



## Turning Water Hyacinth into Bioenergy: Briquettes with Torrefied Cassava Rhizomes

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**Abstract** – This study investigates the feasibility of converting fresh water hyacinth (*Eichhornia crassipes*), a widely recognized invasive aquatic weed, into community-scale bioenergy through briquetting with torrefied cassava rhizomes (TCR). The novelty of this work lies in applying torrefied agricultural residues not only as an energy enhancer but also as a natural preservative to suppress microbial degradation of water hyacinth during storage. A simulated storage system was developed with mixing ratios of 10%, 15%, and 20% TCR by weight, monitored over eight weeks. Key performance indicators—including odor suppression, textural stability, bulk density, and higher heating value (HHV)—were evaluated. Results showed that blending with  $\geq 10\%$  TCR effectively reduced foul odor and structural decomposition. Bulk density increased by approximately 30% for TCR10% and TCR15% formulations, while HHVs remained stable ( $17.6\text{--}20.7\text{ MJ}\cdot\text{kg}^{-1}$ ), closely matching theoretical predictions. Compared to previous biomass densification studies, the present approach demonstrated superior stability during storage with minimal energy losses. These findings highlight a practical and low-cost strategy for producing renewable briquettes, offering both environmental benefits through aquatic weed management and economic value for rural communities.

**Keywords** –Biomass briquette, bulk density, renewable energy, torrefied cassava rhizome, water hyacinth.

### 1. INTRODUCTION

*Eichhornia crassipes* (water hyacinth) is listed among the 100 most invasive plant species globally [1]. It exhibits rapid growth and spreads swiftly across water bodies, often outcompeting native aquatic vegetation. This proliferation significantly reduces light penetration, impairs photosynthesis of local flora, and leads to reduced dissolved oxygen levels, eutrophication, and loss of biodiversity [2]. Additionally, dense mats of water hyacinth serve as breeding grounds for mosquitoes and other vectors of infectious diseases [3]. The economic impact is also severe; for example, one governmental initiative required over 800,000 man-hours and a budget exceeding USD 1 million to control the infestation yet failed to produce lasting results [2]. The plant also damages fishing equipment, obstructs boat navigation [4-5], and contributes to siltation by forming submerged biomass layers that reduce waterway depth, increasing flood risk. In response to its ecological and economic impacts, several utilization pathways have been explored, e.g., as raw material for handicrafts, animal feed, compost, and organic fertilizer. However, these applications have proven insufficient in curbing its rapid growth. Among the more promising alternatives is the conversion of water hyacinth into biofuel. Studies have demonstrated the potential of bioethanol production through fermentation [6], but its

technical complexity limits implementation at the community scale. Therefore, simpler technologies such as biomass densification into briquettes [7], mixed-biomass compaction [8], and pelletization [9] have been proposed. Nevertheless, the high moisture content of water hyacinth, more than 90% [10], poses a major barrier. Producing 10 kg of dry matter requires approximately 100 kg of fresh biomass. Consequently, effective and low-cost drying methods are critical. While open-air sun drying is cost-effective, it demands significant space and labor, and is susceptible to microbial spoilage and foul odors due to biomass pile-up and unfavorable weather conditions [1]. Alternative methods such as multi-tray solar drying [11] and mechanical dewatering [11-12] have been investigated but remain cost-prohibitive.

A key challenge, therefore, is the absence of cost-efficient dehydration technologies tailored for community-level fuel production. Sun drying remains promising but requires improvements to minimize spoilage and odor. One potential approach is the co-treatment of water hyacinth with torrefied biomass, which may inhibit microbial activity during drying. Thermal degradation during torrefaction generates phenolic compounds [13–15], which possess known antimicrobial properties [16]. For cost-efficiency, torrefied agricultural residues, such as cassava rhizomes, offer a promising solution. These residues, which account for 8–14% of harvested root mass [17], are often left unutilized or openly burned, causing smoke and particulate pollution. Moreover, their acidic organic content can elevate BOD and COD levels when discharged into aquatic systems, degrading water quality [18]. On the other hand, cassava rhizomes exhibit heating values comparable to woody biomass, making them viable fuel sources [19]. However, their high alkali

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content leads to slag formation during combustion [9], limiting their use as standalone fuels. Torrefied cassava rhizomes, when blended with water hyacinth, may offer a dual benefit: suppressing microbial degradation during drying and enhancing fuel properties. Such an approach also promotes agricultural waste valorization.

Research questions of this study are as follows:

1. What is the optimal mixing ratio of water hyacinth and torrefied cassava rhizomes to suppress microbial degradation during storage?
2. How do different ratios affect the bulk density and calorific value of the resulting briquettes?
3. Can torrefied cassava rhizomes serve as both a binding enhancer and a stabilizer, thus making biomass densification more viable at the community scale?

By addressing these questions, the study not only demonstrates a novel application of agricultural residues in biomass briquetting but also provides a potential pathway to mitigate the dual problems of aquatic weed proliferation and cassava waste disposal. Furthermore, the findings are expected to contribute to sustainable bioenergy development in rural areas, reducing reliance on conventional fuels and improving local waste valorization practices.

This study investigates the physical changes in mixtures of fresh water hyacinth and torrefied cassava rhizomes over time under varying proportions and mass-loading conditions, simulating biomass pile-up in closed containers. In addition to visual and olfactory assessments, the study also examines changes in calorific value, bulk density, and moisture content of the mixtures. The goal is to determine the optimal mixing ratio for fuel production. The results aim to support the feasibility of decentralized briquettes production systems for rural bioenergy applications, offering a sustainable strategy for aquatic weed management.

## 2. MATERIALS AND METHODS

### 2.1 Preparation of Water Hyacinth

Fresh water hyacinth (*Eichhornia crassipes*) was harvested from Nakhon Pathom Province, Thailand (13°57'38"N, 100°4'53"E). The initial average moisture content was 93.97%. The roots were removed, and the plants were mechanically shredded to pass through a 5 mm mesh. Fibrous residues retained on the shredder screen were collected and included in the experiments. A total of 150 kg of shredded water hyacinth was prepared for the study.

### 2.2 Preparation of Torrefied Cassava Rhizomes

Cassava rhizomes were sourced from Ratchaburi Province (13°41'30"N, 99°51'12"E). The rhizomes were coarsely and finely chopped to achieve particles smaller than 5 mm, air-dried in an open area for one week, and subsequently torrefied in a thermosyphon-torrefaction reactor [20] at 260 °C for 60 minutes. After torrefaction, the material was cooled to ambient temperature and sealed in airtight plastic bags for further use. A total of 15 kg of torrefied cassava rhizomes was prepared.

### 2.3 Experimental Procedure

The shredded fresh water hyacinth was blended with torrefied cassava rhizomes at mixing ratios of 5%, 10%, 15%, and 20% (by weight of fresh water hyacinth). Pure water hyacinth was used as the control. The sample codes and compositions are shown in Table 1. Each mixture was placed in a simulated biomass dewatering container (Figure 1), which consisted of a 150 L airtight plastic drum. Inside each drum, a perforated steel plate (diameter: 450 mm; thickness: 2 mm; 100 holes of 5 mm diameter) was positioned 120 mm above the bottom to facilitate the drainage of water released from the water hyacinth and torrefied cassava rhizome mixture. A drainage valve was installed at the bottom via a ½-inch PVC pipe.

To simulate biomass pile-up under compression and poor ventilation, each mixture was loaded with a 10 kg mass placed on a grid specifically designed to distribute its weight evenly. The lid was then sealed. All containers were stored at ambient temperature in a well-ventilated area. Each treatment was replicated across eight containers, and one container per treatment was opened weekly over an 8-week period (168-hour intervals). Upon opening, the samples were assessed in terms of physical appearance, odor, and moisture content to determine the most suitable mixture for subsequent fuel production. The selected mixture was dewatered using a hydraulic press and a rectangular mold with internal dimensions of 135 mm in width (W), 300 mm in length (L), and 160 mm in height (H). The mold featured 5 mm perforations on the side walls to facilitate water drainage (Figure 2). The dewatered material was then formed into briquettes using the same mold. These briquettes were subsequently analyzed to determine their bulk density and calorific value.

**Table 1. Sample composition and code descriptions.**

| Sample code | Mixing ratio | Weight of fresh water hyacinth (kg) | Weight of torrefied cassava rhizomes (kg) |
|-------------|--------------|-------------------------------------|-------------------------------------------|
| TCR0%       | 0 %          | 30                                  | 0                                         |
| TCR5%       | 5 %          | 30                                  | 1.5                                       |
| TCR10%      | 10 %         | 30                                  | 3                                         |
| TCR15%      | 15 %         | 30                                  | 4.5                                       |
| TCR20%      | 20 %         | 30                                  | 6                                         |



Fig. 1. Simulated biomass dewatering container



Fig. 2. Hydraulic press and mold

#### 2.4 Bulk Density and Calorific Value Determination

Bulk density was determined in accordance with ASTM E873. The prepared mixtures were compacted into rectangular briquettes using a compression pressure of 2.7 MPa. The dimensions and mass of each briquette were measured and used to calculate the bulk density based on the calculated volume, using the following equation:

$$\rho_{\text{bulk}} = \frac{m}{V} \quad (1)$$

Calorific value was determined using a bomb calorimeter following ASTM E711-87. Samples were pre-dried in an oven for 24 hours, transferred to a desiccator, and cooled to room temperature before analysis. Each test was performed in quintuplicate ( $n = 5$ ), and results were reported with a 95% confidence level.

### 3. RESULTS AND DISCUSSION

#### 3.1 Physical Change of Mixtures

To identify the optimal mixture for fuel production, the decomposition behavior of pure water hyacinth (TCR0%) was first examined as a control. As illustrated in Figure 3, the TCR0% samples began emitting a slight putrid odor at 336 hours (Week 2), which intensified until 672 hours (Week 4). Subsequently, at 840 hours (Week 5), the odor diminished, giving way to a musty smell that persisted and became more pronounced from 1008 hours (Week 6) through 1344 hours (Week 8). These olfactory changes suggest an initial acceleration in decomposition, followed by a gradual decline in the rate of decay, although decomposition continued throughout the storage period. This observation highlights that a major challenge in managing water hyacinth is its tendency to decompose and release foul odors. Therefore, the absence of putrid odors is a critical criterion for selecting suitable mixtures for fuel production.

Fig. 3. the changes in physical appearance, odor, and color of the mixtures during storage in the simulated drum environment over time (cont.)

| Time (h) | TCR0%                                                                                                                                                                             | TCR5%                                                                                                                                                                  | TCR10%                                                                                                                                                                        | TCR15%                                                                                                                                             | TCR20%                                                                                                                                            |
|----------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| 504      |                                                                                                  |                                                                                       |                                                                                            |                                                                 |                                                                |
|          | Exhibited a fibrous structure with increased pulpiness, the putrid odor intensified further, and displays an increased yellow hue with a reduced greenish tint.                   | Exhibited reduced fibrous structure with a slightly mushy texture, slight putrid odor with a noticeable torrefied biomass scent, and displays a dark green appearance. | Exhibits a reduced presence of fibrous structures, emits a slight putrid odor mixed with the characteristic scent of torrefied biomass, and displays a dark green appearance. | Exhibits a reduced presence of fibrous structures, musty odor with a detectable torrefied biomass scent, and displays a dark green appearance.     | Exhibits a reduced presence of fibrous structures, emits a faint musty odor with a hint of torrefied biomass, and slightly green with a dark hue. |
| 672      |                                                                                                 |                                                                                      |                                                                                           |                                                                |                                                               |
|          | Retained fibrous characteristics with increased mushiness, the intensity of the putrid odor further increased, and displays an increased yellow hue with a reduced greenish tint. | Displayed reduced fibrous structure with slight mushiness, slight putrid odor with a noticeable torrefied biomass scent, and dark yellowish-black coloration.          | The biomass exhibited a fine texture, slight putrid odor with a noticeable torrefied biomass scent, and dark yellowish-black coloration.                                      | Exhibits a reduced presence of fibrous structures, slight musty odor with a hint of torrefied biomass scent, and displays a dark green appearance. | The biomass exhibited a fine texture, torrefied odor was perceptible, and exhibited a black coloration.                                           |

Fig. 3. the changes in physical appearance, odor, and color of the mixtures during storage in the simulated drum environment over time (cont.)

| Time (h) | TCR0%                                                                                                                                                                                                                                                 | TCR5%                                                                                                                                                                                                                                                                        | TCR10%                                                                                                                                                                                                                                                    | TCR15%                                                                                                                                                                                                                                                     | TCR20%                                                                                                                                                                                                                   |
|----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 840      |  <p>The sample exhibited a mushy texture, the foul odor gradually transitioned into a musty scent, and the greenish-yellow hue became more pronounced.</p>           |  <p>The fibrous texture decreased, while the pulp-like consistency became more prominent, the foul odor gradually transitioned into a musty scent, and dark yellowish-black coloration.</p> |  <p>The texture of the biomass became increasingly finer, musty odor with a detectable torrefied biomass scent, and dark coloration with slight yellowish tint.</p>     |  <p>The biomass exhibited a fine texture, slight musty odor with a hint of torrefied biomass scent, and dark coloration with slight yellowish tint.</p>                 |  <p>The texture of the biomass became increasingly finer, torrefied odor was perceptible, and exhibited a black coloration.</p>       |
| 1008     |  <p>The material exhibited increased mushiness, the putrid odor diminished, transitioning to a musty scent, and the greenish-yellow hue became more pronounced.</p> |  <p>The biomass exhibited a fine texture with slight mushiness, slight musty odor with a hint of torrefied biomass scent, and dark yellowish-black coloration.</p>                         |  <p>The texture of the biomass became increasingly fine, slight musty odor with a hint of torrefied biomass scent, and dark coloration with slight yellowish tint.</p> |  <p>The texture of the biomass became increasingly fine, slight musty odor with a hint of torrefied biomass scent, and dark coloration with slight yellowish tint.</p> |  <p>The texture of the biomass became increasingly fine, the torrefied odor began to diminish, and exhibited a black coloration.</p> |

Fig. 3. the changes in physical appearance, odor, and color of the mixtures during storage in the simulated drum environment over time (cont.)

| Time (h) | TCR0%                                                                                                                                                         | TCR5%                                                                                                                                                           | TCR10%                                                                                                                                                          | TCR15%                                                                                                                                         | TCR20%                                                                                                                       |
|----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|
| 1176     |                                                                              |                                                                                |                                                                               |                                                             |                                           |
|          | The biomass exhibited significantly increased mushiness, an increase in musty odor was observed, and dark yellowish-black coloration.                         | The biomass exhibited a fine texture with slight disintegration, slight musty odor with a hint of torrefied biomass scent, and dark yellowish-black coloration. | The texture of the biomass became increasingly fine, emitted a faint musty odor with subtle torrefied biomass notes, and dark color with a slight greenish hue. | The texture of the biomass became increasingly fine, a slight musty odor was observed, and dark color with a slight greenish hue.              | The texture of the biomass became increasingly fine, the torrefied odor began to diminish, and exhibited a black coloration. |
| 1344     |                                                                             |                                                                               |                                                                              |                                                            |                                          |
|          | Severe disintegration was observed, with the presence of a mucilaginous texture, an increase in musty odor was observed, and dark yellowish-black coloration. | The degree of disintegration increased significantly, the musty odor gradually diminished, and dark color with a slight greenish hue.                           | The biomass exhibited a fine texture with slight disintegration, the musty odor gradually diminished, and dark color with a slight greenish hue.                | The biomass texture exhibited a significantly finer structure, the musty odor gradually diminished, and dark color with a slight greenish hue. | The texture of the biomass became increasingly fine, the torrefied odor began to diminish, and exhibited a black coloration. |

Physically, the TCR0% samples exhibited a mushy texture starting at 336 hours (Week 2), which progressively worsened until 1344 hours (Week 8). Previous studies suggest that initial textural degradation arises from non-microbial processes such as physical leaching and autolysis within the first four days of decomposition, after which microbial activity predominates, breaking down plant cell structures and resulting in a mushy texture [21]. In oxygen-limited environments, microbial decomposition of organic matter produces gases such as hydrogen sulfide ( $\text{H}_2\text{S}$ ), methyl mercaptan, ammonia, methane, and other nitrogenous compounds, which contribute to the observed malodors, corroborating the sensory observations in this study. Moisture content analysis (Figure 4) revealed a significant decrease in the TCR0% samples from 168 hours (Week 1) to 672 hours (Week 4), followed by a slower rate of moisture loss. This trend indicates that the mushy texture, characteristic of hydrophilic materials, impedes water migration from the mixture. Consequently, the presence of a mushy texture serves as an indicator of unsuitable mixtures for fuel production.

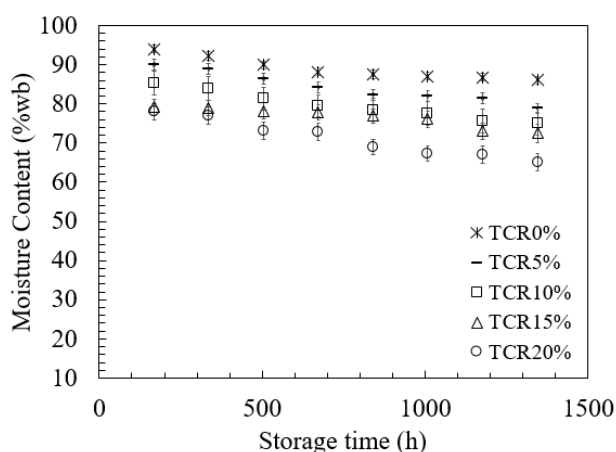


Fig. 4. The relationship between moisture content of mixtures and storage time

Color changes in the TCR0% samples were also noted; initial decomposition was marked by a yellow hue, transitioning to a darker coloration by 1008 hours (Week 6) as the putrid odor subsided. This progression suggests that yellowing signifies the onset of decomposition, while darkening indicates that the degradation process has reached its final stage or has ceased.

In the TCR5% samples, putrid odors were detected from 336 hours (Week 2), with a mushy texture developing by 504 hours (Week 3), persisting through 1344 hours (Week 8). Moisture content trends mirrored those of the TCR0% samples, indicating ongoing decomposition and rendering TCR5% unsuitable for fuel production. Conversely, the TCR10% samples exhibited only mild putrid odors and yellowing, with a mushy texture appearing late in the observation period at 1344 hours (Week 8). Moisture content patterns differed from TCR0%, suggesting that the hydrophilic mushy texture

did not hinder water loss, making TCR10% a viable candidate for fuel property analysis. Similarly, TCR15% and TCR20% samples demonstrated favorable characteristics, indicating that incorporating torrefied cassava rhizomes at a minimum of 10% by weight effectively mitigates decomposition in water hyacinth mixtures.

### 3.2 Bulk Density of Briquette

The bulk density of the TCR10% mixture increased from  $454.45 \text{ kg m}^{-3}$  to  $600.32 \text{ kg m}^{-3}$ , representing a 32.10% rise as the storage duration extended from 168 hours (week 1) to 1344 hours (week 8). For the TCR15% mixture, the bulk density rose from  $445.49 \text{ kg m}^{-3}$  to  $583.23 \text{ kg m}^{-3}$ , an increase of 30.92%. As illustrated in Figure 5, there was no statistically significant difference in bulk density between the TCR10% and TCR15% mixtures. In contrast, the TCR20% mixture showed an increase in bulk density from  $421.73 \text{ kg m}^{-3}$  to  $542.38 \text{ kg m}^{-3}$ , accounting for a 28.61% rise. At 168 hours (week 1), all three mixtures exhibited no statistically significant differences in bulk density. However, with prolonged storage time, the TCR20% mixture consistently demonstrated lower bulk density than TCR10% and TCR15% mixtures, indicating that extended storage duration increases bulk density, while higher proportions of torrefied cassava rhizome reduce it. Previous studies have reported that extracellular polymeric substances (EPS) formed during biomass fermentation contribute to improved inter-particle bonding [22]. Additionally, the densification mechanism involves the physical interlocking of non-spherical particles, such as cellulose fibers, while their rebound effect can reduce particle cohesion [23]. When these findings are considered alongside experimental results, it appears that prolonged storage facilitates microbial degradation, which promotes the formation of natural binding agents and the breakdown of tissue structure. This results in greater cohesion and reduced rebound effects, contributing to increased bulk density in TCR10%, TCR15%, and TCR20% mixtures over time.

The decline in bulk density for the TCR20% mixture may be explained by the inhibitory effect of torrefied cassava rhizome on water hyacinth decomposition. A higher proportion of TCR may thus reduce microbial degradation and natural binder formation, while increasing the rebound effect during compression. Furthermore, torrefied biomass itself has been reported to lose its inherent natural binders [24], which can further contribute to reduced bulk density in TCR-rich mixtures.

The improvement in bulk density observed in TCR10% and TCR15% mixtures aligns with findings from Intagun et al. [22], who reported that microbial fermentation enhances inter-particle bonding in cassava-based residues. Compared with briquettes from rice husk and bran ( $441.18 \text{ kg/m}^3$ ) [25], the present study achieved higher densification under moderate compression, suggesting the combined effect of fermentation-induced

binders and torrefied biomass. However, bulk densities remained lower than those of torrefied woody biomass briquettes (900–1140 kg/m<sup>3</sup>) [26], indicating opportunities for further optimization through pressure adjustments or binder supplementation.

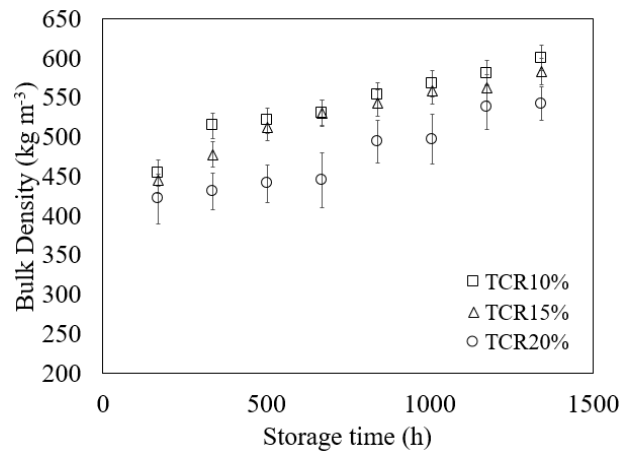


Fig. 5. The relationship between bulk density of briquettes and storage time

### 3.3 Higher Heating Value (HHV)

The higher heating values (HHVs) of the TCR10%, TCR15%, and TCR20% mixtures were in the ranges of 17.61–18.61 MJ·kg<sup>-1</sup>, 18.11–19.75 MJ·kg<sup>-1</sup>, and 20.42–20.69 MJ·kg<sup>-1</sup>, respectively (Figure 6). No statistically significant changes in HHV were observed with increased storage duration, indicating stability of the mixtures over time. Using weighted-average estimation based on component HHVs—14.3 MJ·kg<sup>-1</sup> for dried water hyacinth and 21.99 MJ·kg<sup>-1</sup> for torrefied cassava rhizome [20,22]—theoretical maximum HHVs for the TCR10%, TCR15%, and TCR20% mixtures were calculated as 19.10, 19.79, and 20.21 MJ·kg<sup>-1</sup>, respectively. The experimental HHVs of the TCR15% and TCR20% mixtures were close to their theoretical maxima, while the TCR10% mixture yielded slightly lower values. These results suggest that the decomposition of water hyacinth during storage had only a minor effect on the HHV. This is likely due to the high initial moisture content of fresh water hyacinth (>90%), resulting in a low proportion of dry matter. In this study, 20 kg of fresh water hyacinth was used per batch, which corresponds to approximately 1.81 kg of dry matter. Compared to the mass of torrefied cassava rhizome—3, 4.5, and 5 kg in the TCR10%, TCR15%, and TCR20% mixtures, respectively—the contribution of decomposed water hyacinth to overall energy loss was minimal. Furthermore, the HHV of the TCR20% mixture was significantly higher than that of the TCR10% blend, highlighting the positive influence of torrefied cassava rhizome on the energy content of the briquette mixtures.

Similarly, the HHVs of TCR10%–20% blends (17.6–20.7 MJ·kg<sup>-1</sup>) were consistent with values reported for water hyacinth briquettes (16–18 MJ·kg<sup>-1</sup>) [7] and mixed-biomass formulations [8]. Notably, the

TCR20% mixture yielded energy content above 20 MJ·kg<sup>-1</sup>, comparable to conventional woody biomass. This confirms that torrefied cassava rhizomes significantly contribute to enhancing energy density. Nevertheless, excessive proportions (≥20%) reduced bulk density due to the loss of natural binders in torrefied material [24], highlighting a trade-off between calorific enhancement and structural integrity.

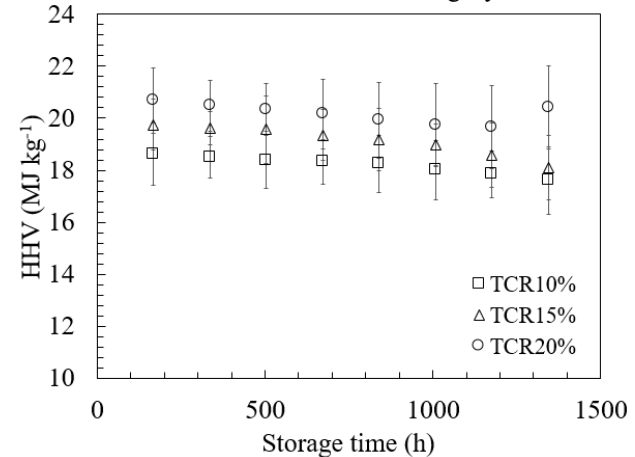


Fig. 6. The relationship between higher heating values and storage time

## 4. CONCLUSION

This study demonstrated that blending fresh water hyacinth with torrefied cassava rhizomes at proportions of 10–15% effectively suppressed microbial decomposition, reduced foul odor, and improved storage stability during biomass densification. Prolonged storage further enhanced bulk density (≈30% increase), while higher heating values (17.6–20.7 MJ·kg<sup>-1</sup>) remained stable and close to theoretical predictions. The results indicate that TCR10% and TCR15% are optimal formulations for community-scale bioenergy production, balancing fuel quality with material stability.

**Limitations:** The study was conducted under laboratory-scale storage conditions and focused on physical and thermal properties without assessing combustion performance, emission profiles, or economic feasibility at larger scales.

**Future work:** Field-scale trials should evaluate drying efficiency, long-term storage stability under variable climates, and cost-benefit analysis in rural settings. Furthermore, integrating additional low-cost binders or optimizing compression pressures may further enhance briquette quality.

Overall, this research provides a novel and practical pathway to transform invasive aquatic weeds into renewable fuel, while simultaneously valorizing agricultural residues for sustainable rural energy systems.

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