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Optimization of *Eichhornia crassipes* Invasive Agro-Waste for Improved Combustion Characteristics

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ABSTRACT

Process optimization is a key strategy for enhancing product performance. This study investigates the influence of process parameters on the combustion behavior of solid fuel briquettes made from water hyacinth (WH), known as *Eichhornia crassipes*, using empirical modeling and parametric optimization. The experimental design was structured according to Response Surface Methodology (RSM) with a Central Composite Design (CCD). The input parameters considered included a particle size range of 0.5 to 1.5 mm, compression pressures from 3 MPa to 7 MPa, and binder ratios between 10% and 30%. The effects of each parameter on combustion kinetics were evaluated, and the constructed model was validated through analysis of variance (ANOVA). Ignition time and combustion rate were the main experimental outputs, and both numerical and physical experiments were statistically validated. This approach aims to develop a predictive model that relates ignition duration and combustion rate to the independent operational parameters. The optimized parameters, achieving a desirability of 1 out of 100 solutions, include a particle size of 0.763042 mm, a compaction pressure of 3.08724 MPa, and a binder ratio of 13.4529 %, resulting in an ignition duration of 70.8386 seconds and a combustion rate of 2.24221 g.min^{-1}. This research significantly contributes to the sustainable valorization of agricultural waste into value-added biomass energy production, supporting the development of renewable, secure, and economical energy solutions while effectively transforming waste into valuable resources.

INTRODUCTION

The unchecked generation of waste is a common issue faced by many communities worldwide, and the problem is exacerbated by ineffective waste management practices (Ndukwe et al. 2025). Water hyacinth, with the scientific name Eichhornia crassipes, is considered one of the most widespread invasive aquatic plants globally (Enyew Assefa & Gezie 2020). This free-floating plant is known for its rapid growth and high reproductive capacity (Malik 2007). While it is native to Brazil and some South American countries, water hyacinth has spread extensively across swamps and lakes in many regions between 40º N and 40º S (Villamagna & Murphy 2010). Its aggressive growth leads to the encroachment of aquatic ecosystems, hindering navigation and fishing, creating habitats for disease vectors, and causing a decline in biodiversity that threatens both human and aquatic life (Su et al. 2018, Ndimele et al. 2011). Managing water hyacinth biologically is a lengthy process, while chemical methods are often costly and typically used only in severe infestations. Mechanical methods are seen as the most practical short-term solution to limit the spread of this invasive species, though they require significant investment in both aquatic and land-based equipment. Thus, it is crucial to adopt control measures for water hyacinth while also utilizing it as a resource. This dual strategy can convert waste into valuable products, tackle the issues caused by water hyacinth proliferation, and provide economic and ecological benefits (Su et al. 2018).

Water hyacinth, often viewed as a harmful weed linked to various socio-economic issues, also offers significant benefits. It can serve as an organic fertilizer to enhance nutrient-poor soils and aid in wastewater treatment. Additionally, it can be used as a feedstock for renewable energy production, livestock feed, and the manufacturing of paper, pulp, and ropes. Research has shown that this problematic floating plant can be converted into products that produce alternative energy, helping to mitigate environmental concerns (Okwu & Emovon 2018).

Biomass fuel is a sustainable energy source made from organic materials such as agricultural by-products, forest residues, and various plant tissues. However, loose biomass and animal waste produce smoke and environmental pollutants, making them less effective for efficient combustion (Onyango et al. 2020). The main components of water hyacinth biomass are cellulose and hemicellulose, which can easily be converted into simple sugars and are suitable for energy production. Additionally, these compounds can produce high-quality biofuel briquettes when combined with appropriate binding agents. This approach offers an alternative use for *E. crassipes*, providing a more effective strategy for managing this invasive alien species (IAS) (Mandal et al. 2017).

Briquetting technology provides a clean and reliable energy source for residents of peri-urban and urban areas in developing economies (Okwu & Emovon 2018, Okia et al. 2016). The addition of binders enhances the calorific value, adhesion, and stability of biofuel briquettes, making them easier to handle, transport, and store (Borowski et al. 2017, Asamoah et al. 2016). Key parameters such as density and strength are crucial in biofuel briquette production, as low-quality briquettes may break or disintegrate during storage, handling, and transport (Muazu & Stegemann 2017). Various materials, including livestock dung, forest residues, municipal waste, and agricultural by-products, have been used to produce biofuel briquettes (Asamoah et al. 2016). While significant attention has been given to the energy potential of water hyacinth for biogas production, its conversion into biofuel briquettes has received less focus. This research aims to optimize the process parameters for producing water hyacinth briquettes as a viable renewable biomass fuel derived from agricultural waste.

Relevant Studies on Water Hyacinth and Water Hyacinth-Based Briquette

Sukarni et al. (2019) examined the physico-chemical properties of water hyacinth (*Eichhornia crassipes*) as a potential alternative energy source. Their findings revealed that the main elemental composition of water hyacinth consists of 49.50% oxygen and 14.46% carbon. The proximate analysis showed moisture content at 4.9%, volatile matter (VM) at 61.2%, fixed carbon (FC) at 13.8%, and ash content (AC) at 20.1% wt.%. The gross calorific value (GCV) of water hyacinth biomass was determined to be 14.46 $MJ.kg^{-1}$. Although it has a relatively high VM and low heating value, it is crucial to explore methods to enhance the fuel quality of water hyacinth biomass for better combustion performance. This can be achieved through various strategies, including pretreatment processes, briquetting, and co-combustion with coal to increase its reactivity during combustion.

Onyango et al. (2020) investigated the potential of using water hyacinth as a source for biofuel briquettes. The water hyacinth was chopped, dried, and pulverized to achieve a particle size of < 5 mm, then mixed with binders in proportions of 10%, 20%, and 30%. It explored eucalyptus globulus leaves powder, molasses, and phytoplankton scum as a binder. The study investigated its effect on durability, calorific value, compressed density, water resistance and relaxation. Experimental results were compared to those of commercially available charcoal briquettes. It was found that biofuel briquettes with a 20 % molasses binder were suitable for both domestic and industrial applications, exhibiting the highest calorific value among all tested mixtures. The calorific value of the charcoal briquettes was measured at 1422.97 $kJ.kg^{-1}$, while the formulation with 20% molasses binder achieved a notable calorific value of 1148.35 $kJ.kg^{-1}$. Thus, water hyacinth briquettes offer a promising alternative to charcoal and other biomass fuels, contributing to a reduction in the risk of forest fires.

Balamurugan et al. (2014) employed a hydraulic press to produce water hyacinth briquettes at various pressure levels (12, 40, 60, and 80 MPa) using different compositions: 100% water hyacinth; 75% water hyacinth mixed with 25% sawdust; and 50% water hyacinth mixed with 50% sawdust, all with a grain size of 1 mm. The study investigated the effect on the Higher Heating Value (HHV) of the briquette. They discovered that the high heating value (HHV) exceeded 3100 $kcal.kg^{-1}$, indicating its suitability as biomass briquettes for cooking and in industrial boilers.

Pratama et al. (2020) investigated the fabrication process of water hyacinth briquettes (WHB), focusing on variations in pressure and pellet shapes. The study assessed parameters such as moisture content and calorific value, utilizing a formulation of 90% water hyacinth charcoal and 10% tapioca starch as a binder. Four different geometric configurations were tested: solid box, hollow box, solid tube, and hollow tube, at three pressure levels: 10 PSI, 20 PSI, and 30 PSI. The results showed that briquettes produced at 20 PSI achieved a calorific value ranging from 91.15 to 150.14 cal.g^{-1}, which was higher than the values for briquettes made at 10 PSI (93.84 to 148.79 cal.g^{-1}) and 30 PSI (89.81 to 135.39 cal.g^{-1}).

Davies et al. (2013) investigated the combustion properties of a composite made from a blend of water hyacinth and plantain peels as a binder, along with mangrove wood, charcoal, and Anthonotha macrophylla as firewood sources. The thermal fuel efficiency of the briquettes produced from these materials showed competitive performance compared to charcoal, firewood, and red mangrove wood. Notably, charcoal achieved the highest fuel efficiency at 31.29±0.19%, while the fuel briquettes closely followed with an efficiency of 28.17±0.88%.

The calorific values of the energy sources varied from 4166.67±4.33 kcal.kg^{-1} for firewood to 6552.00±4.73 kcal.kg^{-1} for charcoal. The recorded boiling times, ignition times, and burning rates were as follows: water hyacinth (WH) briquettes took 11.43±0.43 minutes to boil, ignited in 115.00±0.88 seconds, and had a burning rate of 1.25 g.min^{-1}; charcoal had boiling times of 14.94±0.22 minutes, ignition times of 138.00±0.19 seconds, and a burning rate of 0.97 g.min^{-1}; firewood boiled in 9.25± 0.42 min, ignited in 83.34 seconds, and burned at a rate of 2.49 g.min^{-1}; while mangrove took 8.99±0.22 minutes to boil, ignited in 92.67 seconds, and had a burning rate of 2.05 g.min^{-1}. The thermal fuel efficiency of the water hyacinth briquettes is comparable to that of traditional fuels. Although charcoal demonstrates the highest efficiency at 31.29±0.19%, the briquettes follow closely with an efficiency of 28.17±0.88%, highlighting their potential as a viable energy source.

Oroka & Thelma (2013) investigated different mixing ratios of water hyacinth and cow dung for briquette production, examining ratios of 100:0, 90:10, 80:20, and 70:30. The briquettes with the 70:30 and 80:20 ratios demonstrated the highest relaxed densities, achieving 1157 kg.m^{-3} and 1296 kg.m^{-3}, respectively, after drying. Flue gas temperatures ranged from 60.5-74.5°C, with higher temperatures noted in briquettes containing more cow dung, suggesting improved combustion efficiency with increased cow dung content. The time required to bring water to a boil varied based on the composition, with the 70:30 water hyacinth-cow dung mixture boiling water in 51 min, the fastest among the ratios tested.

Davies & Abolude (2013 characterized briquettes produced from water hyacinth and plantain peel binder. In this study, the effect of the process variable on ignition time and burning rate of the fuel briquette was examined. The process variable/parameter in the experimental study is the particle sizes (0.5, 1.6 and 4 mm) while the pressure (3,5,7 and 9 N.mm^{-2}) with 10, 20, 30, 40 and 50% binder. Result gave a burning rate of 0.92 g.min^{-1} (0.5 mm)- 2.66 g.min^{-1} (4 mm); 1.57 g.min^{-1} (50% binder)- 2.30 g.min^{-1} (10%) and 1.68 g.min^{-1} (9 N.mm^{-2})-2.13 g.min^{-1} (3 N.mm^{-2}). Hence, it can be deduced that the burning rate decreases as the compaction pressure and binder content increase, while the burning rate decreases as the particle size decreases. Ignition time decreases with decreasing binder proportion and decreases with decreasing compaction pressure. However, the ignition time decreases with decreasing particle size.

Similar studies were carried out by Davies & Yusuf (2017), which examine some engineering properties of Water hyacinth briquette with Plantain peel (PP) at different particle sizes (0.5, 1.6, and 4 mm) and a pressure level of 3, 5,7, and 9 MPa and binders of 10,20,30,40 and 50%. The engineering properties, which are compressive strength, shattering index, relaxed density and water resistance, were observed to increase with increased binder proportion, compaction pressure and decreased particle size. This study therefore suggests that optimal briquettes WH-PP production is at particle size, 0.5 mm; binder ratio, 40% and compaction pressure, 9 MPa (D1B4P4).

Murakami & Sato (2024) investigated the fuel properties of briquettes created from a mixture of water hyacinth biochars (WHB), various binding agents, and organic matter. The water hyacinth was dried and subjected to pyrolysis at temperatures of 400°C and 800°C, referred to as WHB 400 and WHB800, respectively. The WH biochar was mixed with different binding agents, specifically molasses and Ethiopian soil, in two ratios: [6:4:0] without organic matter and [6:3:1] with organic matter (water hyacinth biochar: binder: organic matter). The findings revealed that WHB400 with the [6:4:0] ratio produced the most effective briquette, achieving the highest heating value of 15.3 MJ.kg^{-1} and an impressive compressive strength of 349 KPa compared to other formulations.

Mibulo et al. (2023) employed pineapple peels (PP), banana peels (BP), and water hyacinth (WH - *Eichhornia crassipes* (Mart.) Solms) to create both carbonized and uncarbonized briquettes. The physical properties and calorific values of these briquettes were assessed using thermogravimetric analysis and a bomb calorimeter. The study found that carbonized briquettes made from pineapple peels exhibited the highest calorific value at 25.08 MJ.kg^{-1}, followed by a mixture of banana and pineapple peels at 22.77 MJ.kg^{-1}. In contrast, carbonized briquettes made exclusively from water hyacinth had a lower calorific value of 16.22 MJ.kg^{-1}. However, when combined with banana or pineapple peels, the calorific values increased to 20.79 MJ.kg^{-1} and 20.55 MJ.kg^{-1}, respectively.

Oyelaran et al. (2018) investigated briquettes made from various biomass concentrations by blending coal with banana leaves and banana pseudostems in several weight ratios: (100:0, 90:10, 80:20, 70:30, and 60:40), all compressed at a pressure of 7 MPa. The results showed that the moisture content (MC), volatile matter (VM), and ash content (AC) of the composite briquettes ranged from 6.74% to 9.36%, 25.25% to 39.78%, and 6.25% to 8.75%, respectively. Furthermore, the carbon content, porosity index, calorific value, ignition time, combustion rate, and thermal efficiency varied from 54.16% to 76.32%, 23.42% to 44.48%, 31.62 to 31.43 MJ.kg^{-1}, 57.24 to 180.96 seconds, 0.035 to 0.083 g.min^{-1}, and 12.73% to 15.63%, respectively. The composite briquettes exhibited a higher calorific value and lower volatile matter than traditional biomass briquettes, making them a more favorable solid fuel alternative. However, the optimal biomass concentration for maximizing cooking efficiency was determined to be 35% banana waste.

Kimutai et al. (2021) examined the effect of pressure (9.81,19.6, 29.4 MPa), dwell time on cashew nut and cassava binder briquettes. Material variables of particle sizes 0.5, 1 mm and 2 mm, binder content (10, 20 and 30%) were also part of the investigation. The study confirmed that particle size had a greater influence on the density of the briquette, there after the compaction pressure and binder. The Structural Equation modelling (SEM) with the help of AMOS version 23 software was used to establish the interaction of the factors on the density of the briquettes.

Hence, it can be inferred that an increase in compaction pressure and binder content, along with reductions in particle size, led to lower burning rates and longer ignition times for the briquettes.

A few studies indicate that the combustion rate of water hyacinth briquettes is influenced by the interplay of several factors, including particle size, compaction pressure, and binder proportion. Research indicates that smaller particle sizes generally result in higher combustion rates due to the increased surface area, which facilitates better airflow and heat distribution. Compaction pressure also plays a crucial role in shaping the physical and combustion characteristics of water hyacinth briquettes. Typically, higher compaction pressures result in denser briquettes, which can lead to slower combustion rates due to reduced porosity and lower oxygen availability.

The effective use and optimization of agro-waste are central to the principles of a circular economy and waste management. However, no existing literature reported on the interactions between process parameters, specifically compaction pressure, and material behavior, such as cassava starch binder and particle size, on the burning rate and ignition time in Water Hyacinth briquetting.

The parameters and conditions of investigation significantly influence briquette properties, which in turn affect their handling and efficiency as a solid fuel. This highlights the need to optimize material resources for the utilization of waste biomass and improve its performance in heat, boiler, and energy generation.

This study carefully examined the performance and behaviour of a low particle size range of Water Hyacinth, a low range of binder content, and cassava starch as a binder, and their effect on the burning rate and ignition time of water hyacinth briquettes. This is toward enhancing product efficiency without compromising performance in heat and energy applications.

MATERIALS AND METHODS

This investigation focused on three specific process parameters: the particle size of dried and fragmented water hyacinth, which ranged from 0.5 to 1.5 mm; the compaction pressure applied, varying between 3.0 and 7.0 MPa; and the addition of cassava starch as a binder, making up 10-30% of the water hyacinth's weight. Multiple replicate samples were created for each experimental condition to ensure the reliability of the results. The primary response variables assessed were ignition time and combustion rate.

Sample Collection and Preparation

Blends of water hyacinth and molasses were prepared in varying compositions, followed by briquetting and densification using a hydraulic press. The combustion characteristics assessed for the produced briquettes included burning rate and ignition time.

Experimental

Preparation of blends comprising water hyacinth and cassava starch binder at varying compositions, which are then followed by briquetting and densification utilizing a hydraulic press apparatus. The combustion characteristics, which in this case are: burning rate and time, of the produced briquettes were assessed.

The water hyacinth-based charcoal composites were compressed in a hydraulic press. A predetermined mass of the composite mixture for each sample was placed into a steel mold measuring 41 mm by 50 mm and shaped into briquettes using the hydraulic press. The piston was operated at a speed of 30 mm.min^{-1} to compress the material. The applied compaction pressure ranged from 3.0 to 7.0 MPa, with a designated pressure maintained on the material in the die for 45 seconds before release. The resulting briquette was then extruded and appropriately labeled.

Measurement of Burning Rate and Ignition Time of Biomass Briquette

The burning rate refers to the speed at which a specific mass of fuel is consumed in the presence of atmospheric air. A tripod stand, a metallic container, and various solid supports were systematically arranged on a digital weighing scale, with the mass recorded.

A briquette sample of known weight was placed in the metallic container, and 15 mL of kerosene was added to aid in the ignition. The briquette was then ignited, and the mass of the apparatus was measured and recorded at 10-minute intervals throughout the combustion process using a stopwatch. The burning rate of the briquette was calculated using the formula provided by Arewa, Daniel, and Kuye (2016).

$$\text{BR} = \frac{W2-W1}{T} \quad \ldots(1)$$

Where:

BR=Burning rate, g.min^{-1}

W1: Initial briquette weight (g)

W2: Briquette weight after burning (g)

T: Total burning time

Ignition Time

The briquette specimens were subjected to ignition at the edge of their bases utilizing a Bunsen burner. The time required for each briquette to achieve ignition was meticulously documented as the ignition time employing a stopwatch in accordance with the equation outlined in (Kebede, Berhe & Zergaw 2022). The ignition time was computed utilizing the subsequent equation:

$$\text{Ignition time (IT)} = T_i - T_0 \quad \ldots(2)$$

where T_1 represents the ignition time of the briquette (sec), and T_0 denotes the time at which the burner was ignited (sec).

Experimental Design

This methodology is designed to statistically analyze the impact of each parameter and its interactions on the resulting responses of any design (Adesina et al. 2019). It helps reduce the number of trials, repetitions, experimental procedures, labor complexities, and costs involved in the design and manufacturing processes (Mehat et al. 2011, Lee et al. 2011). The response surface methodology (RSM) utilized in experimental design consists of a set of mathematical and statistical techniques that structure experiments. It assists in establishing a clear functional relationship between a target response (output) and multiple relevant input variables (Khuri & Mukhopadhyay 2010). This framework optimizes the influence of process variables.

The optimization process using RSM requires identifying significant independent variables and selecting an appropriate experimental design, such as a central composite design or a three-level factorial design. The experimental protocol is organized according to the generated design table, and the data collected during experimentation are fitted into a polynomial function. Model fitness is assessed, verified, and optimal values are extracted (Bezerra et al. 2008).

The central composite design (CCD) within the response surface methodology (RSM) was employed to determine the levels of various factors and their interactions regarding the combustion properties of the developed briquette. This approach offers valuable insights into the effects of variables and the overall experimental error, even with a limited number of experiments. Utilizing a CCD model provides important information on direct effects, pairwise interactions, and curvilinear effects of the variables. In this design, central points are complemented by a set of axial points known as star points, enabling the rapid estimation of both first-order and second-order terms. The F-test, along with the Analysis of Variance (ANOVA), is used to analyze the influence of each process parameter and its interactions.

In this investigation, the Design Expert 13.0 software is used to analyze the impact of process parameters, including particle size, compression pressure, and binder proportion, on the ignition time and burning rate of water hyacinth biomass briquettes. The design of experiments methodology consists of twenty (20) experimental trials, referred to as runs, which contain some identical data, which are centre points. This implies that in the run, factors are set to their mid-levels. For example, in the particle size range, the high level is 1.50, and the low level is 0.50; the center point is 1.00. Also, compaction pressure, the high level is 7 and the low level is 3; the center point is 5. The binding proportion, the highest level is 30, and the lowest point is 10; the center point is 20. In model validation**,** they indicate if there is a need for a more complex model. In ANOVA**,** it supplies pure error for the lack-of-fit test and quantifies curvature.

RESULTS AND ANALYSIS

RSM of Combustion Properties

The various factors and their interactions affecting the combustion properties of water hyacinth briquettes were

Table 1: Process parameters and actual response for Ignition time and burning rate.

Std	Run	Factor 1: A: Particle Size [mm]	Factor 2: B: Compaction Pressure [MPa]	Factor 3: Binding Proportion %	Response 1 Ignition time [secs]	Response 2 Burning rate [g.min^{-1}]
8	1	1.50	7.00	30.00	95.00	1.52
20	2	1.00	5.00	20.00	74.64	1.85
1	3	0.50	3.00	10.00	79.50	2.30
9	4	0.56	5.00	20.00	71.26	1.75
17	5	1.00	5.00	20.00	74.64	1.85
14	6	1.00	5.00	30.00	101.20	1.28
7	7	0.50	7.00	30.00	98.70	1.40
4	8	1.50	7.00	10.00	66.50	2.15
11	9	1.00	3.64	20.00	62.00	2.40
3	10	0.50	7.00	10.00	85.20	2.07
19	11	1.00	5.00	20.00	74.64	1.85
12	12	1.00	5.00	20.00	74.64	1.85
18	13	1.00	5.00	20.00	74.64	1.85
10	14	1.50	5.00	20.00	73.26	1.82
13	15	1.00	5.00	10.00	63.00	2.60
5	16	0.50	3.00	30.00	90.20	1.61
2	17	1.50	3.00	10.00	62.00	2.15
15	18	1.00	5.00	20.00	74.64	1.85
6	19	1.50	3.00	30.00	88.50	1.65
16	20	1.00	5.00	20.00	74.64	1.85

assessed using Central Composite Design (CCD) within the framework of Response Surface Methodology (RSM). The analysis of variance (ANOVA) produced a model that correlates ignition time and burning rate with the independent process variables: particle size, compaction pressure, and binder proportion. Regression analysis clarified the relationship between these variables and the combustion characteristics of the briquettes. The adequacy and predictive capacity of the model can be evaluated through the significance of the regression model, the coefficients for each variable, and the lack-of-fit test. The results of the tests are delineated in Table 1.

Statistical Analysis of Ignition Time of WHB Briquettes

The Analysis of Variance (ANOVA) related to the Response Surface Methodology (RSM) for ignition time is detailed in Tables 2 and 3. The model demonstrates an F-value of 13.47, indicating statistical significance. The probability of this F-value occurring due to random noise is only 0.02%. A model is considered significant when the associated coefficient yields a probability greater than F of less than 0.05, especially when accompanied by a very small P-value. The terms A, B, C, AC, and C^2 are identified as significant contributors to the ignition time property of the water hyacinth briquette. Terms are deemed insignificant if their values exceed 0.100.

Additional parameters assessing the model's effectiveness include the coefficient of determination (R^2), coefficient of variation (CV), adjusted R^2, and predicted R^2. The R^2 value of 0.9238 is close to unity, indicating that the model effectively captures the optimal data, suggesting that approximately 92.4% of the total variance in ignition time can be attributed to the experimental variables. The model addresses nearly all forms of dispersion. An adjusted R^2 of 0.8552 indicates a robust model, suggesting that no additional terms are needed. The model's standard deviation is 4.44, and the proximity of R^2 to 1 indicates a strong model fit, with predicted values aligning closely with actual values.

The predicted R^2 of 0.6887 and adjusted R^2 of 0.8552 differ by less than 0.2, reflecting reasonable agreement between the values. Adequate precision, defined as the signal-to-noise ratio, should exceed 4; this model achieved a precision value of 12.824, indicating a sufficient signal to

ANOVA results for the response of ignition time of WHB briquettes.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2388.05	9	265.34	13.47	0.0002	significant
A-Particle Size	180.89	1	180.89	9.18	0.0127	
B-Compaction pressure	130.33	1	130.33	6.62	0.0278	
C-Binding Proportion	1074.97	1	1074.97	54.58	< 0.0001	
AB	1.28	1	1.28	0.0650	0.8039	
AC	118.58	1	118.58	6.02	0.0340	
BC	2.88	1	2.88	0.1462	0.7102	
A^2	47.32	1	47.32	2.40	0.1522	
B^2	29.77	1	29.77	1.51	0.2470	
C^2	121.00	1	121.00	6.14	0.0326	
Residual	196.96	10	19.70			
Lack of Fit	196.96	4	49.24			
Pure Error	0.0000	6	0.0000			
Cor Total	2585.01	19				

Table 3: Parameters obtained from ANOVA for Ignition time.

Std. Dev	4.44	Mean	77.94
C.V%	5.69	R^2	0.9238
Adeq. Precision	12.8244	Adjusted R^2	0.8552
		Predicted R^2	0.6887

guide the experimental space. Furthermore, the study found a lack of fit within an insignificant range relative to pure error, further supporting the suitability of the model with the experimental data.

$$\text{Ignition time} = +72.44 - 4.33A + 3.94B + 10.25C - 0.400AB + 3.85AC + 0.600BC + 2.71A^2 + 3.32B^2 + 4.19C^2 \quad \ldots(3)$$

Residuals Plot

Residuals represent the difference between the observed and predicted responses in a dataset. The deviation of the actual values from the predicted values is illustrated by the normal probability plot of the residuals. The model's adequacy is assessed by examining the data used, which is confirmed when the points on the normal probability plot display a linear arrangement. As shown in Fig. 1, random errors were identified, and the residuals exhibited a normal distribution, aligning closely with a straight line. The closeness of the residuals to the diagonal line indicates their minimal deviation. An unusual pattern in the plot of residuals against predicted values suggests a model deficiency. Fig. 1 also presents graphical representations of the residuals alongside the interaction between actual and predicted ignition times. The coefficients of determination, R^2 (0.92384) and adjusted R^2 (0.8552), along with the residual analysis, indicate that the model fits the experimental data well. The response plot in Fig. 2a illustrates the impact of particle size and compaction pressure on ignition time. The strong correlation between actual and predicted ignition values is further supported by Table 6 and Fig. 2b.

Statistical Analysis for the Burning Rate of Water Hyacinth Briquette

The Analysis of Variance (ANOVA) for the combustion rate, related to the Response Surface Methodology (RSM), is detailed in Tables 4 and 5. This analysis indicates that a model with an F-value of 9.04 is statistically significant. The probability of this F-value occurring due to random fluctuations is measured at 0.05%. A model is considered more significant when it has an associated coefficient with a probability greater than F that is less than 0.05, especially when accompanied by a very low P-value. Notably, Case C is identified as a statistically significant term in the model. Terms are classified as insignificant if their values exceed 0.100.

The ANOVA results show that the binding proportion (Factor C) has a significant impact on the combustion rate, supported by a confidence level of 95% and a low P-value (<0.05). Other terms do not significantly affect the output model, as their P-values exceed 0.05. The coefficient of determination, R^2, which indicates the reduction in response variability, is 0.8066, suggesting that 80.6% of

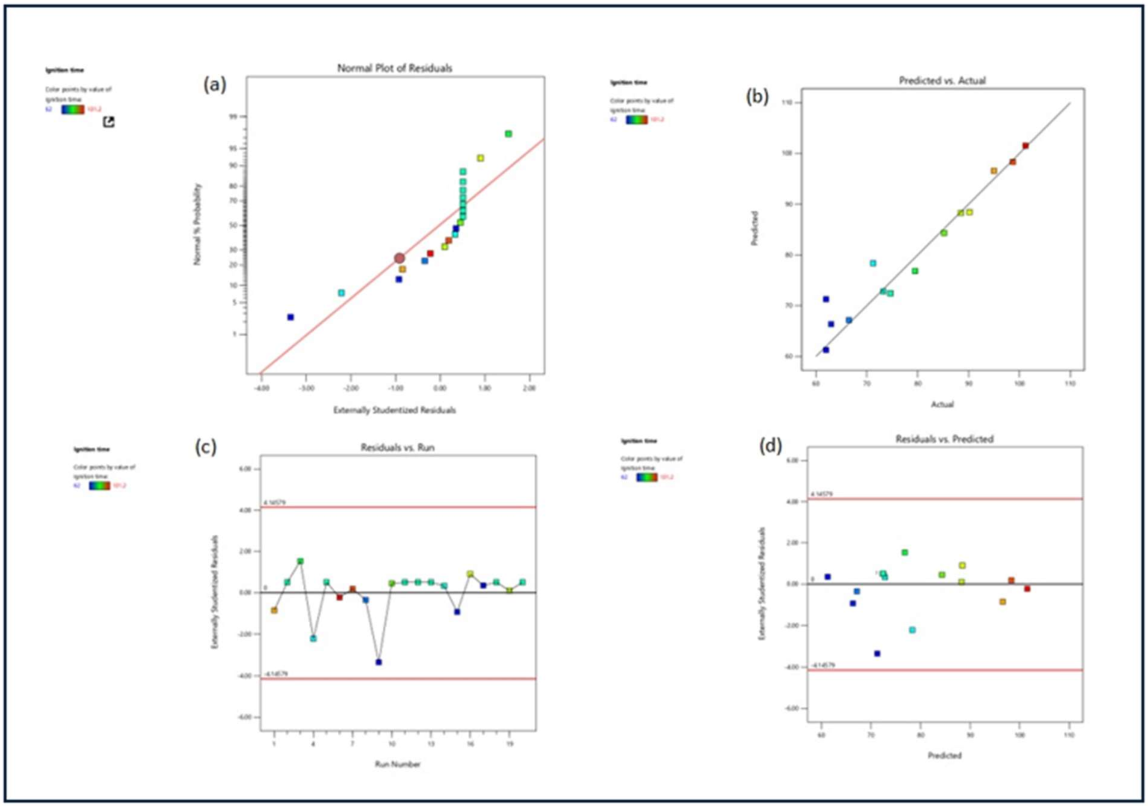

Fig. 1: Ignition time of Water hyacinth briquette as a (a) probability plot of residuals, (b) predicted versus actual values, (c) residual run, (d) residual versus predicted.

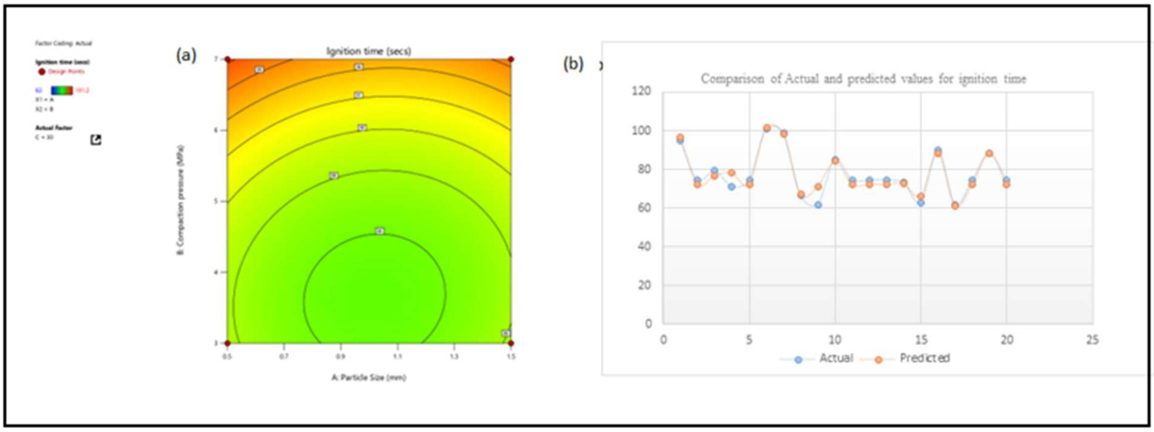

Fig. 2 (a): Contour plot of ignition time with respect to compression pressure and particle size. (b) The plot of the actual value against the predicted ignition values.

the total variance in density measurement is explained by the experimental variables. The model effectively addresses dispersion to a significant extent. A model is deemed to fit the data well when its R² value approaches unity. The adjusted R² is reported at 0.7174, indicating reasonably good model quality, with a standard deviation of 1.733 × 10^{-1}.

An ideal model should have an insignificant standard deviation and an R² value close to 1. The difference between the predicted R² value (0.7174) and the adjusted R² (0.5300) is within the acceptable range of less than 0.2, indicating satisfactory agreement within the model. An adequate precision value should exceed 4; in this case, a precision

Table 4: ANOVA results for the response 2FI model of burning rate of water hyacinth briquette (WHB).

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.63	6	0.2715	9.04	0.0005	significant
A-Particle Size	0.0008	1	0.0008	0.0259	0.8746	
B-Compaction pressure	0.0991	1	0.0991	3.30	0.0924	
C-Binding Proportion	1.51	1	1.51	50.17	< 0.0001	
AB	0.0120	1	0.0120	0.3999	0.5381	
AC	0.0066	1	0.0066	0.2201	0.6467	
BC	0.0015	1	0.0015	0.0504	0.8259	
Residual	0.3905	13	0.0300			
Lack of Fit	0.3905	7	0.0558			
Pure Error	0.0000	6	0.0000			
Cor Total	2.02	19				

Table 5: Parameters obtained from ANOVA for burning rate.

Std. Dev.	0.1733	R²	0.8066
Mean	1.88	Adjusted R²	0.7174
C.V. %	9.21	Predicted R²	0.5300
		Adeq Precision	10.8462

value of 10.846 has been achieved, confirming a sufficient signal to effectively navigate the design space.

The 2FI model prediction of the burning rate property of Water hyacinth briquette with respect to particle size, compaction pressure, and binder proportion is as shown, thus, Equation 4:

$$\text{Burning rate}=+189+0.0082A-0.1084B-0.3573C+0.0388AB+0.0288AC-0.0137BC \qquad \ldots(4)$$

Residuals Plot

Fig. 3a displays the normal distributions of residuals along with the interaction between actual and predicted combustion rates. The model's adequacy was evaluated through a thorough analysis of the dataset used to derive

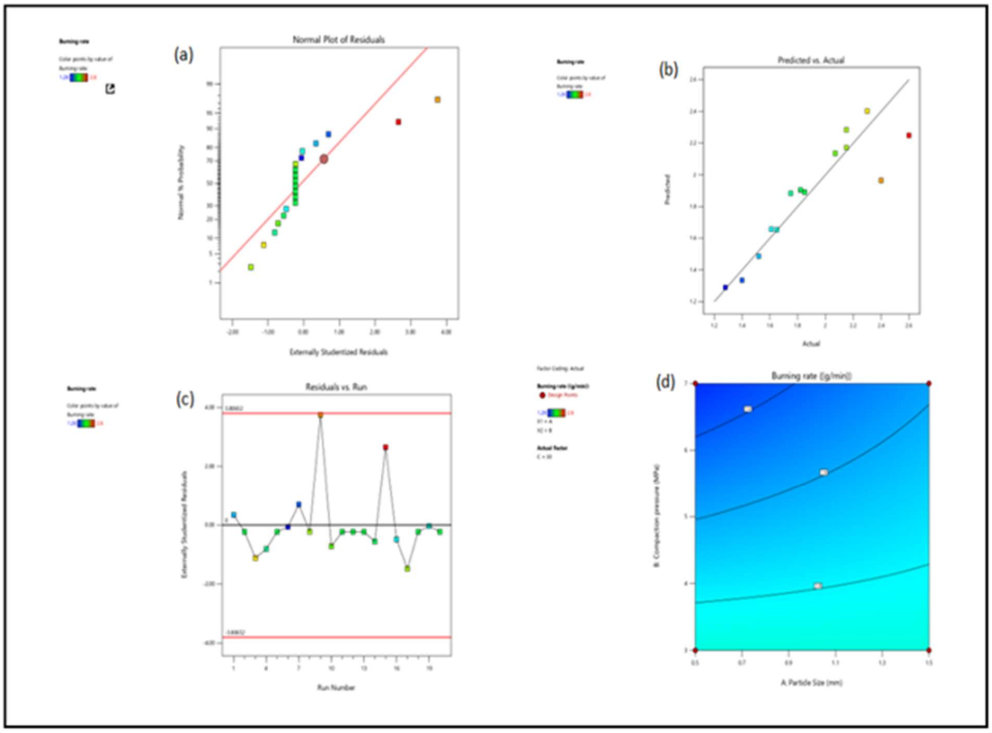

Fig. 3: Burning rate of water hyacinth briquette as a (a) normal plot of residuals, (b) predicted against actual, (c) residual run, (d) residual versus predicted.

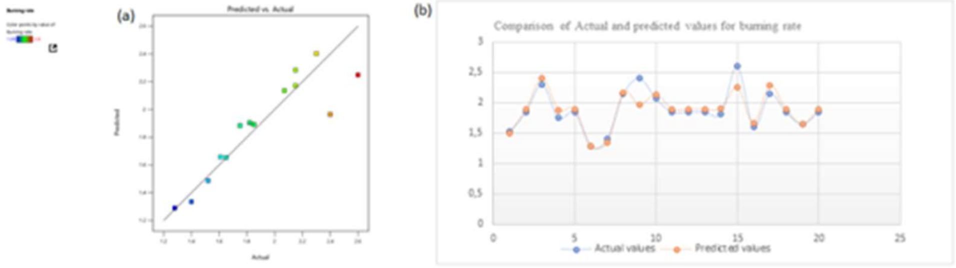

Fig. 4: Burning rate of water hyacinth Briquette as (a) predicted and (b) actual comparison plot of actual and predicted.

Table 6: The value of actual against predicted value of burning rate and ignition time.

Run	Actual Value (Burning rate)	Predicted Value (Burning rate)	Actual Value (Ignition time)	Predicted Value (Ignition time)
1	1.52	1.49	95.00	96.58
2	1.85	1.89	74.64	72.44
3	2.30	2.40	79.50	76.84
4	1.75	1.88	71.26	78.37
5	1.85	1.89	74.64	72.44
6	1.28	1.29	101.20	101.53
7	1.40	1.34	98.70	98.33
8	2.15	2.17	66.50	67.17
9	2.40	1.96	62.00	71.30
10	2.07	2.14	85.20	84.33
11	1.85	1.89	74.64	72.44
12	1.85	1.89	74.64	72.44
13	1.85	1.89	74.64	72.44
14	1.82	1.90	73.26	72.83
15	2.60	2.25	63.00	66.38
16	1.61	1.66	90.20	88.45
17	2.15	2.28	62.00	61.29
18	1.85	1.89	74.64	72.44
19	1.65	1.65	88.50	88.29
20	1.85	1.89	74.64	72.44

these combustion rates. The closeness of the residuals to the diagonal line in the response prediction suggests that the model is robust, although some randomness remains within the error term, accurately reflecting the combustion rate characteristics. An R^2 value of 0.8066 and an adjusted R^2 of 0.7174, along with the residual analysis, indicate that the model fits the experimental data well. The effects of particle size and compaction pressure on the combustion rate are illustrated in the response plots shown in Fig. 3 (a-e). The strong correlation between actual and predicted combustion rates is evident in Fig.s 4a and 4b, as well as in Table 6.

Optimization of Ignition Time and Burning Rate Properties of WHB Briquette

The optimal combination of variables/parameters was carried out via the response surface methodology‘s desirability function of the Design Expert 13. The software gives a desirability within 0 and 1 in the model prediction, with an ideal scenario expecting a value of one. The constraints

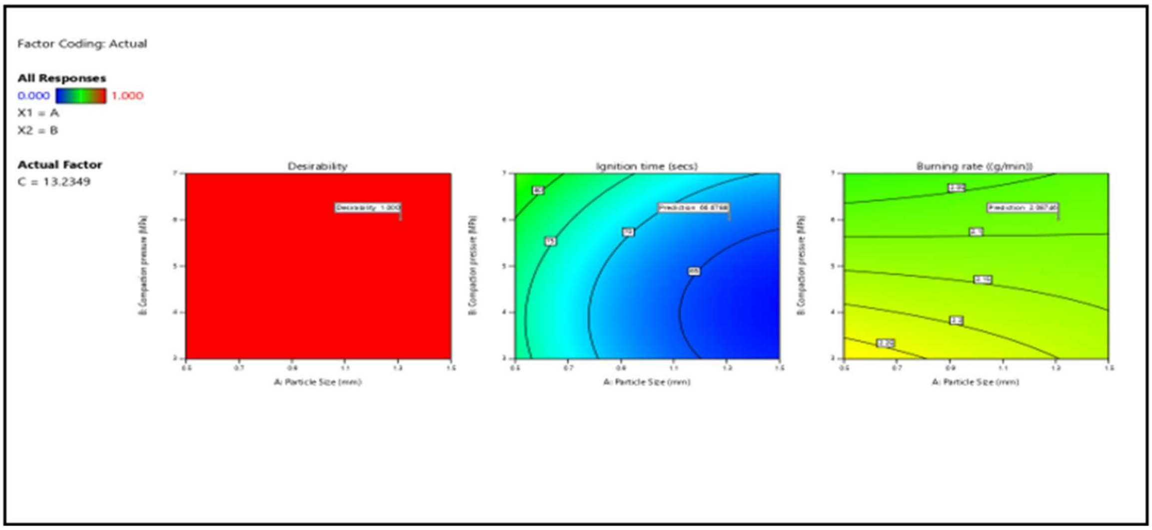

Fig 5: Graphical representation for optimization.

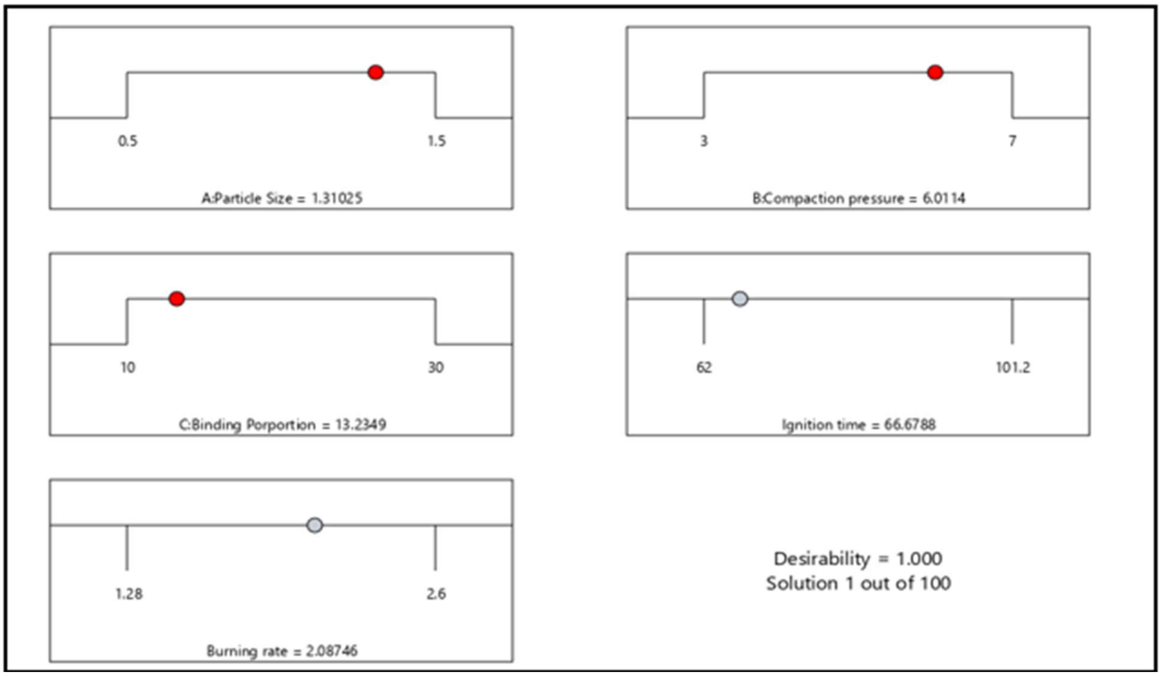

Fig. 6: Solution obtained for optimized process parameter of water hyacinth Briquette with the desirability of 1**.**

selected for this study were to be within a specific parameter range. This is to obtain a maximum response that simultaneously satisfies all the variable properties. The desirability of 1 is achieved when the optimization algorithm identifies factor levels that fully meet the model's prediction criteria. This could have occurred as a result of a high model fit when R^2 is near 1. However, this result is a model-based prediction and not a definitive real-world optimum. Through this analytical framework, a single optimal solution with a desirability value of one was derived from a set of 100 during the optimization of the water hyacinth briquette. The obtained solutions are presented in Figs. 5 and 6. The selected optimal combination includes a particle size of 0.763042 mm, a compaction pressure of 3.08724 MPa, a binding proportion of 13.4529%, an ignition time of 70.8386 seconds, and a burning rate of 2.24221 $g.min^{-1}$.

CONCLUSIONS

The valorization of invasive water hyacinth biomass into valuable bioenergy is a commendable research initiative aimed at promoting sustainable energy production, in line with Sustainable Development Goal (SDG) 7. This transformation can provide affordable and safe energy while increasing the share of renewable sources in the global energy mix. Understanding the factors that influence the combustion efficiency of these biomass-derived briquettes is essential for their optimal use as biofuels. This study examined the effects of processing parameters—specifically particle size, compression pressure, and binder ratio—on the ignition time and combustion rate of water hyacinth briquettes to determine optimal performance. The results indicated that the combustion rate decreased with an increase in binder ratio, while ignition time increased. The analysis revealed statistically significant variations in the effects of particle size, binder ratio, and pressure on both combustion rate and ignition time at the 5% probability threshold. The optimal parameters identified through response surface optimization were a particle size of 0.763042 mm, a compaction pressure of 3.08724 MPa, and a binder ratio of 13.4529%, resulting in an ignition time of 70.8386 seconds and a combustion rate of 2.24221 g.min^{-1}. The minimal difference between actual and predicted values supports the reliability of the model used. The optimization process is vital for identifying the most effective combination of processing parameters, and the statistical adequacy of the model is confirmed through the validation of the developed framework.

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