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ORIGINAL PAPER

Optimisation of the Production of Pyrolysed Corn Stover Briquettes and Its Techno-economic Analysis

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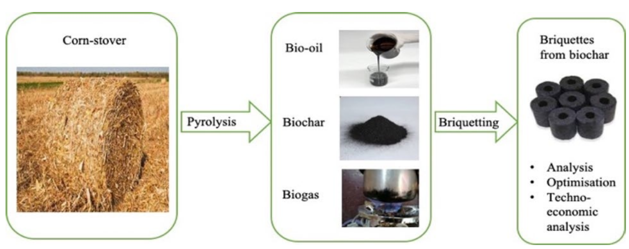
Abstract

Renewable energy sources such as biomass wastes serve as potential alternatives for traditional fossil fuel sources. This study investigated the conversion of corn stover (CS) waste into an eco-friendly solid fuel (briquettes) with high carbon content and high calorific value (HHV) to meet the increasing energy demand in South Africa through slow pyrolysis and densification processes. Biochar and char briquettes were characterised using ultimate and proximate analyses. Central composite design (CCD) was used to optimise the production of briquettes, in terms of HHV, compaction pressure, durability, and density. The optimised conditions were used to develop a process design and economic evaluation of a briquette production scale-up plant. The results indicated that the HHV (25.5–28.81 MJ/kg) of the briquettes was influenced by binder concentration. Whereas the compressive strength (3.45–6.11 N/mm^2) and density (420–788 kg/m^3) of the briquettes were both influenced by compaction pressure and binder concentration. All 3 factors influenced the durability (97–100%) of the briquettes. At these optimised conditions (40 MPa, 8.74% and 21.6 °C), HHV, compressive strength, density and durability as predicted by the respective developed models are 27.32 MJ/kg, 5.48 N/mm^2, 770.40 m^3/kg and 98.87% respectively. Techno-economic analysis of the CS briquetting plant showed that it was able to generate 300 kg/h of dry briquettes. The economic evaluation of this study showed that with a total capital investment (TCI) of $518,791, the plant was economically feasible with a discounted payback period (DPBP) of < 4 years and discounted cash flow rate of return (DCFROR) of > 30%.

Graphical Abstract



Keywords Biochar · Pyrolysis · Densification · Briquettes · Optimisation · techno-economic

Statement of Novelty

Several studies have reported the valorisation of corn stover waste (CSW) into bioethanol, biochar, bio-oil, and gases. There is insufficient literature on the valorisation of CSW into briquettes and factors influencing the process. The current study investigated the optimisation of pyrolysed corn stover briquettes using the response surface method. The briquetting process techno-economic analysis was also carried out. The briquettes produced were comparable to that

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of domestic char bio-briquettes made from wood and South African bituminous A-grade coal used for domestic and industrial purposes.

Introduction

With the increasing global population and industrial activities, the world is currently challenged with energy crisis and waste management issues, owing to the exhaustion of conventional fuel reserves and excessive waste generation. Fossil fuel consumption is increasingly becoming a major concern globally and locally due to their high greenhouse gas emissions, pollution to the environment and global warming contribution [1]. Consequently, these continuously increase the gap between environmental sustainability and economic growth, thus leading to sustainable energy sources and waste management methods being implemented [2]. Mostly, waste management approaches are for pollution reduction and public health protection. However, it is essential to have an integrated approach that not only focuses on waste management but also on energy recovery from these residues.

Bioenergy, which is derived from biological sources, has recently gained interest due to it being renewable, unlike conventional fossil fuels. Renewable energy source, particularly lignocellulosic biomass, is inexpensive and abundant. It is derivable from organic matter such as forest residue, agricultural residue, and municipal waste [3, 4]. Furthermore, the properties of biomass such as low sulphur, and nitrogen content in addition to being CO_2 neutral make it a promising renewable energy source [5]. South Africa is very active in crop production and its major driver is the agricultural sector. This indicates the potential of abundant agricultural residues/wastes attributed to the increase in food demand from population growth and rural-urban migration [6].

South Africa is the largest producer of maize in Africa, estimated to generate approximately 16 million metric tonnes of corn stover (CS) per annum. The untapped CS is around 5.1 million metric tonnes of total CS and is available in excess yearly [7]. Corn stover consists of the leaves, stalks and stems of a maize plant that remain after harvest [8]. In most cases, CS is used as a soil amendment and animal feed and the remaining gets disposed of or destroyed by burning for preparation of the next harvest [9]. The improper disposal of these biomass wastes can pose a threat to the environment by causing pollution and contributing to climate change [6].

Hence, the significant amount of biomass waste generated yearly can be converted into useful products. This essentially shifts the dependency on fossil fuels to using energy conceived from sunlight, which is renewable [10]. In addition to South Africa's major energy challenges such as unplanned outages, high energy tariffs, and poor power infrastructure development, a significant energy shortage in low-income households is a serious issue [11]. To eradicate these, incorporating and harnessing the potential benefits of biomass residues will assist to secure a reliable energy supply to meet the basic living needs of the middle class and urban poor [12].

However, due to biomass' unstable material, high moisture, irregular shapes and sizes, low energy and bulk density, it becomes very difficult to store and transport loose biomass [13]. This is associated with high operational costs [14]. Additionally, directly burning biomass leads to inefficient use of energy due to its hygroscopic nature [15]. Therefore, it is essential to use low-cost, and environmentally friendly technologies to exploit these biomass residues efficiently. Conversion processes such as biological, thermochemical, and physical processes are commonly used or integrated to treat different residue feedstocks to produce value-added products for chemicals, fuel, power, and heat [2].

These biomass types can be utilised using one of the thermochemical processes known as pyrolysis [16]. The pyrolysis process leaves a carbon-rich solid residue (char) from the thermal decomposition of organic polymers that release vapours of various molecular weight compounds [17]. These pyrolytic vapours can be separated into condensable and non-condensable volatiles (oil and gases). This technology can be integrated with the densification process to produce charcoal briquettes from the derived biochar in the pyrolysis process. Thus, biochar as a solid product has found numerous applications in varied areas because of its versatile physicochemical properties, such as high surface area, porosity, and surface chemistry [18]. Densification also known as briquetting/pelletising, is one of the most common ways to convert biomass into solid fuels by compacting the material into a uniform shape thereby increasing its energy and bulk density [13, 15]. Densification not only increases the bulk density of the biomass from approximately 40–200 kg/m^3 up to 600–800 kg/m^3, but it also helps with handling, storage, and transportation-related problems [19]. Pressure agglomeration involves mechanical compression and tumble agglomeration where binding agents are used are the two key approaches in the briquetting process [20]. These Briquettes will supplement the traditional fossil fuel such as coal in small industry furnaces to relieve the need for energy sources.

Briquettes are blocks of combustible energy carriers made from typically compressed biomass residue for heating and cooking purposes [22]. They are sustainable and eco-friendly and their properties are comparable to that of firewood and coal. Many researchers have demonstrated that moisture content is one of the most important factors, in raw biomass densification [21].

However, for biochar which has no/little moisture in it, other factors that affect the densification need to be evaluated for strong and compactable briquettes. Thermal and physical properties such as heating value, ash content, volatile matter content, moisture content, fixed carbon content and density amongst others are used to determine the quality of briquettes [23]. These properties are influenced by factors such as compaction pressure, particle size, moisture content, drying temperature, binder ratio/concentration and others [24]. Previous studies have reported the utilisation of corn stover, for bioethanol, biochar, bio-oil, and gases, and the factors influencing the production of briquettes [6]. There is insufficient literature on factors influencing the pyrolysed biochar briquettes, particularly corn stover (CS). Not only are there inadequate studies, authors rarely report the interactions among these variables on pyrolysed biochar briquettes [25]. A study by [26] investigated various factors under optimised conditions where they studied the effect of pressure, density, and shatter index on char briquettes from charcoal dust. The study, however, did not extend its utilisation of the Response Surface Method (RSM) to further discuss the interactions between these variables. The study only focused on the individual effects of these parameters without discussing how they interact with each other. Further, there is a dearth in the literature on the optimisation of pyrolysed corn stover briquettes using RSM, in combination with looking at its techno-economic analysis. Pyrolysis in conjunction with densification makes the processes challenging and intricate with each biomass material having unique process variables for briquettes to be produced with desirable thermal and physical properties, optimum process variables need to be determined. Additionally, investigation of technical and economic feasibility is critical [27, 28]. It is necessary to account for optimum conditions at which the briquettes are produced to determine a strong comparison with the market for technical and economical purposes.

The main aim of this study is to encourage sustainable growth through the creation of value addition to the CS, into an eco-friendly solid fuel with high carbon content and high calorific value to meet the increasing energy demand in South Africa. This was achieved by determining the influence of the densification parameters on the quality of the product by employing experiments with a factorial design. The physical and densification characteristics of briquettes were assessed via ultimate and proximate analyses. To verify the effect of process parameters on the production of biochar briquettes, process variables were optimised. The targeted variables were compaction pressure, binder concentration and drying temperature. In addition, the economic analysis of the briquetting process was assessed in terms of the major costs, raw materials and products.

Materials and Methods

Biomass Selection and Preparation for Pyrolysis

Corn stover was collected from a maize farm in Western Cape, South Africa, soon after harvesting. Approximately, 50 kg of the collected sample was sun-dried to < 10% moisture content. A hammer mill was used to grind the dried sample to a size of 4 mm. Thereafter pilot shaker apparatus coupled with a series of sieves of different sizes was then used to sift the milled sample particle size to < 2 mm required by the rotating retort reactor. Particle sizes that are greater than 2 mm were re-milled until the particle size was within the desired particle size of < 2 mm. The sample was stored in sample polypropylene bags at room temperature.

Production of Biochar

Biochar production was carried out in duplicate for reproducibility purposes. A rotating retort reactor with a 2-zone heating chamber was purged with nitrogen for 15 min at a rate of 10 L/min (Fig. 1). The reactor was set to a pyrolysis temperature of 400 °C for each set of experiments. CS sample was fed into the rotating retort reactor after it has maintained an oxygen level of 3% concentration at the rate of 1 kg/hour, while constantly purging nitrogen at 1.5 L/min for each set of temperatures. The reactor was followed by a residue collection container which was maintained at 300 °C to limit the condensation of tars where the solid product (char) was collected. A condensation system with 4 containers (C1–C4) housed in separate water tanks (~ 8 °C), was used to collect the volatiles from the char pot. The gas exiting the last condenser was passed through an open-flame pilot burner system to the atmosphere. The sample was held at the set temperature to cool for 24 h. The charred mass and the oil were collected separately, weighed and recorded.

Proximate Analysis

Proximate analysis was conducted on the biomass and biochar samples to determine ash content, volatile matter, and fixed carbon content following the ASTM E1131 standards, using STARe TGA analyser (Mettler Toledo, Ohio, USA). A mass of 10 mg of each sample was separately heated from ambient temperature to 110 °C at

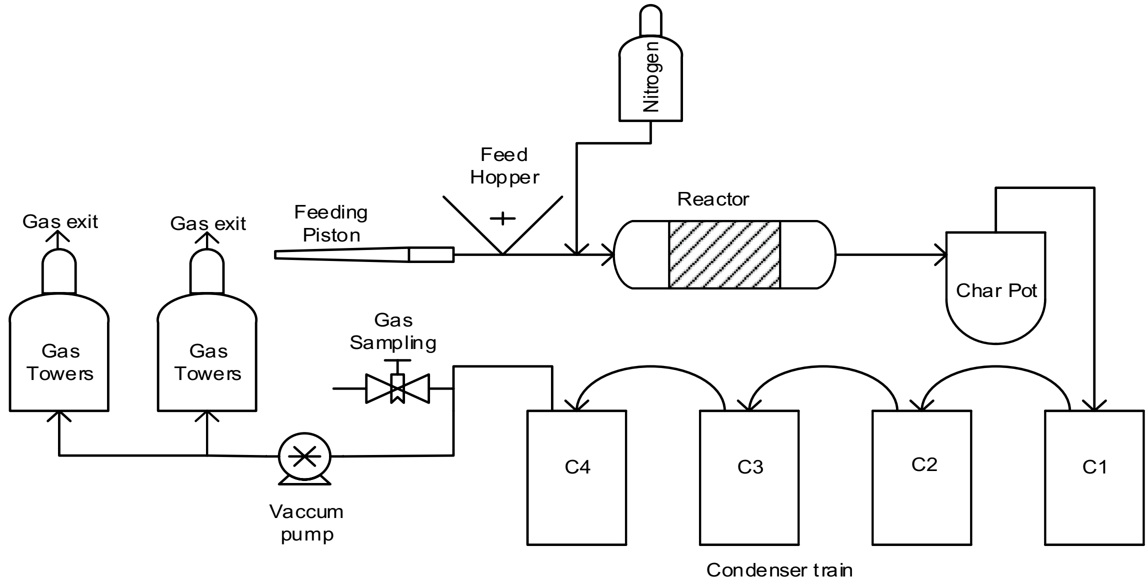

Fig. 1 Pyrolysis pilot-scale set-up

a heating rate of 50 °C/min in a nitrogen atmosphere for 5 min. Thereafter, the temperature was increased from 110 to 900 °C at a heating rate of 100 °C/min for 5 min. In the last step, the sample was held at 900 °C for further 5 min with oxygen replacing nitrogen to allow for complete combustion of the sample. TGA curve drawn was used to estimate the biochar proximate analysis.

Ultimate Analysis

Ultimate analysis was conducted on the biomass and biochar samples to determine their elemental composition of carbon (C), hydrogen (H), nitrogen (N), and sulphur (S), using a Vario EL Cube elemental analyser (Elementar, Langenselbold, Germany). A TruSpec Software program was used To determine the total elemental composition (wt%). The oxygen content was then calculated by difference.

Higher Heating Value (HHV)

The HHV of biomass, biochar, bio-oil and briquette samples were analysed using an Eco Cal2K (DDS, Instruments, Rheinlands, Germany) bomb calorimeter, following ASTM D5865 standard procedure. 0.2 g of each sample was placed in a crucible. Oxygen at a pressure of 1500 kPa was charged to the bomb calorimeter and firing cotton sparked which ignited the combustion reaction. After 20 min the analysis was complete, and the results were displayed on the screen of the Eco Cal2K bomb calorimeter.

Design of Experiments

A total of 20 experimental runs were generated using Design-Expert® software version 10.0.0 (Stat-Ease Inc., Minneapolis, USA) via central composite design (CCD). This approach statistically designed experiments then estimated the mathematical model coefficients and lastly, it predicted the responses (HHV, compression strength, mechanical strength, and density). Drying temperature, densifying pressure, and binder percentage were evaluated as independent variables. They were coded as A, B, and C respectively (Table 1). They were chosen based on the reported ranges for maximum results [29, 30].

The system's behaviour is described by a quadratic equation (Eq. 1), where optimum values were selected by analysing the response surface contour plots and solving the regression equation [31].

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} X_i X_j + \varepsilon \quad (1)$$

Table 1 Process variables used in the CCD for optimisation of briquette production using temperature, pressure, and binder as controllable experimental factors

Variables	Code	Low level (− 1)	Medium level (0)	High level (+ 1)
Temperature (°C)	A	20	45	70
Pressure (40 MPa)	B	20	30	40
Binder (%)	C	5	7.5	10

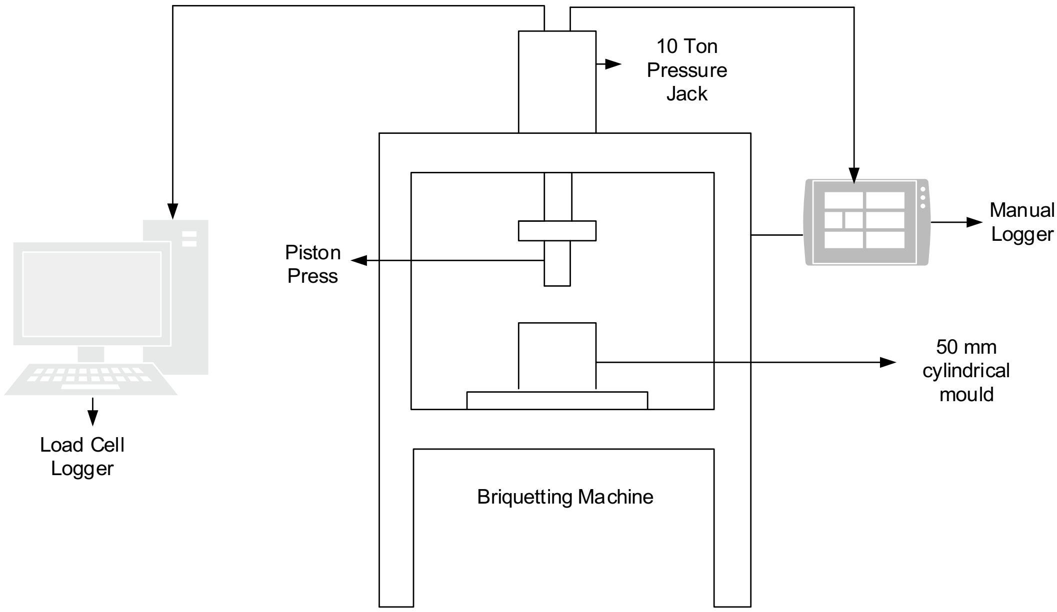

Fig. 2 Briquette machine set-up

where Y is a response variable and β_0, β_i, β_{ii} and β_{ij} are intercepts of the response variables, coefficients corresponding to the factors are $X_i, X_j (i, j = 1, 2, \ldots .n)$. The input variables that influence the response Y are X_i and X_j; the random error was represented by ϵ. A regression equation demonstrates the significance of individual coefficients, overall model significance, multicollinearity, heteroscedasticity, and autocorrelation [32]. A confidence level of 95% ($p < 0.05$) was evaluated by ANOVA asthe statistical significance of the model. The multiple correlation coefficients (R^2) were expressed to fit the quality of the model. The statistical significance of each parameter was determined via p-values [31]. Design-Expert® software version (10.0.0 Stat-Ease Inc, Minneapolis, USA) was used to determine the experimental runs.

Briquette Production Process

Biochar produced via slow pyrolysis at a temperature of 400 °C was used as the starting material for briquette production. Corn starch was selected as a binding material due to its ready and ample availability as waste, and its superior pasting properties. The corn starch was collected as waste from Tongaat Hullet, an agriculture and agri-processing company (Western Cape, South Africa). In preparation for densification, biochar was pounded using a mortar and pestle and then sieved using a mesh size of 2 mm. Both biochar and corn starch were exposed to room temperature conditions for 24 h before briquetting. The binder concentrations of 5, 7.5, and 10% at (3:1, biochar; corn-starch) were prepared to mix with water (80:20, biochar; water) and heating at 80 °C to activate the binder, until gum point. Thereafter, the binder and biochar were mixed to form the mixture to be densified. This methodology was adapted from methods by [29, 33, 34]. To produce the briquette, a piston press (briquetting machine) operated manually, was designed by Pride Lab Equipment (Pty) Ltd (Cape Town, South Africa), using a mild steel material with a capacity of one briquette per turn. The press (Fig. 2) has a 10-Ton jack connected to the pressure gauge. The press is connected to a load-cell logger which is coupled with software that receives data from the piston press. A hardened stainless-steel cylindrical mould (ID = 50 mm; H = 50 mm) aided with a funnel to load the starting material at the top and a collector to receive the product at the bottom. A release valve handle with a piston, connected to the pressure jack was used to compact the feed material manually (Biochar and binder mixture).

To prepare a briquette sample, biochar was fed on top of the mould using a funnel at the required compaction pressure and it was held for 30 s before releasing the handle. Thereafter, a steel mould designed to push out the briquette sample was then used to eject the briquette sample by pressing it out and collecting it at the bottom of the mould. All briquette samples were placed in a drying tray and then dried at desired temperatures using a dryer. The dried briquettes were then taken for laboratory analyses.

Mechanical Strength (Durability)

Mechanical strength was conducted on the briquette samples following GOST 21289-75 standard procedure [29]. A briquette sample was weighed and dropped three times on a metal surface at a height of 1.5 m. The dropped sample was collected, sieved, and weighed again. Equation 2 was used to calculate the relative mass ratio.

$$X = \frac{m - m_1}{m} \quad (2)$$

where: m is the mass of briquette before the test (g), m_1 is the mass of briquette after the test (g) and X is the relative ratio.

Compression Strength

Compression strength was conducted to determine the maximum load the briquette can sustain without failing. Each briquette sample was placed in a cube crusher and the pressure was uniformly increased at a rate of 100 kN/min compressing the sample to failure. The test was done following the study by [29]. A data logger connected to the cube crusher recorded the force (F) applied to the briquette. Equation 3 below was used to calculate the maximum compression strength.

$$P = \frac{F}{A} \quad (3)$$

where: P is the maximum compression strength (MPa). F is the force applied to the briquette (kN) and A is the area of the briquette (mm^2).

Density

The density of briquettes indicates desirability in terms of transportation, storage, handling, and burning time [35]. To determine the density of the briquettes, Eq. 4 [23] was used. The area of each briquette was calculated, and the mass and height were measured to determine the briquette density.

$$\rho = \frac{m}{A \times h} \quad (4)$$

where: ρ is the density of the briquette (kg/m^3), m is the mass of the briquette (kg), A is the area of the briquette (m^2) and h is the height of the briquette (m).

Techno-Economic Evaluation

The capital and operational costs of the large-scale briquetting plant were estimated using an Excel spreadsheet and incorporated with investment factors to calculate the capital expenditures of the project [36]. A profitability analysis based on the discounted cash flow technique that included the project life, start-up period, depreciation method, discount rate and taxation rate was done to provide a wide view of the viability of the project over the whole project life [36, 37]. In this study, reasonable profitability at the minimum project life is expected since the evaluated project is a small plant, hence a project life of 10 years was assumed. The plant was assumed to be constructed and start up within 2 years. The first and second years of construction will be spread out by 60% and 40% of the total fixed capital that does not include the land. It was assumed that the working capital cost (WCC) is 15% of the fixed capital cost (FCC). The simplest and most used depreciation method is the straight-line method. Therefore, a straight-line depreciation was assumed over the first five years after project start-up and a salvage value of zero [36, 37]. In this study, a taxation rate of 28% was used (South African Revenue Services, 2019). The desired discounted rate of 10% was used [36]. Moreover, an average conversion rate of R15.13 = 1USD (the average exchange rate in 2019) for all cases was used. The generated revenue in this study is from sales of briquettes and bio-oil and their selling prices are based on their qualities. The briquette selling price of $650/ton was based on briquette prices that have similar qualities to the one from this study [38]. The bio-oil produced will be sold without any upgrading and its selling price was adapted from a study by [39] where refined bio-oil was sold at $0.55/litre, for this study the price was reduced by 15% ($0.4/l) due to its un-upgraded quality. The utilities in this study are water and electricity, purchased based on consumption. Furthermore, the operating labour costs are based on 10 operating hours for 300 days and the amount of labour required was adapted from a study by [28] that suggested two operators are needed for a small briquetting plant. The cost of labour was averaged based on the South African processing plant standards [40].

Results and Discussion

Ultimate Analysis

The carbon content of the raw biomass was found to be 40.97 wt% dry basis, and this is comparable to previous studies by [41–43] on raw CS. The oxygen content of the biomass was found to be 53.23 wt%. This reveals that raw CS has low carbon content and relatively high oxygen hence, obtaining H/C and O/C ratios of 0.12 and 1.30, respectively. It is believed that the H/C molar ratio should increase while oxygen content (or O/C molar ratio) should decrease for biomass feedstock to produce potential biofuels [44]. The results are consistent with values obtained by other researchers [42, 45]. Higher O/C ratios are expected in biomass due to structurally well-defined compounds [46]. These demonstrate the need for further processing of CS to remove oxygen as much as possible to increase its energy content and make it a valuable biofuel [44]. It is evident from the results in Table 2 that CS is an environmentally friendly source of feedstock for fuel production given that it has low

Table 2 Ultimate analysis and proximate analysis of corn stover biomass and biochar

Feedstock	Corn stover	Biochar
Ultimate analysis (wt%, dry basis)		
C	40.97	67.55
H	5.10	3.66
O* by difference	53.23	27.91
N	0.71	0.88
S	–	–
H/C Molar ratio	1.45	0.64
O/C Molar ratio	0.97	0.30
Proximate analysis (wt%, wet basis)		
Moisture	8.36	2.76
Volatile matter	69.04	19.72
Ash content	4.90	12.52
Fixed carbon	17.70	65.00

concentrations of nitrogen (0.71 wt%) and no sulphur content. Low nitrogen and sulphur contents indicate the capability of the biomass to be suitable for thermochemical conversion [47]. Sulphur and nitrogen oxides are major pollutants produced from burning fossil fuels like coal. Hence, if the raw CS and pyrolysis products from raw CS are combusted, they would give off lower concentrations of these pollutants. Consequently, contributes to the reduction of global warming and climate change.

The hydrogen and oxygen contents of biochar were found to be 3.66 and 67.55 wt% respectively. The hydrogen and oxygen content showed a decrease of 28 wt% and 26. 9 wt% from the raw CS when it pyrolysed at 400 °C. According to [43], the degree of aromatisation is promoted during pyrolysis, which consumes a certain amount of H and O elements in lignocellulosic residues. These results are similar to the values reported in previous studies by [48, 49], on the pyrolysis of safflower and CS at 400 °C. The H and O contents of the safflower were 3.84 and 68.54 wt% and of the CS were 3.67 and 58.09 wt% respectively. Biochar results (Table 2) show the carbon content increased from 40.97 to 67.55 wt% compared to the raw CS. This indicates that after CS went under thermal decomposition, oxygen content and other volatiles were removed, increasing the carbon content [50]. The increase in carbon content is consistent with fixed carbon content. The content observed value in this study is comparable to that of South African coal which has a carbon content of 78.50 wt% [51].

In comparison with raw CS, the H/C and O/C ratios were found to be 0.64 and 0.30, respectively. The biochar values (Table 2) show that there was a decrease in the H/C and O/C ratios when CS went through carbonisation at 400 °C. Lower ratios are desirable after pyrolysis since they indicate that the material has higher energy content. During decomposition, the carbonisation and aromaticity of biochar were fully elevated [52]. The results show that H/C and O/C ratios were like those illustrated on a Van Krevelen diagram in the study by [44] on CS biochar. The authors mentioned that their H/C and O/C ratios were 0.65 and 0.10, respectively. Similarly, the Van Krevelen plot for solid fuels in the study by [53] indicates that the values obtained in the current study are within the coal region (H/C = 0.4–0.8 and O/C = 0.01–0.35). Besides, it is important to know how much nitrogen and sulphur contents are present before the combustion of biochar as they contribute to the greenhouse effect. In this study, nitrogen content was found to be 0.88% and there was no sulphur detected which makes the biochar to be favourable over conventional fossil fuels like coal.

Proximate Analysis

Corn stover biomass was characterised by a high volatile matter value of 69.04 wt% and minimal ash content of 4.9 wt% (Table 2). High volatile matter is advantageous for thermochemical conversions because during heating it readily releases more volatile compounds that produce a solid product with low ash and high fixed carbon [54–56]. Lower amounts of ash in biomass feedstocks during degradation could reduce slagging and fouling in the furnace, which is caused by the alkali content in the high-ash feedstock [57]. The observed high fixed carbon content implies that the heating value of the pyrolysis product will be improved, consequently making CS a desirable starting material for fuel production via pyrolysis [56]. In addition, the raw CS has undesirable qualities as compared to the typical low-grade coal (22.18 MJ/kg) used for domestic heating and cooking purposes [58]. Hence, the need to upgrade CS into a competitive solid fuel is significant. These values are comparable to the characteristics of other biomass previously reported in the literature [41, 44, 59].

The volatile matter content obtained in this study for biochar decreased from 69.04 to 19.72 wt%. The decrease in the volatile matter is because the pyrolysis process removes the volatile constituent of the biomass which increases the fixed carbon content [44]. According to [51], it is favourable to have a volatile matter content in the range of 20–30 wt%, to produce a fuel competitive with coal. After carbonisation, the fixed carbon content observed in this study increased from 17.70 to 65 wt%. This increase can be attributed to its linear relationship with H/C ratios, where the H content gets removed during devolatilisation. This leaves the biochar with low H content that gives rise to higher HHV [60]. The ash content in this study increased from 4.90 to 12.52 wt% after pyrolysis. The rise in ash content can be explained by the progressive concentration of minerals and obstructive volatilisation of biomass when pyrolysed [61, 62]. These results are consistent with the values obtained from other

Table 3 HHV of corn stover biomass and biochar

Feedstock	Corn stover	Biochar
HHV (MJ/kg)	16.8	28.89

Table 4 Product yield distribution at 400 °C

Feedstock	Corn stover
Biochar yield (%)	46.11
Bio-oil (%)	30.40
Biogas (%)	23.49

studies indicating pyrolysing biomass decreases the volatile matter while it increases the fixed carbon and ash content [48, 51, 63]. The presence of high ash content in fuel is not desirable as it may reduce its energy content. The biochar produced in this study has a relatively low ash content than that of a typical industrial C-grade coal which has an ash content of 18.22 wt% [51]. Therefore, with these characteristics the biochar produced has the potential to compete with coal as a source of fuel for heating and cooking.

Heating Value

The HHV is an indicator of how much energy the biomass contains, which is the overall energy content released when the fuel is burnt [53]. The HHV of the raw CS in this study was determined to be 16.80 MJ/kg. To know if biomass needs to be upgraded to a better-quality solid fuel, it is essential to know its HHV to help determine the conversion efficiency of the process [64]. Likewise, the HHV value in this study was close to the one found by [44] for CS biomass and [41] for pinewood biomass utilised as feedstock. The HHV of biochar in this study increased from 16.80 to 28.89 MJ/kg after raw CS was pyrolysed at 400 °C (Table 3). Hence, more favourable as a suitable energy source than the biomass itself. The rise in the HHV is attributed to the removal of oxygen and hydrogen at 400 °C from the biomass feedstock, which increases the carbon content [50]. This validates the claim made in Section "Ultimate analysis" that an increase in carbon content consistently increases the fixed carbon that contributes to the increase in HHV [60]. These values were similar to the results (HHV = 28.77 MJ/kg) reported by [48] after safflower biomass was carbonised at 400 °C. In this study, the biochar had an HHV value comparable to that of South African C-grade coals (22.18–25 MJ/kg) [58]. Also, the biochar had better qualities (low ash and no sulphur contents).

Product Yields

The total mass distribution of CS product yields after thermochemical decomposition at an optimum temperature of 400 °C is shown in Table 4. The product yields of biochar, bio-oil, and biogas were found to be 46.11, 30.40, and 23.49% respectively. Typically, the product yields of solids and liquids tend to decrease with temperature increase while gaseous products increase. This can be attributed to secondary cracking reactions that occur due to pyrolytic vapour caused by lower heating rates and lower to moderate temperatures (400–450 °C). This means that there will be a rise in the production of carbonaceous material and a decrease in liquids and gases [41]. In the same way, the values are consistent with those reported by other studies [44, 65]. The study on slow pyrolysis of hazelnut shells at 400 °C by [65] reported the biochar, bio-oil, and biogas yield to be 47.50, 20.10 and 18.90% respectively. Similarly, [44] reported biochar, bio-oil, and biogas yield to be 37, 31, and 15% correspondingly, from the slow pyrolysis of CS at 400 °C.

The Effect of Process Variables on Higher Heating Value for Briquette Production

The regression model (R^2) of the effect of process variables on the HHV was found to be 0.9814 (Table 5) and shows that it is in reasonable agreement with the adjusted R^2 of 0.9252. The high R^2 demonstrates that there is a good correlation between the actual values with the predicted values, which was found to be 0.9553, confirming that the quadratic model is precise and reliable. The Adeq precision was found to be 25.6499 and a ratio greater than 4 is desirable (Design-Expert® software version (10.0.0 Stat-Ease Inc, Minneapolis, USA)). Therefore, this indicates that the model is adequate to be used for the process design. The model shown

Table 5 ANOVA and fit stats summary for HHV

Factor	P-value	F value	Effect	Fit stats
Compression pressure (A)	0.2057	1.83	Insignificant	$R^2 = 0.9765$
Binder concentration (B)	0.0001	397.09	**Significant**	Adjusted $R^2 = 0.9553$
Drying temperature (C)	0.4016	0.7672	Insignificant	CV%=0.7215
AB	0.4016			Adeq precision = 25.6499
AC	0.8894			
BC	0.6778			

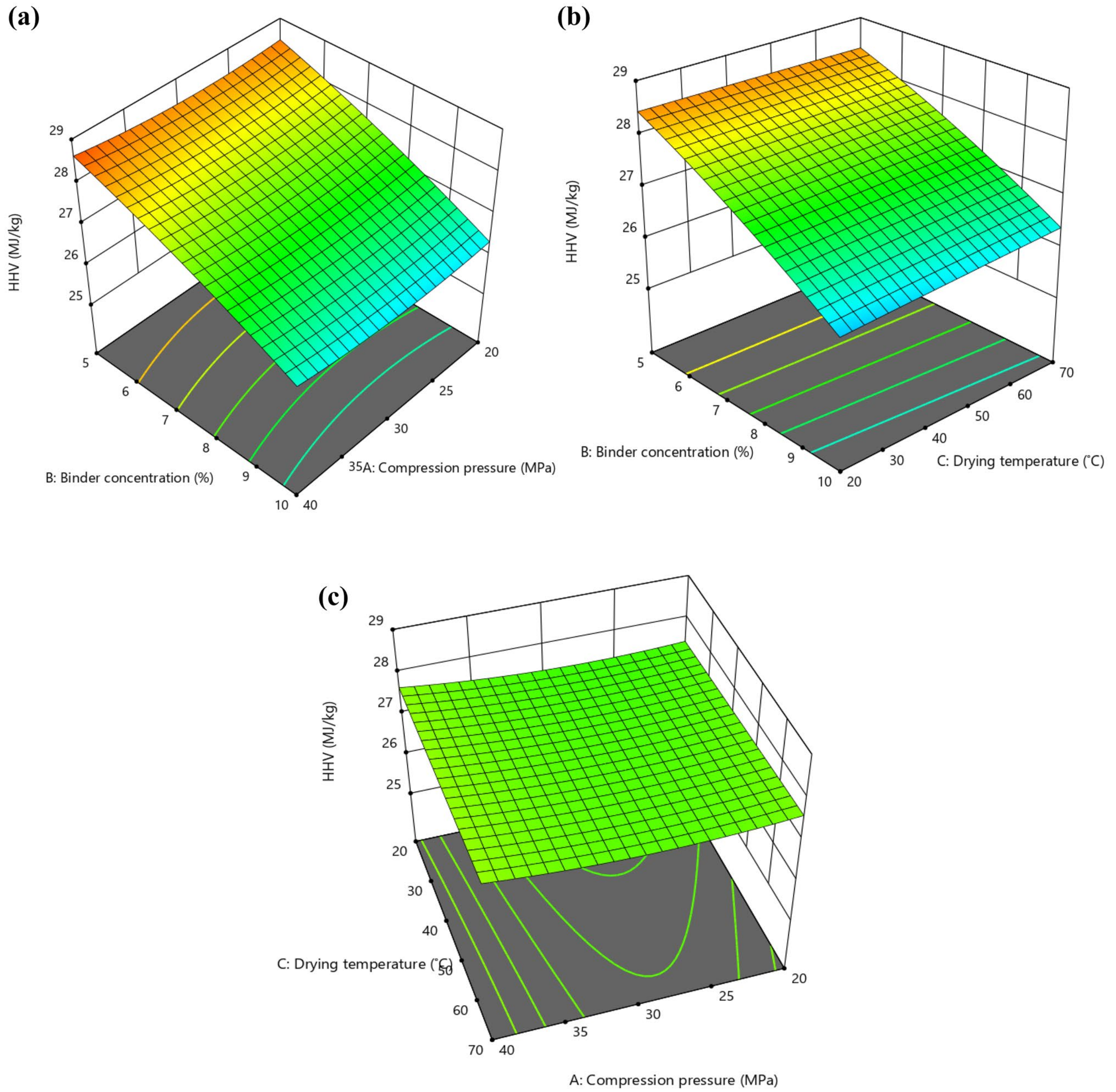

Fig. 3 3-D Response surface plot indicating the effect of **a** compression pressure and binder concentration, **b** binder concentration and drying temperature on the higher heating value, **c** compression pressure and drying temperature

in Eq. 5 describes the variation of the HHV with compaction pressure, binder concentration, and drying temperature. The model terms B, A^2 were found to be significant, where A is compression pressure, B is binder concentration and C is drying temperature. Hence, the final equation for predicting the HHV was attained as follows:

$$HHV = 30.89419 - 0.203006B + 0.001463A^2 - 0.019018C \quad (5)$$

Interactions Between Process Variables and Their Influence on the HHV

The 3-D surface plot shown in Fig. 3a indicates the effects of compaction pressure from 20 to 40 MPa and binder concentration from 5 to 10% on the HHV at a constant drying temperature of 45 °C. The interaction between the compaction pressure and drying temperature was insignificant ($p > 0.05$). Figure 3a shows a linear decrease in the HHV as the binder concentration is increased and a slight decrease in the HHV when pressure is increased. However, the HHV is seen to start to slightly pick up an increase at 30 MPa. Though individually as shown in Table 5, binder concentration influences the HHV, the compaction pressure does not maximise the HHV under the set conditions. Figure 3b shows the absolute nature of the 3-D surface plot for the interaction between binder concentration and drying temperature. The interaction is shown for binder concentration from 5 to 10% and drying temperature from 20 to 70 °C, maintained at 30 MPa. A decrease in HHV is observed as the binder concentration is increased while there is a slight decrease in HHV when the drying temperature is increased any further. The two variables showed an insignificant interaction with the HHV ($p = 0.6778$) (Table 5). Concerning the interaction between compaction pressure from 20 to 40 MPa and the drying temperature of 20 to 70 °C, held at 7.5% binder concentration (Fig. 3c) there was no significant interaction as validated by ANOVA (Table 5). Their individual effects on the HHV further validate and supports the insignificance.

The HHV obtained through the densification process ranged from 25.5 to 28.80 MJ/kg. These values are consistent with charred risk husk [25] and palm kernel briquettes values of 26.8 to 25.2 MJ/kg and 28.18 to 27.51 MJ/kg [66]. The 3-D surface plots illustrated in Fig. 3 and the values shown in Table 5 show the effects of the briquetting process variables and their interactions on the resulting HHV. The results in Table 5 show binder concentration (B) to be the most significant factor influencing the HHV of briquettes as indicated by the larger F-value of 397.09 and smaller p-value of < 0.0001. The HHV significantly decreases from 28.80 to 25.59 MJ/kg as the binder concentration is increased from 5 to 10% (Fig. 3). The decrease in HHV could be attributed to the type of corn-starch quality and the amount [35]. Besides, if the HHV of the binder itself is lower than the material used it decreases its fixed carbon thus decreasing the HHV of the briquettes [67, 68]. Similar behaviour was observed when starch binder concentration was used on kernel palm briquettes, the HHV decreased from 28.18 to 27.51 MJ/kg [66]. On the other hand, the compression pressure does not show any impact on the HHV as indicated by the p-value of 0.2057 and a small F-value of 1.83 (Table 5). This is because the pressure is responsible for enhancing the volumetric value of the briquettes but not the HHV [69, 70]. In this study, it was included to check the possibility of mechanical strength improvement. According to a study by [26], there were similar observations of no statistical influence on the HHV when the pressure was increased from 50 to 150 MPa on eucalyptus briquettes. Additionally, the p-value of 0.4016 and a smaller F-value of 0.7672 (Table 5) indicate that the drying temperature does have not a statistically significant effect on HHV. The limited effect of the drying temperature could be attributed to the fact that this study was limited to a drying temperature of 70 °C. Whilst the studies conducted by [26] observed a slight decrease in the HHV as the drying temperature was increased at temperatures above 80 °C on eucalyptus briquettes.

The Effect of Process Variables on the Compressive Strength for Briquette Production

The ANOVA results show that all the studied factors had significant effects on the compressive strength model (Table 6). The high R^2 of 0.9776 and low CV of 0.8253 shows good precision and reliability of the quadratic model. The adequacy precision of 24.7474 is desirable as it is above 4, proving that the model is significant. The significant model terms for predicting compressive strength are A, B, AB, A^2. Therefore, Eq. 6 gives the mathematical model in terms of compression pressure, binder concentration, and drying temperature.

$$\text{Compressive Strength} = 3.38152 - 0.076512A + 0.035568B + 0.007050AB + 0.001664A^2 \tag{6}$$

Interactions Between Process Variables and Their Influence on the Compressive Strength

The interaction of compression pressure from 20 to 40 MPa and binder concentration from 5 to 10% at a constant drying temperature of 45 °C is shown in Fig. 4a. There was a significant increase in the compressive strength as the compression pressure and binder concentration increased. The figure revealed that there is a significant interaction

Table 6 ANOVA and fit stats summary for compressive strength

Factor	p-value	F value	Effect	Fit stats
Compression pressure (A)	0.0001	351.04	**Significant**	$R^2 = 0.9776$
Binder concentration (B)	0.0001	50.61	**Significant**	Adjusted $R^2 = 0.9574$
Drying temperature (C)	0.4873	0.5201	Insignificant	CV%=0.8253
AB	0.0108			Adeq precison = 24.7474
AC	0.6518			
BC	0.3033			

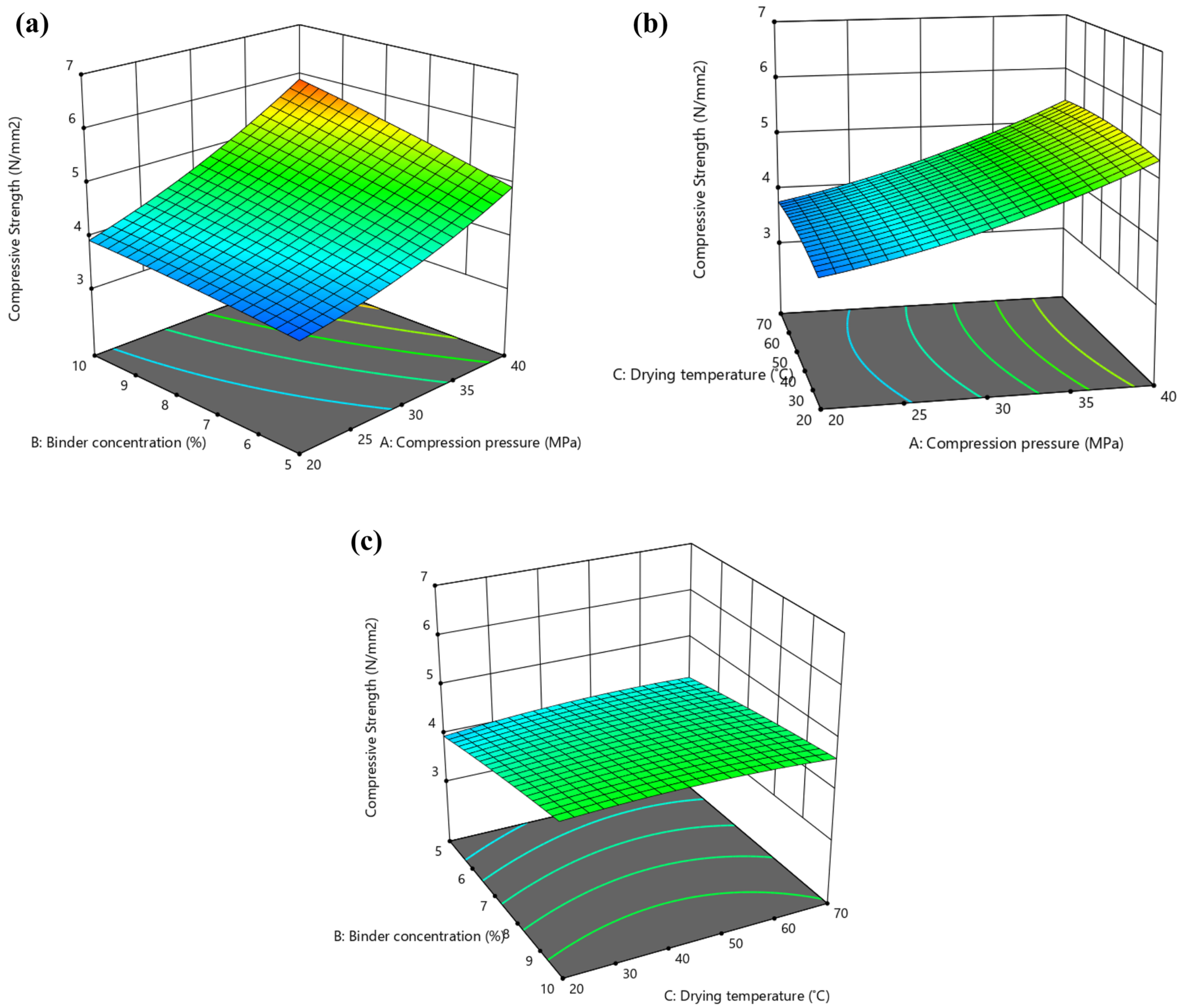

Fig. 4 3-D Response surface plot indicating the effect of **a** compression pressure and binder concentration, **b** compression pressure and drying temperature and **c** binder concentration and drying temperature on the compressive strength

between the compression pressure and binder concentration on the compressive strength. This is further supported by the ANOVA ($p = 0.0108$) in Table 6 and validates the existence of optimum conditions for compression pressure and binder concentration for maximum compressive strength. Figure 4b indicates the effects of compaction pressure from 20 to 40 MPa and drying temperature from 20 to 70 °C on the compressive strength, at a constant binder concentration of 7.5%. There was no interaction between the variables ($p = 0.6518$) (Table 6). Similarly, the interaction between binder concentration from 5 to 10% and the drying temperature of 20 to 70 °C, held at 30 MPa compression pressure (Fig. 4c) was insignificant ($p = 0.3033$) (Table 6). This is consistent with their individual effects on the compressive strength which did not meet the significance ($p > 0.05$).

The effects of the briquetting process variables on the resulting compressive strength are illustrated in the 3-D surface plots shown in Fig. 4 and the correlation is linked to the ANOVA results on the individual factors in Table 6, where only compression pressure and binder concentration show a statistically significant effect on the compressive strength. This is characterised by $p < 0.0001$ and F-value of 351.04 for compression pressure, $p < 0.0001$ and F-value of 50.61 for binder concentration, and $p = 0.4873$ and F-value of 0.5201 for drying temperature. The compression pressure shows a significant effect on compressive strength, an increase in compression pressure from 20 to 40 MPa increases the compressive strength from 3.4 N/mm^2 to approximately 5.5 N/mm^2 (Fig. 4). Correspondingly, binder concentration has a significant effect on compressive strength. Increasing binder concentration increased the compressive strength as illustrated (Fig. 4). These observations can be attributed to the fact that increasing the compressive pressure and the binder concentration create contact between surfaces, which reduces the volume of the pores, and the binder fills all the voids within the material. Hence, creating stronger inter-particle bonds results in stable and firm solid briquettes [1, 71]. The observation agrees with the study by [72] on hardwood spices (*C. mildbreadii*) briquettes where the compressive strength increased from 1.30 to 12.45 N/mm^2. Similarly, [73] on Pongamia (*Pongamia pinnata*) shell briquettes where the compressive strength increases from 6.26 to 20.18 N/mm^2 with an increase in compression pressure and binder concentration. Conversely, the drying temperature showed no statistically significant effect on the compressive strength (p-value of 0.5201 and a low F-value of 0.4873) (Table 6). This could be because, in this study, the drying temperature ranged from 20 to 70 °C within which the drying temperature could be less impactful on the compressive strength (Fig. 4). The influence of the drying temperature on the compressive strength is known to be obtained at higher temperatures (> 80 °C) [26, 44]. A similar trend was observed in a previous study, where peat briquettes showed little/no effect on the compressive strength when drying temperature was increased in the range of 20–80 °C, beyond which a decrease in compressive strength was noticed.

The Effect of Process Variables on Density for Briquette Production

The ANOVA results in Table 7 show the significant model terms for density. The results show high R^2 and low CV of 0.9252 and 2.25 respectively, which indicates good precision and reliability of the quadratic model. The adequacy precision is desirable as it is above 4 (39.4336) verifying the significance of the model. The density had a quadratic relationship with factors A, B, AB, and A^2, by removing terms that are not significant the model was reduced, and Eq. 7 was obtained as follows:

$$Density = -155.07951 + 26.37835A + 36.89090B - 0.460000AB - 0.175344A^2 \quad (7)$$

Interactions Between Process Variables and Their Influence on the Density

There is an increase in density as the compression pressure and binder concentration increase. Figure 5a shows the interaction between compression pressure from 20 to 40 MPa and binder concentration from 5 to 10%, on density, at a constant drying temperature of 45 °C. The relationship between the two variables is linear and directly proportional to the density. Consequently, the interaction of the variables was significant as validated (p = 0.0471) (Table 7). Their significance (p < 0.05) confirms that there exist conditions for these two variables to produce a maximum density. On the other hand, **(**Fig. 5b**)** illustrates the relationship between compression pressure (20–40 M Pa) and drying temperature (20–70 °C) held at a constant binder concentration (7.5%). Although the compaction pressure showed an effect on the density, the drying temperature had no effect as a result there was no interaction between the two variables (p = 0.6002) (Table 7). Likewise, the interaction between binder concentration and drying temperature (Fig. 5c) showed no significant impact (p = 0.6002) (Table 7).

The Influence of Process Variables on the Density

The density obtained through the densification process ranged from 420 to 788 kg/m^3. Figure 5 shows the 3-D surface plot of the effects of compression pressure, binder concentration, and drying temperature on the density. Table 7 results show that compression pressure is the most effective factor on the density of briquettes as indicated by the larger F-value of 938.53 and smaller p-value of < 0.0001 followed by binder concentration (F-value of 41.33 and p-value of < 0.0001). From Fig. 5 the density shows a significant increase when compression pressure increased from 20 to 40 MPa. Consequently, increasing the compression pressure causes particles of the material to be closely packed due to void ratio reduction and deformation of particles resulting in increased density [72, 73]. Also, the

Table 7 ANOVA and fit stats summary for density

Factor	p-value	F value	Effect	Fit stats
Compression pressure (A)	0.0001	938.53	**Significant**	$R^2 = 0.9814$
Binder concentration (B)	0.0001	41.33	**Significant**	Adjusted $R^2 = 0.9252$
Drying temperature (C)	0.1228	2.84	Insignificant	CV% = 2.25
AB	0.0471			Adeq precision = 39.4336
AC	0.6002			
BC	0.6002			

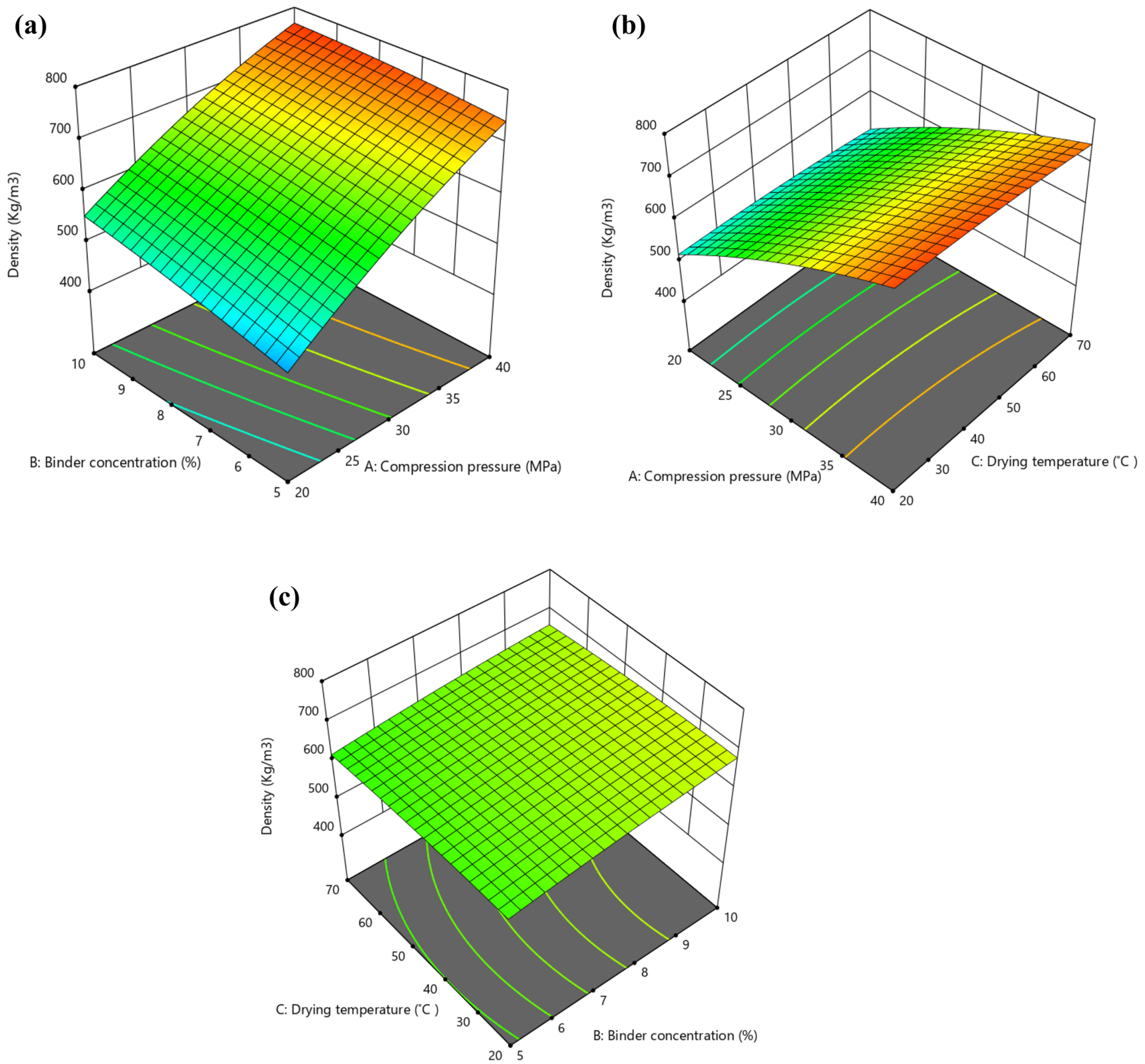

Fig. 5 3-D Response surface plot indicating the effect of **a** compression pressure and binder concentration, **c** compression pressure and drying temperature and **b** binder concentration and drying temperature on the density

density results with an increase in compression pressure from this study are consistent with findings by [72], showing that the equivalent densities at compression pressure of 10–50 MPa ranged from 386 to 658 kg/m^3. The density increases with increased binder concentration from 5 to 10% (Fig. 5). This can be attributed to the increasing addition of binder with a density higher than the actual feedstock [26, 74]. [73, 75] also observed an increment in density from 947 to 1023 kg/m^3 on hardwood spices (C. *mildbreadii*) briquettes and from 358.3 to 425.7 kg/m^3 respectively on corn-cobs briquettes when binder concentration was increased in the range 10–30%. On the contrary, in this study, the drying temperature shows no statistically significant effect on the density with a very low F-value of 2.84 and a p-value of 0.1228 (Table 7). Figure 5c shows that the drying temperature increments had little/no effect on the density. Studies by [70] and [26] also observed no statistically significant effect on the density when the drying temperature was increased from 22.5 to 100 °C on briquettes from sawdust and eucalyptus.

Table 8 ANOVA and fit stats summary for durability

Factor	p-value	F value	Effect	Fit stats
Compression pressure (A)	0.0001	387.19	**Significant**	$R^2 = 0.9831$
Binder concentration (B)	0.0001	97.93	**Significant**	Adjusted $R^2 = 0.9678$
Drying temperature (C)	0.0049	12.91	**Significant**	CV%=0.18645
AB	0.0003			Adeq precision = 27.5857
AC	0.4279			
BC	0.0329			

The Effect of Process Variables on Durability for Briquette Production

All the studied factors had significant effects on the durability property (Table 8). A high R^2 of 0.9831 and a low CV of 0.1864 validated the quadratic model's reliability and precision. Also, the model was confirmed with a desirable Adeq precision of 27.5857. The factors A, B, C, AB, and BC were significant model terms for durability. Therefore, Eq. 8 represents the mathematical model for durability in terms of compression pressure, binder concentration, and drying temperature.

$$\text{Durability} = 98.63656 + 0.031501A - 0.750731B + 0.013729C + 0.013000AB + 0.002400BC \quad (8)$$

Interactions Between Process Variables and Their Influence on the Durability

The interaction between the compaction pressure and binder concentration is significant ($p = 0.0003$) (Table 8). The 3-D surface plot shown in Fig. 6a shows the interaction of compaction pressure (20–40 MPa) and binder concentration (5–10%) on the durability at constant drying temperature (45 °C). There is a linear increase in durability when the compression pressure and binder concentration increase. The significance of the effects of the individual factors ($p < 0.05$) further confirms this. This is further represented by Eq. 8. Similarly, there is a significant interaction ($p = 0.0329$) (Table 8) between binder concentration (5–10%) and drying temperature (20–70 °C) on the durability. It is worthy of note that there is an increase in durability when binder concentration increases, while increasing the drying temperature decreases the durability (Fig. 6b). This implies that keeping the temperatures up to 70 °C reduces the chance of maximising the durability using the set conditions. The results in Table 8; Fig. 6c imply that there is no significant interaction ($p = 0.4279$) between the compaction pressure (20 to 40 MPa) and drying temperature, on the durability at a constant binder concentration (7.5%).

The effects of compression pressure, binder concentration, and the drying temperature are shown in the 3-D surface plots illustrated in Fig. 6. Table 8 represents the ANOVA results for durability. The ANOVA results show that all three factors have significant effects ($p < 0.05$ and larger F-values) (Table 8) on the durability of briquettes. Increasing the compression pressure from 20 to 40 MPa increased the durability of briquettes from 97 to 100% (Fig. 6). It can be attributed to the fact that high pressure (> 10 MPa) causes particles to be close together and can improve the bonding forces in the material [26, 29]. This trend is consistent with the study by [74, 76] that durability increases with increasing pressure. They observed a durability increase on native wood and rice straw briquettes from 93.6 to 98% and 58 to 98.2% respectively when the pressure was increased. Similarly, the binder concentration indicated a positive influence on the durability of the briquettes. The durability increased with increasing binder concentration (5 to 10%) (Fig. 6). This can be attributed to the fact increasing the binder concentration increases the chances of the inter-particles to be more bonded together to form a solid and stable briquette that can handle storage and transportation perturbations [77]. In addition, the particle bonding can be due to pressure reducing the melting point, facilitating inter particulate contact and interactions, moisture increasing the particle bonding due to interfacial forces, capillary pressures, and solid bridges that are formed during densification due to chemical reactions [78]. The durability observed by [74] increased from 70 to 99.2% when the starch binder was increased from 5 to 20% in spruce sawdust briquettes. Furthermore, it can be seen that the drying temperature also had a significant influence on the durability of the briquettes. Increasing the drying temperature from 20 to 70 °C decreased the durability to 97%. The decrease in durability could be explained by the fact that higher drying temperatures result in rapid release of evaporating moisture and cracks forming on the surface of the briquettes making the briquettes too dry and increasing fine particles to fall off [29]. The results are consistent with the study by [79] on rice straw briquettes where the durability reached up to 98.20% when the temperature was kept at < 50 °C, this confirms that strong durable briquettes are better achieved at much lower temperatures.

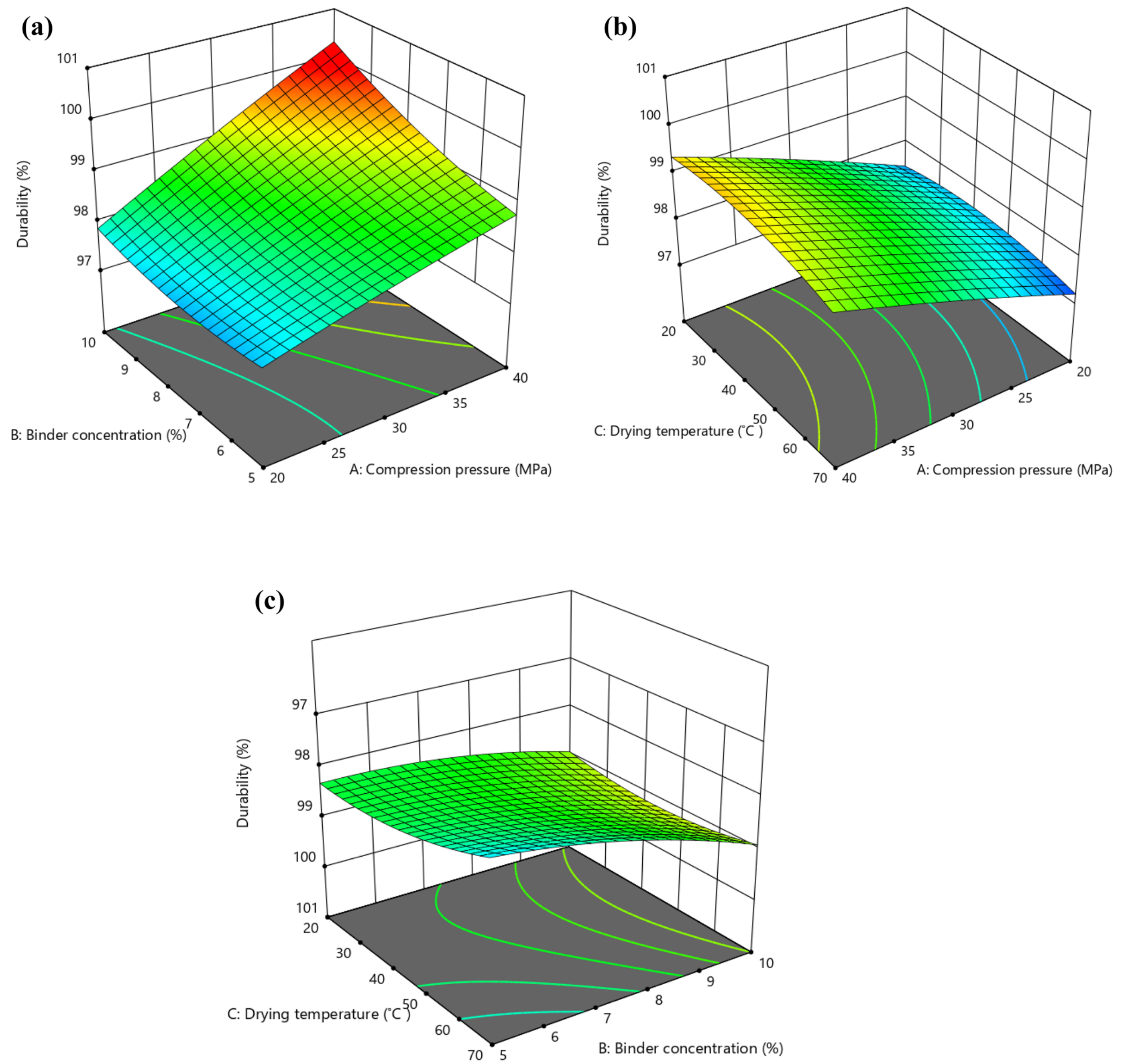

Fig. 6 3-D Response surface plot indicating the effect of **a** compression pressure and binder concentration, **b** compression pressure and drying temperature and **c** binder concentration and drying temperature on the durability

Predictions of Values from RSM

The optimum conditions for carbonised corn stover briquette production were obtained as follows: compression pressure (40 MPa), binder concentration (8.74%) and drying temperature (21.6 °C). At these conditions, the HHV, compressive strength, density and durability as predicted by respective RSM developed models are 30 MJ/kg, 5.76 N/mm^2, 781.11 m^3/kg and 98.62% respectively. The pressure of 38.5 MPa, by [80] contributes to reaching optimal conditions for producing biochar briquettes. This is consistent with the pressure in this study, of 40 MPa where the optimum conditions were met using this pressure range. The reliability of the developed models was verified by preparing carbonised corn stover (CCS) briquettes under the suggested optimum briquetting conditions. These conditions were assessed for HHV, compressive strength, density, and durability, and the mean values were found to be 27.32 MJ/kg, 5.48 N/mm^2, 770.40 m^3/kg, and 98.87% respectively. These were compared with the predicted values from developed models. [81] mentioned that for the reliability of the predictive capability of the developed models, the experimental values should lie within the range of values for a 95% prediction interval (PI). The experimental values obtained are in close agreement with the predicted values, falling within the 95% prediction interval and other values are far above the predicted interval. However, still fall within the 10% error for robust models (Table 9). The experimental and predicted values were significant with considerable small standard deviations, of only 0.19, 0.23, 1.04, and 0.14 for HHV, compressive strength, density, and durability respectively, which further confirms the good correlation between the experimental and predicted values. Figure 7 shows the briquettes produced at optimum conditions.

Fig. 7 Burning smokeless briquettes with a flame

Techno-Economic Analysis

A detailed summary of the process costs that entails the raw material, product, utilities and labour costs is represented in Table 10. The experimental pyrolysis results performed on a small-scale pilot plant estimated the product yields of 46.11% biochar, 30.4% bio-oil and 23.49% biogas. Furthermore, the pyrolysis results were used to propose a briquetting plant with a production capacity of approximately 300 kg/h. This is an average production capacity for small-scale briquetting plants [28, 29]. South Africa is a developing country and the production of carbonised biomass is still in its infancy stage, hence, a lower production rate and batch or semi-batch are attractive.

Total Capital Investment

The total purchase cost of the listed equipment for the briquette production process is $84,255. Table 11 shows that the major contributor to the total purchase cost is the pyrolysis system at 63.74%, which includes the condenser and gas tower. The high installed cost of $53,700 for the pyrolysis system was expected and this is due to the reactor size and operating temperature. Hence, need for materials of construction that can withstand the required temperature (400 °C). The purchase cost of the briquetting machine was estimated to be $10,800, and it is the second contributor at 12.82% of the total purchase cost. This can be attributed to the production rate of the briquette machine. This trend agrees with [27, 28] who reported the combined purchase cost of the pyrolysis system and briquette machine

Table 10 Economic assumptions

Unit	$/Unit	References
Raw material		
Corn stover ($/ton)	40	[82]
Corn starch ($/ton)	45	[38]
Water ($/L)	0.0087	[83]
Product		
Briquettes ($/ton)	650	[38]
Bio-oil ($/L)	0.4	[39]
Biochar ($/ton)	50	[38]
Utilities		
Water ($/L)	0.0087	[83]
Electricity ($/kWh)	0.15	[83]
Labour		
Operator salary ($/Month)	388	[40]

Table 9 Validation experiments for the proposed models

	Pressure (MPa)	Binder (%)	Drying temp (°C)	HHV (MJ/kg)	Strength (N/mm^2)	Density (m^3/kg)	Durability (%)
Predicted value (95% PI)	40.00	8.74	21.60	30.00	5.76	781.11	98.62
Experimental value							
Run 1	40.00	8.74	21.60	27.11	5.42	769.23	98.80
Run 2	40.00	8.74	21.60	27.48	5.73	770.75	99.03
Run 3	40.00	8.74	21.60	27.37	5.28	771.22	98.79
Mean value	–	–	–	27.32	5.48	770.40	98.87
Std dev	–	–	–	0.19	0.23	1.04	0.14

Table 11 Total capital investment

Unit item	Purchase cost ($)	Item cost %
Shredder	5000	5.93
Dryer	4000	4.75
Pyrolysis system	53,700	63.74
Crusher	1105	1.31
Vibrating screen	1200	1.42
Mixer 1	2000	2.37
Mixer 2	5000	5,93
Briquetting machine	10,800	12.18
Drying racks	900	1.07
Bio-oil storage tank	550	0.65
Total purchase cost, C_P	84,255	100
Total bare module cost, $C_{BM-list}=3.63C_P$	305,846	
Total installation, $C_{BM}=1.25C_{BM-list}$	382,307	
Contingency and fee cost, $C_{FC}=0.18C_{BM}$	68,815	
Fixed capital, $FCC=C_{BM}+C_{FC}$	451,122	
Working Capital, $WCC=0.15FCC$	67,668	
Total Capital investment $TCI=FCC+WCC$	518,791	

contributes to the total purchase cost at 89.02% and 73.43% % respectively. To account for all unlisted equipment, an extra 25% of all the listed bare module costs was assumed, to calculate the FCC which was estimated to be $451,122 (Table 11). Thereafter the WCC was determined to be $67,668 assuming 15% of the FCC. Hence, it can be concluded that the required TCI for briquette production will be $518,791. The contribution of each unit of the briquetting system to the life cycle can be highly influenced by the type of equipment employed and the necessity [84].

Total Manufacturing Cost

The breakdown of total manufacturing cost (TMC) for the briquette production process is illustrated in Fig. 8. The direct, fixed, and general expenses were found to constitute 64, 25 and 11% respectively. It can be observed that the direct manufacturing costs (DMC) ($188,514.14) are the highest contributor to the TMC. The high DMC is due to the high cost of raw materials and utility demand of $81,064 and $59,269 respectively. The high raw material and utility demand can be attributed to the demand for the final product, the higher the demand the more utility and the raw material will be consumed. Thus, contributing to increasing in costs. Similar results were observed that raw material and utility costs contributed approximately 25 and 19% respectively to the DMC in wood torrefied briquettes [27]. Whereas [23] reported that raw material and utilities combined contributed about 23.30% in the DMC while operating supplies and labour charges consume about 66.62% combined in pyrolysed maize corncobs. This could be attributed to the fact that the raw material and utilities might have been sourced

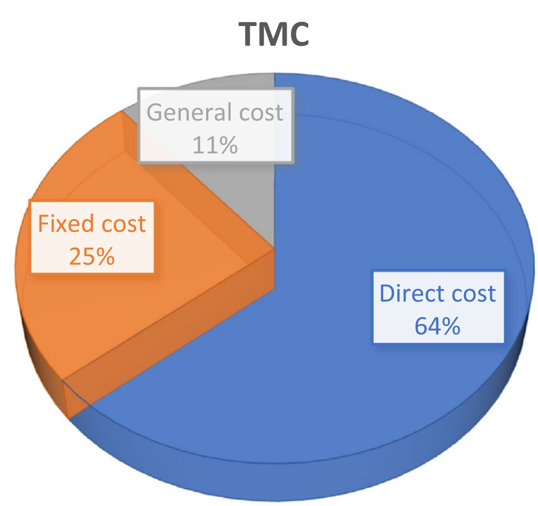

Fig. 8 Breakdown of TMC

for free or at a very lower cost causing the operating supplies and labour charges to be higher in DMC. The fixed manufacturing costs (FMC) are the second contributor at $74,068 to the TMC which is largely due to local taxes and plant overhead in this study. While general manufacturing expenses (GME) are the lowest contributor to the TMC at $30 434 which includes administration, distribution, and selling costs. Hence, the briquette production process requires a TMC of $224,150. From Table 12, it can be concluded that to minimise the DMC which contributes largely to the TMC, the utility usage such as electricity and water needs to be kept as minimum as possible through careful saving because

Table 12 Total manufacturing cost

Cost items	Manufacturing costs ($)
Direct manufacturing cost	
Raw materials	81,064
Utilities	59,269
Waste treatment	0
Operating labour	9312
Direct supervisory labour	1676
Maintenance and repairs	31,127
Operating supplies	4669
Labour charges	1397
Patents and royalties	0
Fixed manufacturing costs	
Depreciation	51,879
Local taxes and insurance	16,601
Plant overhead	5587
General manufacturing costs	
Administration costs	1397
Distribution and selling cost	29,038
Total production cost	212,100
Total manufacturing cost	224,150

Table 13 Generated revenue

Product	Annual revenue ($/y)
Briquette	585,029
Bio-oil	100,320
Total revenue ($)	685,349

it can contribute to a substantial amount of charges in the TMC [85]. It was recommended by a previous study [29], that bio-oil can be alternatively used as a binder instead of starch. This might lower the cost of using water to mix the binder. In addition, the energy used to heat the starch for activation might have significantly contributed to the energy cost. Further, the use of biogas for heating purposes should be considered [86].

Revenue Generated

The total annual sales were determined to be $685,349 as shown in Table 13. The results indicate that the highest contributor to the revenue generated is the briquettes at $585,029 which is 85.36% of the total annual sales (Table 13). This can be attributed to its high selling price of $650/ton, which is due to the quality achieved in this study. Therefore, it can be concluded that the annual sales are dependent on the amount and quality of the briquettes produced. This can

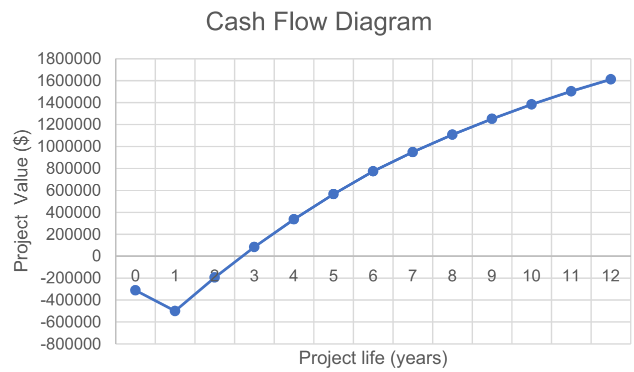

Fig. 9 Cumulative cash flow diagram

Table 14 Economic indicators for base case scenario

PI	This study
DPBP (years)	2.67
NPV ($)	1,612,122
DCFROR (%)	53.10

be corroborated by a study reported by [27] who showed that the quality of briquettes significantly increases the revenue by 19.3% after briquettes undergo carbonisation. Also, [28] reported the minimum selling price of non-carbonised woodchips briquettes was $161.5/MT while the minimum selling price of the woodchips briquette increased the revenue by 69.85% after carbonisation. Table 13 shows that bio-oil contributes the least to the revenue stream as compared to the briquette revenue. The total annual sales for bio-oil were found to be $100 320 which is 14.64% of the total generated revenue and that can be attributed to its low production rate and low selling price as compared to the biochar used to produce briquettes. The low production rate and quality are expected, as the main aim of the slow pyrolysis section is to produce a high volume of quality biochar [85].

Profitability Analysis

The results of profitability indicators (PI) for this study at a discount rate of 10% and from Table 14 discounted cash flow rate of return (DCFROR) and the net present value (NPV) were determined to be 53.1% and $1,612,122, respectively. A higher DCFROR of 48% was observed in the study by [24] for carbonised briquettes from various biomass. However, [87] observed a slightly lower DCFROR of 23.55% in the production of bio-briquettes from cashew nutshell waste. Although these studies are all profitable, their disparities can be due to the cost of feedstock, fixed cost as well as selling price [27, 28]. In this study, the DCFROR is higher than the desired discount rate (> 30%) and the NPV is greater than zero. Hence, the process is considered economically profitable. The attractiveness can be attributed to high revenue profits from the sales of briquettes, and the fact that bio-oil adds to the revenue stream. Likewise, the DPBP (discounted payback period) of 2.64 years meets the desired requirements of less than 4 years, which proves the process is favourable and can increase the attractiveness to investors (Fig. 9). The DPBP is comparable to the study by [88] who obtained a DPBP of 2.5 years for carbonised rice rusk briquette production and [87] who obtained a DPBP of 3.42 years for bio-briquettes from cashew nutshell waste.

Conclusion

This study shows that raw CS under optimised slow pyrolysis conditions produced high-quality biochar with an HHV of 28.89 MJ/kg comparable to those of other biochars produced from biomass using pyrolysis which was converted into briquettes. The effects of compaction pressure, binder concentration, and drying temperature was investigated and was optimised successfully in terms of HHV while obtaining high strength and density for the CCS briquettes. The HHV, compressive strength, density, and durability of the briquettes produced are comparable to that of South African Bituminous A-grade coal. The briquettes were smokeless with low ash and volatile matter content that is suitable for domestic and industrial purposes. Briquette production plant in South Africa from corn stover waste was found to be economically feasible with a DBPB < 4 years, high positive NPV and DCFROR > 30%. This can contribute to relieving South Africa's ever-increasing energy demands. Although this study was seen to be technically and economically profitable, the goals and environmental surroundings of the project should be decided based on the location and availability of feedstock.

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Data Availability No additional information is available for this paper.

Declarations

Conflict of interest The authors declare no conflict of interest.

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