Experimental study of binderless briquetting process: effect of temperature on the fuel briquettes from rice husks

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Abstract. In developing countries' socio-environmental background, fossil fuel use is evolving at the same time as deforestation, resulting in desertification and global warming. There is an urgent need to find alternative sustainable and environmentally friendly sources such as biomass briquettes. This study aims to analyse the effect of densification temperature on characteristics of biomass briquettes produced from rice husks. The densification temperatures applied to each production run varied from 0 to 350°C with an increment of 50°C in a heating screw press. Physical and proximal analysis of briquettes produced at each stage of temperature is done in order to determine bulk density, moisture content, Ash content, volatile matter according to NF standard. A statistical analysis was applied in order model the relationship between briquettes' characteristics and densification temperature. Interpretation of correlation coefficients (0,98) shows that there is a strong correlation between densification temperature and briquette density. As temperature increases, density also increases. However, the correlation (r = 0,44) between densification temperature and ash content is very low, and there is no significant impact.

1. Introduction

In Cameroon, fuel wood is mainly used, about 70% households use it for cooking purposes, with a higher consumption rate in rural areas concerning about 2.5% of households [1]. However, the intensive use of fuel wood contributes to global warming through the phenomenon of deforestation. To this end, it seems crucial to find solutions to the ever-increasing demand for cooking fuel while preserving nature for future generations. Agricultural wastes such as rice husks, coconut husks, fresh water hyacinth, etc., could represent a share of the overall biomass energy resources to be used [2–8]. However, the low energy properties of raw biomass limit the use of their energy potential, thus giving rise to energy recovery to take advantage of this energy as an asset by extension [9]. The conversion of biomass into energy can be achieved in a number of ways, but biomass briquettes might be used to substitute coal, wood, or other fuels in various operations, reducing pollutant emissions and fossil fuel use. Briquetting and densification improve the characteristics of these residues and facilitates transportation, storage, feeding into furnaces, and combustion [5–7,10–17]. Densification consists of compressing biomass to increase its density in order to obtain solid fuel in briquettes form. There are several kind of densification process, the diversity of densification pathways or processes implies a variety of briquettes that differ in their textures, structures, and physico-chemical properties. Thus, the processes generally used are on the one hand densification with the use of binder and on the other hand those without the addition of additives (or binder) [5,18]. Densification with the addition of a binder is commonly used. This additive contributes to improving the agglomeration of the briquette's constituent elements. Nevertheless, briquettes from this process have an average energy yield [6,19]. The other densification process is made by agglomeration under the effect of temperature and pressure of biomass residue fragments using the lignin component of the latter as a natural binder [5,19]. It should be noted that this process guarantees better energy yields according to the literature consulted. These elements lead us to understand that different factors such as temperature and pressure during the densification process contribute to the variation of fuel efficiency. This study contributes to the understanding the effect of temperature on the compaction process of agricultural residues in general and rice husks in particular. and to analyzing the correlation between the densification temperature and the summary physico-chemical parameters of a fuel.

The methodology consists to produce of briquettes with the variation of densification temperatures in a heating press crew varied from 0 to 350°C, and secondly, the summary thermal analysis of the collected samples, and finally a statistical analysis to highlight the existing correlations.

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2. Materials and methods

2.1. Production and sampling of briquettes

The rice husk samples come from the Rice Expansion and Modernization Company of Yagoua (SEMRY). They are stored in a warehouse protected from humidity. They are exposed to the sun for two days before densification. The densifier used to produce the briquettes is a heated mantle screw press, the operating principle of which is illustrated below:

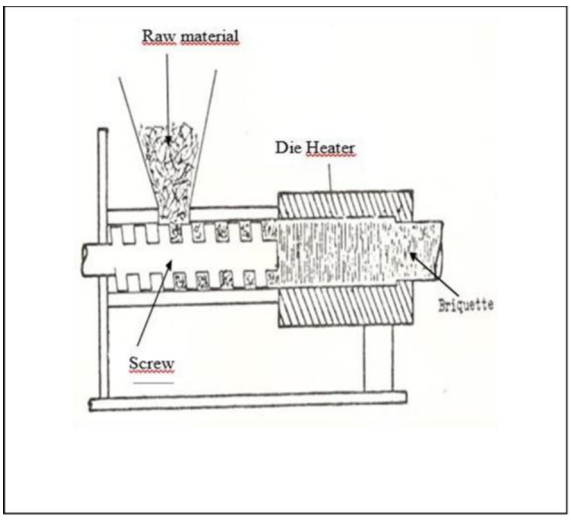
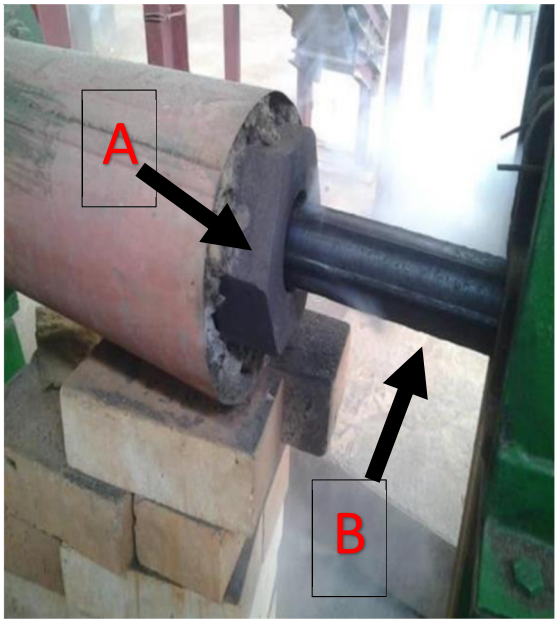


Fig. 1. Operating principle of the heating screw press
Source: LRE, 2018



A: Die heater; B: Briquette

Fig. 2. Rice husk briquette at the outlet of the heating mantle.

by French and European standards. The calliper and the grinding wheel were used to determine the density.

2.2.1. Moisture content (NF EN 14774-2)

A crucible containing the weighed sample is placed in an oven at 105 °C for 24 hours. On removal from the oven, the crucible containing the dry sample is reweighed. The moisture content (MC) on crude represented by a mass fraction is determined according to the following equation:

$$MC(\%)\ \frac{m_i - m_d}{m_1 - m_o} \qquad (1)$$

m_i: initial fuel mass (empty crucible mass + raw sample)

m_d: final mass after drying (empty crucible mass + dehumidified sample)

2.2.2. Volatile matter content (NF M03-004)

The dried sample has been placed in a desiccator to avoid moisture pick-up before being calcined. The dry sample is calcined in an oven at 950°C for 7 minutes to determine the volatile fraction. The determination of the mass loss of the sample then gives the mass fraction of volatile matter. This rate is calculated according to the following expression

$$VM\ (\%) = \frac{m_i - m_f}{m_i} \times 100\% \qquad (2)$$

m_i: initial fuel mass (empty crucible mass + raw sample)

m_f: final mass after devolatilization (empty crucible mass + calcined sample)

2.2.3. Ash content (NF EN 14775)

The biomass in a crucible is heated under a temperature ramp for 30 minutes to 250 °C, held for 1 hour. The sample is then heated under a second temperature ramp for 30 min to a temperature of 550 °C held for 2 h. The ash content is obtained by the following equation which corresponds to the residual non-combustible fraction, the ash content (AC), which gives:

$$AC = \frac{m - m_0}{m_i - m_0} \qquad (3)$$

m: empty crucible mass + incinerated sample
m_0 : empty crucible mass
m_i : empty crucible mass + raw sample

2.2.4. Bulk density

- Rice husk

The density is calculated from the mass of rice husks in a container of known volume (V=100ml). The density (D1) is calculated by the following formula:

$$D1 = \frac{m_i - m_0}{V} \quad \left(\frac{g}{l}\right) \qquad (4)$$

- Rice husk fuel briquettes

The briquettes have an elongated cylindrical shape of height h, outer diameter De with a central opening that gives rise to an inner diameter Di. The hollow cylinder formula (5) is used to determine the volume of briquettes that we have ground down to a mass level m equal to 100gr.

$$Volume(V) = \frac{\pi}{4} \times h \times (D_e^2 - D_i^2)\,,(m^3) \qquad (5)$$

The bulk density is obtained by the following formula:

$$D2 = \frac{m_{br}}{V} \quad \left(\frac{g}{l}\right) \qquad (6)$$

m_{br}: mass of rice husk briquette

2.3. Statistical analysis using the ordinary least squares method

Still called linear regression, this statistical method was chosen to model the relationship between the explanatory variable (densification temperature) and the variables to be explained. Both types of variables are quantitative, continuous and asymmetric. The nature of the relationship between the explanatory variable and the variables to be explained is linear. The explanatory variable in our study is the densification temperature. The variables to be explained are moisture content (MC), density (D), ash content (AC) and volatile matter (VM).

To characterise the relationship between the two categories of variables, we have made different scatter plots which are summarised by the equations 7, 8, 9, and 10. These are simple linear regression models [20–23]:

$$MC_i = \alpha_0 + \alpha_1 \mathbf{T_i} + \varepsilon_i \qquad (7)$$

α_0 and α_1 are the constant and slope coefficients respectively.

$$VM_i = \beta_0 + \beta_1 \mathbf{T_i} + \varepsilon_i \qquad (8)$$

β_0 and β_1 are the constant and slope coefficients respectively.

$$AC_i = \delta_0 + \delta_1 \mathbf{T_i} + \varepsilon_i \qquad (9)$$

δ_0 and δ_1 are the constant and slope coefficients respectively.

$$D_i = \omega_0 + \omega_1 \mathbf{T_i} + \varepsilon_i \qquad (10)$$

ω_0 and ω_1 are the constant and slope coefficients respectively.

For i=1, 2, 3 and 4 taking into account the four sample types on which we applied different temperatures and ε_i the error term.

The linear regression coefficient R^2 between 0 and 1 quantifies the proportion of the variability of the variable to be explained by the linear model. It is in this case of study the equivalent of the square of the correlation coefficient ($-1 \leq r \geq +1$). The closer r is to +1, the more significant the relationship between the variables is and conversely when it tends to -1.

3. Results and discussion

3.1 Interpretation of physico-chemical test results

Figure 3 shows the moisture, ash and volatile matter levels as a function of densification temperature. In general, there is an evolution of the different variables as a function of temperature, no value has remained static. The averages are different from the populations are at different degrees of variance.

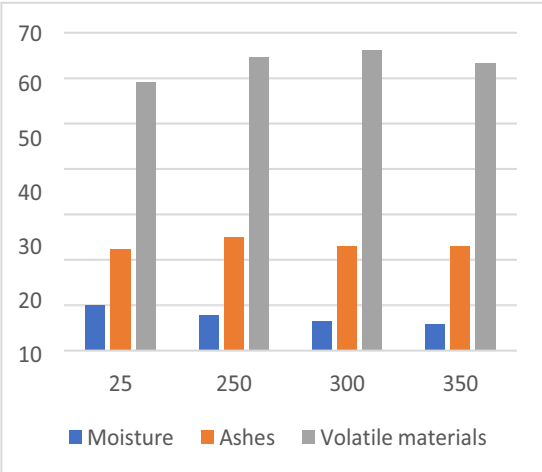


Fig. 3. Bar chart of summary analysis results of rice husks and briquettes at different temperatures.

According to this graph, at 25°C before densification, the rice husks have the highest moisture content among the samples (10%). The briquettes made at 350°C have the lowest moisture content (5.8%). Overall, it can be seen that the moisture content of the samples gradually decreased with temperature. This observation shows that the densification temperature has a considerable impact on the water content of rice husk briquettes. The results of the work of Oladeji [8] and Hounyêvou [18] show moisture contents of 12.67 and 9.82% respectively. The technology they exploited does not include a direct application of temperature during the densification of rice husks. In both cases, compaction is done using a lever press or a manual press and a wet binder is incorporated into the material to be densified.

For the ash content, the diagram shows a slight but constant fluctuation in values. Initially the rice husks in the raw state contain 22.4% ash. This is the lowest level at 25°C. By applying different densification temperatures

this value reaches a peak of 24.9% at 250°C which gradually decreases to 23% at 350°C. The average ash content of the samples is 23.6%. This average is more or less high than the ash content values of each group of samples. It is also slightly higher than the values obtained for the Oladeji briquettes (19%) and those of the Guemene [19] whose content is 21%. As a reminder, Guemene briquettes were densified at 250°C by the same technology we used. The ash results of our work are close to those of Oladeji and Guemene, which means that the different densification temperatures we applied had an impact on the ash content, but it is not significant.

Finally, Figure 3 shows a moderate variation in the volatile matter content as a function of the densification temperature. In the raw state, the rice husks contain 59% volatile matter. At 25°C before densification, this is the lowest level. When applying different densification temperatures this value peaks at 66.2% at 300°C and drops to 63% at 350°C. The average volatile matter of our samples is 63.2%. This average is more or less higher than the volatile matter percentages of each group of samples. It is also significantly lower than the percentages contained in the Oladeji briquettes (67.98%) and those of Guemene which is 67.37%. There is therefore a closeness between the Oladeji, Guemene and our study values which shows that the densification temperature has a very low impact on volatile matter. The graph below is an illustration of the evolution of the density as a function of the densification temperature.

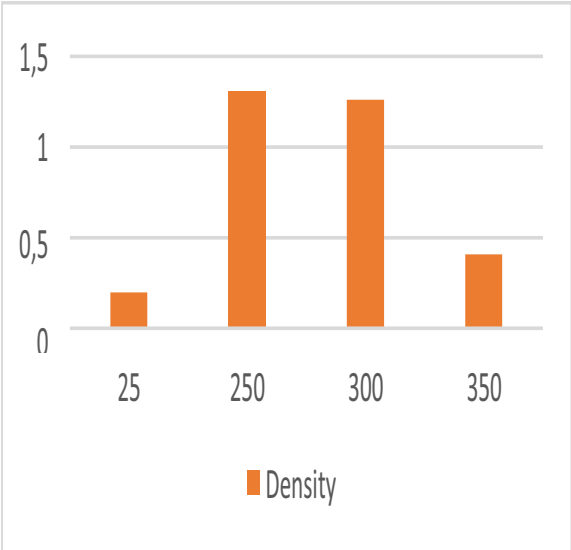


Fig. 4. Bar graph of the density of rice briquettes and rice husks at different temperatures

The density of rice husks in their non-agglomerated state (25°C) is only 0.2. From the moment they are subjected to the densification temperatures and pressure inside the heating mantle, briquettes are obtained with a density value that reaches a peak of 1.3 at 250 and 300°C. Hence the compact and dense character shown in Figure 6.

Fig. 5. Rice husk briquettes at 250 and 300°C.

We can see from Figure 6 that the rice husk briquettes have a long, circular shape with an inner diameter of 20mm that extends lengthwise. This central opening allows air to move through the briquette. However, at 350°C there is a drop in density from 1,3 to 0,4.

Poorly formed briquettes are observed at the exit of the machine, in the form of rice husk aggregates (see Figure 7).

Fig. 6. Rice husk briquettes at 350°C at 70.105 K

We can see from this picture that the densification of the rice husks was not successful. At 350°C, the compaction pressure remained the same, the residence time decreased from 10min to 5min. The binder probably did not form well and/or because of the reduced residence time the compaction of the rice husks could not take place. This could be a case where the densification pressure is not adjusted to the densification temperature. We believe that the compaction pressure should also have been changed at this temperature to favour the conditions for good densification. Based on the densification parameters mentioned, it appears that the increase in temperature without adjusting the densification pressure and/or the residence time of the rice husks would be the cause of the result obtained. Figures 8, 9, and 10 show images of briquettes produced under different densification parameters by Guemene and Oladeji respectively.

The conditions for densification by Guemene are the same as for our research work. The difference is that the densification temperatures are limited to 150 and 200°C for a pressure of 7MPa. Figure 8 below is an image of the agglomerated but not briquetted rice husks when the densification temperature is around 150°C.

Fig. 7. Rice husks densified at 150°C

At 150°C, the rice husk particles start to stick together, but the temperature is not sufficient to induce the physico-chemical forces that cause the lignin to plasticize properly. At the densification temperature of 200°C, an apparent hexagonal briquette-like shape is shown in the following Fig. 9, but the central aperture that allows aeration during combustion has not yet formed.

Fig. 8. Rice husks densified at 200°C

The rice husk particles therefore stick together more, yet the temperature is still not sufficient. As they are not well densified, these pieces of rice husks compacted like those produced at 150°C are not yet (in terms of texture and structure) rice husk briquettes.

Oladeji has made its briquettes with a pressure of 2MPa and the addition of wet binder. This pressure is obtained with a manual press without any application of temperature. The briquettes obtained are shown in the figure below:

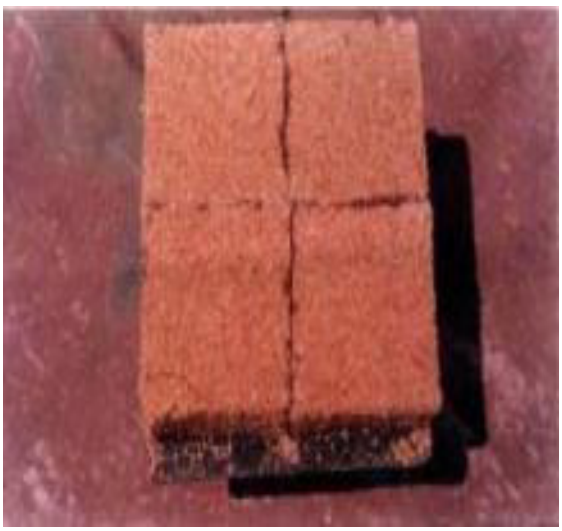


Fig. 9. Rice husk briquettes
Source: Oladeji, 2010

In this picture we can see briquettes of rice husks in a cubic shape. Comparisons with the work of Guemene and Oladeji provide evidence of the impact of temperature on the quality of density. But the latter does not depend only on the densification temperature. To obtain a good densification there should be a good adjustment of the residence time, the quality of the binder and the densification pressure.

3.2. Results of the statistical analysis

Table.1 Correlation and causal links results

	Variables			
Criteria	MC and T°	AC and T°	VM and T°	D and T°
ρ	-0,9841	0,4666	0,4638	0,8352
R^2	0,9684	0,2151	0,2177	0,6976

ρ: correlation coefficient

R^2: coefficient of determination

3.2.1 Link between moisture content (MC) and densification temperature (T°) (ρ=-0,984 ; R^2=0,968)

The correlation coefficient tends towards -1, the negative

linear relationship is strong. This indicates that the temperature and humidity variables move in opposite directions. In figure 3, we saw, while the temperature is high, that of the humidity decreases.

The causality coefficient is close to 1, which implies not only that the temperature has an impact on the amount of water in the fuels, but also that this impact is very significant. In conclusion, the densification temperature explains or causes the moisture content. This confirms the results of the summary analysis

The figure below shows the results of applying the ordinary least squares method to the moisture content data. The linear regression coefficient R^2 (0.9) indicates the proportion of the variability of the moisture content that is explained by the linear model. Its value in this particular case is close to 1, which indicates a good fit of the model to the data.

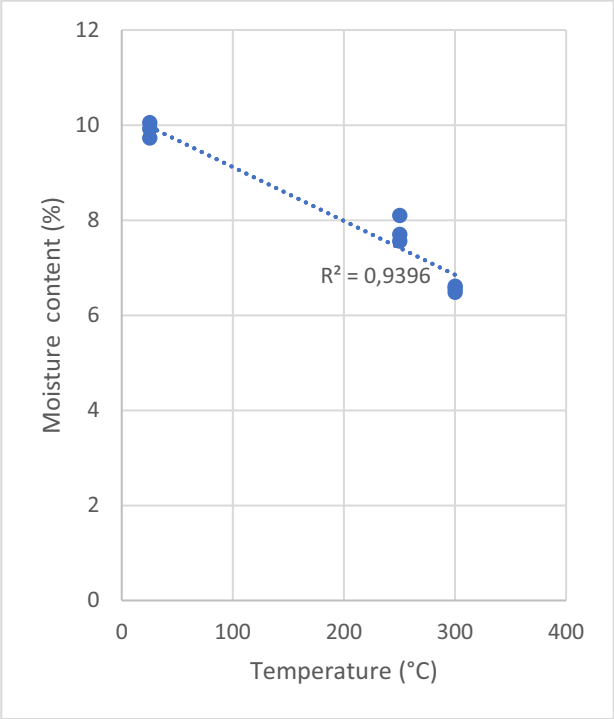


Fig. 10. Scatter plot showing the evolution of moisture content as a function of densification temperature

The correlation coefficient (r≈-1) reflects a strong and negative affine relationship between densification temperature and moisture content of rice husk briquettes. Indeed, according to the results of the moisture content analysis tests, there is an inverse proportional evolution to the densification temperature.

3.2.2 Link between ash content (AC) and densification temperature (T°) (ρ=0,467 ; R²=0,215)

The correlation coefficient displays a value of 0.467 which is not entirely significant. The linear model can not explain de trend. A non-linear model have been used to do so. The following diagram shows the response of applying non-linear regression to the volatile components.

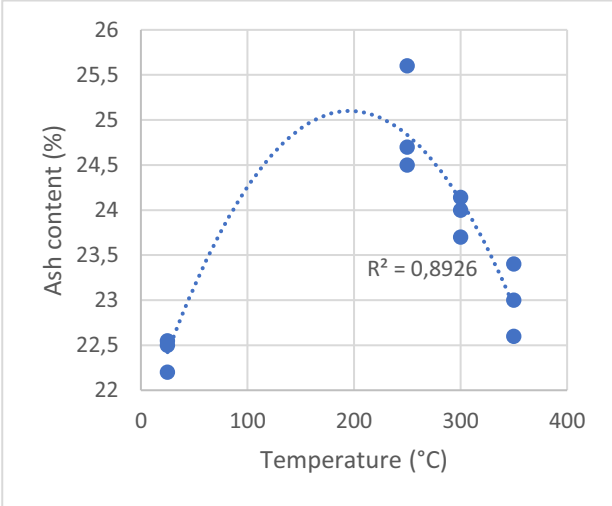


Fig. 11. Scatter plot showing the relationship between ash rate and densification temperature

The non-linear regression coefficient R^2 (0.89) indicates that the proportion of the variability of the ash rate that is explained by the model is very small. In fact, the scatter plot is scattered and far from the regression line. There is a slight fluctuation in the ash content as the different densification temperatures are applied.

3.2.3 Link between volatile matters (VM) and densification temperature (T°) (ρ=0,464 ; R²=0,218)

The correlation coefficient displays a value of 0.467 which is not entirely significant. The linear model can not explain de trend. A non-linear model have been used to do so. The following diagram shows the response of applying non-linear regression to the volatile components.

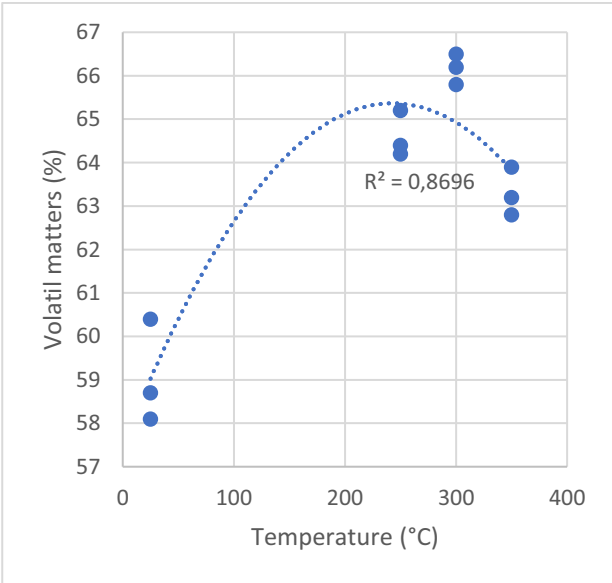


Fig. 12. Scatter plot showing the evolution of volatile matter as a function of the densification temperature

The new linear regression coefficient R^2 (0.86) indicates that the proportion of the variability in volatility that is explained by the model is medium. The scatterplot is irregularly distributed and spaced. The correlation coefficient R^2 (0.86) shows that the relationship between the two variables is significant. By analogy with the analytical results, it can be seen that the volatile matter content evolves gradually in the same direction as the temperature up to 300°C, after which a slight decrease is observed.

3.2.4 Link between density (D) and densification temperature (T°) (ρ=0,835 ; R²=0,698)

The following diagrams show that the temperature variable alone does not explain the density of briquettes. The scatter plot of the first diagram shows a strong affine relationship between the densification temperature and the evolution of the density of rice husk briquettes. The linear relationship is perfect and positive due to the value of the regression coefficient which is approximately equal to 1. This means that the variability of the ash rate which is explained by the model is very strong.

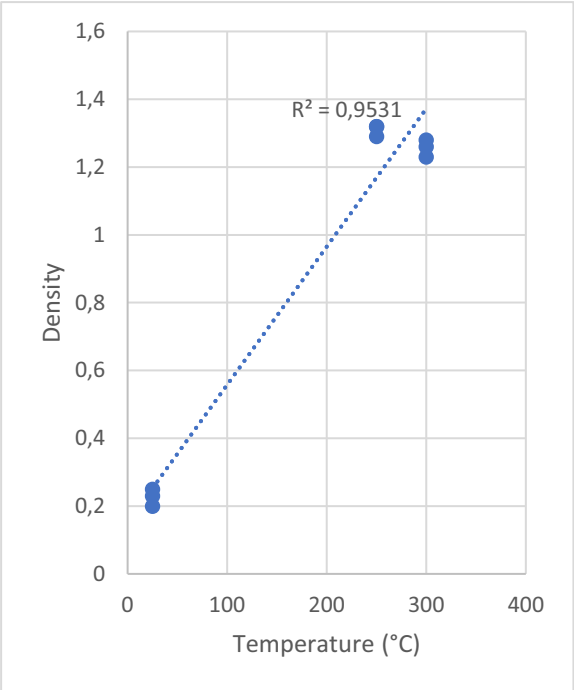


Fig. 13. Scatter plot showing the relationship between densification temperature and density up to 300°C

According to the value of the correlation coefficient R^2 (0.95), the relationship between temperature and density is strong. However, the explanatory model is adequate and the correlation is perfect up to 300°C. The following graph is a continuation of graph a. Here the temperatures extend up to 350°C. Whereas in the previous graph they stop at 300°C.

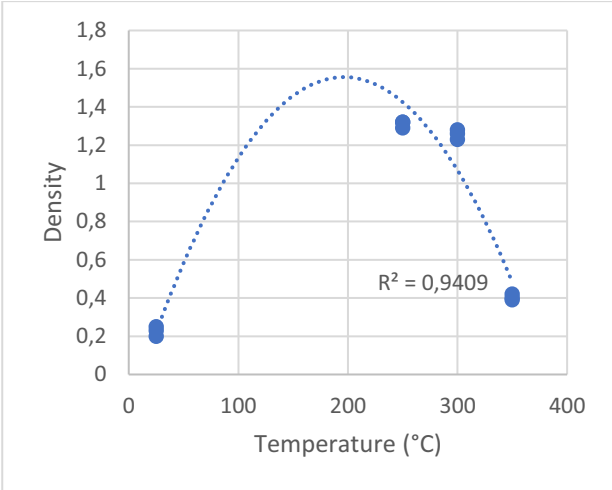


Fig. 14. Scatter plot showing the relationship between densification temperature and density up to 350°C.

According to this illustration, the fit of the regression model to the data is very poor since only a tiny part of the sample population is now explained according to the no linear regression coefficient R^2 (0.94). Furthermore, the correlation coefficient indicates that the relationship between the two variables is now slightly average although still positive. The decrease in correlation coefficients suggests that there are other parameters besides temperature that could be responsible for the density values. This observation means that the density of rice husk briquettes is indeed affected by the densification temperature. But to obtain a good densification of rice husks, it would be necessary to have an adequate adjustment between the different densification parameters, namely: temperature, pressure and residence time.

4. Conclusion

The question raised by our study was to determine the impact of densification temperature on the physicochemical characteristics of rice husk briquettes. It appears that moisture and density changed in proportion to the temperature. The volatile matter and ash content changed little. Thus, the data analysis highlights the strong correlation between water content and densification temperature with an R2 = 0.94. This strong correlation is also observed between density and densification temperature, with a value of R2 = 0.98. Taking into account the results of the statistical analysis, which corroborate the results of our tests, we can state that the choice of the densification temperature determines the water content and density of the briquettes and consequently its energy capacity. The quality of a rice husk briquette can be improved by controlling the densification temperature. The latter should therefore be taken into account when setting up the densification conditions for the heated screw press. Although temperature is to some extent responsible for the evolution of certain.

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