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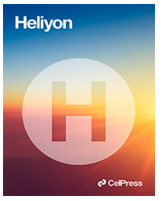

Research article

Energy usage of spruce with waste face masks and spent coffee grounds as fuel in a pellet boiler

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ABSTRACT

It is necessary to reduce dependency on fossil fuels for heating and waste generation, while also utilizing the energy potential of waste materials. One possibility is to create fuel pellets where waste makes up a small proportion so that the properties of the wood are not significantly altered with. This article investigates the energy usage of pellets containing spent coffee grounds (5 % or 10 %) and waste face masks (5 % or 10 %), with spruce sawdust as the primary input material (80 % or 90 %). The elemental, thermogravimetric, calorific value, mechanical durability, emission and performance characteristics, and ash melting temperatures of the pellets were evaluated during the experiment. The results were compared with respect to pure spruce sawdust pellets and the specified limit values for wood pellets in commercial and residential applications as specified in ISO 17225 [18]. Both tested samples met the element content limit (N, S, Cl, As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn) for the highest quality grade (A1). No significant amounts of harmful elements were detected. The samples also complied with the limits of moisture content, ash content, and net calorific value (also known as lower calorific value). All samples met the emission limits in their respective classes (3, 4, or 5) according to STN EN 303-5+A1 [35]. However, the samples failed to meet the limit values for mechanical durability and ash melting temperatures. Despite this, the manufactured pellet samples represent a suitable fuel product for combustion purposes as a more sustainable thermal energy fuel.

1. Introduction

The dependance on fossil fuels for heating must be limited. Recent research indicates a rise in the frequency and intensity of crises, disasters, extreme weather events, and climate change impacts [1]. This necessitates the use of renewable energy sources such as biomass [2]. Utilizing biomass also contributes to greenhouse gas reduction. The demand for feedstock for pellet production is increasing, which is leading to a rise in the cost of purchase and production these materials [3]. However, growing this kind of biomass fuel can displace the cultivation of conventional crops intended for consumption. Therefore, waste biomass can be considered a more suitable energy source. Raw biomass generally has a high moisture content, low mass, and low energy density [4]. Compressing the mass into briquettes or pellets improves these properties, resulting in higher energy density, lower moisture content, improved

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homogeneity, and reduced transport and storage costs [5].

Biomass fuel use is associated with various technological challenges such as low ash melting temperatures, higher ash content, and the formation of harmful emissions during combustion [6]. There are more environmentally friendly and sustainable waste disposal methods than landfilling which decomposes waste and contributes to the ongoing problem with environment. Potential solutions include co-firing alternative biomass with more stable fuels or implementing structural modifications to combustion devices ([7,8]).

The global coffee industry generates a significant amount of waste in the form of spent coffee grounds (SCG). This organic residue has potential as a renewable energy source. Traditional disposal methods for SCG, such as composting, can have environmental drawbacks (methane production). Thermal conversion processes, such as pyrolysis, gasification, and torrefaction, are able to increase the value of SCG in form of fuel production.

Pilusa et al. [9] manufactured briquettes with ratios of 32 % SCG, 23 % coal fines, 11 % sawdust, 18 % mielie husks, 10 % waste paper, and 6 % paper pulp when combusted, demonstrated lower toxic emissions compared to fossil fuels. Limousy et al. [10] investigated the energetic characteristics and combustion behavior of pellets from pure spent coffee ground or blended with pine sawdust in a commercial residential pellet boiler. Their study warns the risk of low boiler efficiency and increased PM and gas emissions during combustion. However, when mixed with pine sawdust in a 50/50 ratio, the emissions and boiler efficiency were found to be similar to those of wood pellets. Based on these findings, SCG pellets can be a viable substitute for traditional fuels.

In order to comply with French regulations, it was necessary to mix them with pine sawdust up to a maximum ratio of 50 %. Nosek et al. [11] investigated the energy utilization of SCG in pellet form in various proportions (wood sawdust/spent coffee grounds): 30/70, 40/60, 50/50, and 0/100. The pure SCG sample (0/100) did not achieve the desired combustion performance due to its low strength. The utilization of spent coffee grounds and guava seeds as representative biomass residues was used to analyze the potential replacement of hexane with alternative green solvents for lipid extraction and biodiesel conversion in the work of Veitía-de-Armas et al. [12]. The goal of the study by Bartolucci et al. [13] was to experimentally investigate the impact of lipid extraction and conversion to biodiesel on the energy yield of pyrolysis products. The research also explored thermochemical processes to valorize the energy content of SGC. Marwan et al. [14] incorporated SCG into the bio-composite for eco-friendly packaging solutions.

The COVID-19 pandemic led to a significant increase in the use and disposal of personal protective equipment (PPE), particularly FFP2 masks. The complex, multi-layered structure of these masks poses multiple challenges for traditional recycling. Thermal conversion, including processes such as incineration, gasification, and pyrolysis offer the ability to break down FFP2 masks under high temperatures. In addition to that, reducing waste volume, thermal conversion offers opportunities for energy generation, synthesis gas production, and recovery of materials from the mask components. This surge in waste generation highlights a new challenge in terms of environmental protection.

Previous research by Čajová Kantová et al. [15] demonstrated the viability of using waste face masks as an additive material in the pelletization process and their potential for combustion. Demir and Moslem [16] developed a new hybrid decision-making tool combining F–PSI (Fuzzy Preference Selection Index) and F-CRADIS (Fuzzy Compromise Ranking of Alternatives from Distance to Ideal Solution) to evaluate viability of medical waste disposal techniques. In the study conducted by Wang et al. [17], the waste medical mask-derived materials were tested as viscosity reducers and pour point depressants to assess their potential as crude oil fluidity improvers. Alam et al. [18] studied the utilization of hospital solid waste in pellets. The study found that hospital waste pellets alone did not meet several European standard specifications. When this waste (at 1 % or 1.5 % content) was combined with Sakhalin fir residue however the pellets met the required standards.

Pellets aimed for commercial and residential applications must meet specific requirements as outlined in ISO 17225 [19], including moisture, ash, net calorific value (also known as low calorific value), and the content of N, S, Cl, As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn. To meet the highest quality limit (A1), it is stated that the moisture level should be lower than 10 %, ash lower than 0.7 %, N lower than 0.3 %, S lower than 0.04 %, Cl lower than 0.02 %, As lower than 1 mg/kg, Cd lower than 0.5 mg/kg, Cr lower than 10 mg/kg, Cu lower than 10 mg/kg, Pb lower than 10 mg/kg, Hg lower than 0.1 mg/kg, Ni lower than 10 mg/kg, and Zn lower than 100 mg/kg.

This article emphasizes the importance of reducing waste generation and utilizing its energy potential. One approach is to create fuel with a small amount of waste material, minimizing its impact on wood properties. This study investigates the energy usage of pellets containing spent coffee grounds (5 % or 10 %) and waste face masks (5 % or 10 %), with spruce sawdust as the primary input material (90 % or 80 %). The novelty of this article lies in the combined utilization of two waste materials as additives in pellets, which have an energy potential based on previous studies and would otherwise end up in landfills or pollute watercourses. It was found that coffee grounds Nosek et al., 2020 and waste face masks Čajová Kantová et al., 2023 can be a suitable fuel for heat production and at the same time can be environmentally friendly disposed of when mixed in certain proportions. Nosek et al. [11] manufactured samples from a mixture of wood sawdust and spent coffee grounds with ratio 30:70 (wood sawdust: spent coffee grounds), 40:60, 50:50 and 100 % of spent coffee grounds. The calorific values were compared with wood sawdust pellets (17.15 MJ kg^{-1}) and the highest calorific value of 21.08 MJ kg^{-1} was measured for 100 % of spent coffee grounds. This sample did not achieve the desired performance during the combustion in the boiler due to the low strength of the sample. Based on the results Čajová Kantová et al. [15], it can be concluded that the presence of face masks FFP2 in pellets increases the content of carbon, hydrogen, and nitrogen, volatile matter, and calorific values, but decreases the content of fixed carbon. According to elemental analysis of produced pellets, no significant amounts of harmful elements were present in the samples. However, if SCG or FFP2 masks are used in higher content, they have an adverse effect on the combustion process, increasing emissions and leading to the formation of sinter and agglomerates.

Therefore, this article does not recommend only one of two used waste materials, but it deals with their together usage in the small percentage. It works on two samples that are made by combining 5 % face masks and 5 % spent coffee grounds, and another containing 10 % face masks and 10 % spent coffee grounds. The pellets were then analyzed for elemental composition, thermogravimetric properties, calorific value, mechanical durability, emissions, performance characteristics, and ash melting temperatures.

Subsequently, the results were compared to those of pure spruce sawdust pellets and the limit values set for wood pellets for commercial and residential applications.

2. Materials and methods

The detailed weight proportions of spruce sawdust, waste face masks, and spent coffee grounds used in the pellet production are provided in Table 1. The spruce sawdust was obtained from wood-cutting waste, the face masks were sourced as production waste, and the coffee grounds were collected from a university cafe. The FFP2 and single-use face masks were first disintegrated by mixing and crushing in industrial devices and processed with a maximum size of 6 mm. Spruce sawdust was air-dried in a laboratory and coffee ground was dried in a Memmert UFP 500 oven for 2–3 h at a temperature of 80 °C. It was not necessary to dry the face masks as their moisture content was below the required level. The moisture content of each input is presented in Table 1. Illustrations of the three samples of pellets are presented in Fig. 1(a–c).

The pelleting process was conducted using a small pellet press Kovo Novák at the University of Agriculture in Krakow. The resulting pellets, shown in Fig. 1(a–c), were produced under identical conditions. They have a diameter of approximately 6 mm and were stored for 20 days at a temperature of 22 °C and a relative humidity of 40–50 %.

This section presents the analyses conducted on the produced pellets, including elemental composition, thermogravimetric properties, calorific value, mechanical durability, emission and performance characteristics, and ash melting temperatures. All tests were repeated 3–5 times for better accuracy. The results are presented as average values with the corresponding standard deviation (SD) in tables or figures. Fig. 2 provides a schematic overview of the individual analyses.

2.1. Elemental analysis

The elemental analysis was conducted using a CHN628 analyzer and an ARL™ QUANT'X EDXRF spectrometer. The CHN analyzer operates at a temperature of 950 °C and combusts weighted samples in an atmosphere devoid of atmospheric gases. ARL™ QUANT'X EDXRF spectrometer employs energy-dispersive X-ray fluorescence spectrometry in a vacuum environment. Spectra are evaluated using the standard-less program UniQuant based on the fundamental parameters principle. By analyzing individual pellet samples, it is possible to accurately identify and quantify the concentration of a wide range of elements, from sodium (^{11}Na) to uranium (^{92}U). These elements were evaluated under the conditions listed in Table 2 for groups 1 to 8.

2.2. Thermogravimetric (TGA) analysis

Thermogravimetric analysis (TGA) was conducted using a TGA 701 analyzer to detect moisture, volatile matter, fixed carbon, and ash. The analyzer comprises a muffle furnace with sample cups located in a carousel. Pellet samples were weighed and combusted according to the specified method. The temperature was controlled according to the STN EN ISO 18134 [20] standard, with a ramp from 25 °C to 107 °C at 7 °C/min in an air atmosphere to detect moisture. Volatile matter was determined by raising the temperature to 900 °C at 50 °C/min in a nitrogen atmosphere, following the STN EN ISO 18123 [21] standard. Finally, the ash detection was performed by decreasing the temperature to 550 °C in an air atmosphere, as per the STN EN ISO 18122 [22] standard.

2.3. Calorific value analysis

Higher calorific value (HCV) analysis was performed using a LECO AC 500 calorimeter. The heat released after combusting the pellet samples was measured. The lower calorific value (LCV) was then calculated from the measured HCV using Equation (1).

$$LCV = HCV - r_{H_2O}\left(W_p + 8.94x_H\right) \quad (1)$$

In equation (1) r_{H2O} is the water heat of vaporization [kJ/kg], W_p is water content in the sample [% wt.], 8.94 hydrogen to water conversion coefficient, and $x_H = H_h.B_p$; where H_h is the hydrogen content in the sample [% wt.], and B_p is the volatile content in the sample [% wt.] Nosek et al., 2021.

2.4. Mechanical durability analysis

The mechanical durability of the pellets was analyzed using a Ligno-Tester Holmen device, according to the EN 15210 [23]

Table 1
Produced pellet samples.

Sample	Weight Proportion Spruce Sawdust [%]	Weight Proportion FFP2 masks [%]	Weight Proportion Single-use masks [%]	Weight Proportion Coffee grounds [%]	Moisture Input mixed material [%]
Reference sample	100	0	0	0	23.24
Sample 90/5/5	90	2.5	2.5	5	20.62
Sample 80/10/10	80	5	5	10	16.40

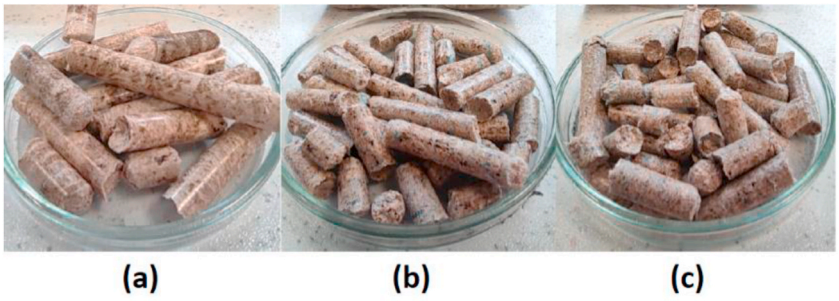

Fig. 1. Pellet samples: (a) Reference sample; (b) Sample 90/5/5; (c) Sample 80/10/10.

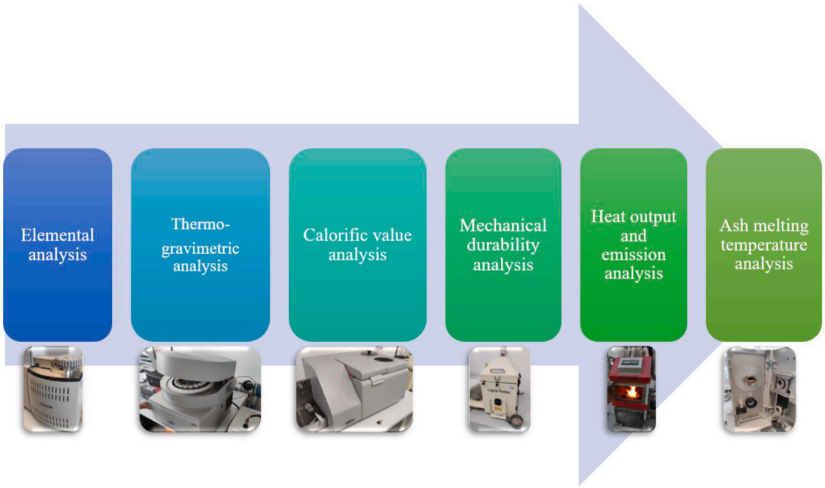

Fig. 2. A schematic overview of conducted analyses in the experiment.

Table 2
Conditions for evaluation of inorganic elements.

Group	Conditions				
	Voltage [kV]	**Live Time [s]**	**Filter**	**Elements**	**Energy range [keV]**
1	50	30	Cu Thick	Rh, Pd Ag, Sb, Te, I, Cs, Ba	20.0–33.0
2	50	30	Cu Thin	Tc, Ru, Cd, In, Sn	18.0–25.5
3	30	30	Pd Thick	As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo, Fr, Ra, and Actinides	10.4–16.5
4	20	30	Pd Medium	Cu, Zn, Ga, Ge, Hg, Tl	7.9–10.4
5	16	30	Pd Thin	Fe, Co, Ni, Hf, Ta, W, Re, Os, Ir, Pt, Au, and Lanthanides (Eu–Lu)	6.3–9.8
6	12	30	Aluminum	Ti, V, Cr, Mn, and Lanthanides (La–Sm)	4.4–6.1
7	8	30	Cellulose	Cl, K, Ca, Sc	2.5–4.3
8	4	60	No Filter	Na, Mg, Al, Si, P, S	1.0–2.4

standard. Prior to testing, the pellet samples were meticulously sieved using a 3.15 mm diameter sieve. The samples were then loaded into the device and subjected to impacts against each other or the device wall. Two tests were performed on 100 g ± 0.5 g samples: a 30-s test (F) and a 60-s test (DU), both calculated using Equation (2).

$$F\,(DU) = \frac{m_2}{m_1}.100 \tag{2}$$

In Equation (2) m_1 [g] represents the weight of pellets before the measurement, and m_2 [g] represents the weight of pellets after the measurement.

2.5. Heat output analysis

Pellet samples were combusted in an automatic pellet boiler with a retort burner for 30 min. The boiler has a maximum heat output

of 18 kW. The heat output (Q) was calculated using Equation (3):

$$Q = m \bullet c \bullet \Delta t \tag{3}$$

In Equation (3) m presents the weight of sample [kg. s^{-1}], c presents the specific heat capacity of water [J. K^{-1}.kg^{-1}] and Δt is a thermal difference between the output and input temperatures of the heating medium [K].

2.6. Emission analysis

Gas emissions, such as carbon monoxide (CO) and nitrogen oxides (NOx), were measured by a flue gas analyzer TESTO 350 in ppm units. The conversion from ppm to mg•m^{-3} was calculated using Equations (3) and (4), following the standard STN EN 16510-1 [24].

$$CO_{10\%} = CO_{ppm} \bullet d_{CO} \bullet \frac{21 - 10}{21 - O_2} \tag{4}$$

$$NO_{X10\%} = NO_{Xppm} \bullet d_{NOx} \bullet \frac{21 - 10}{21 - O_2} \tag{5}$$

In Equation (3) $CO_{10\ \%}$ presents the standard value of CO for 10 % of O_2, CO_{ppm} is the measured value of CO in the value of ppm, d_{CO} [kg•m^{-3}] is the density of CO and O_2 is the measured value of O_2 [%]. In Equation (4) $NO_{X10\ \%}$ presents the standard value of NO_X for 10 % of O_2, NO_{Xppm} is the measured value of NO_X in the value of ppm, d_{NOx} [kg•m^{-3}] is the density of NO_X and O_2 is the measured value of O_2 [%].

The measurement of particulate matter was conducted according to STN ISO 9096 [25] using a gravimetric probe placed in the flue pipe. The probe was connected to a Tecora ISOSTACK BASIC, a Pitot tube, a cooling box, and a silica gel dryer. Measurements were performed under isokinetic conditions, with a deviation ranging from −4.5 % to +3.8 %. The mass concentration (C) of particulate matter was calculated using Equation (5).

$$C = \frac{m_2 - m_1}{V_{gn}} \tag{5}$$

In Equation (5) m_1 [mg] presents the weight of the pure filter (before measurement) and m_2 [mg] presents the weight of the filter with captured particulate matter (after measurement) and V_{gn} [m^3] presents the sample volume. The mass concentration given by reference conditions C_r [mg•m^{-3}] is stated in Equation (6).

$$C^r = \frac{21 - O_{2\ ref}}{21 - O_{2\ oper}} \bullet C \tag{6}$$

In Equation (6), $O_{2\ ref}$ [%] is the reference oxygen content and $O_{2\ oper}$ [%] is the oxygen content for operating conditions during measurement.

An automatic pellet boiler with a retort burner and a maximum heat output of 18 kW served as the heat source. The air supply was controlled by a fan, which was supplied in two ways: primary air along with the pellets and secondary air through the retort burner. An

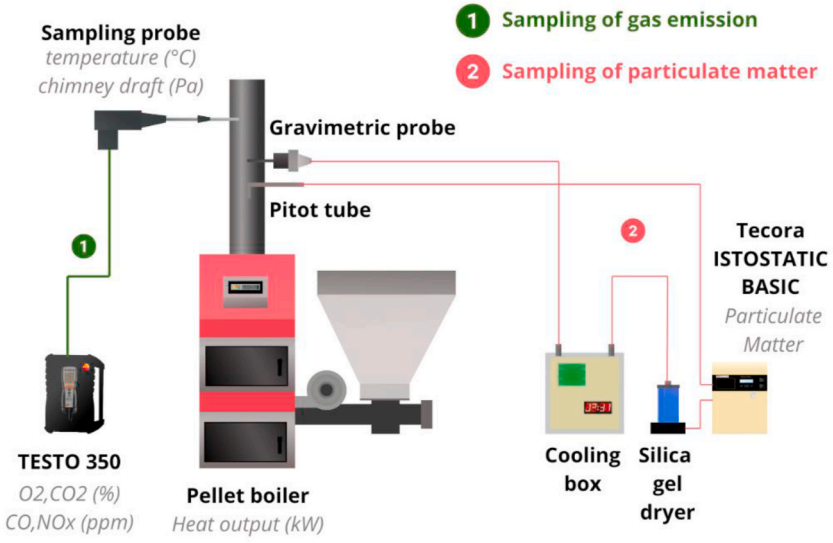

Fig. 3. The schematic diagram of the experimental setup of combustion and emission measurement.

electronic control unit regulated the supply of air and fuel. The entire system was hermetically sealed, and automatic operation was protected against backfiring with two safety sensors. The air supply was implemented with a mass airflow of 40 %, corresponding to 108 kg/h. A flue fan maintained a constant draft of 12 ± 2 Pa in the chimney, while a frequency regulator controlled the velocity. A differential pressure sensor with an accuracy of 0.5 % and a range of up to 100 Pa was measured in this draft. The surrounding pressure was maintained at 996.6 hPa ± 0.5 hPa. The fuel supply time was set at a ratio of 18 s supply to 25 s standstill. The schematic diagram of the experimental setup of combustion and emission measurement is presented in Fig. 3.

2.7. Ash melting temperature analysis

The ash melting temperature was measured using the LECO AF 700 ash fusion analyzer. Ash samples were collected during the combustion of pellets in an automatic pellet boiler with a retort burner. Ash paste was created by mixing the ash with a few drops of Dextrin, and the resulting specimens were molded into pyramids using the LECO mold and glued onto ceramic slabs. These specimens were then heated up to 1500 °C in the ash fusion analyzer. The system's integrated digital camera captured images of the melting specimens individually. The digital camera captured images of the melting specimens, while the ash melting temperatures were determined in an oxidizing atmosphere using nitrogen for purging up to 750 °C and compressed air up to 1500 °C. The evaluation followed a specific procedure. The testing process recorded the following temperatures: (I) Deformation temperature (DT) was noted when the first signs of rounding off the tip of the test sample were observed; (II) Sphere temperature (ST) was recorded when the height of the sample was equal to its width; (III) Hemisphere temperature (HT) was noted when the height of the sample was equal to half the diameter of the base; (IV) Flow temperature (FT) was recorded when the height of the sample was one-third of its total height.

3. Results and discussion

3.1. Elemental analysis

The elemental composition of tested pellet samples is shown in Fig. 4(a–c) and more details are stated in Table 3 with standardized values according to ISO 17225 [19] for A1. Carbon is the primary component of all samples. As the weight proportion of face masks and coffee grounds increases, the content of carbon, hydrogen, and nitrogen also increases, while the oxygen content decreases. The inorganic element content remains consistently low at around 0.4 % across all samples. Previous research by Čajová Kantová et al. [15] on face masks (single-use/FFP2 masks) revealed the following elemental composition: 84.59/85.08 % for carbon content, 13.78/13.38 % for hydrogen content, 0.67/0.66 % for nitrogen content and 0.66/0.67 % for oxygen content. However, Park et al. [26] reported the following results: 75.9 % carbon, 14.9 % hydrogen, 8.4 % oxygen and 0.8 % nitrogen for face masks. Nosek et al. [11] investigated the elemental composition of coffee grounds and found 54.56 % carbon, 7.44 % hydrogen, and 17.78 % nitrogen content, while Kang et al. [27] provided varying results: 46.42–71.6 % carbon, 6.04–8.99 % hydrogen, and 2.03–15.5 % nitrogen for coffee grounds. The ISO 17225 [19] standard establishes critical limits for various elements (N, S, Cl, As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn) found in wood pellets for commercial and residential applications. This standard ensures the safety and quality of these pellets for their

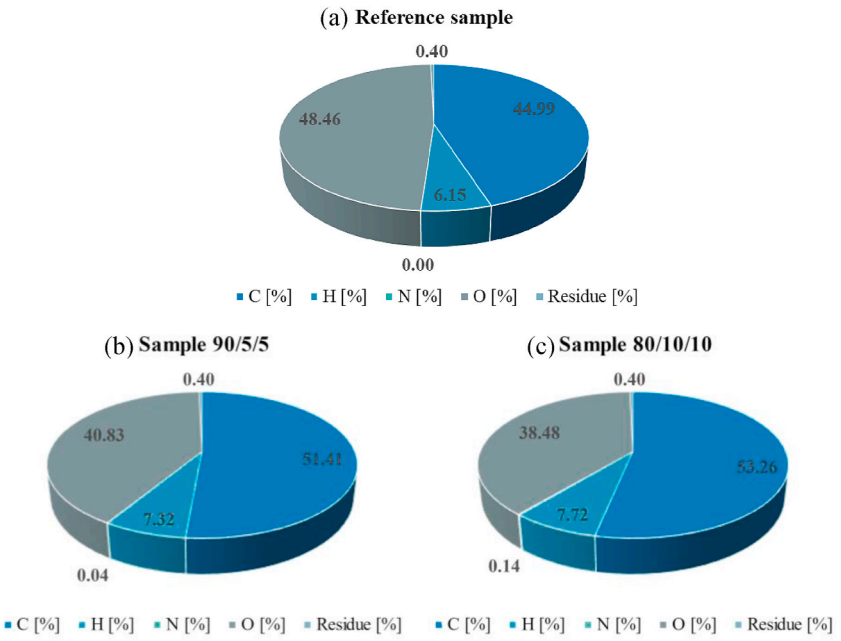

Fig. 4. Elemental composition of pellet samples: (a) Reference sample; (b) Sample 90/5/5; (c) Sample 80/10/10.

Table 3
Complete composition of elements of the pellet samples: Reference sample; Sample 90/5/5; Sample 80/10/10.

Element	Reference sample		Sample 90/5/5		Sample 80/10/10		Standardized
	Amount [%]	SD [%]	Amount [%]	SD [%]	Amount [%]	SD [%]	Amount [%]
C	44.9900	0.9600	51.4100	0.9800	53.2600	0.7400	–
H	6.1500	0.3500	7.3200	0.1800	7.7200	0.5600	–
N	0.0000	0.0100	0.0400	0.0400	0.1400	0.0100	≤0.3
O	48.4600	–	40.8300	–	38.4800	–	–
Si	0.1670	0.0080	0.1340	0.0070	0.1090	0.0050	–
Ca	0.1210	0.0060	0.1220	0.0060	0.1140	0.0060	–
K	0.0535	0.0027	0.0697	0.0035	0.0963	0.0048	–
P	0.0166	0.0023	0.0245	0.0026	0.0258	0.0023	–
Mn	0.0118	0.0006	0.0119	0.0006	0.0102	0.0005	–
Fe	0.0110	0.0005	0.0089	0.0004	0.0098	0.0005	–
S	0.0062	0.0025	0.0124	0.0030	0.0226	0.0032	≤0.04
Cl	0.0058	0.0013	0.0103	0.0016	0.0071	0.0014	≤0.02
Cu	0.0023	0.0001	0.0000	0.0000	0.0000	0.0000	≤0.001
Ti	0.0020	0.0002	0.0026	0.0002	0.0030	0.0002	–
Zn	0.0012	0.0001	0.0013	0.0001	0.0011	0.0001	≤0.01

intended uses. We can confidently state that both samples, 90/5/5 and 80/10/10, meet the highest quality classification (A1) defined by the standard, indicating they are free from significant amounts of harmful elements.

3.2. TGA analysis

The thermogravimetric analysis of tested pellet samples is shown in Fig. 5(a–c) in the wet state and is additionally provided in Table 4 in the dry state. Volatile matter was the predominant component in all samples. With the increasing weight proportion of face masks and coffee grounds, the volatile matter content also increased, while the fixed carbon content decreased. The ash content ranged from 0.48 % to 0.63 % in the dry state.

The standard ISO 17225 [19] outlines the limit values for moisture and ash content for wood pellets used in commercial and residential applications. The moisture content in wet basis should be less than 10 %, and the standardized value for ash content is detailed in Table 4. It is noteworthy that both samples, namely sample 90/5/5 and sample 80/10/10, meet the highest quality limit (A1).

3.3. Calorific value analysis

Fig. 6 illustrates the values of calorific values (HCV and LCV). As the weight proportion of face masks and coffee grounds increased,

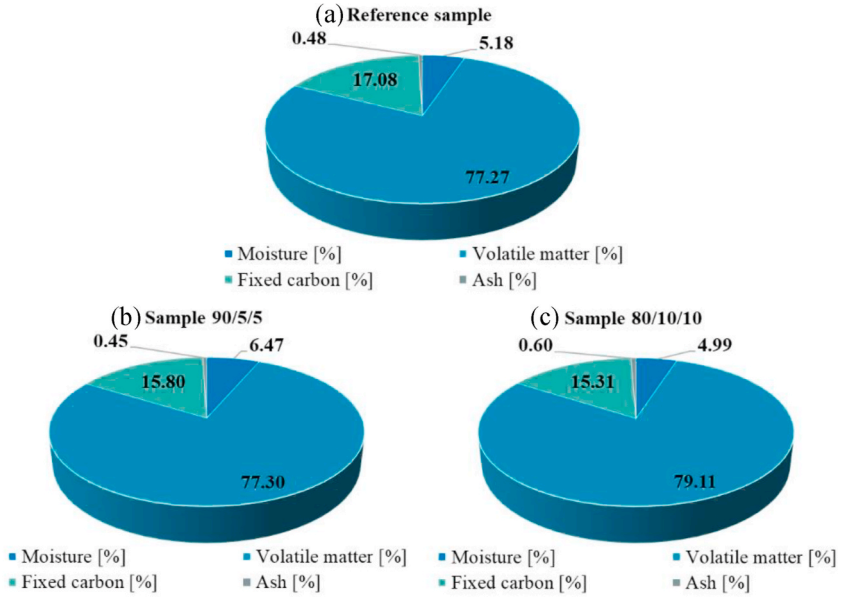

Fig. 5. TGA composition of pellet samples in the wet state: (a) Reference sample; (b) Sample 90/5/5; (c) Sample 80/10/10.

Table 4
TGA composition of the pellet samples in the dry state: Reference sample; Sample 90/5/5; Sample 80/10/10.

Sample	Volatile matter		Fixed carbon		Ash	
	Amount [%]	SD [%]	Amount [%]	SD [%]	Amount [%]	SD [%]
Reference sample	81.49	0.02	18.01	0.06	0.51	0.04
Sample 90/5/5	82.64	0.63	16.89	0.64	0.48	0.02
Sample 80/10/10	83.27	0.04	16.11	0.09	0.63	0.06
Standardized	–	–	–	–	≤0.7	–

the calorific values also rose (LCV: from 17.91 MJ/kg to 21.22 MJ/kg). The LCV reported in previous research by Čajová Kantová et al. [15] for FFP2 masks was 44.92 MJ/kg. However, Tomsej et al. [28] identified a value of 46.2 MJ/kg as the LCV for polyethylene plastic. The LCV of coffee grounds was measured at 21.08 MJ/kg by Nosek et al. [11], while Atabani et al. [29] indicated a range of 19.3–24.9 MJ/kg for the LCV of dried coffee grounds.

The calorific values of RDF (refuse-derived fuel) pellets were investigated by Suryawan et al. [30]. The RDF pellets consisted of different blending ratios of paper waste and garden waste. Based on the results, it was noticed that a higher proportion of garden waste increased the calorific value. Pasek et al. [31] came to the same conclusion, noting that the calorific value of garden waste is higher compared to paper waste.

The calorific values from the collected results of sample 90/5/5 and sample 80/10/10 were 20.22 and 22.57 MJ/kg respectively. The standard calorific value (HCV) produced by the RDF ranges from 18 to 23 MJ/kg. The higher values of calorific values are linked with increasing carbon content [32,33]. The lower calorific value of dried spent coffee grounds ranges between 19.3 and 24.9 MJ/kg Atabani et al., 2019. The effect of different variations of SCG on calorific values was investigated in this study, and results showed an increase in values with a higher proportion of coffee grounds. The studies conducted by Lachman et al. [34] and Nosek et al. [11] confirm that higher SCG concentrations increase LCV values.

According to the ISO 17225 standard (2021), the net calorific value (LCV) for commercial and residential applications must be at least 16.5 MJ/kg. Both samples, sample 90/5/5 and sample 80/10/10 have been found to meet this limit.

3.4. Mechanical durability analysis

The results from mechanical durability tests are depicted in Fig. 7. All tested samples exhibited mechanical durability values higher than 99 % during the F tests. However, both the reference sample and the sample demonstrated mechanical durability values exceeding 96 % during the longer DU test, while the sample 80/10/10 showed a lower value of 90.9 % during this test. However, it is worth noting that neither of the tested samples (sample 90/5/5 and sample 80/10/10) met the standardized values of mechanical durability outlined in ISO 17225 [19]: more than 98 % for A1 quality, more than 97.5 % for A2 quality, and more than 96.5 % for B quality. The mechanical durability values are expected to decrease with the increasing content of face masks or coffee grounds in the pellets due to the decreasing lignin content.

In the research works of Jewiarz et al. [35] and Kozina et al. [36], samples containing municipal solid waste (mainly composed of plastic) and mustard residue were processed into pellets. The DU test of the first sample resulted in a durability of 98.6 %, which is higher compared to the results presented in Fig. 7 (right). In the case of pellets containing mustard residue, the mechanical durability was 95.6 %. This value is higher compared to the results of sample 80/10/10 and lower compared to sample 90/5/5. Rezaei et al. [32]

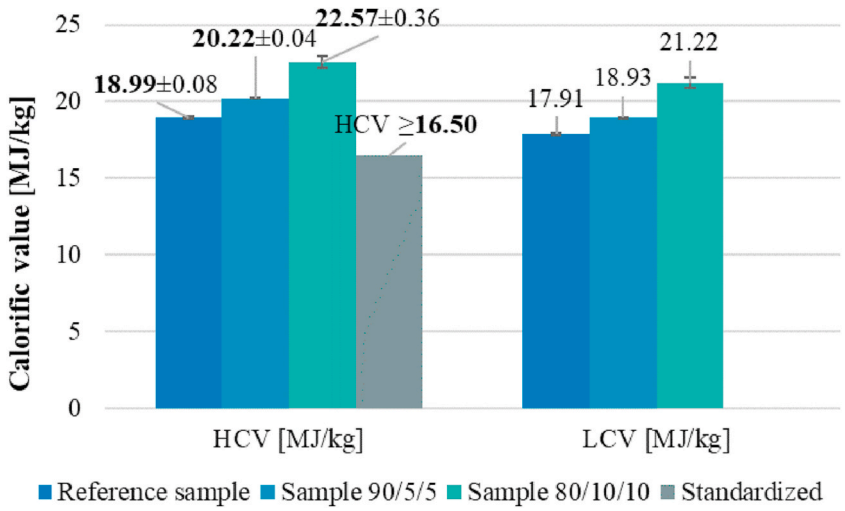

Fig. 6. Calorific values of pellet samples: Reference sample; Sample 90/5/5; Sample 80/10/10.

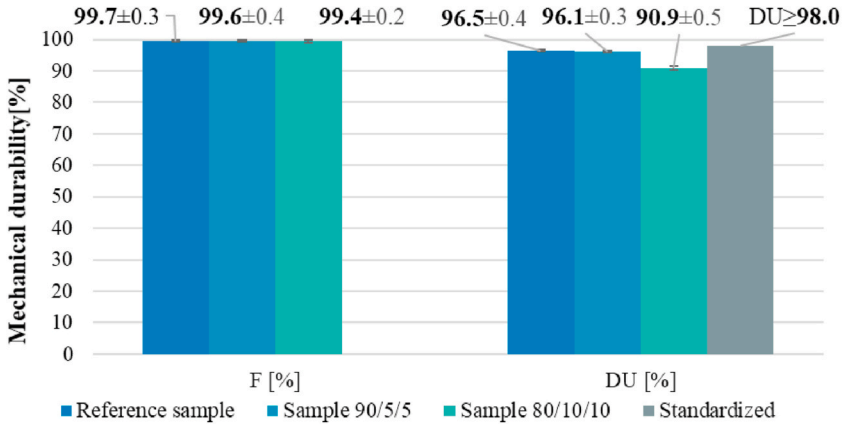

Fig. 7. Mechanical durability of pellet samples: Reference sample; Sample 90/5/5; Sample 80/10/10.

also analyzed the mechanical durability of RDF pellets. The RDF composition was as follows: 50 % paper and cardboard, 20 % plastic, 20 % organics, and 10 % wood. Pellets with fractions of 2, 4, and 6 mm were produced, with tested durability of 97.3 %, 98.7 %, and 99.9 %, respectively. These pellets exhibited higher durability compared to the samples in Fig. 7 (right), indicating that larger particles contributed to more durable pellets.

3.5. Heat output analysis

Fig. 8 displays the calculated values of heat output. The reference sample and the sample 90/5/5 exhibited very similar values of heat output. However, sample 80/10/10 demonstrated a higher value of heat output than both of these samples. Nosek et al. [11] observed that the durability of the pellets from 100 % coffee grounds was low and the boiler heat output (3.98 kW) was four times lower compared to wood pellets (15.18 kW). The heat output is primarily influenced by the fuel quality and the proper settings of the control system of the boiler. Lachman et al. [34] observed the highest thermal efficiency with pure SCG pellets, likely due to their high value of low calorific value. On the other hand, Limousy et al. [10] found that using pure SCG as fuel resulted in lower boiler efficiency. However, when SCG was mixed with pine sawdust (50/50 wt%), combustion parameters such as emissions and boiler efficiency were very close to those obtained for wood pellets.

3.6. Emission analysis

Fig. 9 presents the results from the emission measurements. The concentration of CO was highest during the combustion of sample 90/5/5 and lowest during the combustion of sample 80/10/10. Conversely, NO_X concentration was highest when burning sample 80/10/10 and lowest during combustion of the reference sample. PM concentration increased steadily with increasing amounts of face masks and coffee grounds in the pellets. Nosek et al. [11] found that pure coffee pellets had significantly higher CO emissions compared to standard certified wood pellets. This could be attributed to lower pellet strength. However, NO_X production during the combustion of pure coffee pellets was lower due to a lower combustion temperature and incomplete combustion. Limousy et al. [10] found that the use of pure SCG led to lower boiler efficiency, which was followed by an increase of particle and gas emissions. Lach-man et al. confirmed that it is possible to operate a wood-certified boiler on pure SCG and also the 50/50 blend and meet the CO emission limit of 500 mg/Nm^3.

The standard STN EN 303-5+A1 [37] defines maximum emission limits for CO concentration based on automatic stoking and biogenic fuel. These limits are categorized by class: class 3: 3000 mg m^{-3}, class 4: 1000 mg m^{-3} and class 5: 500 mg m^{-3}. Similarly, for PM concentration, the established limits are as follows: class 3: 150 mg m^{-3}, class 4: 60 mg m^{-3}, class 5: 40 mg m^{-3}. Sample 80/10/10 exhibited a CO concentration below 500 mg/m^3, meeting the limit value for class 5. The reference sample and sample 90/5/5 complied with the limit values for class 4. Only the reference sample had a PM concentration lower than 40 mg/m^3, achieving the class 5 limit value. Sample 90/5/5 met the limit value for class 4, while sample 80/10/10 fell under class 3.

3.7. Ash melting temperature analysis

The ash melting temperatures of the tested pellet samples are presented in Table 5 alongside the standardized values according to ISO 17225 [19] for A1 quality. There were no significant differences observed in the individual ash melting temperatures among the samples. However, sample 90/5/5 exhibited higher values of ST, HT, and FT compared to the other tested samples, while the reference sample had the highest value of DT. Overall, the sample 80/10/10 demonstrated the lowest melting temperatures. According to the research by Van Loo and Koppejan [38], the individual ranges for ash melting temperatures of spruce wood were as follows: DT ranged from 1110 °C to 1340 °C, ST ranged from 1410 °C to 1640 °C, HT ranged from 1630 °C to 1700 °C, and FT exceeded 1700 °C. Jezerska

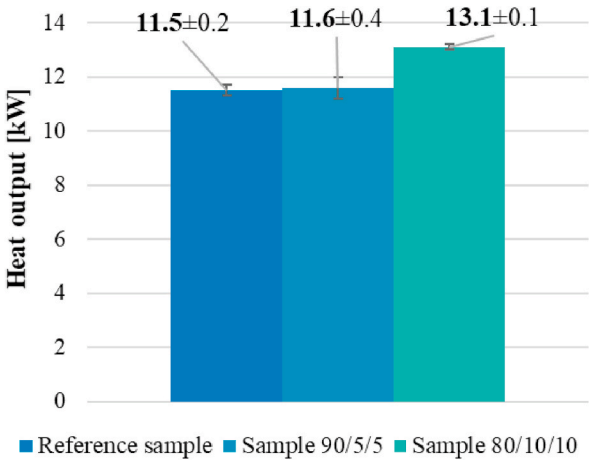

Fig. 8. Heat output of pellet samples during combustion: Reference sample; Sample 90/5/5; Sample 80/10/10.

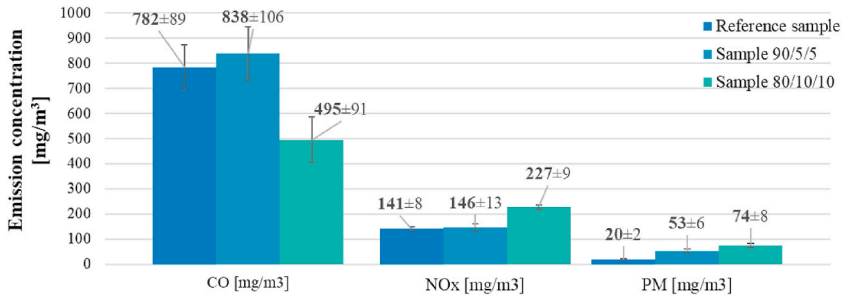

Fig. 9. Emissions of pellet samples during combustion: Reference sample; Sample 90/5/5; Sample 80/10/10.

Table 5
Ash melting temperatures: Reference sample; Sample 90/5/5; Sample 80/10/10.

Sample	DT		ST		HT		FT	
	Amount [°C]	SD [°C]	Amount [°C]	SD [°C]	Amount [°C]	SD [°C]	Amount [°C]	SD [°C]
Reference sample	1074	9.2	1266	29.7	1297	16.3	1313	12.7
Sample 90/5/5	1067	10.1	1328	25.2	1381.5	33.2	1404.5	2.1
Sample 80/10/10	1058	5.7	1231.5	13.4	1279.5	7.8	1295.5	2.1
Standardized	≥1200	–	–	–	–	–	–	–

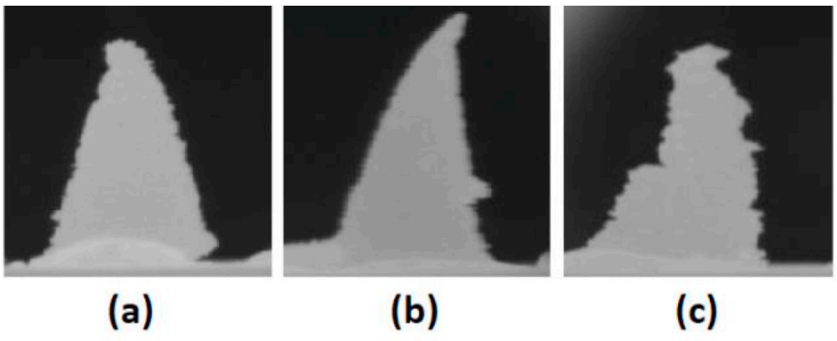

Fig. 10. Specimen shapes at 1100 °C: (a) Reference sample; (b) Sample 90/5/5; (c) Sample 80/10/10.

et al. [39] reported that the ash melting point for coffee grounds was sufficiently high, with values of 850 °C as the shrinkage starting temperature and 1340 °C as the deformation temperature. These characteristics create favorable conditions for combustion in low-power mechanical furnaces with capacities ranging from 15 to 20 kW.

The deformation temperature (DT) is required to be more than 1200 °C for A1 quality, and more than 1100 °C for A2 and B quality, as per ISO 17225 [19] standard. However, all samples (sample 90/5/5, sample 80/10/10, and the reference sample) exhibited DT values lower than 1100 °C. Ash melting temperatures should decrease with the increasing content of face masks or coffee grounds, which could lead to deposit formation, slagging, sintering, and other combustion problems.

Fig. 10(a–c) depicts the shape of specimens at 1100 °C in the LECO AF 700 analyzer while Fig. 11(a–c) shows their shape at 1200 °C. Notably, all tested samples exhibited a similar deformation process.

4. Conclusion

This study investigated the potential utilization of waste materials as a fuel source, specifically spruce sawdust blended with a small proportion of single-use masks, FFP2 masks, and spent coffee grounds. A series of experiments were conducted, including elemental analysis, thermogravimetric analysis, calorific value determination, mechanical durability testing, emission analysis, and performance evaluation. Additionally, the study examined the ash melting temperatures of the fuels in pellet form. Based on the analysis results, an increase in the amount of face masks and spent coffee grounds in pellets led to elevated levels of carbon, hydrogen, and nitrogen, while reducing oxygen content. Furthermore, it resulted in higher volatile matter content, and possibly increased ash content, alongside reduced fixed carbon content. Both higher and lower calorific values saw an increase, although mechanical durability decreased. Heat output was augmented, but it is important to note that NO_X and PM emissions also rose. Additionally, it is significant to consider that ash melting temperatures were decreased.

Samples 90/5/5 and 80/10/10 contained various inorganic elements like Si, Ca, K, P, Mn, Fe, S, Cl, Cu, Ti, and Zn. Among these, silicon (Si) exhibited the highest content, with 0.109 % for sample 80/10/10 and 0.1334 % for sample 90/5/5. Calcium (Ca) followed with contents of 0.114 % and 0.122 % for samples 80/10/10 and 90/5/5, respectively. All other elements were present only in trace amounts, totaling less than 0.4 % collectively. Moreover, both samples met the limits for element content (N, S, Cl, As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn) for the highest quality grade (A1) as per ISO 17225 [19]. No significant amounts of harmful elements were found in these samples. Additionally, the samples met the standard's limits for moisture content, ash content, and net calorific value (lower heating value). In terms of emissions, all samples complied with the prescribed limits in their respective classes (3, 4, or 5) according to the standard STN EN 303-5+A1 [37]. However, they did not meet the specified values for mechanical durability and ash melting temperatures. Therefore, samples did not meet full limit values. The problems with lower mechanical durability and ash melting temperatures can be solved by adding additives, which can improve these properties. Based on these findings, it could be proposed that the pellet samples generated demonstrate potential as a viable fuel source for thermal energy. This potential can be further enhanced by incorporating specific additives to improve their properties.

Data availability statement

Data will be made available on request.

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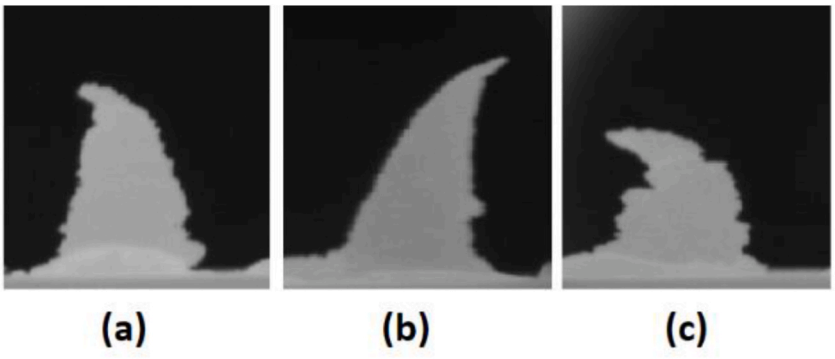

Fig. 11. Specimen shapes at 1200 °C: (a) Reference sample; (b) Sample 90/5/5; (c) Sample 80/10/10.

CRediT authorship contribution statement

Nikola Čajová Kantová: Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Radovan Nosek:** Writing – review & editing, Funding acquisition. **Alexander Backa:** Validation, Data curation. **Alexander Čaja:** Investigation, Data curation. **Marcin Jewiarz:** Methodology, Formal analysis. **Krzysztof Mudryk:** Methodology, 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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