4,604,435	Manouchehrinejad et al. (2021)
Wet torrefaction reactor	2016	268.0	396,246	Saba et al. (2019)
Filter	2016	268.0	1,092,394	Saba et al. (2019)
Pelletizer	2017	4.5	254,118	Manouchehrinejad et al. (2021)
Pellet cooler	2017	4.5	105,452	Manouchehrinejad et al. (2021)
Receiving station	2017	34.5	140,417	Manouchehrinejad et al. (2021)
Storage	2017	34.5	1,069,328	Manouchehrinejad et al. (2021)
Site and site preparation	2017	34.5	240,932	Manouchehrinejad et al. (2021)
Plant buildings and offices	2017	34.5	1,101,732	Manouchehrinejad et al. (2021)

Table S2.
The scale factor for major equipment.*

Equipment	Scale factor
Dryer	0.4
Reactors	0.6
Grinder	0.4
Pelletizer	0.4

* Source: Peters et al. (2003)

Table S3.
Economic assessment of the capital investment.

Capital investment	Dry torrefaction		Wet torrefaction	
	MUSD	Percent breakdown (%)	MUSD	Percent breakdown (%)
Direct Costs				
Dryer	0.68	3.6	0.61	4.4
Grinding	0.13	0.7	0.12	0.9
Dry torrefaction reactor	2.79	15.0	-	-
Wet torrefaction reactor	-	-	0.32	2.3
Filter	-	-	0.89	6.3
Pelletizer	0.35	1.9	0.38	2.7
Pellet cooler	0.14	0.8	0.16	1.1
Site and site preparation	0.22	1.2	0.22	1.6
Plant buildings and offices	1.03	5.5	1.03	7.3
Receiving station	0.13	0.7	0.13	1.0
Storage (feedstock + product)	1.00	5.4	1.02	7.3
Installation	3.36	18.1	2.53	18.1
Freight	0.26	1.4	0.19	1.4
Total direct equipment cost (TDEC)	**10.08**	**54.3**	**7.60**	**54.3**
Indirect Costs				
Construction expenses	2.02	10.9	1.52	10.9
The engineering and supervision	0.60	3.3	0.46	3.3
Legal expenses	0.40	2.2	0.30	2.2
Contractor's fee	1.01	5.4	0.76	5.4
Contingency fee	2.02	10.9	1.52	10.9
Total indirect cost (TIC)	**6.05**	**32.6**	**4.56**	**32.6**
Fixed capital investment (FCI)	**16.13**	**87.0**	**12.16**	**87.0**
Working capital	2.42	13.0	1.82	13.0
Total capital investment (TCI)	**18.55**	**100.0**	**13.98**	**100**

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Table S4.
Economic assessment of the total operating cost.

Operating cost	Dry torrefaction		Wet torrefaction	
	MUSD/yr	**Percent breakdown (%)**	**MUSD/yr**	**Percent breakdown (%)**
Variable Costs				
Natural gas	1.73	51.6	5.05	60.8
Electricity	0.80	26.3	0.81	9.7
Water	-	-	0.75	9.0
Wastewater treatment	-	-	1.19	14.3
Total variable cost	**2.53**	**77.9**	**7.79**	**93.8**
Fixed Costs				
Labor & Supervision	0.01	0.5	0.01	0.2
Overhead	0.01	0.4	0.01	0.2
Maintenance	0.48	15.9	0.36	4.4
Insurance & Tax	0.16	5.3	0.12	1.5
Total fixed costs	**0.67**	**22.1**	**0.51**	**6.2**
Total operating cost (TOC)	**3.20**	**100**	**8.31**	**100**

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