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Insight into the production factors influencing the physicochemical properties of densified briquettes comprising wood shavings and rice husk

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ABSTRACT

The present work aims at elucidating the impact of various densification parameters on the physicochemical and combustion properties of fuel briquettes issued from the co-processing of wood shavings (W) and rice husks (RH) using a mechanical piston press machine. To that end, a design of experiments integrating three feeding speeds (15.76, 18.56, and 21.73 mm·s^{-1}), two wood particle sizes (< 7 mm and between 7 and 10 mm) and six different RH contents ranging from 0 to 100 wt% was built. The obtained results showed that all the above operating factors influence the apparent density of the produced briquettes. Values ranging from 1143 to 1247 kg·m^{-3} were notably measured, with the highest one determined when considering a low feeding speed, small wood particles and an RH proportion of 80 wt%. While increasing the RH content led to an increase in the briquette density, the obtained results also showed that the higher the RH content, the lower the water resistance index. Measured values indeed went from 94 % on average for pure wood to ~85 % for pure RH, attesting to the potential challenge associated with the storage of briquettes containing high RH contents. As for the net calorific value, it was shown to rise from ~11 to ~ 16 MJ·kg^{-1} when varying the proportion of wood between 0 and 100 wt%. This trend was especially traced to an increase of the wt% of volatile matters in the produced briquettes accompanied by a decrease of their ash content. Combustion tests performed with different briquette samples then allowed inferring burning rates between 10.9 and 13.4 g·min^{-1}, specific fuel consumptions ranging from 115.8 to 138.4 g·l^{-1} and combustion efficiencies of around 12 %. As highlights, these tests demonstrated that the higher the wood content, the higher the burning rate, the lower the specific fuel consumption and the higher the combustion efficiency. Finally, two tested briquette formulations containing 80 and 100 wt% of wood were shown to have better combustion properties than a commercial firewood used for comparison. Total greenhouse gas (CO_2 and CH_4) emissions were even found to be reduced by 9.4 % when burning the RH-containing sample instead of firewood, while providing the same amount of sensible heat to a 3-l volume of water. These findings thus highlight the potential interest of beneficiating biomass wastes into briquettes for heat generation, further noting that the development of this type of alternative energy carrier offers multiple advantages in terms of waste management, reduction of the deforestation induced by the intensive use of firewood and mitigation of climate change through a potential reduction greenhouse gas emissions.

1. Introduction

Global concern over the depletion of fossil fuels and the increasing greenhouse gas (GHG) emissions issued from their combustion has surged the search for alternative, renewable, and sustainable energy sources. In this context, biomass, a carbon-neutral resource, has attracted particular interest. It includes lignocellulosic biomass as forestry and agricultural wastes (Wang et al., 2017), municipal organic solid wastes (MSW), as well as algae and aquatic plants (Goyal et al., 2008; Guedes et al., 2018). Compared with conventional energy sources, lignocellulosic biomass is characterized by a high moisture content (up to 15–50 % in mass (Asamoah et al., 2016)), relatively low bulk and energy densities (between 40 and 250 kg·m^{-3} (Mani et al., 2003; Kaliyan and Vance Morey, 2009; Tumuluru et al., 2011) and mainly below 20 MJ·kg^{-1} (Ali et al., 2024), respectively) and high heterogeneity in terms of shape and size. Consequently, it is challenging to handle, transport

Abbreviations: DoE, Design of experiments; GHG, Greenhouse gas; MSW, Municipal solid wastes; SSA, Sub-Saharan Africa.

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and store in loose form (Kaliyan and Vance Morey, 2009; Duca and Toscano, 2022; Nganko et al., 2024). Furthermore, the direct combustion of raw biomass is generally characterized by a low thermal efficiency, further noting that biomass combustion is commonly associated with the emission of pollutants which negatively impact human health and the environment (Ly et al., 2013; Krishnamoorthi et al., 2023; Mekonen et al., 2024). More efficient conversion methods or techniques must therefore be used and/or developed to produce efficient fuels from biomass.

Different routes can be considered for converting biomass into biofuels and chemical products (Sharma et al., 2015; Okolie et al., 2022), including biochemical (Kwietniewska and Tys, 2014; Maurya et al., 2015), thermochemical (Wang et al., 2017; Liu et al., 2017; Uddin et al., 2018), and physical or mechanical processes. With physical methods, which this paper focuses on, biomass and/or wastes or by-products issued from the agricultural and agri-food industries are processed into densified and uniform solids, called briquettes, which can be used to meet household, commercial or industrial energy needs, and as substitutes for firewood or charcoal. This low-cost process improves product properties, in terms of moisture content, density, and calorific value (Ibitoye et al., 2021; Marreiro et al., 2021) and enables easier storage and handling of the obtained fuel, reducing transportation costs (Theerarattananoon et al., 2011; Chen et al., 2015; Bajwa et al., 2018; Azargohar et al., 2019; Marreiro et al., 2021; Zhang et al., 2023; Gizaw et al., 2024).

Several technologies used to produce briquettes have been reviewed in the literature. These include the manual press, the mechanical and hydraulic piston press, the screw press, and the roller press (Dinesha et al., 2019; Kpalo et al., 2020a). These machines are usually classified based on their intrinsic compaction pressure: low (up to 5 MPa), medium (from 5 to 100 MPa) and high (100 MPa and above) (Orisaleye et al., 2023). They have been used in numerous studies to produce briquettes from a variety of residues (Muazu et al., 2015; Okot et al., 2018; Gill et al., 2018; Kpalo et al., 2020b; Bot et al., 2023; Duangkham and Thuadaij, 2023; Orisaleye et al., 2023; Akam et al., 2024). The selection of a given technology for briquetting, however, depends on several factors, including the expected properties of the products, the production scale, and the characteristics of the raw biomass used. Generally, mechanical piston press machines are used for large-scale production and offer several advantages. These include a high compaction pressure (roughly 200 MPa), a high production capacity (from 200 to 2500 $kg \cdot h^{-1}$), adaptability to various particle sizes (between 1 and 10 mm), low specific energy consumption and extended machine service life (Kpalo et al., 2020a). In addition, such machines produce briquettes with high densities ranging from 1.0 to 1.2 $g \cdot cm^{-3}$ (Demisu and Muluye, 2023), although they require regular maintenance and are unsuitable for producing briquettes with carbonized biomass (Ibitoye et al., 2021). The quality of briquettes produced using a mechanical piston press machine is mainly a function of the feedstock properties (i.e., type of biomass, particle size, and moisture content) and operating conditions characterizing the densification process, such as the temperature and pressure (Yunusa et al., 2023; Ali et al., 2024), as further discussed below. It is classically assessed through the proximate and ultimate analyses of the briquettes and by their calorific values. Other essential criteria, such as the stability and durability during storage, and transport and handling, are evaluated by measuring the strength and water resistance of the briquettes (Marreiro et al., 2021; Obi et al., 2022). Finally, the combustion properties and environmental impacts of the produced fuels are often characterized by determining their burning rate (Yunusa et al., 2023) while measuring the gas emissions issued from their oxidation (e.g., CO_2, CH_4, NO_x, etc.).

As part of ongoing initiatives aimed at substituting firewood or charcoal with different types of biomass while reducing GHG emissions and indoor pollutants, several lab-scale studies, discussed in the reviews by Gilvari et al. (2019), Marreiro et al. (2021), Gong et al. (2023) and Yunusa et al. (2023), have evaluated the influence of the operating conditions of the densification process on the quality of the briquettes produced. A summary of these reviews indicates that several operating factors need to be considered to guarantee the production of high-quality densified fuels. The first is the moisture content of the feedstocks. This content mainly influences the density and calorific value of the briquettes. Feedstocks having a high moisture content (above 12 %) indeed produce low density briquettes (as indicated in (Li and Liu, 2000), for example) whose combustion generates less useful thermal energy due to the amount of heat required to evaporate water. On the other hand, dry feedstocks require more energy input to be compacted (Dinesha et al., 2019). An optimal moisture content, typically ranging from ~5 to ~10 %, must therefore be selected, as recommended by Li and Liu (2000), Kaliyan and Vance Morey (2009), Brožek (2016) and Ali et al. (2024), to foster the production of high-quality solid fuels. The second parameter, which also affects the physicochemical properties of densified briquettes and their production cost, is the particle size. Studies, including those by Mitchual et al. (2013) and Setter et al. (2021) for example, have reported that fine particles (with a size less than 2 mm) promote mechanical interlocking when being compacted at high temperature and pressure, thus resulting in stronger and denser briquettes. In contrast, Tumuluru et al. (2015) investigated the effect of the feedstock granulometry on the density of briquettes produced from wheat straw (*Triticum aestivum* L.) while considering particle sizes ranging from 19.10 mm to 31.75 mm. The authors observed that particles between 24.00 mm and 31.75 mm in size produced denser briquettes, thereby reducing the production cost associated with the crushing of raw biomass. In a previous study, Ahmed et al. (2014), for their part, mentioned that combining particles 6–8 mm in size with 13–15 wt% of particles whose size was less than 4.75 mm improved the briquette durability by aiding the mechanical interlocking of the particles while minimizing the void space in the solid. To conclude, and contrary to the observations from Mitchual et al. (2013) and Setter et al. (2021), Song et al. (2010) concluded that an increase in particle size could result in better particle binding and compaction. According to Gong et al. (2023), increasing the particle size could notably induce a better mechanical interlocking of biomass fibers, as well as a stronger bonding between particles and an improved product mechanical strength. That diverging trends emerge from the literature suggests the existence of significant interactions among the densification variables (temperature, pressure, etc.), which influence the properties of the obtained products. The above discrepancies regarding the effect of the particle size on the briquette density, moreover, underline the need for further research, which explains why this parameter is especially investigated in the present work. Of note also, the influence of the particle size on other briquette properties is still unclear. For instance, it was found in a recent study by Ngangyo Heya et al. (2022) that the particle size had no impact on the ash content at a 95 % confidence level. The briquettes produced from fine particles (0.42 mm) therein still had a higher ash content (11.55 %) than those issued from the use of larger particles (1.6 mm) having an 8.20 % ash content. Since the ash content can heavily damage combustion equipment due to corrosion issues while reducing the thermal efficiency of facilities (Marreiro et al., 2021), reducing this content in briquettes is highly desirable, hence justifying the interest in further analysis of the factors prone to influence this property.

As far as operating parameters governing the densification process are concerned, increasing the temperature and compaction pressure globally improves the production of high-quality briquettes. Indeed, high temperatures allow biomass to expand, leading biopolymers to become flexible and to transition from a glassy to a rubbery state, while high pressures facilitate their bonding (Dinesha et al., 2019; Gong et al., 2023). Among the works which have investigated the influence of these parameters, Zhang et al. (2019) notably concluded that a temperature of 101.9°C and a pressure of 127.7 MPa (which can be easily achieved using a mechanical piston press as considered herein) were ideal for the production of denser briquettes when using foxtail millet bran waste

(*Setaria italica* (L.) P. Beauv.) as a feedstock. However, the identification of optimal temperature and pressure values generally depends on the feedstock properties and on the equipment used (Gong et al., 2023), thus prompting the need for systematic parametric studies.

As for the influence of the composition of the materials used to produce briquettes, lignocellulosic biomass has a complex structure, with biopolymers whose proportions vary depending on the considered feedstock (Wang et al., 2017). These differences in terms of biochemical composition are known to influence the physical and combustion properties of the obtained densified fuels. Biomass rich in lignin, protein and starch and having a low ash content indeed produces briquettes with a high density and calorific value under optimal operating conditions (Kpalo et al., 2020a; Demisu and Muluye, 2023; Gong et al., 2023). Alternatively, for biomass with lower lignin, starch and protein contents, it is recommended to use binders (such as cassava starch (*Manihot esculenta*), molasses, and red soil, among others) to facilitate the bonding of the particles during the briquetting process (see the reviews by Olugbade et al. (2019) and Obi et al. (2022) as examples). For biomass samples having a high ash content, it is recommended to combine them with other feedstocks characterized by a lower ash content to obtain higher quality briquettes (see (Ajimotokan et al., 2019; Waheed et al., 2023) among others).

The above literature review highlights the importance of considering multiple operating factors when producing densified fuels. It is essential to carefully select these factors before starting the briquetting process. While many studies focus on the production and characterization of the physical properties of briquettes (see (Dinesha et al., 2019; Gilvari et al., 2019; Marreiro et al., 2021; Demisu and Muluye, 2023; Gong et al., 2023) as examples, and references therein), little attention has been devoted to assessing heat production and pollutant emissions resulting from the combustion of biomass briquettes in the context of cooking applications. Finally, relatively few studies deal with the impact of the feeding rate of the feedstock in the briquetting unit on the quality of the produced briquettes. One rare study covering this was proposed by Orisaleye et al. (2023), who evaluated the impact of the feeding speed (from 2.4 to 3.3 $mm \cdot s^{-1}$) on the physical properties (i.e., density and durability) of obtained products. The results of their study indicated that a feeding speed of 3.3 $mm \cdot s^{-1}$ provided higher quality briquettes. Nevertheless, little followed by way of analysis of this trend.

In view of the forgoing, the objective of the present study is to elucidate the influence of the press feeding speed, particle size, and feedstock mixing ratio on the quality and combustion behavior of briquettes produced from the densification of wood shavings and rice husk (*Oryza sativa* L.) using a mechanical piston press. A mixed factorial design of experiments whose results were statistically processed through an analysis of variance was accordingly used. As for the quality of the obtained briquettes, it was characterized by analyzing their physical properties (i.e., density and water resistance) and chemical properties (moisture, ash, volatile matter and fixed carbon contents and calorific value). Furthermore, the burning rate, combustion efficiency and fuel specific consumption of some briquette samples selected based on their density and calorific value were also evaluated, while CO_2, CH_4 and NO_2 emissions following their combustion were measured.

Among the novelties of this study is the fact that it aims to assess the impact of adding rice husks to wood residues on the physicochemical and environmental performances of briquettes used for household cooking applications. Indeed, although densified fuels are commonly burnt for domestic use (cooking, water and space heating) in some developing countries (Mwampamba et al., 2013; Ferronata et al., 2022), investigations focusing on the characterization of briquettes in this specific context are quite rare, as can be seen by looking at the numerous references listed in the above literature survey. Note also that while different works investigated the impact of production factors, such as the particle size or the compaction pressure, on the physical properties of obtained briquettes, few of them, however, analyzed the influence of the press feeding speed, as mentioned above. This is still achieved herein for completeness. Finally, the main combustion features of the densified fuels (heat production and pollutant emissions) are also addressed herein considering realistic combustion conditions with respect to the targeted application. Here again, this contribution is quite new since among the few works which investigated the performances of biomass briquettes for cooking applications, none analyzed the emissions resulting from their oxidation, with the exception of the studies by Narzary et al. (2023) and Ganesan and Vedagiri (2024), which, however, do not deal with blends of wood shavings and rice husk. Thanks to all these aspects, the present work is quite comprehensive and original, and can provide insights into how to select briquette formulations and densification operating conditions beneficial to the overall quality of the produced fuels.

2. Materials and methods

2.1. Feedstocks

Table 1 presents the physical properties and the proximate analysis of the feedstocks used in the present work. Wood shavings (W) and rice husks (RH) were provided from wood sawmills and rice processing plants in Somanya, Ghana. Of note, wood (mixture of neem (*Azadirachta indica*), ayous (*Triplochiton scleroxylon* K. Schum), and mahogany (*Khaya spp*) wood residues) and rice husks, which represent forestry and agricultural wastes, respectively, were selected due to their abundance in the area. Note that the results reported in Table 1 are in line with those issued from Asamoah et al. (2016) and Wang et al. (2022a).

Table 2 provides the biochemical analysis of the raw biomass samples. The hemicellulose, cellulose, and lignin wt% values for wood are relatively close to those estimated in (Wang et al., 2017; Fischer et al., 2024). Similarly, the hemicellulose, cellulose and lignin values reported in (Abbas and Ansumali, 2010; Bazargan et al., 2020; Ali et al., 2024) for rice husk were comprised between 11.96 and 20.90 wt%, 28.70 and 35.00 wt% and 15.38 and 28.25 wt%, respectively, which is consistent with the results depicted in Table 2. Note that the ash content of RH is quite high (see Table 1), while its lignin content is relatively low (see Table 2). These features thus make the mixing of RH with W a good option for beneficiating the former, while still obtaining high-quality briquettes as explained earlier.

2.2. Briquette production

Fig. 1 illustrates the briquette production process. Wood shavings were first ground using a biomass crushing machine (JKMT105, 50 HP, manufactured by Jay Khodiyar Company) to obtain wood particles with sizes of less than 10 mm. Wood and rice husks were dried in an indirect solar dryer for 48 hours. This process allowed to obtain feedstocks with a moisture content ranging between 7 % and 10 %. Wood was sieved manually to obtain two particle size levels (less than 7 mm and 7–10 mm). Subsequently, feedstocks were weighed using a digital scale (My Weigh KD-8000) according to the desired mixing ratios (see sect. 2.3) to obtain a total mass of 100 $\pm$ 2 kg for each formulation.

An automated mechanical piston press machine having a capacity of 100 to 800 $kg.h^{-1}$ (depending on the feedstock), and operating with a compaction pressure of 120 MPa, was used for the briquetting process (JK 65, Model: JKMT 105, manufactured by Jay Khodiyar Company). This device is equipped with a feed hopper and a screw conveyor connected to a variable-speed motor (ratio: 30/1, 3 HP, 1440 RPM, 440 volts, 50 Hz) to carry the feedstocks to the compaction zone. A 60 mm-diameter die and a transmission system, consisting of a connecting rod and an eccentric disc connected to a motor (ratio 10/1, 10 HP, 1140 RPM, 440 volts, 50 Hz), convert raw biomass into uniform solid briquettes. A control panel displaying the temperature and the main characteristics of the conveyor motor (voltage, current, and frequency) allows monitoring the main operating parameters of the production line. The facility finally includes a water cooling system, activated when the

Table 1
Physicochemical properties of the feedstocks used in this study.

Feedstock	Density/ $g\cdot cm^{-3}$	Proximate analysis/ wt%				Net calorific value/ $MJ\cdot kg^{-1}$
		Moisture[c]	Ash[d]	Volatiles[d]	Carbon[d,e]	
Rice husk	0.09 – 0.14[a]	6.40	20.22	64.56	15.22	11.39
Wood (size < 7 mm)	0.20[b]	7.16	2.03	83.08	14.89	15.33
Wood (Size of 7–10 mm)	0.20[b]	8.04	1.73	83.11	15.16	15.38

[a] value taken from Mansaray and Ghaly (1997);
[b] value taken from Tumuluru et al. (2011);
[c] as received (ar);
[d] dry basis (db);
[e] by difference

Table 2
Biochemical analysis of tested biomass samples.

Raw biomass	Biochemical analysis/wt% - db		
	Hemicellulose	Cellulose	Lignin
Rice husk	13.9	33.6	19.5
Wood	10.0	50.4	26.6

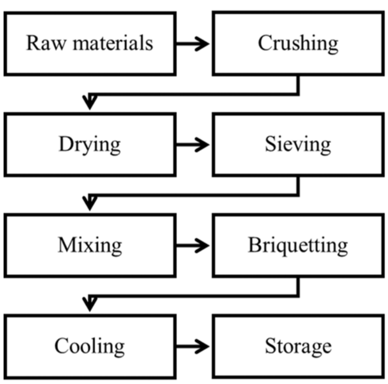

Fig. 1. Diagram of the briquetting process.

temperature of the die exceeds 100°C, and a cooling line for the briquettes. Before the production of the samples begins, a start-up protocol which involves preheating the die to ~100°C was implemented to follow the recommendation of the manufacturer. The above experimental arrangement was used to produce 36 different formulations of briquettes, as described in the following section. Finally, the produced samples were stored in a room (at a temperature ranging between 25 and 29°C) before being analyzed.

2.3. *Design of experiments*

To investigate the impact of the feeding speed (FS), the wood particle size (PS), and the wood/rice husk mixing ratio (W/RH) on the physicochemical and combustion properties of the produced briquettes, a three-variable mixed factorial design of experiments (DoE) was used. To that end, three feeding speeds were set (15.76, 18.56, and 21.73 $mm\cdot s^{-1}$), two wood particle size levels were selected (less than 7 mm and comprised in the 7–10 mm range) and six mixing ratios were chosen such that briquettes containing 0, 20, 40, 60, 80 and 100 % of rice husks were obtained. Of note, the FS were selected to cover the range of speeds which can be set using the press machine used herein while the mixing ratios were defined to obtain compositions going from pure W to pure RH. This design of experiments resulted in 36 formulations as summarized in Table 3. Note that to designate a specific formulation, the following nomenclature is adopted: FS‘a’-PS‘b’-W/RH‘c’/‘d’, where ‘a’ corresponds to the level associated with the feeding speed (1 for 15.76 $mm\cdot s^{-1}$, 2 for 18.56 $mm\cdot s^{-1}$, and 3 for 21.73 $mm\cdot s^{-1}$), ‘b’ corresponds to the level characterizing the wood particle size (1 for less than 7 mm and 2 for 7–10 mm), while ‘c’ and ‘d’ correspond to the mass percentages of wood and rice husks in the blends, respectively. As an example, the formulation identified as FS2-PS1-W/RH40/60 denotes briquettes produced with a feeding speed of 18.56 $mm\cdot s^{-1}$, wood particles having a size below 7 mm and weight percentages of wood and rice husks of 40 and 60 wt%, respectively.

Table 3
Mixed factorial DoE.

Run	Formulation	FS /$mm\cdot s^{-1}$	PS /mm	W/RH/wt%	
				W	RH
1	FS1-PS1-W/RH100/0	15.76	< 7	100	0
2	FS1-PS2-W/RH100/0	15.76	7–10	100	0
3	FS1-PS1-W/RH80/20	15.76	< 7	80	20
4	FS1-PS2-W/RH80/20	15.76	7–10	80	20
5	FS1-PS1-W/RH60/40	15.76	< 7	60	40
6	FS1-PS2-W/RH60/40	15.76	7–10	60	40
7	FS1-PS1-W/RH40/60	15.76	< 7	40	60
8	FS1-PS2-W/RH40/60	15.76	7–10	40	60
9	FS1-PS1-W/RH20/80	15.76	< 7	20	80
10	FS1-PS2-W/RH20/80	15.76	7–10	20	80
11	FS1-PS1-W/RH0/100	15.76	< 7	0	100
12	FS1-PS2-W/RH0/100	15.76	7–10	0	100
13	FS2-PS1-W/RH100/0	18.56	< 7	100	0
14	FS2-PS2-W/RH100/0	18.56	7–10	100	0
15	FS2-PS1-W/RH80/20	18.56	< 7	80	20
16	FS2-PS2-W/RH80/20	18.56	7–10	80	20
17	FS2-PS1-W/RH60/40	18.56	< 7	60	40
18	FS2-PS2-W/RH60/40	18.56	7–10	60	40
19	FS2-PS1-W/RH40/60	18.56	< 7	40	60
20	FS2-PS2-W/RH40/60	18.56	7–10	40	60
21	FS2-PS1-W/RH20/80	18.56	< 7	20	80
22	FS2-PS2-W/RH20/80	18.56	7–10	20	80
23	FS2-PS1-W/RH0/100	18.56	< 7	0	100
24	FS2-PS2-W/RH0/100	18.56	7–10	0	100
25	FS3-PS1-W/RH100/0	21.73	< 7	100	0
26	FS3-PS2-W/RH100/0	21.73	7–10	100	0
27	FS3-PS1-W/RH80/20	21.73	< 7	80	20
28	FS3-PS2-W/RH80/20	21.73	7–10	80	20
29	FS3-PS1-W/RH60/40	21.73	< 7	60	40
30	FS3-PS2-W/RH60/40	21.73	7–10	60	40
31	FS3-PS1-W/RH40/60	21.73	< 7	40	60
32	FS3-PS2-W/RH40/60	21.73	7–10	40	60
33	FS3-PS1-W/RH20/80	21.73	< 7	20	80
34	FS3-PS2-W/RH20/80	21.73	7–10	20	80
35	FS3-PS1-W/RH0/100	21.73	< 7	0	100
36	FS3-PS2-W/RH0/100	21.73	7–10	0	100

Of note, formulations produced from pure wood in the design of experiments were specifically included to better evaluate the relative quality of the briquettes issued from blends containing rice husks as compared with that of briquettes produced from wood, which are commonly available on the local market. Note also that different formulations were actually duplicated. These especially included the FS1-PS1-W/RH0/100 (Run 11) and FS1-PS2-W/RH0/100 (Run 12) samples, which are identical since they are produced from pure rice husk and do not contain any wood particle affected by the PS. Similarly, the FS2-PS1-W/RH0/100 (Run 23) and FS2-PS2-W/RH0/100 (Run 24), as well as the FS3-PS1-W/RH0/100 (Run 35) and FS3-PS2-W/RH0/100 (Run 36) formulations correspond to identical pairs. As a consequence, only 33 different types of briquettes were considered and ultimately tested. That being said, comparing the results obtained with these duplicated formulations, allowed to verify that the production tests were reproducible, which turned out to be the case, as illustrated below.

2.4. Characterization of briquettes

The characterization of the physicochemical properties of the briquettes includes the measurement of their apparent density (ρ), also referred to as relaxed density in (Obi et al., 2022; Yunusa et al., 2023), water resistance index (WRI) and net calorific value (NCV). Each measurement was repeated three times. Mean values are thus presented below, noting that error bars in the graphs account for the dispersion of the experimental data around mean values.

The procedure allowing to measure the apparent density was similar to that described in (Gill et al., 2018; De Conti et al., 2022). Density, by definition, is the ratio of sample mass to volume. The mass of the samples was determined using a digital balance (Sartorius CPA623S), while their diameter and height were measured using a digital caliper (MAKTIC H-7352). Finally, ρ (expressed in $kg \cdot m^{-3}$) was calculated as follows:

$$\rho = \frac{mass\ of\ the\ briquette\ sample}{\pi \times (D_B{}^2/4) \times H_B} \tag{1}$$

where D_B and H_B respectively denote the diameter and the height of the briquette.

The water resistance index, which allows to estimate the water retention rate when briquettes are exposed to wet environments or rainfall during transport, storage, or handling, was determined as described in (Rajaseenivasan et al., 2016; Kpalo et al., 2020b). The samples were weighed using a digital balance (Sartorius CPA623S), immersed in water at room temperature (25°C) for 30 seconds, and reweighed. The typical starting weight was set to around 200 g. The WRI (in %) was finally calculated as per Eq. (2):

$$WRI = 100 - \frac{W_2 - W_1}{W_1} \tag{2}$$

where W_1 and W_2 are the initial and final mass of the samples (expressed in g), respectively.

As for other analyses, they included the estimation of the moisture (ASTM E-871), volatile matter (ASTM D-1102), and ash (ASTM E-812) contents, as well as the measurement of the net calorific value (ASTM D2015–96). The theoretical ash content of each produced briquette was, moreover, also computed using an additivity rule of type:

$$Ash_{Briquette} = wt\%W \times Ash_W + wt\%RH \times Ash_{RH} \tag{3}$$

where $Ash_{Briquette}$, Ash_W, and Ash_{RH} represent the ash content of the briquette, wood and rice husk materials, respectively, while $wt\%W$ and $wt\%RH$ denote the weight percentages of wood and rice husk in the considered formulation. Similarly, the theoretical content of volatile matters in each briquette (referred to as $VM_{Briquette}$) was computed using Eq. (4):

$$VM_{Briquette} = wt\%W \times VM_W + wt\%RH \times VM_{RH} \tag{4}$$

with VM_W and VM_{RH} being the volatile matter content of wood and rice husk, respectively.

The detailed procedure used to perform the proximate analyses can be found in (Ndecky et al., 2022), noting that a Fisher Isotemp programmable furnace apparatus (Model 497) was used. The net calorific value of the briquette samples was measured using a calorimetric bomb (Gallenkamp Ballistic CBB 330) and the fixed carbon content was finally calculated by difference.

2.5. Statistical analysis of the DoE results

A comparative Analysis of Variance (ANOVA) with a post-hoc Tukey honestly significant difference test was conducted to statistically analyze the impact of the production parameters (i.e., FS, PS, and W/RH) on the density, water resistance, and chemical properties (i.e., moisture, ash, volatile matter, and fixed carbon content) of the produced briquettes. All these analyses were performed using the R statistical software while considering a significance level of 0.05.

2.6. Combustion tests

The combustion tests first consisted in measuring the time required to heat a fixed volume of water to a target temperature when burning a given mass of briquette sample. To that end, indoor experiments were carried out in a kitchen measuring 3.3 m × 3.3 m × 2.2 m, in which the ambient temperature was 25°C. The cook stove, which is depicted in Fig. 2, is an improved version of the traditional "three-stone" stove widely used for cooking in Somanya, Ghana, and sub-Saharan Africa by rural and urban populations. This experimental arrangement was especially considered to mimic realistic conditions leading to results of interest with respect to the targeted application. The stove was built based on a recycled rim (45 cm in diameter and 20 cm in height), with a metal plate added underneath to collect residual material after the briquette samples burnt. The equipment used, moreover, included a metallic vessel capable of holding 5 liters (l) of water, a timer, a thermocouple (Reotemp 72841 A) allowing to continuously measure the water temperature T as a function of time t, and an earthenware bowl for cooling the remaining briquette residue and ash after combustion. A volume of 3 l of water was heated up to a temperature of 80°C during the experiments. To that end, a briquette with a mass of 500 g was placed on the cook stove. The specific briquette formulations which were tested were selected based on the briquettes' density and net calorific value, as detailed in sect. 3. To uniformly initiate combustion, 50 ml of kerosene was poured over the briquettes, which were lit with a gas lighter following the procedure used in (Nikiema et al., 2022). The test duration was set to 60 minutes, during which the water temperature was recorded every 5 minutes. Before being weighed, the combustion residues as well as the unburnt briquette samples were cooled down by covering them with an earthenware bowl. During the tests, it was observed that the combustion of some briquette samples did not allow to reach the above-mentioned target temperature of 80°C. A second series of tests were therefore carried out in order to estimate the mass of briquettes needing to be burnt in order to heat the 3 l of water up to 80°C. This

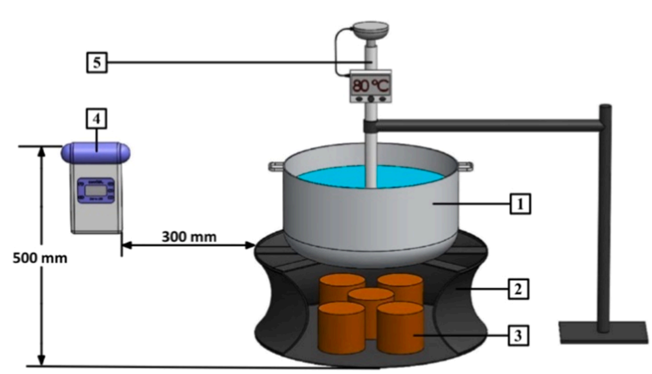

Fig. 2. Diagram of the experimental setup implemented for the combustion tests: 1: metal vessel; 2: cook stove; 3: briquette samples; 4: gas detector; 5: thermocouple.

experimental procedure allowed to estimate different combustion properties, including the burning rate, the combustion efficiency, and the specific fuel consumption of the briquette samples, as detailed below.

The burning rate (BR, in g·min^{-1}), defined as per Eq. (5), corresponds to the ratio of the mass of solid fuel burnt during the set time (Narzary et al., 2023; Sunnu et al., 2023; Ganesan and Vedagiri, 2024), so that:

$$BR = \frac{m_i - m_f}{t_t} \quad (5)$$

where m_i (expressed in g) is the initial briquette mass, m_f is the mass (in g) of ash and remaining briquette weighed after the combustion, while t_t is the total time (in min).

The specific fuel consumption (SFC, expressed in g·l^{-1}) represents the mass of briquette burnt per unit liter of water heated up to the target temperature. Following (Narzary et al., 2023; Sunnu et al., 2023; Ganesan and Vedagiri, 2024), it was calculated as per Eq. (6):

$$SFC = \frac{m_i - m_f}{V_{wf}} \quad (6)$$

where V_{wf} stands for the final volume of water (in l).

As for the combustion efficiency (CE, in%) which was computed based on Eq. (7), it is defined, according to Ganesan and Vedagiri (2024), as the ratio of the energy involved in heating water over the energy released during the combustion of the solid fuel, so that:

$$CE = \frac{m_{wf} \times c_{pw} \times (T_f - T_i) + (m_{wf} - m_{iw}) \times L_w}{(m_i - m_f) \times NCV} \quad (7)$$

where m_{iw} is the initial mass of water (expressed in kg), T_i is the initial temperature of water (in °C), m_{wf} stands for the final mass of water after the combustion test (in kg), T_f is the final temperature of water (in °C), c_{pw} is the specific heat capacity of water (4.18 kJ·kg^{-1}·°C^{-1}), L_w is the latent heat of vaporization of water (2260 kJ·kg^{-1}), and NCV is the briquette sample net calorific value (in kJ·kg^{-1}). Note that since the target temperature was set to 80°C herein, the focus was hence on the left-hand term of Eq. (7) denoting the sensible heat provided to the water, as detailed in sect. 3.3.

To conclude, the concentrations of CO_2, CH_4, and NO_2 released during the combustion tests were also measured using an Aeroqual Series 505 gas detector positioned as depicted in Fig. 2.

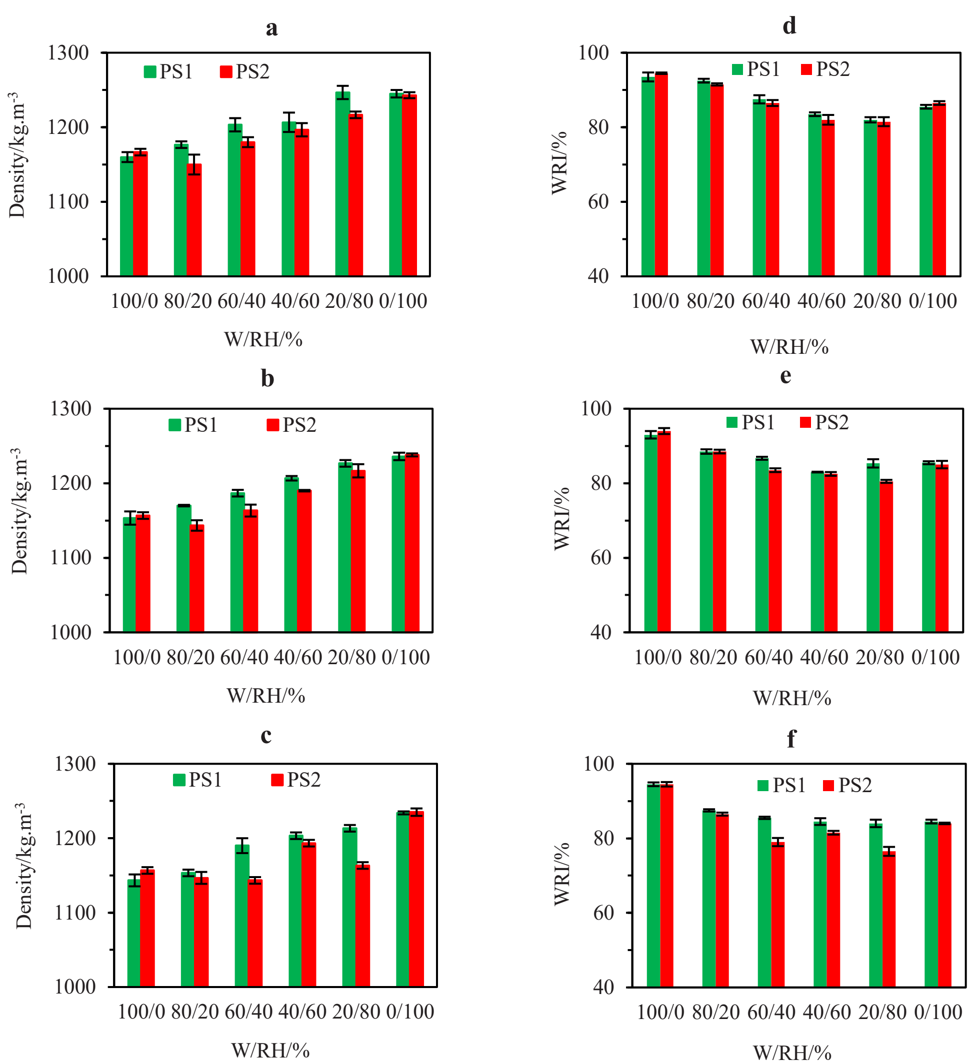

Fig. 3. Variation of the apparent density (a, b, and c) and water resistance index (d, e, and f) as a function of the particle size (PS1 = <7 mm and PS2 = 7–10 mm) and of the wood/rice husk mixing ratio for feeding speed of 15.76 mm·s^{-1} (a and d), 18.56 mm·s^{-1} (b and e) and 21.73 mm·s^{-1} (c and f).

3. Results and discussion

3.1. Impact of the operating parameters of the densification process on the physical properties of the obtained briquettes

3.1.1. Apparent density

Fig. 3a, b, and c depict the variation of the apparent density of the briquette samples for feeding speeds of 15.76, 18.56, and 21.73 mm·s^{-1}, respectively. Note that the values used to obtain these graphs are summarized in Table SM1, provided in the Supplementary Materials to this article, for completeness. Similarly, the results of the statistical analysis of the DoE are detailed in Table SM2 in the Supplementary Materials. The reader is thus referred to this table for more details regarding the analysis of variance, noting that the discussion proposed below will mainly focus on the F and p values, which respectively denote the variance ratio and the probability factor indicating whether or not the difference between group means is statistically significant (verified when $p < 0.05$).

As can be seen by looking at the results summarized in Fig. 3 and Tables SM1 and SM2, the mixing ratio tends to influence the apparent density of the briquettes, as corroborated by the analysis of variance showing that the impact of this parameter on ρ is statistically significant (F (5,72) = 220.660, $p < 0.001$). The general trend emerging from the obtained data especially shows that the higher the rice husk content, the higher the density. This is notably exemplified by the values reported in Table SM1, which monotonically increase with the W/RH ratio. As an illustration, for PS1, ρ varies from 1143 ± 8, for pure wood, to 1234 ± 2 kg·m^{-3}, for pure RH, when using an FS of 21.73 mm·s^{-1}. This trend is actually in line with the observations from Ibitoye et al. (2023), who showed that compressed and relaxed densities of briquettes produced from corncob (*Zea mays* L.) and rice husk increase with the RH content. This specific behavior can likely be explained by the fact that rice husk may contain starch and proteins (Saha et al., 2008; López et al., 2011; Friedman, 2013; Yang et al., 2015; Le Guen et al., 2019; Srivastava et al., 2021). At high densification temperatures (~100°C, as in this study), proteins can plasticize, while starch is likely to gelatinize to serve as a binder, causing the bonding of biomass particles and improving the quality of the obtained densified materials (Gong et al., 2023).

As for the effect of the wood particle size on ρ, the analysis of variance shows that this parameter significantly impacts the apparent density of the obtained briquettes (F (1,72) = 71.760, $p < 0.001$). Specifically, and as depicted by the plots of Fig. 3a, b, and c, the lower the wood particle size, the higher the density, which is consistent with the conclusions drawn in (Mani et al., 2006; Mitchual et al., 2013; Gill et al., 2018; Setter et al., 2021). This phenomenon can notably be traced to a reduction of the void spaces and to an increase of the contact surfaces between the particles composing the briquettes when finer granulometries are considered.

The analysis of variance, moreover, leads to conclude that the feeding speed also significantly influences the apparent density of the produced briquettes ((F (2,72) = 33.323, $p < 0.001$). This is particularly exemplified by the graphs of Fig. 3a, b, and c, as well as by the values listed in Table SM1, which highlight a decrease of ρ when increasing the FS value. This observation, however, contrasts with the conclusions by Orisaleye et al. (2023), who reported an increase in the density of briquettes produced from poplar wood fiber when increasing the feeding screw speed (from 2.4 to 3.3 mm·s^{-1}) of the hydraulic-powered densification machine they used. Actually, these diverging trends can originate from numerous factors, including the selection of feedstocks having different properties, in addition to the use of distinct densification technologies whose intrinsic operating variables vary significantly and directly affect the properties of the obtained densified products, as underlined by Gong et al. (2023). On the other hand, that a decrease of ρ is noted when the feeding speed increases is still consistent with the fact that the greater the FS, the shorter the retention time of the feedstocks in the die and the lower the density, which is in line with the conclusions by Li and Liu (2000), who especially showed that increasing the retention time favors the production of briquettes having a higher density. This is, moreover, in line with the results previously reported by Zafari et al. (2013).

The results from Fig. 3a, b, and c and Table SM2 also show that the density of the FS1-PS1-W/RH0/100 and FS1-PS2-W/RH0/100 samples are statistically identical (1245 ± 5 kg·m^{-3} versus 1243 ± 4 kg·m^{-3}), as is the case for the samples FS2-PS1-W/RH0/100 and FS2-PS2-W/RH0/100 (1236 ± 5 kg·m^{-3} versus 1238 ± 2 kg·m^{-3}) and FS3-PS1-W/RH0/100 and FS3-PS2-W/RH0/100 (1234 ± 2 kg·m^{-3} versus 1235 ± 5 kg·m^{-3}). This thus illustrates that the properties of the duplicated samples are highly identical, hence showing that the production tests performed in this study are well reproducible, as previously stated in sect. 2.3.

Finally, it is noteworthy that although the density values measured in the present work (comprised between 1143 and 1247 kg·m^{-3}) are higher than those reported in different studies considering widely varying biomass types and densification facilities (see (Gendek et al., 2018; Okot et al., 2018; Kpalo et al., 2020b; Orisaleye et al., 2023), for instance), they are still in line with those reported in a series of works dealing with the briquetting of biomass using a hydraulic press machine (between 1000 and 1300 kg·m^{-3}) (Kpalo et al., 2020a; Niño et al., 2020; Setter et al., 2021), hence strengthening the overall consistency of the results obtained. To conclude, and since a high density is particularly desired when converting biomass into fuel briquettes, the results reported in this section suggest that considering a low PS and FS together with a relatively high RH content can be of interest.

3.1.2. Water resistance index

The evolution of the water resistance index of the produced briquettes as a function of the mixing ratio and wood particle size is depicted in Fig. 3d, e, and f for feeding speeds of 15.76, 18.56, and 21.73 mm·s^{-1}, respectively. Obtained data, which are also detailed in Table SM2, show that the three above-listed parameters influence the WRI. This is notably confirmed by the analysis of variance results (see Table SM2), which lead to conclude that the effects associated with the W/RH ratio (F (5,72) = 293.281, $p < 0.001$), the PS (F (1,72) = 64.029, $p < 0.001$) and the FS (F (2,72) = 25.138, $p < 0.001$), are all statistically significant.

As far as the effect of the mixing ratio is concerned, one can note that the greater the RH content, the lower the WRI. Indeed, increasing the RH wt% from 0 % to 100 % when setting the FS to 15.76 mm·s^{-1} as an example leads to the WRI decreasing from 93.5±1.2 % to 85.5.0±0.5 % and from 94.5±0.2 % to 86.5±0.5 % for PS1 (less than 7 mm) and PS2 (between 7 and 10 mm), respectively. Although being slightly higher than in (Rajaseenivasan et al., 2016), the WRI of the wood briquettes produced herein is similar to the values from Orisaleye et al. (2023), which, here again, confirm the validity of the results obtained. Furthermore, and as was the case for the density, the WRI of the samples which were duplicated merge on a signal curve (see FS1-PS1-W/RH0/100 versus FS1-PS2-W/RH0/100, FS2-PS1-W/RH0/100 versus FS2-PS2-W/RH0/100 and FS3-PS1-W/RH0/100 versus FS3-PS2-W/RH0/100), thus strengthening the reproducibility of the tests performed in this work. That the higher the RH content, the higher the density (as shown in sect. 3.1.1) and the lower the WRI, is consistent with the fact that structural modifications of biomass occur during the densification process, including the collapse of the loose tissues and the binding of the cell walls, among others (Gong et al., 2019), which affects the hydrophilicity of biomass. This has been evidenced by Zhang et al. (2017), who observed that water was absorbed more rapidly and was more constrained in densified biomass samples as compared with unprocessed ones. According to Zhang et al. (2017), a smaller fiber size and less intracellular air in briquetted biomass could explain this phenomenon. Furthermore, the fluffy nature of RH is likely to generate more internal pores within briquettes, thus reducing their resistance to water penetration (Sunnu et al., 2023).

The obtained results also show that the WRI tends to increase when decreasing the wood PS. As can be seen by looking at the results plotted in Fig. 3d for an FS of 15.76 mm·s^{-1} as an example, the briquettes for which RH≥20 % exhibit a higher WRI when the wood particle size is less than 7 mm. Here again, this observation is in line with the trend reported in the literature. Indeed, while investigating the effects of the particle size and the composition of sawdust and carbon from rice husk on the performance of densified briquettes, Anggraeni et al. (2021) reported a decrease of the WRI with an increase of the PS. According to the explanation provided in sect. 3.1.1, this behavior could be traced to the higher porosity of the briquettes produced when large particles are used. This finding also extends to charred briquettes, as observed by Sunnu et al. (2023), for which the resistance to water penetration decreases with an increase in the particle size of various feedstocks, including rice husk.

Regarding the impact of the feeding speed, the obtained results show that the WRI globally decreases when FS increases regardless of the PS. For instance, the WRI of briquettes produced with wood particles having a diameter comprised between 7 and 10 mm passes from 86.5±0.8 % to 79.0±1.1 % and from 81.5±1.2 % to 76.5±1.0 % for the samples containing 40 wt% and 80 wt% of RH, respectively, when the FS increases from 15.76 to 21.73 mm·s^{-1}. As was the case for the density, this behavior can be related to the fact that the greater the FS, the shorter the retention time of the feedstocks in the die, the lower the density of the briquettes, the higher their porosity and the lower the WRI.

To conclude, the results presented in this section clearly show that even though briquettes produced with high RH contents have the advantage of exhibiting a high density, they are prone to face challenges in terms of their water absorption propensity. Following the recommendations from Bazargan et al. (2014) and Yilmaz et al. (2018), densified fuels obtained should thus not be exposed to wet conditions so as to avoid adversely affecting their quality.

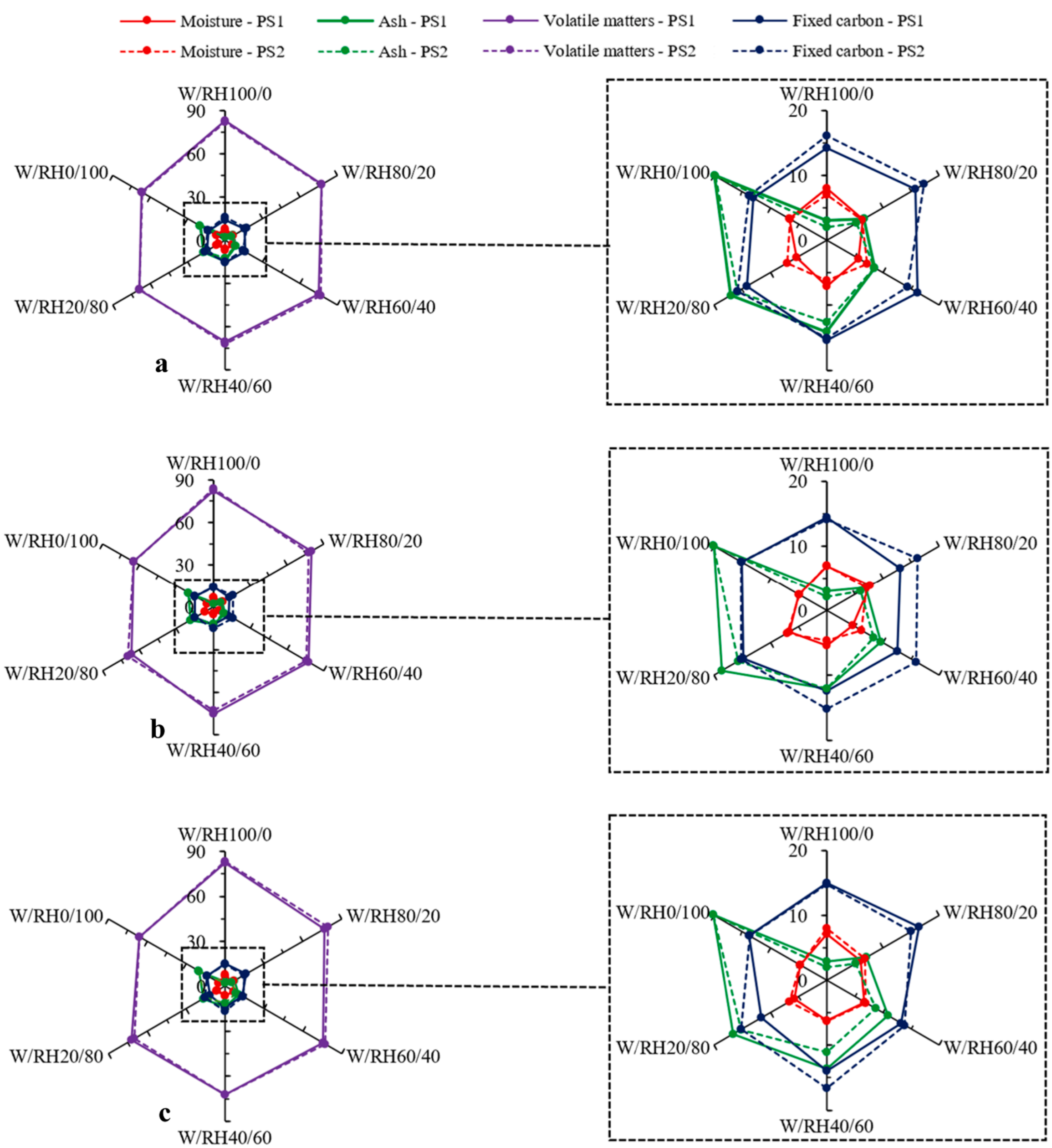

Fig. 4. Variation of the moisture, ash, volatile matter, and fixed carbon content of the produced briquettes as a function of the particle size (PS1 and PS2) and of the W/RH mixing ratio for feeding speeds of (a) 15.76 mm·s^{-1}, (b) 18.56 mm·s^{-1} and (c) 21.73 mm·s^{-1}.

3.2. Impact of the operating parameters of the briquetting process on the chemical properties of the obtained briquettes

3.2.1. Moisture

Too low or too high moisture contents in solid fuels have a negative effect on their physical properties, and consequently, on their combustion behavior. This parameter must therefore be considered in thoroughly characterizing the intrinsic features of densified briquettes for use as fuels. The variations of the moisture content of the briquettes produced as a function of the process parameters (i.e., W/RH ratio, FS and PS) were therefore analyzed, as shown in Fig. 4 and detailed in Table SM3, which is provided in the Supplementary Materials to this article.

As can be seen by looking at the values reported in Table SM3, the moisture content of pure wood briquettes varies between 6.88 ± 0.07 % and 8.04±0.17 %. For briquettes containing 20–100 wt% of rice husks, the measured humidity varies to a greater extent. Moisture contents between 4.60±0.05 % and 7.75±0.21 % are indeed determined depending on the operating parameters. It is first noteworthy that the briquettes produced from pure wood globally exhibit higher moisture contents than those issued from the formulations integrating RH as a feedstock. A mean humidity of 7.33 % can indeed be computed for the wood briquettes versus a value of 6.12 % in the case of the samples produced with RH or W/RH blends. This trend is, however, consistent with the moisture content of the wood used herein (between ~7.2 and ~8.0 wt%), which is higher than that of rice husk (6.4 wt%), as illustrated in Table 1. These observations are, moreover, in line with the analysis of variance results, which show that the W/RH ratio significantly affects the moisture content of the produced briquettes (F (5,72) = 19.918, $p < 0.001$).

The PS is also shown to significantly influence the humidity of the briquettes (F (1,72) = 7.261, $p = 0.009$). The results plotted in Fig. 4 notably show that the higher the PS, the higher the moisture content. As examples, for an FS of 15.76 mm·s^{-1} and for briquettes produced based on formulations integrating 40 and 80 % of rice husk, the humidity reaches values of 7.24±0.11 % and 7.04±0.09 %, for PS2, versus 5.73 ±0.38 % and 5.34±0.15 %, for PS1. Similarly, considering a W/RH ratio of 40 % while setting FS to 18.56 mm·s^{-1}, a moisture content of 6.15 ±0.30 % can be measured with PS2 versus 4.60±0.05 % for PS1. Among the different factors likely to explain this trend, one can first refer to the humidity of the wood particles having a size ranging between 7 and 10 mm, which was found to be higher than that of the particles whose size was below 7 mm (see Table 1). Furthermore, fine particles are expected to be heated more intensely than large ones when exposed to the high temperatures encountered in the press machine. Consequently, more dehydration is likely, which, here again, tends to support the above observations regarding an increase of the moisture content of the densified fuels with an increase in the particle size.

One can finally note that the moisture contents of the duplicated samples (those produced from pure RH) are identical, as is the case for the other properties measured as part of the proximate analyses (see Fig. 4). This confirms the good reproducibility of the production tests, as mentioned above. Note, however, that for brevity, this point will not be further emphasized below. To conclude, it is noteworthy that 30 of the 33 considered briquette formulations allow obtaining a moisture content ranging between 5 % and 10 %, which is consistent with the general recommendations found in the literature for obtaining high-quality densified fuels (see sect. 1 and references therein).

3.2.2. Ash

Ash denotes the solid residue resulting from the combustion of biomass. While ash can potentially be used for soil amendment and GHG capture (González et al., 2013; Lehmann et al., 2015), its presence still has adverse impacts on the combustion properties of biomass. In addition to reducing the net calorific value of solid fuels, elements in ash (including heavy metals) can cause problems arising from the deposition of slag and ash in combustion facilities and in an increased rate of wear of metal boiler elements due to corrosion (Eriksson et al., 2018). As a consequence, and as was the case for moisture, the evolution of the ash content of the briquette samples as a function of the operating parameters of the densification process (i.e., W/RH ratio, FS, and PS) were also investigated. Here again, the obtained results are depicted in Fig. 4 and summarized in Table SM3 for convenience.

The analysis of variance results (see Table SM2) first indicate that the mixing ratio significantly affects the ash content of the briquettes (F (5,72) = 2743.219, $p < 0.001$). As shown in Fig. 4 and Table SM3, the proportion of ash in the produced briquettes increases from 1.96±0.09 to 20.19±0.42 wt% when the RH content passes from 0 to 100 wt%. This was, however, quite expected since agricultural and herbaceous residues typically contain a higher ash content than woody biomass (Wang et al., 2017), as confirmed by the data provided in Table 1. To further examine the consistency of the obtained results, the evolution of measured ash contents was plotted as a function of theoretical ones computed using Eq. (3). As can be seen by looking at Fig. SM1 provided in the Supplementary Materials to this article, a strong positive correlation is then obtained with a high coefficient of determination ($r^2=0.98$), reflecting the dispersion of plotted data around the identity line. This result, thus, confirms the consistency of the measurements performed on produced samples while corroborating the direct relation between the W/RH ratio and the ash content.

Contrary to what was found in (Ngangyo Heya et al., 2022) (see sect. 1), the effect of PS on the ash content is also shown to be significant (F (1,72) = 122.962, $p < 0.001$). The plots of Fig. 4 notably show that the briquettes produced while using wood particles having a size between 7 and 10 mm exhibit a lower ash content. For feeding speeds of 15.76 and 21.73 mm·s^{-1} as examples, using fine particles results in the ash content rising from 6.67 ± 0.44 wt% to 17.01 ± 0.29 wt% and from 7.10 ± 0.12 wt% to 16.64 ± 0.13 wt%, for W/RH ratios of 80/20 and 20/80 versus values ranging from 5.33 ± 0.40 wt% to 15.89 ± 0.13 wt%, and from 5.21 ± 0.61 wt% to 15.19 ± 0.61 wt% when PS2 is considered. While being in line with the fact that the finer wood particles are characterized by a higher ash content as illustrated in Table 1, this trend is also consistent with the observations by Ngangyo Heya et al. (2022), who noted that briquettes made up of pecan pericarp waste had a higher ash content when the size of the particles used was 0.42 mm instead of 1.6 mm, hence suggesting that using fine particles is likely to yield briquettes having a higher inorganic matter content.

As for the effect of the feeding speed, it has no significant impact on the ash content (F (2,72) = 0.401, $p = 0.671$), which is in line with expectations, since this operating parameter is not supposed to modify the mineral composition of the feedstocks.

To conclude, it is noteworthy that the ash content of the briquettes produced with pure rice husk is in line with the results from Brand et al. (2017), although the authors of this work measured a slightly lower value due to the fact that they used a raw feedstock containing less ash. Similarly, the results obtained herein also match those reported by Ajimotokan et al. (2019) as far as wood briquettes are concerned, hence supporting the consistency of the data presented in the present work. Since the ash content needs to be low to obtain quality solid fuels, the above results suggest that using large wood particles while considering relatively low proportions of RH can represent an interesting option in that respect.

3.2.3. Volatile matters

When being heated up, biomass emits volatile fuels and flammable hydrocarbons (Mierzwa-Hersztek et al., 2019), which, in an oxygen-containing atmosphere, ignite and burn. Since the burning of these volatile matters (*VM*) typically accounts for about two thirds of the total energy released by a wood fire (Kumar et al., 2013), the *VM* content of solid fuels is thus a key parameter that must be characterized, as it will directly and significantly affect their combustion behavior.

While neither the wood particle size (F (1,72) = 0.159, $p = 0.692$) nor the feeding speed (F (2,72) = 2.186, $p = 0.120$) influences the volatile matter content of the briquettes, the W/RH ratio conversely significantly impacts this property (F (5,72) = 354.443, p < 0.001). Indeed, and as can be seen by looking at Fig. 4 and Table SM3, the proportion of volatile matters in the briquettes monotonically decreases from ~83 % to ~65 % on average when the rice husk content increases from 0 % to 100 %. It is first noteworthy that these *VM* contents are in line with the values reported in (Brand et al., 2017; Ajimotokan et al., 2019; Ganesan and Vedagiri, 2024) for briquettes produced from pure wood and pure rice husk. Furthermore, the above reduction of the *VM* content as a function of the proportion of RH used is consistent with the lower volatile content of RH as compared with wood (see Table 1). This analysis is further confirmed by the plot of the evolution of measured volatile contents as a function of expected ones (computed by means of Eq. (4)), which is depicted in Fig. SM1. A strong positive correlation is indeed, and here again, obtained with an r^2 of 0.93, hence corroborating the fact that the initial proportion of volatile matters contained in the base feedstocks is the main factor governing the *VM* content of the densified briquettes. Finally, that the feeding speed does not influence the volatile matter content is in line with the fact that this operating parameter does not modify the composition of the feedstocks. Similarly, that the *VM* content is not modified by the wood particle size is in line with the results of the proximate analyses provided in Table 1 as well as with the conclusion by Mambo et al. (2017).

To conclude, and since a fuel having a high *VM* content will be more reactive and easily ignited (Fernandes et al., 2013), high proportions of W should preferentially be considered to obtain high-quality fuels.

3.2.4. Fixed carbon

The fixed carbon (*FC*) is the mass remaining after the release of the volatile matters, excluding ash and moisture contents. As is the case for *VM*, the *FC* content provides a measure of the ease with which a given biomass can be ignited and subsequently oxidized (Fernandes et al., 2013).

The analysis of the results obtained (see Fig. 4 and Table SM3) shows that both the particle size of wood (F (1,72) = 15.111, p < 0.001) and the W/RH mixing ratio (F (5,72) = 2.813, p = 0.022) influence the fixed carbon content of the produced briquettes. Values ranging from 11.60 ±0.78 % to 16.37±0.59 % and from 13.67±0.27 % to 17.37±0.96 are measured, depending on the W/RH ratio for PS1 and PS2, respectively. These trends could still have been anticipated since both the PS and the W/RH ratio were shown to influence the wt% of ash in the produced briquettes while the proportion of RH also proved to impact their *VM* content (see sects. 3.2.2 and 3.2.3). With the fixed carbon content being computed by difference (on a dry basis) based on the fractions of volatile matters and ash comprised in the samples, it is thus quite logical that the particle size and the W/RH ratio, which influence the ash and *VM* contents, will also impact the *FC* content.

Finally, the above results match the proportions of fixed carbon typically contained in sawdust (Waheed et al., 2023) and RH (Brand et al., 2017) briquettes. Since a high fixed carbon content is an indication of a high heating value (Ajimotokan et al., 2019), while being associated with a slower combustion (Akam et al., 2024), selecting formulations with limited RH contents and large wood particles should thus be beneficial to the overall quality of the produced briquettes.

3.2.5. Net calorific value

The net calorific value (NCV) represents the net heat released by a unit quantity of fuel during combustion in the presence of oxygen without considering the energy given by water vapor during condensing. As shown by the results depicted in Table 4, the NCV of the obtained briquettes decreases from ~15.6 MJ·kg^{-1} to ~12.1 MJ·kg^{-1} on average when the RH content passes from 0 to 100 wt%. This trend is actually in line with the fact that the NCV of RH is lower than that of wood (see Table 1). The above values are, moreover, quite close to those obtained by Waheed et al. (2023) and Saeed et al. (2021), who respectively reported NCVs of ~15 MJ·kg^{-1} and ~13 MJ·kg^{-1} for sawdust and RH briquettes. On the other hand, neither the FS nor the PS seem to influence the NCV.

Table 4
Net calorific value of the produced briquettes.

W/RH /%	Net calorific value/MJ·kg^{-1}					
	FS1 = 15.76 mm·s^{-1}		FS2 = 18.56 mm·s^{-1}		FS3 = 21.73 mm·s^{-1}	
	PS1	PS2	PS1	PS2	PS1	PS2
100/0	15.70 ± 0.14	16.42 ± 0.23	14.69 ± 0.21	15.31 ± 0.14	14.90 ± 0.39	15.55 ± 0.03
80/20	16.27 ± 0.09	17.28 ± 0.31	15.54 ± 0.01	15.01 ± 0.04	15.55 ± 0.12	15.53 ± 0.01
60/40	13.53 ± 0.07	13.50 ± 0.29	14.85 ± 0.24	14.96 ± 0.02	13.70 ± 0.31	14.19 ± 0.19
40/60	13.43 ± 0.02	12.97 ± 0.14	14.81 ± 0.13	14.60 ± 0.10	13.44 ± 0.02	14.18 ± 0.05
20/80	12.74 ± 0.08	12.49 ± 0.05	12.67 ± 0.04	13.69 ± 0.49	12.32 ± 0.54	12.13 ± 0.45
0/100	12.35 ± 0.31	12.71 ± 0.18	10.69 ± 0.61	11.04 ± 0.06	11.63 ± 0.49	11.75 ± 0.09

In analyzing the results obtained in greater detail, one can note that the NCV is proportional to the wt% of *VM* in the briquettes and inversely proportional to their ash content. This is notably exemplified by the plots of Fig. SM2, provided in the Supplementary Materials, in which NCV values computed based on an empirical correlation issued from the work of Ozyuguran and Yaman (2017) are also plotted, for comparison. To that end, the 8 equations proposed by Ozyuguran and Yaman (2017) were tested before the obtained HHV was converted into NCV by subtracting the heat of vaporization of the water initially present in the fuel samples (issued from Table SM3) and produced during combustion (estimated based on the stoichiometric combustion reaction equation while considering the averaged ultimate composition for W and RH taken from Wang et al. (2022a)). Although all the proposed correlations gave very close results and similar agreements with measured data (a point also noted by Ozyuguran and Yaman (2017)), Eq. (8) was still considered as it was found to perform slightly better:

$$HHV = 44.336 + 0.286FC - 2394.7/VM \quad (8)$$

As can be seen by looking at the plots of Fig. SM2, both measured and predicted NCV exhibit the same general trends, although computed values tend to overestimate their experimental counterparts. This observation may be related to numerous factors, including the fact that the correlations proposed by Ozyuguran and Yaman (2017) were developed by processing a dataset comprising 27 different samples – excluding wood shavings and rice husk – which are the two feedstocks considered herein. That being said, the agreement between measured and predicted NCV is still acceptable, while clearly evidencing that the higher the *VM* content and the lower the ash content, the higher the NCV. Similarly, and although not detailed for brevity, the analysis of the obtained results also tends to show that the higher the *FC* content, the higher the NCV, which is in line with the observations provided in sect. 3.2.4.

To conclude, and since the higher the RH content, the lower the NCV, considering briquette formulations produced with high proportions of wood could be regarded as a good option. On the other hand, the higher the RH content, the lower the moisture content of the briquettes and the higher their density, as shown in sects. 3.2.1 and 3.1.1, respectively. This hence makes the identification of an optimal formulation quite complex, thus explaining why combustion tests were also carried out as part of this work to better characterize the combustion features of a series of briquettes selected based on their intrinsic qualities.

3.3. Analysis of the combustion behavior of selected briquette samples

Seven briquette samples were considered to conduct combustion tests. These included the formulation FS1-PS2-W/RH100/0, which contains no RH and could thus serve as a reference sample. The operating parameters FS1 and PS2 were, moreover, chosen as they provided the highest density and the lowest moisture and ash contents among all the samples produced from pure wood. The FS1-PS1-W/RH20/80 and FS1-PS2-W/RH80/20 formulations were then selected as they correspond to the samples having the highest density and net calorific value, respectively. In addition, the FS2-PS1-W/RH60/40, FS2-PS1-W/RH40/60 and FS2-PS2-W/RH20/80 samples were chosen to assess the impact of an increase of the RH content on the combustion properties of the obtained briquettes, further noting that these formulations led to obtaining densified fuels having relatively high net calorific values ranging between 13.69 and 14.85 MJ·kg^{-1}. To conclude, a sample of firewood typically used for cooking in Somanya was included for comparison. As detailed in sect. 2.6, the evolution of the temperature and energy involved in heating 3 l of water (see the left-hand term of the numerator of Eq. (7)) was monitored for 60 minutes (denoted 'min' below), thus leading to obtaining the graphs reported in Fig. 5.

The plots of Fig. 5a first show that the heating phase is characterized by an increase in the temperature T of the water, which reaches values between ~60 and ~84°C when 15 min < t < 35 min. T then progressively decreases to values between 50 and 60°C, which are measured at the end of the combustion test due to heat losses of the water vessel exceeding the thermal energy provided by the briquette flames. As was quite expected, the curves depicted in Fig. 5b exhibit a shape highly similar to the temperature profiles of Fig. 5a, which is consistent with the fact the energy accumulated by water through sensible heat is directly correlated with the temperature reached by the water.

As for the FS1-PS2-W/RH100/0 and FS1-PS2-W/RH80/20 samples, their combustion allows reaching the highest water temperatures (i.e., ~80 °C) and sensible heats (~625 and ~658 kJ, respectively), which may be related to their high NCV. Conversely, the lowest temperature (~60 °C) and sensible heat (~375 kJ) are obtained when using the FS1-PS1-W/RH20/80 sample, which is characterized by the lowest NVC. Overall, the results from Fig. 5 show that the higher the RH content, the lower the NCV, the lower the peak temperature reached by the water, and the lower the computed sensible heat. Furthermore, the lower the ash content and the higher the wt% of *VM* in the briquettes, the sooner the peak temperature of water is reached, which is consistent with the fact that samples rich in volatile matters ignite more rapidly. The formulations containing 40–80 wt% of RH fail to heat the water up to 80°C due to their relatively low calorific value coupled with high ash and low *VM* contents, which reduces the ability of the briquettes to ignite (Lubwama et al., 2020). On the other hand, the firewood sample also fails to heat the water up to 80°C despite an NCV and *VM* content of 19 MJ·kg^{-1} and 83 wt%, respectively. This trend can, however, be explained by the fact that commercial briquettes are issued from a densification process involving a different type of wood and a different compaction pressure. Since these factors are known to influence the apparent density, the ρ of the firewood sample is thus likely to differ from that of the wood sample produced in the present work, hence impacting its ignition and burning properties. Indeed, any decrease of the fuel density will decrease its thermal conductivity and reduce the amount of heat needed for a specific volume of briquette to attain the ignition temperature and burn (Dinesha et al., 2019). Furthermore, it is well documented in the literature that the lower the fuel density, the faster its combustion (Abdulrasheed et al., 2015; Aguko Kabok et al., 2018). Consequently, a rapid combustion of the firewood, as supported by the curves of Fig. 5 and by a relatively high burning rate (see below), may possibly explain why this fuel did not allow to reach the target temperature although being quite close (~75°C).

Since some formulations did not allow reaching the target temperature of 80°C, a second series of tests were performed (as mentioned in sect. 2.6). To that end, the mass of fuel to be burnt was adjusted as a function of the considered sample (from 0.5 kg for FS1-PS1-W/RH20/80 and FS1-PS2-W/RH80/20 to 0.8 kg for FS1-PS1-W/RH20/80) in order to reach the above-mentioned target temperature. The data collected during these tests (including the temperature and sensible heat profiles, which are depicted in Fig. SM3 in the Supplementary Materials) enabled the calculation of different combustion parameters, including the fuel burning rate (BR), the specific fuel consumption (SFC) and the combustion efficiency (CE), as detailed in Table 5 (see sect. 2.6 for details concerning the equations used to compute these performance metrics).

The results of Fig. SM3 first show that the time required to reach a temperature of 80°C (which is associated with a sensible heat of ~650 kJ), is longer for the FS2-PS2-W/RH20/80 sample (~ 35 min) than for the FS2-PS1-W/RH40/60 (~ 30 min) and FS1-PS2-W/RH100/0 (~ 25 min) ones. Here again, this trend is consistent with the fact that the higher the wt% of RH in the briquettes, the higher the briquette density, the lower the *VM* content, and the slower the fuel ignition. As for the burning rates summarized in Table 5, they globally indicate that the higher the RH content, the lower the BR, which is, moreover, inversely proportional to the net calorific value. While agreeing with the observations by Narzary et al. (2023), this trend is also consistent with the fact that RH exhibits a high ash content and a low *VM* content, which

Table 5
Combustion characteristics of selected briquette samples.

Sample	NCV /MJ·kg^{-1}	BR /g·min^{-1}	SFC /g·l^{-1}	CE /%
Firewood	19.01	17.6	124.0	−8.7
FS1-PS2-W/RH100/0	16.42	13.4	115.8	12.5
FS1-PS2-W/RH80/20	17.28	13.1	116.0	12.7
FS2-PS1-W/RH60/40	14.85	11.8	118.6	12.1
FS2-PS1-W/RH40/60	14.81	11.3	119.7	10.5
FS2-PS2-W/RH20/80	13.69	11.0	138.4	11.1
FS1-PS1-W/RH20/80	12.74	10.9	135.3	11.7

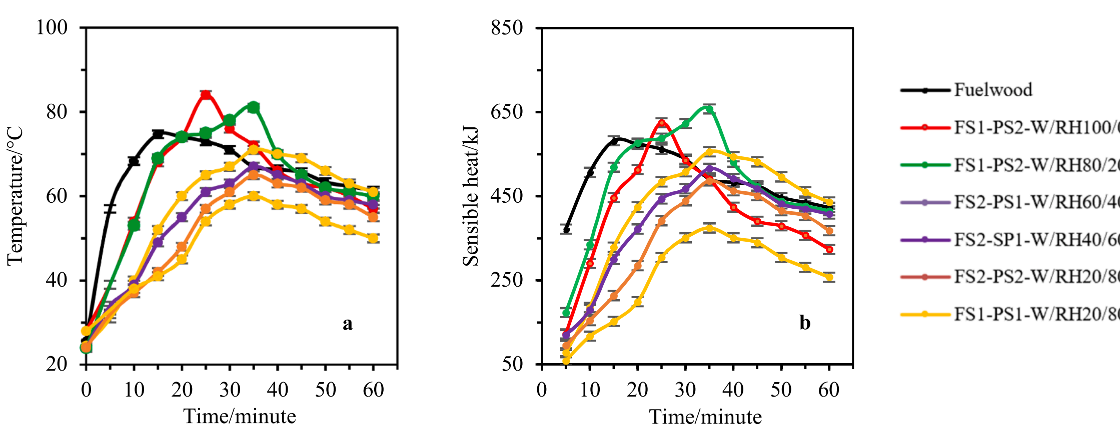

Fig. 5. Evolution of the water temperature (a) and sensible heat (b) as a function of time during the combustion tests.

thus reduces the ignitability of the briquettes containing this feedstock (see above). Furthermore, and according to Lubwama and Yiga (2018), the high level of inherent SiO_2 in rice husks may induce the formation of silica ash and silicon carbide while strengthening the silica-carbon bonds during heating, hence hindering the combustion of RH-containing fuels. Lubwama et al. (2020), who also highlighted this point, especially noted that the presence of silica in RH induces a thermal resistance which gradually retards the combustion and reduces the BR of the briquettes containing this feedstock. Conversely, the burning rates of the 100 % wood and firewood samples are higher than those of the other tested fuels. This thus corroborates the above statement regarding the fact that wood burns faster, hence leading to the target temperature being reached sooner. In addition to its high NCV and *VM* content, it is noteworthy that the wood used in this work also has higher inherent alkali and alkaline earth metals (AAEMs) contents as compared with rice husks. Indeed, an analysis of the mineral contents of these two feedstocks showed that wood contains more Ca (3853 $mg\cdot kg^{-1}$), Mg (537 $mg\cdot kg^{-1}$), and Na (92 $mg\cdot kg^{-1}$) than RH (for which corresponding values are 552, 321 and 46 $mg\cdot kg^{-1}$, respectively). Since AAEMs are known to shift the fuel pyrolysis (which is the first step in combustion) to lower temperatures (Wang et al., 2022b; 2022c), the higher proportions of alkali and alkaline earth metals in wood probably also contribute to its rapid ignition. Finally, measured burning rates are in line with previous results from the literature, as exemplified by the BR of sawdust, which was estimated by Sunnu et al. (2023) and Ganesan and Vedagiri (2024) to range between ~10.3 $g\cdot min^{-1}$ (Sunnu et al., 2023) and 13.6 $g\cdot min^{-1}$ (Ganesan and Vedagiri, 2024) versus 13.4 $g\cdot min^{-1}$ herein. As for the specific fuel consumption, it is shown in Table 5 to increase, although not linearly, with the RH content. This increase is actually consistent with the fact that the higher the wt% of RH, the lower the *VM* content, the higher the ash content, and the lower the NCV. Of note, a similar behavior was observed by Sunnu et al. (2023) and Ganesan and Vedagiri (2024), who both reported that the lower the NCV of the briquettes, the higher the SFC. To conclude, combustion efficiencies ranging from 10.5 % to 12.7 % are obtained with the densified fuels produced in this work. While being globally in line with the results from Ganesan and Vedagiri (2024), who notably measured a CE of 15.5 % when burning sawdust briquettes versus 12.5 % herein, it is noteworthy that the formulations we proposed have better CE than commercial firewood, whose combustion performance might have been impacted by rapid and intense oxidation. Since quality briquettes typically have a relatively low specific fuel consumption and a good combustion efficiency, the formulations containing 80 wt% of W can therefore be considered as one of the best suited, followed by the FS1-PS2-W/RH100/0 sample, which is also very attractive due to its high NCV, low SFC, and high CE.

To conclude this analysis of the combustion features of the briquettes produced, the concentrations of selected combustion gases (namely, CO_2, CH_4, and NO_2) emitted when burning 500 g of sample was measured. The obtained profiles are reported in Fig. SM4 in the Supplementary Materials to this article. Furthermore, and to give an overview of the emissions induced by the combustion of the different types of briquettes, the integrated quantities of greenhouse gases emitted during each test are summarized in Table 6. As can be seen by looking at Fig. SM4a, the combustion of the samples with high RH contents is associated with relatively low CO_2 emissions, with peak concentrations (below 4300 $mg\cdot m^{-3}$) measured after 30 min. Conversely, the oxidation of the FS1-PS2-W/RH100/0 sample generates a higher CO_2 peak about 20 min after the beginning of the combustion, with a concentration reaching 6300 $mg\cdot m^{-3}$. The behavior of this fuel, moreover, approximates that of the firewood sample, which also has a high BR and SFC (see Table 5). Overall, these observations confirm the comments above regarding the fact that a faster and more complete combustion occurs when fuels having a high VM content, a low ash content and a high NCV are burnt. As for Fig. SM4b, it shows that the combustion of the briquettes containing a high wt% of RH leads to measuring higher concentrations of CH_4 than when burning wood samples with peak values above 2600 $mg\cdot m^{-3}$, for the FS2-PS1-W/RH40/60 and FS2-PS2-W/RH20/80 samples versus ~1500 $mg\cdot m^{-3}$, for the FS1-PS2-W/RH100/0 and firewood samples. These observations may actually be related to the generation of more smoke, as observed during the combustion tests performed with RH-containing samples, thus indicating the emission of higher quantities of unburnt hydrocarbons, including methane. Finally, and although measured concentrations are very low (less than 0.6 $mg\cdot m^{-3}$), Fig. SM4c still illustrates that the higher the wt% of W (and thus the higher the NCV), the higher the NO_2 emissions. Since W and RH are supposed to have a relatively similar nitrogen content (less than 1.5 wt% for sawdust (Asamoah et al., 2016; Wang et al., 2022a) and less than 1.7 wt% for RH (Zhao and Li, 2016; Yuan et al., 2019; Wang et al., 2022a), the above trend is probably not solely related to a difference in fuel-NO_x formation. Instead, it can probably be traced to the fact that the higher the fuel NCV, the higher the flame temperatures, which induces a higher production of thermal NO_x.

Table 6
Integrated quantity of combustion gases released during the oxidation of 500 g of different briquette types. Note that the total GHG values expressed in g of $CO_{2\ eq.}$ were computed by summing the quantities of CO_2 and CH_4 after converting the methane mass using the global warming potential factor related to this gas.

Sample	CO_2 /g	CH_4 /g	Total GHG /g of $CO_{2\ eq.}$
Firewood	109.854	19.099	587.348
FS1-PS2-W/RH100/0	97.342	24.153	701.159
FS1-PS2-W/RH80/20	92.603	25.836	738.496
FS2-PS1-W/RH60/40	92.970	30.101	845.501
FS2-PS1-W/RH40/60	76.714	28.335	784.847
FS2-PS2-W/RH20/80	80.469	31.840	876.473
FS1-PS1-W/RH20/80	73.446	29.889	820.661

By integrating the CO_2 and CH_4 emissions over the entire duration of the tests, which consist in burning 500 g of each considered fuel while considering the volume of the kitchen in which the tests were performed (see sect. 2.6), the values reported in Table 6 were obtained. They were then summed and expressed into CO_2 equivalent after converting the quantities of CH_4 emitted using the global warming potential (GWP) factors associated with this gas. This led to obtaining an approximated estimation of the GHG emissions listed in the fourth column of Table 6. As can be seen by looking at the results obtained, all the tested briquette formulations gave total GHG emissions higher than those associated with the commercial firewood sample. This is mostly due to the lower related CH_4 emissions of the latter (see the third column of Table 6). That being said, and as previously mentioned, the water temperature measured when burning 500 g of the firewood sample was lower than that reached when using the FS1-PS2-W/RH100/0 and FS1-PS2-W/RH80/20 formulations, for instance. According to the results presented in Table 5 and discussed above, the lower SFC and higher CE of the briquettes produced herein are key factors likely to explain these observations. Additional calculations were therefore made based on the data collected during the second series of combustion tests aimed at finding the mass of each fuel required to heat water up to 80°C. Since the mass of firewood needing to be burnt to reach this target temperature was determined to be ~1.26 times that of the FS1-PS2-W/RH100/0 sample, for example, it was thus found that the total GHG emissions were reduced by ~9.4 % when burning the FS1-PS2-W/RH100/0 briquette formulation (701.159 g of $CO_{2\ eq.}$) instead of firewood (773.752 g of $CO_{2\ eq.}$). We, moreover, also estimated that the combustion of the FS1-PS2-W/RH80/20 formulation led to total GHG emissions (close to 800 g of $CO_{2\ eq}$) levels quite similar to those issued from the use of the firewood sample for an identical amount of useful thermal energy. All the other briquette formulations, however, failed to generate GHG emissions lower than those measured when burning firewood (with values ranging from 1000.295 to 1287.312 g of $CO_{2\ eq.}$ for the FS2-PS1-

W/RH40/60 and FS1-PS1-W/RH20/80 samples, respectively), notably due to their low NCV and relatively high SFC.

In view of the forgoing, the FS1-PS2-W/RH100/0 and FS1-PS2-W/RH80/20 formulations thus appear to be quite interesting since they benefit from a low SFC and a high CE, as previously noted. Furthermore, their combustion leads to similar and even reduced GHG emissions for an identical amount of useful energy as compared with firewood, which is another important strength of these alternative fuels generated from biomass wastes.

4. Conclusion

The objective of the present work was to analyze the potential strengths and weaknesses of fuel briquettes produced from wood shavings and rice husk. It, moreover, aimed at elucidating the influence of various parameters on the quality of the obtained products. Wood and rice husk were selected as feedstocks to promote the circular economy in Ghana through the beneficiation of abundant, while partly underexploited, wastes from the wood and agri-food industry. In this study, a design of experiments was used to define 33 different briquette formulations intended to be used for cooking applications. To that end, the feeding speed of the mechanical piston press machine used, the size of the wood particles, and the W/RH feedstock mixing ratio were varied. The intrinsic quality of the obtained fuels was then assessed by characterizing their density, water resistance index, calorific value, as well as their moisture, volatile matter, ash, and fixed carbon contents. Their combustion behavior was finally investigated to derive key properties, including the fuel burning rate, the specific fuel consumption and the combustion efficiency, while estimating the amount of GHG emitted during the oxidation of the produced briquettes. To the best of the authors' knowledge, this is probably the first time such a comprehensive characterization of the impact of various densification parameters on the physicochemical and combustion properties of briquettes produced from W/RH blends is proposed in the context of cooking applications. Based on the results obtained, the following conclusions and recommendations can be drawn:

- The mixing ratio, the wood particle size, and the feeding speed all significantly impact the briquette density and water resistance index, whose values were found to vary between 1143 and 1247 $kg \cdot m^{-3}$ and between 76.5 % and 94.5 %, respectively. While the greater the RH, the higher the briquette density, the results obtained also showed that the lower the RH, the higher the WRI. As a consequence, and although exhibiting a high apparent density, pure RH briquettes may face a major challenge in terms of their propensity to absorb water.
- The majority of the briquette formulations tested in this work allowed obtaining fuels having a moisture content ranging between 5 % and 10 %, which are in keeping with the recommendations from the literature for obtaining high-quality densified fuels.
- In accordance with expectations, the W/RH mixing ratio directly influences the proportions of volatile matters, ash and fixed carbon of the briquettes. The proximate analyses of the produced fuels, moreover, showed that the higher the RH content, the lower the wt% of *VM* and the higher the wt% of ash in the briquettes. These observations therefore suggest that high proportions of wood should be preferentially considered to obtain more reactive and easily ignited fuels.
- While exemplifying the proportionality between the fuel *VM* and ash contents and the net calorific value, measured NCV values (comprised between 10.69 and 17.28 $MJ \cdot kg^{-1}$) clearly showed that the higher the RH content, the lower the calorific value of the briquettes. Here again, this trend is in line with expectations since the NCV of RH is lower than that of wood.
- The combustion tests performed to characterize the oxidation behavior of the produced briquettes led to conclude that the higher the wood content, the higher the burning rate, the lower the specific fuel consumption, and the higher the combustion efficiency. As key findings, the obtained results, moreover, showed that the FS1-PS2-W/RH100/0 and FS1-PS2-W/RH80/20 formulations performed better than a commercial firewood sample. Furthermore, their combustion was shown to generate total GHG emissions similar to (FS1-PS2-W/RH80/20) and even 9.4 % lower (FS1-PS2-W/RH100/0) than those issued from the oxidation of firewood for a given amount of energy (650 kJ) absorbed by a cooking pot filled with a 3-l volume of water.

These observations thus show that briquettes produced through the co-processing of wood shavings and rice husk are good candidates for producing heat, notably in the context of cooking applications. Samples containing high proportions of wood were especially shown to represent the best suited option due to their high WRI, high *VM* content, low ash content and high NCV. They also benefit from low SFC and high CE. Finally, their combustion allows to reduce GHG emissions as compared with those measured when burning a conventional firewood sample. Although briquettes containing RH levels higher than 20 % led to higher GHG emissions, they still present interesting features, including a high density, a relatively low SFC and an overall good CE. Furthermore, the development of densified briquettes integrating RH as a feedstock represents an interesting and innovative means to limit the deforestation induced by the intensive use of firewood, while aligning with the principles of a circular economy. This method not only has the potential to significantly advance the economic development of emerging nations but also effectively addresses critical energy needs while tackling waste management challenges across various sectors (Gebrezgabher et al., 2018). By improving livelihoods within targeted communities, briquette production can play a pivotal role in promoting sustainable development and enhancing overall well-being (Asamoah et al., 2016). The adoption of briquettes as substitutes for firewood and charcoal remains limited in many African countries, however. To tackle this issue, it is essential to conduct feasibility studies that assess the financial viability specific to the unique circumstances of each locality (Mansour et al., 2021). The market competitiveness of briquettes is often constrained by the cost and availability of traditional fuel alternatives. Demand for briquettes originates primarily from households, institutions (such as schools and restaurants), the informal manufacturing sector, and established industries. Nonetheless, marketing opportunities are generally more pronounced in the institutional, manufacturing, and industrial sectors compared to households (Gebrezgabher et al., 2018). The costs associated with briquette production are heavily influenced by logistical factors related to the storage and collection of raw materials, as well as the distribution of finished products. Additionally, production expenses (including electricity and labor) must be meticulously considered to ensure financial sustainability (Nikiema et al., 2022). By addressing these challenges, briquette production can become a more viable and competitive solution in the energy landscape of many developing countries. Further works are, however, required to improve the quality (i.e., water resistance and combustion properties) of briquettes containing high quantities of RH. For these, the mixing of RH with other feedstocks could represent an interesting option to be explored. In addition, further analyzing the mechanisms at play during the pyrolysis and oxidation of briquettes composed of W and RH would also be of high interest, notably to determine whether or not synergistic effects (Wang et al., 2023; Lemaire et al., 2023) likely to promote the yields of volatiles emitted are present when these two feedstocks are co-processed, which could thus pave the way for future works to be undertaken.

CRediT authorship contribution statement

Josiane Nikiema: Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Romain Lemaire: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Brice Martial Kamdem:** Writing – original draft, Visualization, Investigation, Formal analysis.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2024.120134.

Data availability

Data will be made available on request.

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