# ผลกระทบจากอุณหภูมิและผลได้เชิงมวลต่อคุณสมบัติทางเชื้อเพลิงของฟางข้าวที่ผ่านกระบวนการทอร์รีแฟคชัน

# Effect of temperature and mass yield on fuel properties of torrefied rice straw

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งานวิจัยนี้ได้รับทุนสนับสนุนจากงบประมาณกองทุนเพื่อการวิจัย ประจำปีงบประมาณ พ.ศ.2567
คณะวิศวกรรมศาสตร์ มหาวิทยาลัยเทคโนโลยีราชมงคลพระนคร

ชื่อเรื่อง ผลกระทบจากอุณหภูมิและผลได้เชิงมวลต่อคุณสมบัติทางเชื้อเพลิงของฟางข้าวที่ผ่าน
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## บทคัดย่อ

งานวิจัยฉบับนี้ได้ศึกษาผลกระทบของเวลาในการทอร์รีแฟคชัน อุณหภูมิในการทอร์รีแฟคชัน และการสูญเสียน้ำหนักของฟางข้าว ต่อคุณสมบัติของฟางข้าวที่ผ่านกระบวนการทอร์รีแฟคชัน โดยดำเนินการทอร์รีแฟคชันที่อุณหภูมิ 220 °C, 250 °C และ 280 °C โดยตั้งเป้าหมายการสูญเสียน้ำหนักที่ 10%, 20% และ 30% ของน้ำหนักเริ่มต้น ผลการศึกษาชี้ให้เห็นว่า การเพิ่มอุณหภูมิในการทอร์รีแฟคชันช่วยลดเวลาที่ต้องใช้ในการบรรลุการสูญเสียน้ำหนักของฟางข้าวได้อย่างมีนัยสำคัญ การวิเคราะห์ทางกายภาพเผยให้พบว่าปริมาณคาร์บอนคงที่ของฟางข้าวเพิ่มขึ้นหลังจากกระบวนการทอร์รีแฟคชัน โดยมีค่าระหว่าง 22.45% ถึง 28.48% ขึ้นอยู่กับอุณหภูมิและการสูญเสียน้ำหนักของฟางข้าว ในทางตรงกันข้าม ปริมาณสารระเหยและความชื้นลดลง ซึ่งสะท้อนถึงคุณสมบัติพลังงานที่ดีขึ้นของชีวมวลที่ผ่านการทอร์รีแฟคชัน ปริมาณเถ้าสูงขึ้นหลังจากการทอร์รีแฟคชัน แสดงให้เห็นถึงสารอนินทรีย์ที่เหลืออยู่มากขึ้น การวิเคราะห์องค์ประกอบทางเคมีแสดงให้เห็นว่าปริมาณไนโตรเจนคงที่ขณะที่ปริมาณคาร์บอนเพิ่มขึ้นอย่างมีนัยสำคัญเมื่อปริมาณไฮโดรเจนและออกซิเจนลดลงตามความรุนแรงของกระบวนการทอร์รีแฟคชัน ค่าอุณหภูมิความร้อนสูงสุด (HHV) ของฟางข้าวเพิ่มขึ้นจาก 16.55 MJ/kg ก่อนการทอร์รีแฟคชัน เป็นค่าในช่วง 17.59 ถึง 18.88 MJ/kg ซึ่งแสดงให้เห็นถึงความมีประสิทธิภาพของกระบวนการในการเพิ่มพลังงานของเชื้อเพลิง โดยรวมแล้ว ผลการศึกษาชี้ให้เห็นถึงความสัมพันธ์ระหว่างเงื่อนไขการทอร์รีแฟคชันและคุณสมบัติของชีวมวล โดยการควบคุมอุณหภูมิและการสูญเสียน้ำหนักของชีวมวลอย่างเหมาะสมสามารถปรับปรุงคุณภาพเชื้อเพลิงของฟางข้าวได้อย่างมีนัยสำคัญ

Title Effect of temperature and mass yield on fuel properties of torrefied rice straw

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## Abstract

This study investigates the effects of torrefaction time, temperature, and mass loss on the properties of torrefied rice straw. Torrefaction was conducted at temperatures of 220 °C, 250 °C, and 280 °C, targeting mass losses of 10%, 20%, and 30%. Results indicate that increasing torrefaction temperature significantly reduces the time required to reach target mass losses. Proximate analysis revealed that the fixed carbon content of rice straw increased after torrefaction, with values ranging from 22.45% to 28.48% across different temperatures and mass losses. In contrast, volatile matter and moisture content decreased, reflecting the enhanced fuel properties of the torrefied biomass. The ash content rose post-torrefaction, indicating higher inorganic residues. Ultimate analysis showed stable nitrogen content while carbon increased significantly as hydrogen and oxygen levels decreased with increasing torrefaction severity. The higher heating value (HHV) of the rice straw improved from 16.55 MJ/kg before torrefaction to values between 17.59 and 18.88 MJ/kg afterward, demonstrating the process's effectiveness in enhancing energy content. Overall, the findings underscore the relationship between torrefaction conditions and biomass properties, suggesting that optimal control of temperature and mass loss can significantly improve the fuel quality of rice straw.

# กิตติกรรมประกาศ

ผู้วิจัยขอขอบพระคุณ กองทุนเพื่อการวิจัย มหาวิทยาลัยเทคโนโลยีราชมงคลพระนคร ที่สนับสนุนงบประมาณในการทำวิจัย

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# สารบัญ

หน้า

# สารบัญ (ต่อ)

# สารบัญตาราง

ตารางที่ หน้า

# บทที่ 1
# บทนำ

## 1.1 ความเป็นมาและความสำคัญของปัญหา

Thailand is witnessing a rise in the use of biomass as a renewable energy source, thanks to the promotion of the bio-circular-green (BCG) economic model by its government. This BCG model takes advantage of the country's abundant biological diversity and cultural heritage, combining technology and innovation to transition Thailand into an economy focused on value and driven by innovation. The BCG model is concentrated on advancing four key industries: agriculture and food; medicine and well-being; bioenergy biomaterials and biochemistry; and tourism and the creative economy. Particularly, the bioenergy, biomaterials, and biochemistry sector hold significant growth potential, fueled by the government's policy aiming to make renewable energy account for 30% of the total final energy consumption by the year 2036.

Vassilev et al. [1] highlighted two significant advantages of biomass concerning its composition and properties: high values of volatile matter (VM) and low values of carbon, fixed carbon content, and ash yield. The elevated volatile matter content leads to several benefits for thermochemical conversion, including (1) a low ignition temperature, (2) easier and faster ignition, devolatilization, and burning, and (3) a higher production of combustible gas.

However, despite these advantages, most fuel properties of biomass still fall short compared to coal [2]. One of the major drawbacks of biomass is its high moisture content, which causes several negative effects such as (1) issues during pre-treatment, preparation, and upgrading, and (2) lower calorific value and grinding capacity, resulting in poor ignition, reduced combustion efficiency, and longer residence time in combustion units. Another significant disadvantage of biomass is its low energy density, which includes both low bulk density and heating value [1]. Biomass has an energy density of only 10-40% of that of fossil fuels, and its heating values are just over half of those found in coal.

To achieve these benefits, torrefaction stands out as one of the pretreatment methods employed to enhance the fuel properties of biomass. Torrefaction typically occurs within a temperature range of 200-300°C in an inert atmosphere with slow heating rates. As a result of this process, the torrefied biomass exhibits several improvements compared to raw biomass [2], [3]. It has lower moisture content, higher energy density, and heating value, along with good hydrophobicity and improved grindability. Consequently, torrefied biomass becomes a promising alternative to replace fossil fuels and meet the growing demand for sustainable and environmentally neutral energy sources.

Thailand's economy heavily relies on agriculture, where rice cultivation dominates over half, 51%, of its total agricultural land. Consequently, this massive rice cultivation generates approximately 35 million tons of agricultural waste annually, primarily in the form of rice straw. Unfortunately, a significant portion of this rice straw is disposed of through burning, as farmers use this method to clear the fields and prepare the soil for the upcoming cultivation season. However, this practice not only squanders valuable energy resources but also contributes to detrimental air pollution. The objective of this study is to investigate the impact of torrefaction temperature and mass yield on the fuel properties of torrefied rice straw. By doing so, the research aims to gain a deeper understanding of the torrefaction process and its potential implications. Additionally, the study seeks to explore the feasibility of utilizing agricultural waste, specifically rice straw, as a viable and sustainable energy source for the future

## 1.2 วัตถุประสงค์ของโครงการวิจัย

1.2.1 To study the effect of torrefaction temperature on torrefied rice straw fuel properties

1.2.2 To study the effect of torrefaction temperature on mass yield

## 1.3 ประโยชน์ที่คาดว่าจะได้รับ

1.3.1 To gain knowledge about the effects of temperature in the torrefaction process on the fuel properties of rice straw that has undergone torrefaction.

1.3.2 To understand the effects of temperature in the torrefaction process on the mass yield of rice straw that has undergone torrefaction.

# บทที่ 2

# ทฤษฎีและวรรณกรรมที่เกี่ยวข้อง

## 2.1 Biomass

Biomass is primarily made up of cellulose, hemicellulose, and lignin. In biomass, cellulose and lignin form a matrix that is surrounded by hemicellulose chains. Cellulose, a polysaccharide-based organic compound, is the main chemical component of plant primary cell walls. Hemicellulose, another group of carbohydrates, consists of various sugar units, including xylose, arabinose, mannose, galactose, and glucose. Together, cellulose and hemicellulose provide structural support to the cell wall. Lignin, the third key component, is a polymer made up of phenylpropane units, connected by ether or carbon-carbon bonds. Lignin enhances the mechanical strength of the cell wall through covalent linkages [4].

Although all types of biomass share these three major components, their compositions vary, as shown in Table 2.1. Biomass contains different amounts of cellulose (30% to 51%), hemicellulose (17% to 31%), and lignin (17% to 44%). These variations in composition are influenced by factors such as climatic conditions, seasonal changes, harvesting time, and the specific type of biomass, including species and plant parts [5]–[7].

Biomass can be classified into two categories: woody and non-woody biomass. Woody biomass is derived from trees, while non-woody biomass comes from herbaceous plants, agricultural sources, and aquatic organisms. Non-woody biomass generally has lower lignin content and energy value [5], but it is abundant and cost-effective. Table 2.2 provides examples of woody and non-woody biomass, along with their uses.

**Table 2.**ผิดพลาด! ไม่มีข้อความของสไตล์ที่ระบุในเอกสาร Properties of biomass (%) [5]

| Biomass | Cellulose | Hemicellulose | Lignin |
|---|---|---|---|
| Sugarcane top | 29.85 | 18.85 | 25.69 |
| Cornstalk | 34.45 | 27.55 | 21.81 |
| Bagasse | 30 | 35 | 18 |
| Wheat straw | 38.7 | 19 | 17.3 |
| Rice straw | 35.8 | 21.5 | 24.4 |
| Rapeseed | 51.3 | 17.3 | 44 |
| Corn stover | 36.3 | 31.4 | 17.2 |

**Table 2.2** Biomass groups and examples of utilisation [5], [6]

| Groups | Biomass sub-groups, species and varieties coniferous | Example of utilisation |
|---|---|---|
| **Woody biomass** | i.e. barks, branches (twigs), leaves (foliage), bushes (shrubs), chips, lumps, pellets, briquettes, sawdust, sawmill | Wood chips, particles, firewood briquettes and pellets |
| **Non-woody biomass** | **Herbaceous and agricultural biomass**<br>i.e. grasses and flowers, straws, stalks, fibres, Shells and husks, pit | **Oilseed crops**: for biodiesel production<br>**Sugar and starch crops**: for bioethanol<br>**Lignocelluloses**: for heat and power production |
| | **Aquatic biomass**<br>i.e. marine or freshwater, macroalgae, etc. | Algae: production of biogas for energy production |

Rice straw falls under the category of agricultural biomass and is produced as a byproduct of rice harvesting. During the rice harvest, the straw is collected along with the rice grains and is either piled or spread out in the field, depending on whether the harvest was done manually or using machines. The ratio of straw to paddy (rice grains) varies from 0.7 to 1.4, depending on the rice variety and its growth conditions. Globally, an estimated 800 to 1,000 million tons of rice straw are produced each year, with approximately 600 to 800 million tons coming from Asia.

## 2.2 Torrefaction

Some properties of biomass are inferior to coal for fuel use. They have high moisture content, high oxygen content and low energy density. To overcome these limitations, thermochemical pretreatment such as torrefaction is used to improve the biomass properties. Torrefaction process was first investigated in France in 1930's [8]. This process is considered to be similar to the roast coffee beans technique that had been started in the late 13th century [9], [10].

Torrefaction consists of the slow heating of biomass at temperatures ranging between 200 °C and 300 °C in an atmosphere with no oxygen. Prins et al. [11] suggested the torrefaction temperature should below 300 °C to prevent a fast thermal cracking of cellulose which may cause tar formation that occurred above 300 °C. Rousset et al. [12] divided the torrefaction process into two categories including light torrefaction with torrefaction temperature is below 240 °C and severe torrefaction with torrefaction temperature is above 270 °C. Unlike pyrolysis, the maximisation of the solid yield is the major motivation of torrefaction, biomass weight reduced while the energy content sustained [13]. The high solid yield can be accomplished with the removal of water and carbon dioxide by heating biomass at low heating rate (below 50 °C/min) [14]. A consequence of torrefaction is to remove oxygen from biomass. As the result, torrefied biomass has lower O/C ratio compared to raw biomass [15] and higher energy density.

During torrefaction, biomass undergoes physicochemical changes, especially the three main components (cellulose, hemicellulose, and lignin). Tumuluru et al. [16] divided torrefaction into three zones: nonreactive zone (50 - 150 °C), reactive drying zone

(150 - 200 °C), and destructive drying (200 - 300 °C). During the temperature range 50 to 150 °C, the moisture content is eliminated and no chemical reaction occur. At the end of this range (120 - 150 °C), lignin starts softening. In reactive drying zone (150 - 200 °C), the hydrogen and carbon bonds begin to break and the structural deformation and depolymerisation of hemicellulose occur. Depolymerisation of hemicellulose causes shortened and condensed solid polymers. In destructive drying (200 - 300 °C), complete degradation of hemicellulose and partial degradation of cellulose and lignin take place. The degradation of cellulose might have enhanced by acids and water vapour generated from degradation of hemicellulose. Thus, torrefied biomass has more lignin content, which is more stable than the other two components. However according to Bergman et al. [17], torrefaction can be divided into five stage with the drying process is subdivided into two stages, as described in Table 2.3.

Torrefaction process improve the chemical and physical properties of raw biomass and changes these properties closer to those of bituminous coal [18]. Torrefaction can produce a torrefied biomass with an energy density higher than those of wood and with a solid denser than wood, make the properties of biomass fall in between those of coal and wood [19]. Rousset et al. [12] found the characteristics of torrefied bamboo is close to low-rank coal. The same finding also found in Tapasvis [20], where the characteristics of torrefied birch and spruce were closer to coal. Thus, the torrefied biomass can be used in some application such as domestic heating, residential cooking stoves, to substitute charcoal.

**Table 2.3** Five stages of torrefaction process, adapted from [17]

| Stages | Description |
|---|---|
| 1 Heating | Biomass is heated until the drying temperature is reached and at the end of this stage moisture starts to evaporate. |
| 2 Pre-drying | Over 100 °C, free water in biomass is evaporated at constant temperature. |
| 3 Post-drying | Temperature is increased to 200 °C, physically bound water present on biomass chemical bonds is completely evaporated. During this stage, light organic compounds can evaporate result in the presence of some mass loss. |
| 4 Torrefaction | Main stage of the torrefaction process. This stage is entered when the temperature exceeds 200 °C and is ends when the temperature becomes below 200 °C again.  The torrefaction temperature is the maximum temperature used during this process. |
| 5 Cooling | The torrefied biomass is cooled down to a temperature below 200 °C, which is the ignition temperature of wood, before it contacts the air and until room temperature is reached. |

# บทที่ 3
# วิธีดำเนินงานวิจัย

## 3.1 วิธีการดำเนินการวิจัย

This research follows a procedure, comprising four main steps, which are as follows:

**Step 1** Rice straw preparation

Firstly, the rice straw is ground using a ball mill, Retsch PM100, to achieve a fine particle size. The ground rice straw is then sieved to obtain particles that are smaller than 100 μm in size. These finely ground particles are then used in the subsequent torrefaction process.

**Step 2** Torrefaction

The torrefaction of rice straw will be carried out at different temperatures: 220°C, 250°C, and 280°C, until the desired mass yield is achieved at 70%, 80%, and 90%, respectively. The torrefaction process will be conducted using a TGA/DSC 1 Mettler-Toledo, with a nitrogen flow rate of 50 ml/min to prevent biomass combustion.

Once the torrefaction process is completed for each temperature and mass yield combination, the torrefied biomass will be subjected to various characterizations. These characterizations include proximate analysis, which provides information about the moisture content, volatile matter, fixed carbon, and ash content of the torrefied biomass. Ultimate analysis will also be performed, determining the carbon, hydrogen, nitrogen, and oxygen content of the torrefied biomass. Lastly, the Higher Heating Value (HHV) of the torrefied biomass will be determined, indicating the energy content of the material. These characterizations will help assess the quality and energy potential of the torrefied rice straw for potential applications as a fuel source or other uses.

**Step 3** Characterisation of torrefied biomass

### Proximate analysis

Proximate analysis is a method used to determine moisture, fixed carbon, volatile matter and ash content in biomass sample. The thermogravimetric system was used to conduct proximate analysis using the standard method in ASTM Standard Test Method D7582-15 [21]. This ASTM method allows to conduct proximate analysis in a single run. Compared with international standards commonly used for that aim, TGA is a faster and easier to determine moisture, volatile matter and ash content [22]. Fixed carbon, meanwhile, is calculated by the difference between a hundred percent and the total of the percentage of moisture, volatile matter and ash content.

### Ultimate analysis

Ultimate analysis is used to determine the elemental composition of biomass by weight percentage of Carbon, Hydrogen, Nitrogen, Sulphur and Oxygen. This analysis was carried out using CHNS analyser with XP CEN/TS 15104 standard.

### Calorific value

The Gross Calorific Value (GCV) or High Heating Value (HHV) is an amount of energy released from a complete combustion of sample including condensation of water produced by combustion. As the quantity of biomass sample used was small, the calorific value of biomass was calculated from a developed correlation rather than using the experimental determination.

Nhuchhen and Afzal [23] studied the HHV prediction of torrefied biomass using proximate and ultimate analysis and proposed two newly-selected correlations for predicting the HHV of torrefied biomass on a dry basis as following correlations:

$$\mathrm{HHV} = 0.1846\big(\text{Volatile Matter content (\%)}\big) + 0.3525\big(\text{Fixed Carbon content (\%)}\big) \qquad (1)$$

$$\mathrm{HHV} = 32.7934 + 0.0053\mathrm{C}^2 - 0.5321\mathrm{C} - 2.8769\mathrm{H} + 0.0608\mathrm{CH} - 0.2401\mathrm{N} \qquad (2)$$

These newly-selected correlations were validated using another set of 26 torrefied biomass data, they provide good prediction accuracy. The first correlation (1) uses the proximate analysis to predict HHV, while the second (2) uses the ultimate analysis.

**Step 4** Analysis the results

Once all the experimental tests are completed and the data is gathered, thorough analysis will be conducted to examine the impact of torrefaction temperature and mass yield on the fuel properties of torrefied rice straw. The obtained results will be carefully assessed to understand how varying torrefaction temperatures and mass yields influence the final characteristics of the torrefied biomass.

The aim of this analysis is to identify the optimal torrefaction conditions that lead to the most desirable fuel properties, considering factors like energy content, stability, and combustion characteristics. These findings will provide valuable insights into the potential applications and benefits of torrefied rice straw as a sustainable and efficient energy source.

# บทที่ 4

# ผลการศึกษา

## 4.1 Torrefaction time

This study focuses on mass loss levels of 10%, 20%, and 30% using torrefaction temperatures of 220 °C, 250 °C, and 280 °C. However, at 220 °C, it was not possible to achieve a 30% mass loss, so only 10% and 20% mass loss were studied at this temperature. At 280°C, the sample reached a 10% mass loss before the temperature stabilized at 280°C, so only 20% and 30% mass loss were considered for this condition. At 250°C, all three mass loss levels (10%, 20%, and 30%) were achieved and analyzed.

Table 4.1 presents the time required to reach the desired mass loss. It was observed that as the torrefaction temperature increased, the time needed to reach the target mass loss decreased.

**Table 4.1** Torrefaction time with different mass loss and torrefaction temperature

| **Mass loss (%)** | | | | | | |
|---|---|---|---|---|---|---|
| 10 | 20 | 10 | 20 | 30 | 20 | 30 |
| **Torrefaction temperature (°C)** | | | | | | |
| 220 | | 250 | | | 280 | |
| **Torrefaction time (min)** | | | | | | |
| 46.50 | 600.00 | 6.35 | 44.50 | 155.50 | 3.22 | 15.35 |

## 4.2 Proximate Analysis Results

From the analysis results presented in Table 4.2, it was found that the fixed carbon content of rice straw before the torrefaction process was 19.21%. For rice straw after torrefaction at a temperature of 220 °C with a 10% and 20% mass loss, the fixed carbon content increased to 22.45% and 24.25%, respectively. At 250 °C, with 10%, 20%, and 30% mass loss, the fixed carbon contents were 22.54%, 24.4%, and 28.32%, respectively. At 280 °C, with 20% and 30% mass loss, the fixed carbon contents were 24.5% and 28.48%, respectively.

Compared to the fixed carbon content before the torrefaction process, it was observed that the fixed carbon content of rice straw after torrefaction was higher than that before the process, and the fixed carbon content increased with the severity of the torrefaction process. However, it was found that at the same mass loss, the fixed carbon content was similar across different temperatures. The fixed carbon content with the highest value was observed in the rice straw after the torrefaction process with a 30% mass loss, ranging from 28.32% to 28.48%. This value falls within the fixed carbon content range of coal, which is between 17.9% and 70.7% [24]. This confirms that the torrefaction process can enhance the fuel properties of rice straw to levels comparable to those of coal.

The volatile matter content of rice straw before the torrefaction process was 68.82%. After torrefaction at a temperature of 220 °C, the volatile matter content for rice straw with a 10% and 20% mass loss was 63.52% and 60.33%, respectively. At 250 °C, with 10%, 20%, and 30% mass loss, the volatile matter contents were 63.42%, 60.25%, and 53.05%, respectively. For rice straw after torrefaction at 280 °C, with 10% and 20% mass loss, the volatile matter contents were 60.30% and 53.17%, respectively.

The volatile matter content of rice straw after the torrefaction process is lower than that of rice straw before the process, and it was also observed that the volatile matter significantly decreases with increasing severity of the torrefaction process. During torrefaction, enhancing the process's severity leads to greater release of volatile compounds from the biomass [25]. The volatile matter consists of flammable gases, such as hydrocarbons ($C_xH_y$), hydrogen ($H_2$), and carbon monoxide (CO), as well as non-flammable gases like carbon dioxide ($CO_2$), sulfur dioxide ($SO_2$), and nitric oxide (NO) [26]. The reduction in volatile matter results from the decomposition of hemicellulose and partial breakdown of cellulose [27]. This decrease in volatile matter contributes to an increase in the carbon content, leading to a higher heating value.

The analysis indicates that the volatile matter content of rice straw after torrefaction is lower than that before the process, and it was also observed that the volatile matter decreases significantly with the severity of the torrefaction process. However, it was found that at the same mass loss, the volatile matter content was similar across different temperatures.

The ash content of rice straw after the torrefaction process is higher than that of rice straw before torrefaction. It was found that the ash content of rice straw prior to the torrefaction process was 11.97%, which increased to a range of 14.15% to 18.35% after the process. The ash content of rice straw after the torrefaction process is higher than that of rice straw before the process. Ash is an inorganic residue remaining after combustion. Biomass generally has a naturally alkaline ash, and while woody biomass typically has lower ash content, some types can have ash content as high as 20% [28]. One of the main disadvantages of using rice straw for combustion is its high ash content, which ranges from 9% to 22% [29]. This elevated ash content can lead to several issues, such as lower heating value and increased maintenance costs due to ash accumulation during combustion [30].

From the initial moisture content of rice straw before and after the torrefaction process, it was found that the moisture content significantly decreased after torrefaction. The moisture content of rice straw before the process was 8.77%, which reduced to a range of 1.17% to 2.25% after undergoing torrefaction.

The moisture content of rice straw significantly decreases after the torrefaction process. This reduction occurs because the amount of hydroxyl groups decreases considerably during torrefaction, resulting in the formation of hydrophobic, non-polar, and unsaturated compounds. Consequently, the moisture content of rice straw decreases following the torrefaction process [31], [32].

It was found that at the same mass loss, regardless of the torrefaction temperature, the proximate analysis of torrefied biomass remained within the same range. This indicates that the changes in the biomass composition are more dependent on the degree of mass loss than the specific temperature used during the torrefaction process.

**Table 4.2** Proximate analysis of rice straw before and after the torrefaction process

| Proximate analysis | Raw rice straw | Torrefied rice straw | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Torrefaction temperature | | | | | | |
| | | 220 | | 250 | | | 280 | |
| | | Mass Yield (%) | | | | | | |
| | | 90 | 80 | 90 | 80 | 70 | 80 | 70 |
| Moisture content (%, as received) | 8.77 | 2.25 | 1.58 | 2.2 | 1.52 | 1.19 | 1.6 | 1.17 |
| Volatile matters (%, Dry basis) | 68.82 | 63.4 | 60.2 | 63.42 | 60.25 | 53.05 | 60.33 | 53.18 |
| Fixed carbon (%, Dry basis, by difference) | 19.21 | 22.45 | 24.25 | 22.54 | 24.4 | 28.32 | 24.5 | 28.48 |
| Ash (%, Dry basis) | 11.97 | 14.15 | 15.55 | 14.04 | 15.35 | 18.63 | 15.17 | 18.34 |

## 4.3 Ultimate Analysis Results

Ultimate analysis of rice straw before and after torrefaction at 220°C, 250°C, and 280°C, with mass losses of 10%, 20%, and 30%, is presented in Table 4.3. The analysis results indicate that the nitrogen content remained relatively unchanged after torrefaction, ranging from 1.07% to 1.32%. However, hydrogen and oxygen content showed a decreasing trend post-torrefaction. Before torrefaction, hydrogen was 7.32%, and oxygen was 51.38%. After torrefaction, hydrogen levels dropped to 4.94%-6.28%, while oxygen levels ranged from 47.49%-50.2%.

When comparing rice straw before and after torrefaction, a reduction in oxygen and hydrogen was observed, while carbon content increased. This trend intensified as torrefaction severity increased. These findings align with previous research by Campbell, Coller & Evitts (2019) [33]., Cruz Ceballos, Hawboldt & Hellleur (2015) [34], Rousset et al. (2011) [35], and Sabil et al. (2013) [36].

During torrefaction, oxygen and hydrogen are partially removed from biomass in forms such as (1) water due to dehydration, (2) organic reaction products like acetic acid ($CH_3COOH$), furan, and methanol ($CH_3OH$), and (3) gases like carbon dioxide and carbon monoxide [37]. Wang et al. (2013) [38] reported that oxygen and hydrogen content in torrefied biomass decreases due to the loss of volatile compounds containing these elements, such as water and carbon dioxide.

Similar to the proximate analysis, at the same mass loss, regardless of the torrefaction temperature, the ultimate analysis results fell within the same range. This suggests that changes in biomass composition are influenced more by mass loss than by the specific temperature during torrefaction.

**Table 4.3** Ultimate analysis of rice straw before and after the torrefaction process

| **Ultimate analysis** | **Raw rice straw** | **Torrefied rice straw** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **Torrefaction temperature** | | | | | | |
| | | **220** | | **250** | | | **280** | |
| | | **Mass loss (%)** | | | | | | |
| | | **10** | **20** | **10** | **20** | **30** | **20** | **30** |
| N (%) | 1.07 | 1.28 | 1.31 | 1.07 | 1.3 | 1.31 | 1.32 | 1.32 |
| C (%) | 40.23 | 42.38 | 44.32 | 42.45 | 44.35 | 46.15 | 44.42 | 46.25 |
| H (%) | 7.32 | 6.21 | 5.75 | 6.28 | 5.78 | 4.89 | 5.81 | 4.94 |
| O (%) *by difference | 51.38 | 50.13 | 48.62 | 50.2 | 48.57 | 47.65 | 48.45 | 47.49 |

## 4.3 HHV determination

The higher heating value (HHV) is the amount of energy released during complete combustion of a sample, including the condensation of water formed during combustion. Due to the small amount of rice straw used in the experiment, the HHV of the rice straw, both before and after torrefaction, was calculated using an equation that relates the elemental analysis results and HHV.

Nhuchhen & Afzal (2017) [23] studied the prediction of HHV for biomass after torrefaction using elemental analysis and proposed a correlation equation to predict the HHV of torrefied biomass, as shown in Equation 1:

$$\mathbf{HHV = 32.7934 + 0.0053C^2 - 0.5321C - 2.8769H + 0.0608CH - 0.2401N} \tag{1}$$

Where:

- HHV represents the higher heating value (MJ/kg)
- C represents the carbon content (%)
- H represents the hydrogen content (%)
- N represents the nitrogen content (%)
-

From Table 4.4, which shows the HHV of rice straw before and after torrefaction, the HHV of rice straw before torrefaction was 16.55 MJ/kg, and after torrefaction, it ranged from 17.59 to 18.88 MJ/kg. Compared to the pre-torrefaction HHV, the increase was between 6.26% and 14.07%. This increase in HHV is attributed to the decomposition of hemicellulose, which typically breaks down and undergoes carbonization at temperatures below 250°C [38].

Similar to the proximate and ultimate analysis, at the same mass loss, the HHV results were consistent across different torrefaction temperatures. This indicates that the changes in biomass composition are more dependent on the extent of mass loss rather than the specific temperature used during torrefaction.

**Table 4.4** HHV of rice straw before and after the torrefaction process

| **HHV** | **Raw rice straw** | **Torrefied rice straw** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **Torrefaction temperature** | | | | | | |
| | | **220** | | **250** | | | **280** | |
| | | **Mass loss (%)** | | | | | | |
| | | **10** | **20** | **10** | **20** | **30** | **20** | **30** |
| HHV (MJ/kg, dry basis) | 16.55 | 17.59 | 18.26 | 17.64 | 18.26 | 18.86 | 18.27 | 18.88 |

# บทที่ 5
# สรุปผลงานวิจัย

## 5.1 สรุปผลการทดลอง

In this study, the torrefaction process was applied to rice straw at three temperatures: 220°C, 250°C, and 280°C, aiming for mass losses of 10%, 20%, and 30%. However, at 220°C, only 10% and 20% mass losses were achievable, while at 280°C, a 10% mass loss occurred before reaching the target temperature, limiting the study to 20% and 30% mass losses. All three mass loss levels were successfully achieved at 250°C.

The analysis revealed that as torrefaction temperature increased, the time required to reach the desired mass loss decreased. Proximate analysis showed that the fixed carbon content of rice straw increased post-torrefaction, with the highest value reaching 28.48% at 30% mass loss, making it comparable to coal in terms of carbon content. The volatile matter content decreased with increasing torrefaction severity, due to the release of volatile compounds during the process. Similarly, ash content increased after torrefaction, while moisture content significantly reduced, enhancing the fuel properties of the biomass.

Ultimate analysis indicated that nitrogen content remained relatively unchanged, while hydrogen and oxygen levels decreased, with carbon content rising as torrefaction severity increased. This trend was consistent with other studies, demonstrating that mass loss, rather than temperature, had a greater influence on the chemical composition of rice straw.

Higher heating value (HHV) results also indicated an increase post-torrefaction, with the highest values reaching up to 18.88 MJ/kg. The increase in HHV is linked to the breakdown of hemicellulose and the concentration of carbon. Across different torrefaction temperatures, similar trends were observed: at the same mass loss, the composition and HHV of rice straw remained consistent, suggesting that mass loss is the primary driver of changes in biomass properties, rather than the torrefaction temperature itself.

In conclusion, selecting higher torrefaction temperatures for the torrefaction process is advisable because they significantly reduce the time required for processing while ensuring that the properties of the biomass remain within the same range. This efficiency not only enhances the overall effectiveness of the torrefaction process but also improves the fuel characteristics of the biomass, making it more comparable to conventional fuels. The results indicate that increasing the torrefaction temperature leads to beneficial changes in biomass composition, aligning with the objectives of enhancing biomass usability.

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