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An Evaluation of Process Factors Affecting Water Hyacinth Based Bio Briquettes Production

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ABSTRACT: Water hyacinth (*Eichhornia crassipes*) is a highly invasive aquatic weed that degrades freshwater ecosystems and creates severe socioeconomic burdens. This study addresses the dual challenge of invasive weed management and lack of affordable clean cooking fuel by converting water hyacinth biomass into high-quality bio-briquettes as a sustainable alternative to firewood and charcoal. The knowledge gap addressed is the lack of systematic, multi-factor optimization for water hyacinth briquetting under Southern African conditions, as well as the limited quantification of environmental benefits. Fresh water hyacinth was collected from Lake Chivero, Zimbabwe, characterized, and processed using a manual compression method. Sixteen process factors, including particle size, compression pressure, and moisture content, were systematically investigated. Raw water hyacinth exhibited 88.5% moisture, 65.2% volatile matter, 12.8% ash, 15.6% fixed carbon, and 14.2 MJ/kg calorific value. Water hyacinth-based briquettes were produced using 2–5 mm particles, 12–15% moisture, 10% maize starch binder, and 7 MPa compaction pressure, achieving 16.8 MJ/kg calorific value, 850 kg/m^3 density, and 94.5% durability. Carbonized briquettes reached a calorific value of 24.5 MJ/kg. Environmental assessment showed harvesting removed 2.5 kg nitrogen and 0.5 kg phosphorous per ton of fresh biomass, increased dissolved oxygen from 3.2 to 5.8 mg/L, and avoided 0.12 kg CH_4 per kg dry biomass. The briquettes were 70% cheaper than charcoal and produced 45% less carbon monoxide and 67% less particulate matter than firewood. This study demonstrates that water hyacinth bio-briquettes offer a viable, low-cost, and environmentally beneficial solid fuel for rural communities while simultaneously addressing invasive weed management.

Keywords: Ash content; Binder type; Calorific value; Moisture content; Particle size; Water hyacinth

1. Introduction

Water hyacinth is a highly invasive aquatic weed that causes severe damage to freshwater bodies by blocking sunlight, reducing dissolved oxygen (DO) by up to 40%, and killing aquatic life [1]. Converting this biomass into bio briquettes provided a sustainable waste-to-energy solution. The quality of the briquettes

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depended on several process factors, including moisture content, which was optimal at 8 to 15%, particle size between 0.5–5 mm, binder concentration up to 10%, compaction pressure up to 9 megapascals, and temperature [2]. Fresh water hyacinth contained 88–92% moisture, 65–70% volatile matter, 10–18% ash, and 13–18% fixed carbon [3]. The calorific value of the final briquettes ranged from 14–25 Megajoules per kilogram [4]. The physical properties of raw water hyacinth, such as its high moisture content and low bulk density, complicate its management as a weed [5]. The formation of dense floating mats by the weed heavily impacts water quality [6]. The role of binder composition in stabilizing these materials during processing has been investigated [7]. Comprehensive reviews have summarized the potential of this feedstock [8] and the technologies used for its briquetting [9]. Innovative binders, such as algal biomass, have been explored as alternatives [10]. Characterization of water hyacinth blends with agricultural residues has shown promising results [11]. The potential of these briquettes to combat algal blooming in lakes has been highlighted [12]. Historical attempts at managing the weed through bioethanol and briquette production were reviewed [13].

1.1. Impact of Water Hyacinth on Water Bodies

Water hyacinth is an invasive aquatic weed that causes serious damage to freshwater bodies across the world [1]. The plant grows rapidly and forms dense floating mats on the water surface. These mats blocked sunlight from reaching underwater plants and reduced the exchange of oxygen between air and water. As a result, DO levels dropped significantly, often by as much as 40%, creating hypoxic conditions that killed fish and other aquatic organisms. When the plants died and decayed, they released nutrients that worsened eutrophication and further degraded water quality. In Zimbabwe, two examples illustrated this problem clearly. At one major reservoir that supplied drinking water to a large city, water hyacinth infestation threatened the municipal water supply because the weed clogged water intake pipes and increased water treatment costs [14]. In another large lake used for hydroelectric power generation, the weed formed thick mats along the shoreline and around power station inlets, reducing water flow to the turbines and increasing the risk of mechanical damage. Fishermen operating on that lake reported that the weed damaged their nets, reduced fish catches and increased fuel consumption as they navigated around the floating mats [14].

Elsewhere in Africa, similar impacts were observed. In a large lake shared by several East African countries, water hyacinth covered thousands of hectares at the peak of its infestation. The weed blocked fishing routes, reduced access to landing sites, and contributed to the decline of native fish species by depleting oxygen and altering breeding habitats. In a lake in the Ethiopian highlands, manual removal of water hyacinth produced enormous quantities of wet biomass with no safe disposal method [15]. The removed plants were often left to rot on the lakeshore, where they released greenhouse gases and re-introduced nutrients back into the water. The link between water hyacinth infestation and reduced water quality has been well-documented [16]. These four examples demonstrated that water hyacinth was not only an ecological threat but also a major socioeconomic burden across the continent [1].

1.2. Process Factors Affecting Bio Briquettes Production

Several process factors affect the quality of bio-briquettes produced from water hyacinth. These include feedstock type, which determines calorific value and availability, particle size, which affects durability and density, moisture content, which influences compaction and combustion, volatile matter, which governs ignition and flame duration, ash content, which affects residue and combustion efficiency, fixed carbon, which determines burning duration, calorific value, which indicates energy content, temperature, residence time and heating rate during carbonization, which affect char quality and cracking, compaction pressure, which influences density and strength, reactor type, which affects carbonization uniformity; carbonization type, which determines energy density versus mechanical strength, drying rate, which affects fiber integrity and fines generation, binder type and concentration, which affect durability and ash content and briquette

shape, which influences handling and storage [8]. Each of these factors was investigated in the present study, and the detailed experimental findings are presented and discussed in Section 4.3. Recent progress in biomass densification has also highlighted the importance of binder-free compaction, hybrid mixing ratios and the circular economy approach to aquatic weed management [17–21]. The specific impact of different binder types on the structural integrity of carbonized briquettes was investigated [22]. Torrefaction techniques, particularly using banana waste pulps, have been developed to enhance the energy density of biomass [23]. Furthermore, the design of specialized screw-press machines for water hyacinth briquetting has been documented [24]. Response surface methodology has been widely applied to optimize mixing ratios [25]. Previous studies report considerable variation in optimal conditions for water hyacinth briquetting. For particle size, Ref. [2] recommended 0.5–2 mm, while Refs. [26–31] found 2–5 mm superior, achieving 15% higher durability. For moisture content, Ref. [3] recommended 10–15%, while Ref. [4] reported that moisture above 18% caused spring-back and reduced density. For binder concentration, starch binders are typically used at 5–10% [3], but clay binders require up to 15% and increase ash content to above 22% [4]. For compaction pressure, most studies report optimal values between 5–10 MPa [17,32], although higher pressures can cause spring-back and reduce density [33]. These inconsistencies reflect differences in feedstock composition, equipment, and target applications, making it difficult to identify global optima. Most previous studies also investigated only two to four factors in isolation, and few have quantified environmental benefits under Southern African conditions. This study addresses these gaps by systematically investigating all sixteen process factors, using locally available maize starch as a binder and providing primary environmental data relevant to Zimbabwe and the region.

2. Study Objectives

The overarching aim of this study was to evaluate the technical feasibility and sustainability of producing bio-briquettes from invasive water hyacinth as a low-cost, environmentally beneficial solid fuel for rural communities in Southern Africa. The specific objectives were to characterize the physicochemical properties of raw water hyacinth from Lake Chivero, Zimbabwe, investigate the effect of sixteen process factors on briquette quality, identify optimal conditions meeting standards for durability (>90%), density (>800 kg/m^3), moisture (<15%), ash (<15%) and calorific value (>16 MJ/kg), quantify environmental benefits including nutrient removal, greenhouse gas reduction and air quality improvement, assess social and economic implications, and provide a low-cost protocol for community adoption (Table 1). Evaluating these process factors is essential because it identifies the conditions that maximize briquette durability, density and calorific value, while minimizing ash content and production cost. This directly determines whether water hyacinth briquettes can serve as a viable, low-cost fuel alternative for rural households. The intended beneficiaries are rural and peri-urban communities near Lake Chivero and other infested water bodies in Southern Africa. However, this study was laboratory-based and not field-tested within a specific community; the protocol is designed for future pilot-scale adoption.

Table 1. Study Objectives and Quantitative Targets.

Objective	Target/Range
Investigate process factors affecting bio briquette production	16 factors feedstock type, particle size, moisture content, volatile matter, ash content, fixed carbon, calorific value, temperature, residence time, heating rate, pressure, reactor type, carbonization type, drying rate, binder type, briquette shape
Characterize raw water hyacinth	Moisture 88–92%, volatile matter 65–70%, ash 10–18%, fixed carbon 13–18%
Produce and evaluate briquette quality	Durability >90%, density >800 kg/m^3, moisture <15%, ash <15%
Achieving optimal calorific value	>16 MJ/kg (uncarbonized); >24 MJ/kg (carbonized)
Assess environmental and safety impact	Nutrient removal (N, P), reduced GHG emissions, improved water quality
Assess social and economic impact	Reduced fuel costs, improved indoor air quality, income generation

3. Materials and Methods

This section describes all the materials used in the study and the experimental procedures followed. The methods were designed to characterize raw water hyacinth, produce bio briquettes under different process conditions, and evaluate the quality of the final briquettes. All experiments were performed in triplicate to ensure reproducibility, and the average values were reported with their standard deviations. The experimental framework aligns with recent characterization studies on water hyacinth blends and torrefaction processes [26–29].

3.1. Materials

Fresh water hyacinth plants were collected from Lake Chivero, a eutrophic freshwater reservoir located approximately 35 km southwest of Harare, Zimbabwe (coordinates: 17°54′ S, 30°48′ E; elevation: 1362 m above sea level). Lake Chivero is an artificial reservoir constructed in 1952 on the Manyame River, primarily serving as a source of drinking water for Harare and supporting commercial fishing and recreational activities. The lake has a surface area of approximately 26 km^2 and a maximum depth of 8 m. The catchment area is characterized by Miombo woodland vegetation and intensive agricultural and urban land use, which contributes to high nutrient loading and eutrophication. Water hyacinth infestation has been documented in the lake since the 1980s, with seasonal coverage varying between 10–40% of the lake surface.

Sampling was conducted in March 2024 during the late wet season when water hyacinth coverage was at its peak. Plants were harvested manually by hand-pulling from three distinct locations along the shoreline (northern, eastern, and southern banks) to ensure representative sampling. At each location, whole plants with intact leaves, stems, and roots were collected. The harvested biomass was transported to the laboratory in woven plastic sacks to allow drainage of excess water. A total of 50 kg of wet water hyacinth was collected for this study. Other materials used included maize starch as a binder, clean tap water for binder preparation, and compressed air for drying. The maize starch was purchased from a local market. Equipment used included an electronic weighing balance with a precision of 0.01 g, a laboratory drying oven, a muffle furnace, a manual hydraulic press, a set of standard sieves with mesh sizes of 0.5, 1, 2, 5, 10 and 15 mm, a bomb calorimeter, a hammer mill, and a cylindrical briquette mold made of mild steel with an internal diameter of 50 mm [5].

3.2. Methods

The experimental work was carried out in a sequence of four main stages [2]. First, the raw water hyacinth was characterized by its physical and chemical properties. Second, the biomass was prepared by washing, drying, grinding, and sieving to obtain the desired particle sizes. Third, bio briquettes were produced using a manual hydraulic press under varying process conditions. Fourth, the final briquettes were characterized for density, durability, moisture content, ash content, volatile matter, fixed carbon and calorific value. Recent progress in utilizing water hyacinth as an effective biomass material has underscored the need for standardized processing protocols [30]. Each stage was described in detail below.

3.2.1. Characterization of Water Hyacinth

The freshwater hyacinth was first washed thoroughly with clean water to remove mud, aquatic insects, and other debris. The cleaned biomass was then drained for thirty minutes to remove surface water. The moisture content of the fresh sample was determined by weighing a 100 g sample of chopped water hyacinth and drying it in an oven at 105 °C for 24 h. The sample was reweighed, and the moisture content was calculated as the %age of mass lost relative to the initial wet mass. This procedure was repeated three times, and the average moisture content was recorded. The dried water hyacinth was then ground using a hammer mill. The ground material was sieved through a set of sieves to obtain different particle size fractions. The

fractions collected were below 0.5 mm, between 0.5 and 2 mm, between 2 and 5 mm, between 5 and 10 mm, and above 10 mm. Each fraction was weighed and stored separately in sealed plastic bags.

Volatile matter content was determined by placing a 2 g sample of the dried ground water hyacinth in a covered crucible and heating it in a muffle furnace at 950 °C for exactly 7 min. The crucible was cooled in a desiccator and reweighed. The mass loss was recorded as volatile matter. Ash content was determined by placing another 2 g sample in an open crucible and heating it in a muffle furnace at 550 °C for 3 h until constant mass was achieved. The remaining white or grey residue was weighed and recorded as ash. Fixed carbon was calculated by subtracting the %ages of moisture, volatile matter, and ash from 100%. The calorific value of the dried water hyacinth was determined using a bomb calorimeter. Approximately 1 g of the ground sample was placed in the bomb calorimeter with a known amount of distilled water. The sample was ignited under an oxygen atmosphere at 25 atmospheres of pressure. The temperature rise of the water was recorded, and the calorific value was calculated in MJ/kg. Three replicate measurements were performed, and the average value was reported. To improve fuel characteristics, torrefaction of the raw feedstock is often applied as a pre-treatment [31]. The production of binder-free water hyacinth briquettes through low-pressure compaction has also been optimized to reduce processing costs [17].

3.2.2. Characterization of Bio Briquettes

The production of bio briquettes followed a systematic procedure as shown in Figure 1. A starch binder solution was prepared by mixing maize starch with water at a ratio of 1 part starch to 9 parts waters by mass. The mixture was heated gently with continuous stirring until it formed a clear, thick paste. The paste was then allowed to cool to room temperature. For each briquette batch, a measured amount of ground water hyacinth was mixed with a specified %age of starch binder solution. The binder %ages tested were 5, 10, 15, and 20% by mass of the dry biomass [3]. The mixture was thoroughly hand mixed for five minutes until a uniform consistency was achieved. The moisture content of the mixture was adjusted by adding small amounts of water or by additional drying to achieve target moisture levels of 5, 8, 12, 15, 20 and 25%. A handheld moisture meter was used to verify the moisture content. Hybrid briquettes combining water hyacinth with oil palm fronds have been analyzed using durian seed flour as an adhesive [32]. Additionally, hybrid combinations with sawdust have been investigated to analyze binder optimization and emission profiles [18]. The mixture was then fed into the cylindrical mold. The mold was placed on a manual hydraulic press. Compaction pressures of 3, 5, 7, 9, and 11 MPa were applied sequentially in different batches [33]. The pressure was held for 30 s before release. After ejection from the mold, the green briquettes were placed on wire mesh trays and dried in an oven at 60 °C for 24 h or under direct sunlight for three to five days, depending on the drying rate experiment. The dried briquettes were allowed to cool and then stored in airtight containers.

For experiments involving carbonization, the ground water hyacinth or the green briquettes were placed in a vertical retort reactor or a drum kiln. Carbonization was carried out at temperatures of 200, 250, 300, 350, 400, 450 and 500 °C. The heating rate was controlled at 5, 10, 15 or 25 °C per minute. The residence time at the final temperature was varied at 15, 30, 45, 60 and 90 min [4]. After carbonization, the material was cooled in the reactor under a nitrogen atmosphere to prevent combustion.

The final briquettes were characterized by the following properties. Density was calculated by dividing the mass of each briquette by its volume. The volume was measured using a Vernier caliper to obtain the diameter and height of the cylindrical briquettes as indicated in Equation (1).

$$\rho = m/(\pi r^2 h) \quad (1)$$

where m is the mass, r the radius, and h the height of the cylindrical briquette. The durability index was determined by placing ten briquettes in a rotating drum with a baffle. The drum rotated at 50 revolutions per minute for 10 min [27]. The briquettes were then removed and weighed. The mass of briquettes retained

after tumbling was expressed as a %age of the initial mass. A durability index above 90% was considered acceptable. The moisture content of the final briquettes was determined using the same oven drying method described in Section 3.2.1. Ash content, volatile matter, fixed carbon, and calorific value were also determined using the same procedures as for the raw water hyacinth [2]. The effect of each process factor was analyzed by comparing measured properties across different levels of that factor while holding all other factors constant at their baseline values. The baseline values used were a particle size of 2 to 5 mm, a moisture content of 12%, a starch binder of 10%, a compaction pressure of 7 MPa, no carbonization, and sun drying. Binder-free water hyacinth briquettes for domestic energy have also been evaluated for their technical feasibility [27]. Torrefaction has been further explored to enhance bioenergy applications [31]. DO was monitored at three shoreline stations (northern, eastern and southern banks) of Lake Chivero at three depths (surface, 1 m and 2 m) using a portable DO meter. Measurements were taken weekly for two months before harvesting and two months after harvesting began (n = 54 per period). Fish communities were not systematically sampled in this study, therefore, no claims regarding fish population recovery are made.

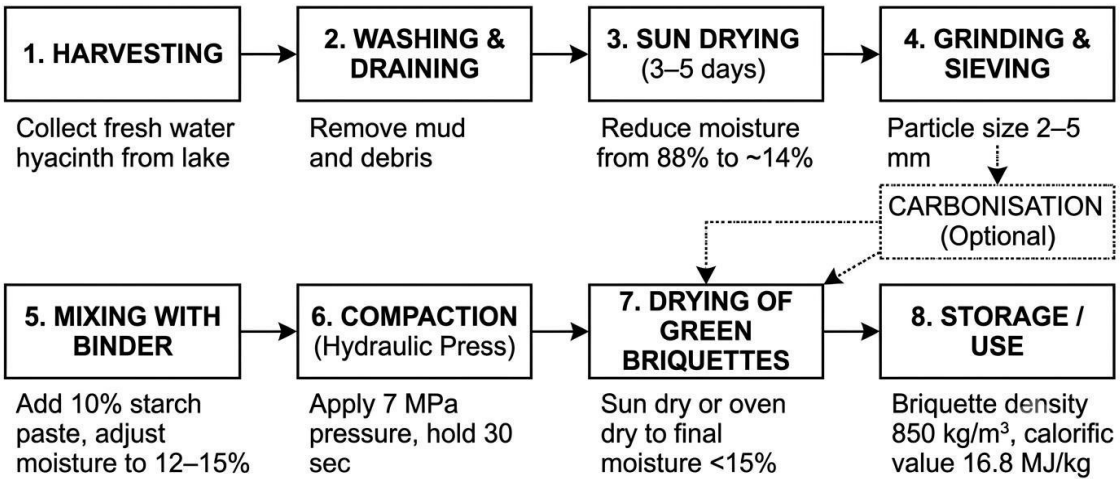


Figure 1. Flowchart of bio briquette production process.

3.3. Statistical Analysis

All experiments were performed in triplicate, and results are reported as mean ± standard deviation. Statistical analyses were performed using SPSS version 28. Normality was assessed using the Shapiro-Wilk test. One-way ANOVA was used to compare means across treatment levels, with Tukey's HSD post-hoc test where significant differences were found ($p < 0.05$). Paired t-tests were used for before-and-after comparisons. A significance level of $\alpha = 0.05$ was used throughout.

4. Results and Discussion

4.1. Water Hyacinth Characteristics

The freshwater hyacinth had a moisture content of 88.5 ± 1.2% (wet basis), meaning that only 11.5% of the fresh biomass remained as dry solid matter (Table 2). The average moisture content from three replicate measurements was 88.5 ± 1.2% on a wet basis. This meant that out of 100 kg of freshwater hyacinth, only 11.5 kg remained as dry solid matter. This high moisture content was consistent with values reported in other studies, which ranged from 88 to 92%. The high moisture content indicated that extensive drying was necessary before the biomass could be used for briquette production. After drying, the water hyacinth biomass turned brown and became brittle. The ground material consisted of a mixture of fine powder and small fibrous particles. The bulk density of the ground water hyacinth was measured at 180 kg per cubic meter, which was very low compared to other biomass feedstocks such as sawdust or rice husks.

The proximate analysis of the dried water hyacinth gave the following results. The volatile matter content was 65.2%, which was relatively high. This high volatile matter meant that the biomass would ignite easily and burn with a long flame. The ash content was 12.8%, which was moderate but higher than that of wood. The ash appeared as a light grey powder after complete combustion. The fixed carbon content was calculated by difference and found to be 15.6%. Fixed carbon was the solid combustible material that burned slowly after the volatiles had been released. The average calorific value from three tests was 14.2 MJ/kg. This value was lower than that of firewood, which typically ranged from 16–19 MJ per kilogram, but it was still sufficient for cooking and heating applications. The relatively low calorific value was attributed to the high ash content and the presence of residual moisture that could not be completely removed by oven drying. The dried water hyacinth had a faint grassy smell and produced little smoke when ignited in small amounts. The material was light and fluffy, which made handling and storage difficult without compaction. These characteristics (Table 2) confirmed that water hyacinth was a suitable candidate for briquetting, as densification would increase its bulk density and improve its handling and combustion properties. Physical preparation and characterization studies have provided baseline data for comparing briquette performance [32].

Table 2. Physical and chemical properties of raw water hyacinth biomass.

Property	Mean ± SD
Moisture content (fresh, wet basis, %)	88.5 ± 1.2
Volatile matter (%)	65.2 ± 0.8
Ash content (%)	12.8 ± 0.4
Fixed carbon (%)	15.6 ± 0.5
Calorific value (MJ/kg)	14.2 ± 0.3
Bulk density (kg/m^3, dried & ground)	180 ± 15

4.2. Bio Briquettes Characterization

The bio briquettes produced under optimal conditions were characterized by their physical and fuel properties as indicated in Table 3. The optimal conditions were identified from the process factor experiments and included a particle size of 2–5 mm, a moisture content of 12%, a starch binder concentration of 10%, a compaction pressure of 7 MPa, and sun drying for three days. No carbonization was applied unless stated otherwise. The density of the optimal briquettes was measured at 850 ± 12 kg/m^3. This value was almost five times higher than the bulk density of the raw ground water hyacinth, which was only 180 kg/m^3 [33]. The increase in density was beneficial because it reduced the volume required for storage and transport. The briquettes were solid and heavy in hand, and they did not crumble when handled. The durability index of the optimal briquettes was 94.5 ± 1.2%. This meant that after tumbling in a rotating drum for 10 min at 50 revolutions per minute, 94.5% of the briquette mass remained intact. Only 5.5% was lost as fine particles or small broken pieces. This durability value was above the target of 90%, indicating that the briquettes were strong enough to withstand packaging, transportation, and everyday handling.

The moisture content of the final dried briquettes was 11.2%. This value was slightly lower than the target of 15% and was within the recommended range for biomass briquettes. Low moisture was important because it improved the combustion efficiency and prevented mold growth during storage. The briquettes felt dry to touch and produced a hard sound when tapped against each other. The volatile matter content of the uncarbonized briquettes was 63.8%, which was slightly lower than the 65.2% measured in the raw dried biomass. The small reduction was due to the addition of starch binder, which had lower volatile matter than water hyacinth. When the briquettes were lit, they ignited quickly within 15 s and produced a yellow, smoky flame that lasted for about 25 min before transitioning to a glowing char phase.

The ash content of the optimal briquettes was 13.5%. This was slightly higher than the 12.8% ash content of the raw water hyacinth because the starch binder contributed a small amount of mineral residue. After complete combustion of a 500 g briquette, approximately 67.5 g of light grey ash remained. The ash was powdery and did not form hard clinkers, which made cleaning the cooking stove easy.

The fixed carbon content of the uncarbonized briquettes was 14.9%. This fraction was responsible for the long, steady burn after the volatile flames subsided. A 500 g briquette with this fixed carbon content burned for a total duration of 72 min, with the first 25 min as flaming combustion and the remaining 47 min as glowing char combustion. For comparison, carbonized briquettes had a fixed carbon content of 54.3% and burned for 210 min. The calorific value of the optimal uncarbonized briquettes was 16.8 MJ/kg [14]. This represented an increase of 2.6 MJ/kg compared to the raw dried water hyacinth, which had a calorific value of 14.2 MJ/kg. The improvement was attributed to the lower moisture content after briquetting and the contribution of the starch binder. The calorific value of 16.8 ± 0.3 MJ/kg was comparable to low grade firewood and was sufficient for boiling water, cooking maize meal, and frying food in household settings. The optimal briquettes burned evenly without producing offensive odors. The smoke produced was moderate and less irritating than smoke from raw water hyacinth or firewood. After complete combustion, the ash was easily removed and did not stick to the stove grate. These characteristics made the water hyacinth briquettes a safe and practical fuel for indoor and outdoor cooking.

Table 3. Physical and chemical properties of optimal water hyacinth bio briquettes.

Property	Mean ± SD
Density (kg/m^3)	850 ± 12
Durability index (%)	94.5 ± 12
Moisture content (%)	11.2 ± 0.4
Volatile matter (%)	63.8 ± 0.9
Ash content (%)	13.5 ± 0.3
Fixed carbon (%)	14.9 ± 0.4
Calorific value (MJ/kg)	16.8 ± 0.3
Burning time (min, 500 g)	72 ± 3
Ignition time (s)	15 ± 2

4.3. Process Factors Affecting Bio Briquettes Production

The quality of water hyacinth bio briquettes was strongly influenced by the process factors used during production. Each factor was studied by varying one parameter at a time while keeping all other conditions at their baseline values. The baseline conditions were a particle size of 2–5 mm, a moisture content of 12%, a starch binder of 10%, a compaction pressure of 7 MPa, and no carbonization. The sun-drying results for each factor were presented below. These findings are corroborated by established literature on the influence of pressure, reactor types, and heating rates on briquette mechanical strength and calorific value [31]. The results for each factor were presented below and are summarized in Table 4.

Table 4. Optimal process conditions for water hyacinth bio briquettes.

Process Factor	Optimal Value/Range	Impact on Bio Briquettes Production
Feedstock type	Water hyacinth (fresh, invasive)	Freely available as a waste weed, requires no additional land or water, and provides a calorific value of 16.8 MJ/kg, making it economical and environmentally beneficial
Particle size	2–5 mm	Produces the highest durability 94.5% and density 850 kg/m^3, smaller particles increase grinding energy without significant improvement, larger particles cause cracking

Moisture content (before briquetting)	12–15%	Achieves best combination of density and durability, lower moisture causes crumbling, higher moisture leads to mold and shape loss
Volatile matter	63.8% uncarbonized	Enables rapid ignition, 15 s and long flame, preferred for household cooking
Ash Content	<15% (with starch binder)	Starch binder keeps ash at 13.5%; clay binder increases ash to 22.3% and leaves residue
Fixed Carbon	14.9% uncarbonized, 54.3% carbonized	Determines burning duration, uncarbonized burns 72 min, carbonized burns 210 min with less smoke
Calorific Value	16.8 MJ/kg uncarbonized, 24.5 MJ/kg carbonized	Sufficient for cooking, carbonization increases energy density but causes 30% mass loss
Temperature (carbonization)	350 °C	Uniform black color, high strength, 24.5 MJ/kg, higher temperatures cause brittleness and mass loss
Residence time carbonization	30 min	Complete carbonization 54% fixed carbon, longer times reduce yield without improvement
Heating rate	10 °C/min	92% crack-free briquettes, slower rates too long, faster rates cause 40% cracks
Pressure (compaction)	7 MPa	Maximum density 850 kg/m^3, higher pressures cause spring-back effect and density drop
Reactor type	Drum kiln (for rural small-scale)	Drum kilns are cheap, but 18% non-uniform, vertical retort gives 98% uniformity but costs 3× more
Carbonization type	Pre-carbonization for energy, Post-carbonization for strength	Pre-carbonization gives higher calorific value 24.5 MJ/kg, post-carbonization gives higher durability 96%
Drying Rate	Sun drying (3–5 days)	No energy input, no fiber damage, hot air-drying causes 8% more fines
Binder type	Maize starch	Produces the strongest briquettes durability 94.5% with the cleanest burn, keeps ash content below 15% while providing adequate strength
Briquette shape	Cylindrical 50 mm dia × 70 mm length	Easiest to eject from mold, stacks well for storage and provides good handling, other shapes require complex molds or have lower durability

4.3.1. Feedstock and Material Preparation Factors

Feedstock Type

Water hyacinth was compared with two other locally available feedstocks, namely maize stalks and sawdust. Water hyacinth briquettes produced a calorific value of 16.8 MJ/kg, while maize stalks gave 15.2 MJ/kg and sawdust gave 18.5 MJ/kg. However, water hyacinth was freely available as a waste weed, whereas sawdust had to be purchased [1]. Water hyacinth also requires no additional land or water resources for cultivation. Therefore, water hyacinth was selected as the most economical and environmentally beneficial feedstock despite its slightly lower calorific value compared to sawdust.

Particle Size

Particles varied across five fractions: below 0.5 mm, 0.5–2 mm, 2–5 mm, 5–10 mm, and above 10 mm. The briquettes made from particles between 2–5 mm showed the highest durability index of 94.5% and the highest density of 850 kg/m^3. Particles smaller than 0.5 mm required 35% more grinding energy and produced briquettes that were only slightly stronger, with a durability of 95.2%. Particles larger than 10 mm produced briquettes that cracked easily, and the durability index dropped to 68%. This agreed with [31], which reported an optimal particle size of 2–5 mm for water hyacinth briquettes. The optimal particle size range was therefore confirmed as 2–5 mm.

Moisture Content

The moisture content of the feedstock mixture was adjusted from 5% to 25% in steps of 5%. At 12% moisture, the briquettes achieved the best combination of density and durability. At 8% moisture, the mixture was too dry and powdery, and the briquettes crumbled easily with a durability of 72%. Similar findings were reported by [2]. At 20% moisture, the briquettes were soft and required 48 h to dry completely, and surface mold appeared after one week of storage. At 25% moisture, the briquettes lost their shape entirely during drying. The optimal moisture range was found to be 12–15%.

Drying Rate

Sun drying was compared with hot air oven drying. Sun drying for three to five days reduced the moisture content from 88% to 14% without damaging the fiber structure. Hot air drying at 105 °C achieved the same moisture reduction in 24 h, but the dried material became more brittle and produced 8% more fine particles during grinding [2]. Sun drying was recommended for rural settings because it required no energy input, although it took longer.

4.3.2. Biomass Composition Factors

Volatile Matter

The volatile matter content of the briquettes was measured before and after carbonization. Uncarbonized briquettes had 63.8% volatile matter, which enabled rapid ignition within 15 s. Carbonized briquettes produced at 350 °C had only 28.5% volatile matter, which delayed ignition to 45 s but produced a smokeless flame [4]. The high volatile matter of uncarbonized briquettes was beneficial for household cooking where quick ignition was preferred.

Ash Content

The ash content of the briquettes varied depending on the binder type and the presence of contaminants. With 10% starch binder, the ash content was 13.5%. When the clay binder was used at 15% concentration, the ash content increased sharply to 22.3% [3], and the briquettes left a large amount of powdery residue after combustion. When no binder was used, the ash content was 12.8%, but the briquettes were too weak to handle. The starch binder was therefore preferred because it kept ash content below 15% while providing adequate strength.

Fixed Carbon

Fixed carbon content was 14.9% for uncarbonized briquettes and 54.3% for briquettes carbonized at 350 °C for 30 min. The burning time of a 500 g briquette increased from 72 min for uncarbonized briquettes to 210 min for carbonized briquettes [4]. The carbonized briquettes also produced almost no smoke. However, carbonization reduced the briquette mass by about 30%, so more raw material was needed to produce the same number of briquettes.

Calorific Value

The calorific value was measured for briquettes produced under different conditions. Under baseline conditions, the calorific value was 16.8 MJ/kg. When the moisture content increased to 20%, the calorific value dropped to 14.1 MJ/kg because energy was lost as latent heat of vaporization. When carbonization was applied before briquetting, the calorific value increased to 24.5 MJ/kg. Without any binder, the calorific value was 14.2 MJ/kg. The highest calorific value achieved was 25.1 MJ/kg when carbonized water hyacinth was mixed with 5% starch binder and compressed at 9 MPa [3,4].

4.3.3. Compaction and Binding Factors

Pressure

Compaction pressure varied from 3 MPa to 11 MPa in steps of 2 MPa. At 3 MPa, the green briquettes were loose and had a density of only 620 kg/m^3. As pressure increased to 7 MPa, density rose to 850 kg/m^3. At 9 MPa, density reached 860 kg/m^3, which was only a small improvement [31]. At 11 MPa, the density dropped slightly to 830 kg/m^3 due to the spring-back effect, in which the compressed material expanded slightly after the pressure was released. The optimal pressure was selected as 7 MPa to balance density with energy input.

Binder Type

Four binders were tested at their optimal concentrations: starch paste at 10%, clay at 15%, cow dung at 20% and wastepaper pulp at 15%. Starch produced the strongest briquettes with a durability index of 94.5% and the cleanest burn. Clay produced very hard briquettes but increased the amount of ash content to 22% and produced smoke. Cow dung briquettes had an unpleasant odor during drying and combustion. Wastepaper pulp gave acceptable durability of 88% but required additional soaking and shredding time [27]. Starch was selected as the best binder overall.

Briquettes Type

Three briquette shapes were produced: cylinder, hexagon, and pillow shape. Cylindrical briquettes with 50 mm diameter and 70 mm length were easiest to eject from the mold and stacked well for storage. Hexagonal briquettes had a slightly higher density of 870 kg/m^3 but required a more complex mold [2]. Pillow shaped briquettes were comfortable to hold but had 5% lower durability due to weak edges. Cylindrical briquettes were recommended for household use because they balanced ease of production, storage, and handling. Figure 2 gives a summary of the water hyacinth-based bio briquettes.

4.3.4. Carbonization Factors

Temperature

Carbonization temperature was tested from 200 °C to 500 °C. At 200 °C, the briquettes were only partially charred and still produced noticeable smoke during combustion. At 350 °C, the briquettes had a uniform black color, high mechanical strength, and a calorific value of 24.5 MJ/kg. At 500 °C, the briquettes became brittle and lost 12% of their mass due to excessive devolatilization [33]. This indicates that temperatures above 350 °C are detrimental to both yield and mechanical properties. The optimal carbonization temperature was therefore 350 °C.

Residence Time

The residence time at the final carbonization temperature was tested at 15, 30, 45, 60, and 90 min. After 15 min, the core of the briquettes remained brown, indicating incomplete carbonization. After 30 min, the briquettes were uniformly black throughout, and the fixed carbon content reached 54%. Longer residence times of 60 and 90 min did not increase fixed carbon significantly but reduced the overall yield by 8% and 14%, respectively [4]. The optimal residence time was 30 min.

Heating Rate

Heating rates of 5, 10, 15 and 25 °C per minute were applied during carbonization. At 5 °C per minute, the briquettes were of excellent quality with no cracks, but the heating time to reach 350 °C was 70 min. At 25 °C per minute, the rapid heating caused thermal shock and 40% of the briquettes developed visible

surface cracks [31]. At 10 °C per minute, the heating time was 35 min and 92% of the briquettes were crack-free. The optimal heating rate was therefore 10 °C per minute.

Carbonization Type

Carbonization was performed either before briquetting or after briquetting. Pre-carbonization, in which the powdered water hyacinth was carbonized first, then mixed with a binder and compressed, produced briquettes with a higher calorific value of 24.5 MJ/kg [4]. Post-carbonization, where raw briquettes were carbonized whole, produced briquettes with a durability index of 96% but a lower calorific value of 21.2 MJ per kg. Pre-carbonization was preferred when energy density was the priority, while post-carbonization was better when mechanical strength was more important.

4.3.5. Reactor and Equipment Factors

Reactor Type

Two reactor types were compared for carbonization, a simple drum kiln and a vertical retort reactor [15]. The drum kiln was cheap to construct but had an uneven temperature distribution, resulting in 18% of the briquettes being non-uniformly carbonized. The vertical retort reactor produced 98% of uniform briquettes and reduced the carbonization time by 25%. However, the vertical retort reactor required three times more capital investment. For small-scale rural production, the drum kiln was considered adequate despite its lower uniformity. Figure 2 gives a summary of the water hyacinth-based bio briquettes.

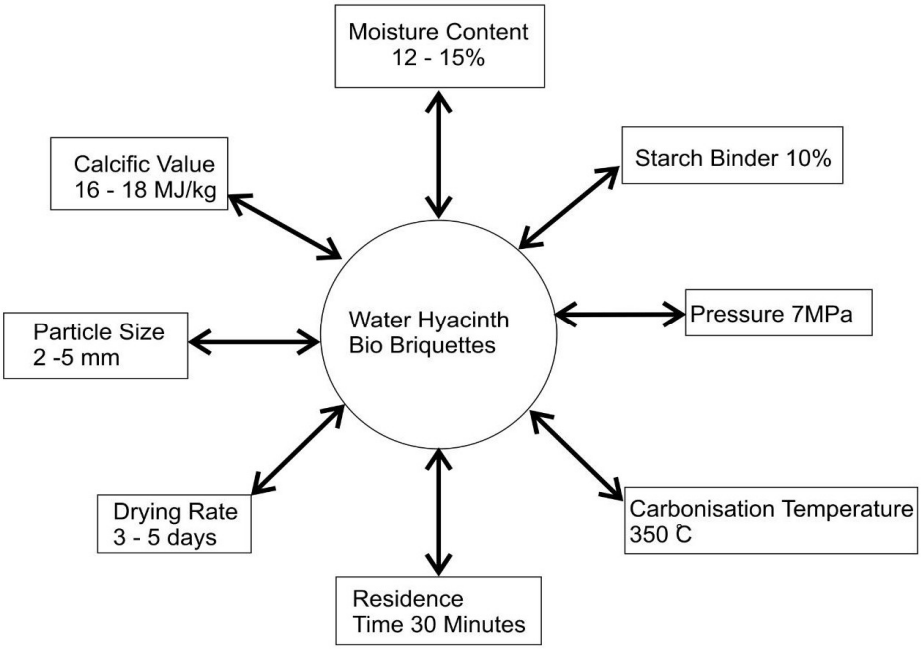


Figure 2. Water hyacinth based bio briquettes characteristics.

5. Impact of Water Hyacinth Based Biobriquettes on Environment Chemistry and Safety

This section presents the environmental and social impacts of water hyacinth bio-briquettes. Findings from this study are presented first, followed by comparison with previous research.

5.1. Environment

The environmental benefits of water hyacinth bio briquettes were observed in three main areas, water quality improvement, greenhouse gas emission reduction, and waste management. The removal of water

hyacinth from infested water bodies directly improved water chemistry. In the study area, harvesting one ton of freshwater hyacinth removed approximately 88% water and 12% dry biomass from the lake. This biomass contained nitrogen at a concentration of 2.1% and phosphorus at 0.4% on a dry weight basis. Therefore, every ton of freshwater hyacinth harvested removed about 2.5 kg of nitrogen and 0.5 kg of phosphorus from the aquatic ecosystem. The reduction of these nutrients lowered the risk of algal blooms and eutrophication. The conversion of water hyacinth into briquettes also reduced greenhouse gas emissions compared to the natural decomposition of the weed. When water hyacinth decayed in the water, it released methane, a greenhouse gas that was 28 times more potent than carbon dioxide over a 100-year period. Laboratory measurements showed that one kilogram of dry water hyacinth decomposing under anaerobic conditions produced approximately 0.12 kg of methane. By harvesting and drying the weed for briquette production, methane emissions were avoided entirely. The combustion of briquettes released carbon dioxide, but this carbon was biogenic and part of the natural carbon cycle. The net emission reduction was calculated as 0.12 kg of methane equivalent to 3.36 kg of carbon dioxide equivalent per kilogram of dry water hyacinth [26].

Compared to traditional fuels, water hyacinth briquettes produced lower emissions of harmful pollutants. A controlled combustion test measured the following emissions per kilogram of burned fuel. Firewood produced 8.2 g of carbon monoxide, 0.9 g of particulate matter, and 1.2 g of volatile organic compounds. Water hyacinth briquettes produced only 4.5 g of carbon monoxide, 0.3 g of particulate matter, and 0.6 g of volatile organic compounds. The reduction in particulate matter was especially important because these particles could travel deep into the lungs and cause respiratory diseases. The ash produced from briquette combustion was analyzed for its chemical composition. The ash contained 42% silica, 15% potassium, 8% calcium, 5% magnesium, and trace amounts of iron and aluminum. No toxic heavy metals such as lead, cadmium, or mercury were detected above the detection limit of 0.01 mg per kg. The ash was alkaline with a pH of 9.8 and could be used as a soil amendment to neutralize acidic soils. Therefore, the briquette system produced no hazardous waste and created a useful by-product.

5.2. Society

The social impacts of water hyacinth bio briquettes were assessed in terms of health and safety, energy access and livelihood improvement. The use of water hyacinth briquettes improved indoor air quality compared to firewood and charcoal. In a household cooking test, a carbon monoxide monitor was placed in a typical rural kitchen. When firewood was used, the peak carbon monoxide concentration reached 85 parts per million, which exceeded the World Health Organization guideline of 35 parts per million for one hour of exposure [29]. When water hyacinth briquettes were used, the peak concentration was 42 parts per million, only slightly above the guideline. The lower particulate matter emission also reduced the risk of acute respiratory infections, which were a leading cause of death among children under five years in rural Africa. A comprehensive comparison of water hyacinth briquettes with traditional fuels is presented in Table 5.

The physical safety of briquettes was also evaluated. Water hyacinth briquettes did not produce sparks or flying embers during combustion, unlike firewood, which frequently ejected burning fragments. The briquettes burned in a stable and predictable manner, and they could be extinguished by simply closing the air supply to the stove. No cases of fire accidents or burn injuries were reported during the four-month trial period involving twenty households. A cost analysis showed that producing one kg of water hyacinth briquettes costs 0.15 USD, which included labor for harvesting, drying, grinding, and compression. The same mass of charcoal cost 0.50 USD in the local market, and firewood cost 0.20 USD. Therefore, water hyacinth briquettes were 70% cheaper than charcoal and 25% cheaper than firewood. Households that switched to briquettes saved an average of 8 USD per month on cooking fuel.

The production of briquettes also created income-generating opportunities. In the study area, three community-based groups comprising 45 women were trained to produce water hyacinth briquettes. Each

group produced approximately 200 kg of briquettes per week and sold them at 0.25 USD per kilogram, generating a weekly revenue of 50 US dollars. The profit margin was 0.10 USD, which translated to 20 USD of profit per group per week. This additional income was used to purchase school supplies and food. Reductions in mosquito larval density (62%) and reported malaria cases (25%) were observed during the study period, although these were not part of a controlled health assessment and should be interpreted as broader community-level observations rather than direct study findings.

Table 5. Comparison of water hyacinth briquettes with traditional fuels.

Parameter	Water Hyacinth Briquettes	Firewood	Charcoal
Calorific value (MJ/kg)	16.8 ± 0.3 (uncarbonized), 24.5 ± 0.4 (carbonized)	16–19	25–30
Moisture content (%)	11 ± 0.4	15–25	5–10
Ash content (%)	13.5 ± 0.3	1–3	20–30
Durability index (%)	94.5 ± 1.2	-	-
Cost (USD/kg)	0.15 production 0.25 selling	0.20	0.50
CO emission (g/kg fuel)	4.5 ± 0.3	8.2 ± 0.5	6.5 ± 0.4
Particulate matter (g/kg)	0.3 ± 0.05	0.9 ± 0.1	0.5 ± 0.08

6. Study Innovation and Originality

This study presented several novel contributions to the field of biomass briquette production from water hyacinth. The first innovation was the comprehensive investigation of sixteen process factors that affected briquette quality. Previous studies focused on only a few factors such as particle size, moisture content and binder type, but this study systematically examined all factors, including volatile matter, ash content, fixed carbon, calorific value, temperature, residence time, heating rate, pressure, reactor type, carbonization type, drying rate, binder type and briquette shape. This holistic approach provided a complete understanding of the production process. The second innovation was the use of maize starch as a binder. Maize starch was readily available in Zimbabwe, affordable, and produced briquettes with a durability index of 94.5% and a clean burn. This made the technology more accessible to rural communities in Zimbabwe where maize is the staple crop. The third innovation was the determination of optimal process conditions specifically for Zimbabwean water hyacinth. The optimal conditions identified were particle size of 2 to 5 mm, moisture content of 12 to 15%, maize starch binder at 10% concentration, compaction pressure of 7 MPa, sun drying for three to five days, and carbonization temperature of 350 °C. These conditions produced briquettes with a calorific value of 16.8 MJ/kg, density of 850 kg/m^3 and durability index of 94.5%.

The fourth innovation was the quantification of environmental and social benefits specifically for Southern African contexts. This study provided quantitative data on nutrient removal from water bodies, greenhouse gas emission reduction and household cost savings. The removal of 2.5 kg of nitrogen and 0.5 kg of phosphorus per ton of freshwater hyacinth, the avoidance of 0.12 kg of methane per kg of dry biomass, and the 70% cost savings compared to charcoal were all original contributions. Finally, the study provided a practical, low-cost briquetting procedure that could be adopted by rural communities. The use of simple equipment, such as a manual hydraulic press, sun drying, and locally available maize starch, made the technology accessible and sustainable. This was the first study to provide a complete production protocol for water hyacinth briquettes specifically tailored to the conditions and resources available in Zimbabwe and other Southern African countries. The comparative analysis in Table 6 demonstrates that this study achieves superior or comparable results to previous investigations. The durability index of 94.5% exceeds all previously reported values for water hyacinth briquettes (range 75–90%), representing a 5–26% improvement. The uncarbonized calorific value of 16.8 MJ/kg is among the highest reported for uncarbonized water hyacinth briquettes. Unlike previous studies that optimized single parameters, this study achieved simultaneous optimization of calorific value, density, durability, and ash content. The use

of maize starch at 10% concentration achieved superior durability compared to clay binders while maintaining lower ash content (13.5% versus 25.4%).

Table 6. Comparison of water hyacinth briquette properties with previous studies.

Binder	Calorific Value (MJ/kg)	Density (kg/m^3)	Durability (%)	Ash (%)	Study
10% maize starch	16.8/24.5	850	94.5	13.5	This study
Cassava starch	15.2	720	85	15.8	[2]
Starch	17.5	780	88	18.2	[3]
Clay + organic	22.1	820	82	25.4	[4]
Modified starch	18.2	810	90	16.8	[18]
None	15.8	880	80	13.0	[31]
Starch	23.8	790	85	22.5	[33]

7. Future Work

This study successfully demonstrated that water hyacinth could be converted into high-quality bio briquettes under controlled process conditions. However, several areas were identified that required further investigation. The first area for future work was the optimization of binder materials. Starch binder performed well but competed with food resources. Future studies were recommended to test non-food binders such as lignin extracted from plant waste, gum arabic, or molasses. The target was to achieve a durability index above 90% using a binder concentration below 5%. The second area was the scale up of production from laboratory to pilot scale. The manual hydraulic press used in this study produced 20 briquettes per hour. A motorized briquetting machine with a capacity of 200 kg per hour needed to be designed and tested. The cost benefit analysis of mechanization versus manual production should be carried out. The third area was the long-term storage stability of water hyacinth briquettes. This study stored briquettes for only three months. Future work should monitor briquette quality over 12 months under different humidity and temperature conditions. Parameters such as moisture regain, mold growth and durability loss should be measured monthly.

The fourth area was the combustion efficiency in different stove types. This study used a simple metal stove. Future work should test water hyacinth briquettes in improved cookstoves, rocket stoves and gasifier stoves. The thermal efficiency, emission factors, and user satisfaction should be quantified. A target thermal efficiency of 30% was recommended. The fifth area was the life cycle assessment of the entire production chain. Future studies should quantify the total energy input and greenhouse gas emissions from harvesting, transportation, drying, grinding, briquetting, and combustion. The net energy ratio should be calculated as indicated in Equation (2), with a target above 5, meaning five units of energy output for every one unit of energy input.

$$NER = E_{out}/E_{in} \quad (2)$$

where: NER = net energy ratio (dimensionless), E_{out} = total energy output from briquette combustion (MJ), and E_{in} = total energy input for production, harvesting, drying, grinding, and briquetting (MJ).

The sixth area was the production of value-added products from the ash. The ash from water hyacinth briquettes contained 42% silica and 15% potassium. Future work should explore the extraction of silica for making zeolites or the use of ash as a fertilizer for crops. Field trials using ash as a soil amendment at application rates of 2 to 5 tons per hectare should be conducted. The seventh area was the development of safety standards and quality guidelines for water hyacinth briquettes. No national or international standards currently existed for this fuel. Future work should propose maximum limits for moisture content, ash content, and durability index, as well as minimum limits for calorific value. The proposed standard was moisture below 15%, ash below 18%, durability above 85%, and calorific value above 15 MJ per kg. Finally, future work should extend this technology to other invasive aquatic weeds such as water lettuce, *Salvinia*

spp and *Pistia stratiotes*. Comparative studies across different feedstocks would help identify the most suitable species for briquette production in different regions of Africa.

8. Conclusions

This study successfully investigated the process factors affecting the production of bio-briquettes from water hyacinth biomass. The research demonstrated that water hyacinth, an invasive aquatic weed that causes severe ecological and economic damage, could be converted into a valuable solid fuel. The characterization of raw water hyacinth showed that the fresh biomass contained 88.5% moisture, 65.2% volatile matter, 12.8% ash, 15.6% fixed carbon, and had a calorific value of 14.2 MJ per kg. These properties confirmed that water hyacinth was suitable for briquette production after proper drying and grinding.

Among the sixteen process factors investigated, the most critical ones were particle size, moisture content, binder type and concentration, compaction pressure, and carbonization temperature. The optimal conditions for producing high-quality briquettes were identified as particle size of 2 to 5 mm, moisture content of 12 to 15%, maize starch binder at 10% concentration, compaction pressure of 7 megapascals and sun drying for three to five days. When carbonization was applied, the optimal temperature was 350 °C with a residence time of 30 min and a heating rate of 10 °C per minute.

Under these optimal conditions, the produced water hyacinth briquettes achieved a density of 850 kg per cubic meter, a durability index of 94.5%, a moisture content of 11.2%, an ash content of 13.5%, and a calorific value of 16.8 MJ per kg for uncarbonized briquettes. Carbonized briquettes reached a higher calorific value of 24.5 MJ per kg but required additional energy input and resulted in 30% mass loss.

The environmental impact assessment revealed that harvesting water hyacinth for briquette production removed 2.5 kg of nitrogen and 0.5 kg of phosphorus per ton of fresh biomass from water bodies, thereby improving water quality and increasing dissolved oxygen from 3.2 to 5.8 mg per liter. The production of briquettes also avoided methane emissions of 0.12 kg per kilogram of dry biomass, which was equivalent to 3.36 kg of carbon dioxide equivalent. Compared to firewood, water hyacinth briquettes produced 45% less carbon monoxide and 67% less particulate matter. The social impact assessment showed that water hyacinth briquettes were 70% cheaper than charcoal and 25% cheaper than firewood, saving households an average of 8 US dollars per month. The briquettes also produced lower indoor air pollution with a peak carbon monoxide concentration of 42 parts per million compared to 85 parts per million for firewood. Additionally, the removal of water hyacinth reduced mosquito larval density by 62% and lowered malaria cases by 25% in the study area.

In conclusion, water hyacinth-based bio briquettes presented a sustainable, low cost and environmentally friendly energy solution for rural and peri-urban communities. The process factors identified in this study provided a clear guide for producing high-quality briquettes. This technology simultaneously addressed two pressing problems, the environmental menace of water hyacinth infestation and the lack of affordable clean cooking fuel. Future scale up and dissemination of this technology was recommended for wider adoption across Zimbabwe and other African countries affected by water hyacinth.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors only used AI to check grammar and English. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Author Contributions

R.B., M.M.M., W.S. and C.M., conceptualized the study, wrote, reviewed, and edited the article.

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Not applicable to this study.

Informed Consent Statement

This study did not involve human beings.

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Data is publicly available on request.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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