Agro-residual biomass and disposable protective face mask: a merger for converting waste to plastic-fiber fuel via an integrative carbonization-pelletization framework

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Abstract
In incineration and landfilling offer possibilities for addressing high-rate management of COVID-waste streams. However, they can be costly and environmentally unsustainable. In addition, they do not allow to convert them to fuels and chemicals as waste-to-energy and waste-to-product technologies. Therefore, we analyzed whether integrating hydrothermal carbonization (HTC) and pelletization can allow converting the surgical face mask (SFM) and biomass to composite plastic-fiber fuel (CPFF). We blended the plastic material and corn cob, peanut shell, or sugarcane bagasse at the proportion of 50:50 (%, dry mass basis) for HTC. We performed the thermal pretreatment of blends in an autoclaving reactor at 180 °C and 1.5 MPa. Then we pelletized the hydrochars in a presser machine at 200 MPa and 125 °C. By analyzing the evidence from our study, we recognized the viability of combining the SFM and agricultural residues for CPFF from comparable technical features of our products to standards for premium-grade wood pellets. For instance, the elemental composition of their low-melt ash was not stoichiometrically sufficient to severely produce slagging and fouling in the equipment for thermal conversion. Although they contained synthetic polymers in their structures, such as polyethylene from filter layers and nylon from the earloop, they emitted CO and NOx below the critical limits of 200 and 500 mg m⁻³, respectively, for occupational safety. Therefore, we extended the knowledge on waste-to-energy pathways to transform SFM into high-quality hybrid fuel by carbonization and pelletization. Our framework can provide stakeholders opportunities to address plastic and biogenic waste in the context of a circular economy.

Keywords Agricultural waste · 3-Ply face mask · COVID-19 · Plastic waste · SARS-CoV-2 · Waste-to-energy pathway

Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| ASTM         | American Society for Testing and Materials |
| CEN          | European Committee for Standardization (French: Comité Européen de Normalisation) |
| COVID-19     | Coronavirus disease 2019 |
| CPFF         | Composite plastic-fiber fuel |
| DTG          | Derivative thermogravimetric |
| DTGc         | Combustibility-related thermogravimetric index |
| DTGf         | Flammability-related thermogravimetric index |
| DTGi         | Ignitability-related thermogravimetric index |
| DTGt         | Thermostability-related thermogravimetric index |
| EDXRF        | Energy-dispersive x-ray fluorescence |

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EN  European Norm
FRI  Fouling-related index
FTIR  Fourier-transform infrared
GCMS  Gas chromatography-tandem mass spectroscopy
HTC  Hydrothermal carbonization
IWPB  Initiative for Wood Pellet Buyers
LOQ  Limit of quantification
NMVOC  Non-methane volatile organic compound
PCA  Principal component analysis
PC_I  First principal component
PC_{II}  Second principal component
PC_{III}  Third principal component
PC_{IV}  Fourth principal component
PC_{V}  Fifth principal component
PE  Polyethylene
POM  Polycyclic organic matter
PP  Polypropylene
PPE  Personal protective equipment
PS  Polystyrene
PSW  Plastic solid waste
PVC  Polyvinyl chloride
SARS-CoV-2  Severe acute respiratory syndrome coronavirus 2
SFM  Surgical face mask
SMW  Solid medical waste
SRI  Slagging-related index
STP  Standard pressure and temperature
TPP  Thermoreactive plastic polymer
VFF  Volatile fuel factor
WSFM  Waste surgical face mask
WTE  Waste-to-energy
WTP  Waste-to-product

1 Introduction

The surgical face mask offers people an effective and affordable device to protect against SARS-CoV-2 (COVID-19) [1]. However, it can be a source of hazardous medical waste to human health and the environment through its disposal [2]. The generation of WSFM is approximately 3.3 billion units per day worldwide [3]. Asia, Europe, Africa, Latin America, North America, and Oceania share 55.5, 13.1, 12.1, 11.2, 7.2, and 0.8% of the total production, respectively [4].

Large-scale companies rely on incineration and landfilling to handle COVID-waste streams from medical facilities and public areas [5]. Burning (1100 °C) can degrade them intensively over time. However, it can be costly and not an eco-friendlier solution than landfilling [6]. For instance, incomplete combustion of plastic polymers, such as PE, PP, PS, and PVC, can generate NO_x, SO_x, VOCs, and POMs [7]. In addition, neither incineration nor landfilling allows for recovering fuels and chemicals from SFM [8].

The European Union provides directives to address the sustainable management of plastic waste [9]. However, the significant and growing generation of COVID-waste streams makes it challenging for high-income and emerging countries to approach high-rate treatment [10]. Therefore, the need for rearranging flows and trades of plastic waste between and within continents for adaptation and migration toward a post-pandemic wider zero-plastic or circular plastic economy [11] offers opportunities to develop catalytic and strategic recycling models for SFM via thermochemical techniques [7].

Pyrolysis [6], torrefaction, and gasification [12] are technically viable WTE and WTP pathways for environmentally friendly disposing of PSW from the COVID-19 pandemic. They can convert the SFM to chars, oils, and condensable gasses. Such by-products are flexible for industrial processing. For instance, they can allow for the development of high-density fuels [13] and nano-catalysts [14] for heating systems and materials and products for electrochemical engineering and civil building, such as supercapacitors for lithium batteries [15], nano-fillers, and epoxy composites for concrete and mortar [16]. These technologies also enable the treatment of biogenic feedstocks [17].

Torrefaction partly decomposes biomass into biochar [18]. A homogeneous, dense, and dry load is technically desirable for coalification [19]. However, biogenic feedstocks generally are heterogenous, porous, and hygroscopic. Hence, they make it challenging to develop an effective conversion without pretreatment (e.g., drying) [19]. Adding plastic to low-quality biomass for dry co-carbonization can improve the technical performance of the thermochemical process while allowing for the development of an energy-dense composite fuel via co-pelletization [19] or co-briquetting [13]. Plastic is hydrophobic. Hence, it reduces the quantity of water in the blend for co-torrefaction [20]. It also upgrades the thermal quality and mechanical resistivity of the fuel. As its polymers break up to heat, they release energy, thereby increasing the calorific value during burning [21]. Their synergies with natural fibers develop the binding functionality of the product, strengthening it structurally [13]. However, the co-occurrence of TPPs in the blend can intensify toxic emissions, decreasing the environmental footprint of the intervention [13]. Therefore, the need for developing the knowledge to progress the field’s prominence in transforming COVID-waste streams into fuels and products for sustainable development motivates our research.

To our knowledge, researchers focus on performing pyrolytic pathways to recover energy from pandemic medical waste. Studies on the possibility of combining hydrothermal carbonization and pelletization for their WTE treatment are not available in the literature. Therefore, we analyzed
the technical viability of converting the SFM to composite plastic-fiber fuel via an integrative carbonization-pelletizing framework. We investigated a range of biogenic raw materials for an opportunity to develop a premium-grade product.

2 Materials and methods

We hypothesized that SFM and biomass develop a blend for generating heat and electricity. Therefore, we integrated hydrothermal carbonization and pelletization into a waste-to-energy framework to produce composite plastic-fiber fuel (Fig. 1). We analyzed the product technically by performing physical, mechanical, thermogravimetric, spectroscopic, and combustion experiments. Then we compared its quality to standards for solid biofuel within ENPlus and IWPB for validation. We summarized conventional methods and tests while referencing them to ensure the reproducibility of our study.

2.1 Acquisition of surgical face mask and agricultural residues

The biogenic raw materials included the peanut shell, sugarcane bagasse, and corn cob. We were not allowed by the COVID-19 Committee to employ potentially infectious waste from a medical or public place in the laboratory. Therefore, we acquired SFM as a clean material from a pharmacy. We characterized the materials for fundamental energy properties, namely, moisture, volatile matter, solid carbon, ash, C, H, O, N, S, and calorific value, as per technical specifications by ASTM and CEN/TS (Table S1, Supplementary material). An additional level of characterization for agricultural residues included the analysis of cellulose,
hemicellulose, and lignin by digestion in neutral and acidic detergents [22].

2.2 Production of plastic-fiber blends via an integrative carbonization-pelletization framework

2.2.1 Hydrothermal co-carbonization

We pretreated the SFM and agricultural residues for blending and, consecutively, co-HTC. We chopped the SFM into nearly uniform rectangular pieces [7]. We grounded the biogenic raw materials in a Willey mill and then sieved them on a stainless wire screener to bring particles into uniformity between 0.25 and 0.45 mm. Then we blended the SFM and peanut shell (Blend#1), sugarcane bagasse (Blend#2), or corncob (Blend#3) at the proportion of 50:50 (%, dry mass basis) mechanically in a rotating chamber at 40 rpm until homogenization. We prepared 50 kg for every blend. Hence, we conducted the thermal pretreatment in five batches of 10 kg. We introduced the solid load and 150 L of de-ionized water into the reactor (Table S2, Supplementary material). Then we sealed the equipment and programmed it to perform hydrothermal co-carbonization at 180 °C and 1.5 MPa for 120 min [23]; we set the heating ramp to 5 °C min⁻¹ for the autoclave to gradually transit the internal temperature via its heaters throughout the conversion. The process yielded 20–25% of hydrochar. Therefore, the activities in the post-HTC included the recovery of the solid by-product from the reactor, immersion in water to avoid overreaction, filtration in a cellulose-nitrate membrane to remove impurities, and oven-drying at 105 °C until constant mass [24]. We stored the hydrochar in an airtight receptacle in the laboratory in an ambient atmosphere until co-pelletization.

2.2.2 Co-pelletization

The assembly of pelletization consisted of the components, namely, screw feeder silo, hydraulic presser machine, vibrating screener, and gravitational conveyor with a set of cooling devices. The pelletizer can provide up to 300 MPa and 150 °C in the compressing chamber for making woody and non-woody material into cylindrical solid fuel from 6 to 8 mm in diameter and with a maximum bulk density of 1400 kg m⁻³ (Table S3, Supplementary material). Therefore, we prepared samples of 10 kg for every blend for co-compaction. We introduced the starting material into the silo. Then we set the pelletizer to operate at 200 MPa and 125 °C for 90 s [25]. The load passed off through the flat channel-forming die underneath pressing rollers to yield single pellets by frictional compression. The machine dropped them from compressing chamber directly onto the vibrating screener. Subsequently, the gravitational conveyor moved them to the sampling unit while ventilators forced the air to pass off through them to cool. We turned off and thoroughly cleaned up the manufacturing line after the co-pelletization of every batch to avoid contamination of a new workflow. We arranged the pellets into five subsamples of 1.5 kg for every treatment and then stored them dry in airtight receptacles in the laboratory in an ambient atmosphere for technical assessment.

2.3 Assessing the technical quality of plastic-fiber blends

We tested the quality of the models for CPFF for standard variables, namely, length, diameter, bulk density, durability, and calorific value. We included the tensile strength and hygroscopicity in our technical assessment to provide further knowledge of their mechanical resistivity and interaction with the environment by uptaking and retaining moisture at the microscopic level.

Length (L, mm) and diameter (Ø, mm): We measured the longitudinal and axial planes of twenty random specimens, respectively, with an electronic ruler (FBA-ip54, MrToolz, Brazil, 0.01-mm resolution) [26].

Bulk density (ρ, kg m⁻³): To determine the degree of compactness of pellets, we measured the volume unit of 0.1 kg in a cylinder with 2.5 L of water in triplicate [27].

Durability (%): We performed the tumble test to determine the ability of pellets to resist breaking force. Therefore, we exposed triplicate samples of 0.1 kg to repetitive free drops from the tabletop of 1.5 m height onto the floor to promote shock and abrasion. Subsequently, we sieved the material on a stainless wire screener (3.15-micron mesh) and weighed it on an analytical digital scale (ATX-220, Shimadzu, Brazil, 0.0001-g resolution). The quantities retained on and passing the sieve represented the durability and production of fines, respectively [28].

Calorific value (MJ kg⁻¹): To quantify the isothermally available energy from pellets to the heating system, we burned down triplicates samples of 0.1 kg in an adiabatic calorimeter (C200, IKA, Brazil) as per ASTM D2015-96.

Tensile strength (σ, MPa): We calculated the mechanical resistivity of pellets to pulling force by Eq. 1. Therefore, we downsized twenty random specimens to 2 mm for standardization. Then we set the universal testing machine (6800 Series, Instron, USA) to apply 5 kN to them until breaking down at a crosshead speed of 1 mm min⁻¹ [29].

\[
\sigma = \frac{2F}{\pi dL}
\]  

(1)

where F, d, and L stood as the breaking force (N), diameter (m), and length (m), respectively.

Hygroscopicity (%): We determined the ability of pellets to attract water from the surroundings through either absorption...
or adsorption on triplicate dry samples of 0.1 kg in a humidity chamber (KBF 115, Binder Inc., USA). We programmed the instrument to operate at 25 °C and 90% moisture for 72 h. Then we weighted samples on an analytical digital scale to calculate percent hygroscopicity by variation in mass [30].

2.3.1 Thermal stability of plastic-fiber blends

We determined the blends’ thermal stability on triplicate samples of 0.05 kg in a thermogravimetric analyzer (PGA-8000, PerkinElmer, Brazil) by raising the temperature from 25 to 1000 °C at a heating ramp of 10 °C min⁻¹. We injected an inert gaseous mixture (N₂/O₂, 4:1 v/v⁻¹) at 50 mL min⁻¹ into the reactor for carrying oxidative kinetics for samples [31]. In addition, we estimated the indicators of combustion performance, namely, DTG_c, DTG_i, DTG_f, and DTG_t, by solving equations (Eqs. 2–5) involving critical temperatures and rates of thermal conversion [32].

\[
DTG_c = \frac{R_p 	imes R_v}{T_i^2 \times T_b}
\]  

(2)

\[
DTG_i = \frac{R_v}{T_i \times T_p}
\]  

(3)

\[
DTG_f = \frac{R_p}{T_i^2}
\]  

(4)

\[
DTG_t = \frac{8.5875 \times 10^7 \times R_v}{T_i 	imes T_p}
\]  

(5)

where \(R_p\) and \(R_v\) were the maximum (% min⁻¹) and average (% min⁻¹) loss of matter while \(T_i\), \(T_b\), and \(T_p\) were the temperatures (°C) of ignition, burnout, and peak, respectively.

2.3.2 Profile of metal oxides and the propensity of plastic-fiber blends to slag and foul

We performed EDXRF spectroscopy to determine the metal oxides in blends [33]. In addition, we estimated their propensity to slag (Eq. 6) and foul (Eq. 7) by solving equations involving such compounds [34].

\[
SRI = \left( \frac{\text{CaO} + \text{Fe}_2\text{O}_3 + \text{K}_2\text{O}}{\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2} \right) \times \text{SO}_3
\]  

(6)

\[
FRI = \frac{\text{CaO} + \text{MgO} + \text{K}_2\text{O}}{\left( \text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2 \right)} \times \text{K}_2\text{O}
\]  

(7)

2.3.3 Fourier-transform spectra of absorption of infrared energy of raw materials and composite plastic-fiber blends

We performed an FTIR spectroscopy to determine the absorption of infrared energy by functional groups in SFM, biogenic raw materials, and blends at 4000–400 cm⁻¹ [1].

2.3.4 Emissions of permanent gasses and non-methane volatile organic compounds from plastic-fiber blends

We conducted a chemometric analysis to quantify the emissions of permanent gasses and NMVOCs from blends during combustion. Therefore, we inserted a portable multi-gas analyzer (MRU Vario Plus, Germany) into the boiler to detect NOx, SO2, CO, and CO2 from the flue through chemiluminescent, paramagnetic, and non-dispersive infrared sensors [35]. We also quantified aldehydes, furans, naphthalenes, and terpenes by performing GCMS spectroscopy [36] to provide further knowledge of the generation of hazardous fast-acting chemicals from burning composite pellets.

2.4 Data analytics

We applied descriptive analysis to data on physicochemical characterization and standard technical assessment to calculate summary statistics, such as the arithmetic mean, to communicate the information on raw materials and blends as simply as possible. We designed custom diagrams (i.e., thermograms and Fourier-transform spectrograms) to illustrate the dynamics of combustion and absorption of infrared energy, respectively, and bar graphs to present the profile of metal oxides and the propensity of blends to slag and foul. A deeper level of data analytics included the application of PCA as a data-reduction multivariate technique [37] to calculate explanatory variables and provide insights into the conceptual and technical ramifications of the production of composite plastic-fiber fuels. We conducted the analyzes in the environment of the R-project for statistical computing and graphs.

3 Results and discussion

3.1 Fundamental energy properties of raw materials and blends

We characterized raw materials for fundamental energy properties, namely, moisture, volatile matter, solid carbon, ash, cellulose, hemicellulose, lignin, C, H, O, N, S, and calorific value (Table 1). We extended the physicochemical characterization to blends to legitimate the synergies between SFM and agro-residual biomass and their technical
viability for making composite fuels via an integrative HTC-pelletizing framework.

The SFM brought 0.1% water into the non-combustible fraction of its proximate composition. Therefore, its nearly dry character would intensify the need for introducing water from an external source into the reactor for catalytic co-carbonization with biomass. Such plastic material also contained 83.75% volatile matter, 12.35% solid carbon, and 3.8% ash. In addition, it consisted of 81.3% C, thereby developing the highest calorific value of 31.3 MJ kg\(^{-1}\). The occurrence of PP (73.55%) and PE (14.1%) in filter layers and nylon (8.2%) in the earloop (Table S4, Supplementary material) supported the dryness, volatility, and high calorific value of SFM. These polymers strongly repulse water. In addition, they are highly reactive to heat and thus release a significant quantity of energy for the burning system [38]. A VFF of approximately 1 (Table S4, Supplementary material) further supported the balance between volatile matter and solid carbon in SFM. We also detected 3.9% iron and 0.25% other trace metals (i.e., Ca, Mn, Ti, and Zn) in such material from the nose frame or band (Table S4, Supplementary material).

Jung et al. [8] characterized SFM for thermal conversion. The filter layers consisted of 73.3% PP and 13.7% PE, while the quantity of nylon in the earloop or strap was 8.25%. In addition, the nose frame or band consisted of 4.55% iron. Brillard et al. [39], Lee et al. [38], and Farooq et al. [40] also characterized the SFM for recovery of energy via pyrolysis and catalytic gasification. By analyzing these independent studies, we could identify quantities of moisture, volatile matter, solid carbon, and ash in ranges of 0–2.1, 81.3–85.9, 9.2–11.7, and 0.3–9.5%, respectively. In addition, Sun et al. [41] provided a reference value of 0.25% for S, while we could not detect such an element in our samples. The composition of SFM varies from manufacturer to manufacturer. Although such a protective device can contain up to 9.5% ash [40], it can release 56.3 MJ kg\(^{-1}\) [38]. Brillard et al. [39] measured approximately 23.6 MJ kg\(^{-1}\) from burning SFM with 0.3% ash, which is consistent with our record.

The peanut shell consisted of 7.8% water, making it the driest biogenic raw material. Proportions of water in corncob and sugarcane bagasse were 9.05 and 8.15%, respectively. Therefore, all agricultural residues were wetter than SFM. They developed blends with 7.5–8.95% water. As HTC generally demands 75–80% water to convert biomass to hydrochar, we introduced liquid into the reactor to guarantee an effective thermal pretreatment; otherwise, the availability of diluent from the feedstock-reactor system would not be stoichiometrically sufficient to trigger a series of chemical reactions, such as dehydration, demethylation, and decarboxylation, for wet coalification. In addition, the peanut shell (80.3%) was less volatile than sugarcane bagasse (82.9%) and corncob (81.3%) and thus brought the highest proportion of ash into the inorganic (inert) phase of the proximate composition amongst biogenic raw materials. The burning of corncob produced the highest quantity of solid carbon (15.3%) since it contained less volatile matter and ash (3.35%).

The peanut shell (16.05%) and sugarcane bagasse (12.25%) generated ash excessively, compared to corncob. Mechanical harvest and dragging of soil from outdoor stockpiles during handling brought extrinsic inorganics to these raw materials, contaminating samples. Therefore, the on-site management and acquisition of raw materials must be

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**Table 1** Fundamental energy properties of raw materials and plastic-fiber blends

| Material                | Proximate analysis [%] | Ultimate analysis [%] | Physical analysis [MJ kg\(^{-1}\)] | Reference                  |
|-------------------------|-----------------------|-----------------------|-------------------------------------|---------------------------|
|                         | Moisture | Volatile matter | Solid carbon | Ash | C | H | O | N | S |                           |
| Surgical face mask      | 0.1      | 83.75          | 12.35        | 3.8 | 81.3 | 8.3 | 10.2 | 0.05 | –   | 31.3 | This study              |
| Peanut shell            | 7.8      | 80.3           | 3.65         | 16.05 | 43.8 | 14.5 | 41.4 | 0.25 | 0.2 | 16.1 |
| Sugarcane bagasse       | 8.15     | 82.9           | 4.85         | 12.25 | 45.05 | 11.8 | 42.7 | 0.2  | 0.6 | 17.2 |
| Corncob                 | 9.05     | 81.35          | 15.3         | 3.35 | 37.35 | 14.4 | 47.5 | 0.2  | 0.15 | 16.85 |
| Pinewood sawdust        | 8.9      | 83.2           | 10.2         | 6.6  | 44.5 | 12.6 | 42.6 | 0.15 | 0.1 | 15.3 |
| Blend#1                 | 7.5      | 78.55          | 14.3         | 7.15 | 48.4 | 11.5 | 39.5 | 0.25 | 0.1 | 26.7 |
| Blend#2                 | 8.1      | 79.05          | 12.65        | 8.3  | 57.2 | 9.85 | 32.65 | 0.3  | 0.6 | 27.45 |
| Blend#3                 | 8.95     | 76.5           | 20.4         | 3.1  | 57.1 | 8.7  | 33.65 | 0.2  | 0.15 | 25.5 |
| Surgical face mask      | 2.1      | 85.9           | 11.7         | 0.3  | 62.4 | 6  | 28.1 | 3.5  | 0.25 | –   | Brillard et al. [39] |
|                         | –        | 81.3           | 9.2          | 9.5  | 75.9 | 14.8 | 8.5  | 0.8  | –   | 56.3 | Farooq et al. [40]     |

 blending framework.

The SFM brought 0.1% water into the non-combustible fraction of its proximate composition. Therefore, its nearly dry character would intensify the need for introducing water from an external source into the reactor for catalytic co-carbonization with biomass. Such plastic material also contained 83.75% volatile matter, 12.35% solid carbon, and 3.8% ash. In addition, it consisted of 81.3% C, thereby developing the highest calorific value of 31.3 MJ kg\(^{-1}\). The occurrence of PP (73.55%) and PE (14.1%) in filter layers and nylon (8.2%) in the earloop (Table S4, Supplementary material) supported the dryness, volatility, and high calorific value of SFM. These polymers strongly repulse water. In addition, they are highly reactive to heat and thus release a significant quantity of energy for the burning system [38]. A VFF of approximately 1 (Table S4, Supplementary material) further supported the balance between volatile matter and solid carbon in SFM. We also detected 3.9% iron and 0.25% other trace metals (i.e., Ca, Mn, Ti, and Zn) in such material from the nose frame or band (Table S4, Supplementary material).

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The peanut shell (16.05%) and sugarcane bagasse (12.25%) generated ash excessively, compared to corncob. Mechanical harvest and dragging of soil from outdoor stockpiles during handling brought extrinsic inorganics to these raw materials, contaminating samples. Therefore, the on-site management and acquisition of raw materials must be
striction to meet manufacturing standards. Perhaps the supplier or manufacturer needs to elaborate on a cleaning system to remove inorganic impurities from the feedstock. An alternative to upgrading the peanut shell and sugarcane for co-pelletization would be their blending with SFM since it contains significantly less ash than these agricultural by-products. For instance, Blend#1 and Blend#2 provided 8.15 and 8.3% ash into samples for physicochemical characterization. All blends were less volatile than pinewood sawdust. However, only Blend#3 (3.1%) produced less ash than the reference (6.6%) since corncob contained slightly less N (0.2%) and S (0.15%). As corn sets a cob in the middle section of its structure aboveground, its harvesting does not occur near the soil or underground as the harvesting of sugarcane and peanut (i.e., digging up), respectively. Thereby, the possibility of extrinsic contamination from the field decreases. Early control of N-containing and S-containing compounds could streamline workflow and optimize processes in the industrial pelleting plant (for instance, by decreasing the need for intensive cleaning) while reducing potential toxic emissions of NOx and SO2 during burning [42]. The SFM also upgraded the thermal quality of blends by increasing the calorific value from 16.1–17.2 to 25.5–26.7 MJ kg\(^{-1}\).

### 3.2 The technical quality of composite plastic-fiber fuels and their potential applications for energy-producing systems

We tested the quality of pellets for standard properties, namely, length and diameter, bulk density, durability, calorific value, moisture, ash, moisture, N, and S (Table 2). We also investigated tensile strength and hygroscopicity to determine the ability of specimens to resist pulling force and absorb water onto their structures, respectively.

The combination of SFM and biomass determined the quality of the product. For instance, the length and diameter of HydroMask#1 were 19.9 mm and 7.7 mm, respectively; hence, it developed the highest L/Ø of approximately 2.6. The L/Ø for HydroMask#2 was the lowest at 1.3 since its length and diameter were 10.5 mm and 7.95 mm, respectively. Therefore, the peanut shell acted as a bulking agent to the pellet by increasing its longitudinal section. The introduction of sugarcane bagasse into the co-pelletization shortened the structure, making it suitable for easy handling. In addition, as the length and diameter of HydroMask#3 were 12.4 mm and 7.9 mm, respectively, its L/Ø was intermediate at 1.6. ENPlus sets the length and diameter to be 3.15–40 mm and 6–8 mm, respectively. All blends fulfilled these standards for premium-grade solid fuels. Therefore, they would ensure a non-problematic utilization for customers. For instance, they would not cause stricter equipment to misfeeding due to blockage of the pneumatic system while not breaking easily during handling.

Northern standardization bodies demand producers to develop a bulk density of at least 600 kg m\(^{-3}\) for certification. Therefore, all blends also met the minimum degree of compactness for premium-grade solid biofuels, further supporting their utility for the strictest energy-producing systems at both residential and industrial scales. For instance, HydroMask#2 developed the highest bulk density of 756.4 kg m\(^{-3}\) amongst the models for CPFF. Therefore, synergies between SFM and sugarcane bagasse enabled particles to bond the closest possible together, thereby decreasing empty spaces in the fuel. Thermoreactive plastic polymers in SFM, such as PP and PE, and polysaccharides in the biogenic material acted as binders and fillers to the blend, enhancing the bulk density [43]. Understanding bridging mechanisms between SFM and sugarcane bagasse can provide insights for developing high-quality manufacturing lines for CPFF. Therefore, future research must focus on scanning pellets to produce high-resolution micrographs of their structures and thus overcome this limitation of our study. HydroMask#1 (720.35 kg m\(^{-3}\)) outperformed HydroMask#3 (605.15 kg m\(^{-3}\)) in developing bulk density. Therefore, the peanut shell acted as effectively as sugarcane bagasse in enhancing the binding functionality of the blend. However, it may contribute to compaction by establishing auto-crosslinks of carbohydrates and lipids [44], stressing the need for microscopic analysis. The bulk density of HydroRef was the highest at 785.1 kg m\(^{-3}\). Therefore, blending SFM with pinewood sawdust would improve the degree of compactness of the fuel. We focused our study on agro-residual biomass due to the need for diversifying pelleting [45] and the structure of the Brazilian agribusiness sector. However, co-pelletizing SFM with woody biomass would provide insights into composite plastic-fiber frame-works to the progress of the global solid fuel market. Northern manufacturers often rely on forest residues to produce fuel-flexible pellets for generating heat and electricity [45].

Bulk density is the most reliable indicator of the degree of compactness of a material. It generally impacts durability positively [25]. However, we could not identify such a functional relationship amongst the models for CPFF. For instance, HydroMask#2 was the densest CPFF; however, it developed the lowest durability of 96.75%. While such a product deformed more to shock and abrasion, HydroMask#1 (99.1%) and HydroMask#3 (98.5%) were more durable, releasing lower quantities of fine particles to the environment. Both met the requirement of at least 97.5% durability for premium-grade solid fuel. HydroMask#2 would not offer a reliable heating source for commercialization across the strictest supply chains. Its lower durability is compatible with more flexible markets. Comparatively, HydroMask#2 can produce hazardous inhalable solid matter
Table 2: The technical performance and potential applications of composite plastic-fiber fuels

| Feature                        | HydroMask#1 | HydroMask#2 | HydroMask#3 | HydroRef | Pellet quality’s standard |
|--------------------------------|-------------|-------------|-------------|----------|---------------------------|
|                                |             |             |             |          | ENPlus                    |
|                                |             |             |             |          | International             |
|                                |             |             |             |          | Residential market        |
|                                |             |             |             |          | Class A₁, Class A₂, Class B|
|                                |             |             |             |          | Group I, Group II, Group III|
|                                |             |             |             |          |                            |
| Length [mm]                    | 19.9        | 10.5        | 12.4        | 10.6     | 3.15–40                   |
|                                |             |             |             |          | ≤ 40                       |
|                                |             |             |             |          |                            |
| Diameter [mm]                  | 7.7         | 7.95        | 7.9         | 7.9      | 6–8                       |
|                                |             |             |             |          | 6–8                       |
|                                |             |             |             |          |                            |
| Bulk density [kg m⁻³]          | 720.35      | 756.4       | 605.15      | 785.1    | ≥ 600                     |
|                                |             |             |             |          | > 650                     |
|                                |             |             |             |          | > 580                     |
|                                |             |             |             |          |                            |
| Durability [%]                 | 99.1        | 96.75       | 98.5        | 99.5     | ≥ 97.5                    |
|                                |             |             |             |          | ≥ 97.5                    |
|                                |             |             |             |          |                            |
| Calorific value [MJ kg⁻¹]      | 36.5        | 42.3        | 34.25       | 23.45    | ≥ 16.5                    |
|                                |             |             |             |          | ≥ 16.5                    |
|                                |             |             |             |          |                            |
| Moisture [%]                   | 11.5        | 10.5        | 10.95       | 10.6     | ≤ 10                      |
|                                |             |             |             |          | ≤ 10                      |
|                                |             |             |             |          |                            |
| Ash [%]                        | 1.15        | 1.3         | 1.1         | 0.95     | ≤ 0.7                     |
|                                |             |             |             |          | ≤ 1.5                     |
|                                |             |             |             |          | ≤ 3                       |
|                                |             |             |             |          | ≤ 1                       |
|                                |             |             |             |          | ≤ 1.5                     |
|                                |             |             |             |          | ≤ 3                       |
| N [%]                          | 0.1         | 0.25        | 0.2         | 0.1      | < 0.3³                    |
|                                |             |             |             |          | –                         |
|                                |             |             |             |          | –                         |
| S [%]                          | < LOQ       | 0.05        | < LOQ       | < LOQ   | < 0.04³                   |
|                                |             |             |             |          | –                         |
|                                |             |             |             |          | –                         |
|                                |             |             |             |          | –                         |
|                                |             |             |             |          | –                         |
|                                |             |             |             |          | –                         |
|                                |             |             |             |          |                            |
| Tensile strength [MPa]         | 1.2         | 1.1         | 1           | 0.9      | –                         |
|                                |             |             |             |          | –                         |
|                                |             |             |             |          | –                         |
|                                |             |             |             |          | –                         |
|                                |             |             |             |          | –                         |
|                                |             |             |             |          |                            |
| Hygroscopicity [%]             | 5.65        | 5.1         | 6.8         | 8.35     | –                         |
|                                |             |             |             |          | –                         |
|                                |             |             |             |          | –                         |
|                                |             |             |             |          | –                         |
|                                |             |             |             |          |                            |

HydroMask#1, composite fuel of surgical face mask plus peanut shell; HydroMask#2, composite fuel of surgical face mask plus sugarcane bagasse; HydroMask#3, composite fuel of surgical face mask plus corncob; HydroRef, reference wood biofuel; LOQ, limit of quantification; ENPlus, European certification scheme; IWPB, Initiative for Wood Pellet Buyers

³DIN EN 15,270
Low-N fuel < 0.4%; medium-N fuel 0.4–1%; high-N fuel 1–10% [48]
as intensively as the lowest-class solid biofuels (i.e., ENPlus’ class B and IWPB’s group III). Therefore, improving its durability is necessary for developing occupational safety and industrial hygiene [46]. HydroMask#1 and HydroMask#3 would not manifest as sources of serious pathologies (e.g., acute sensory irritation and chronic allergies), explosions, or toxic emissions through their release of fine particles.

The calorific value refers to the quantity of energy in the form of available heat for the system. Hence, it stands as the most reliable indicator of the thermal quality of material during burning. The higher the calorific value, the more intense the fuel releases energy for combustion. For instance, HydroMask#2 developed the highest calorific value of 42.3 MJ kg\(^{-1}\); hence, it outstripped HydroMask#1 (36.5 MJ kg\(^{-1}\)) and HydroMask#3 (34.25 MJ kg\(^{-1}\)). As HydroMask#2 developed the highest bulk density amongst blends, it yielded the highest quantity of energy per volume of approximately 32 GJ m\(^{-3}\). The estimates for HydroMask#1, HydroMask#3, and HydroRef were 26.3, 20.7, and 18.4 GJ m\(^{-3}\), respectively. Therefore, the co-pelletization of SFM and agro-residual biomass, irrespective of origination, enabled the development of composite fuels of superior thermal quality. The composition of hydrocarbons (i.e., PP, PE, and nylon) of the plastic component increased the proportion of elemental carbon in the blend. The HTC intensified the carbonization by removing O-containing and H-containing functional groups from the material through dehydration, decarboxylation, and demethylation [12]. For instance, Blend#1 consisted of a calorific value of 26.7 MJ kg\(^{-1}\); however, coalification added 9.8 MJ kg\(^{-1}\) to its solid fuel (HydroMask#1). Analogously, we measured 14.85 and 8.75 MJ kg\(^{-1}\) more energy from HydroMask#2 and HydroMask#3, respectively. All blends met the requirement of at least 16.5 MJ kg\(^{-1}\) for premium-grade solid fuel. However, as HydroMask#2 developed lower mechanical durability, only HydroMask#1 and HydroMask#3 would allow for operating stricter heat-and-power systems effectively. The co-pelletization of SFM and biomass is not available in the literature, making it challenging to ground our research in the context of WTE platforms for COVID-waste streams. However, the investigation by Park et al. [47] on co- pyrolysis of SFM with agro-food residue can assist in highlighting the role of such a plastic component in developing energy-dense fuels. The authors performed the thermal treatment of SFM and food waste for fuel-range hydrocarbons. The calorific value of composite chars ranged from 14.4 to 21.1 MJ kg\(^{-1}\), qualifying them technically for energy applications. Powder hydrochars in our study provided up to 27.45 MJ kg\(^{-1}\) (Blend#2) for the heating system. Their compaction upgraded the release of energy up to 42.3 MJ kg\(^{-1}\) (HydroMask#2). Therefore, co-pelletization can improve the recovery of renewable and sustainable energy from SFM by densification.

Blends contained ash excessively, thus limiting their potential applications in the strictest private and public energy niches worldwide. ENPlus sets the quantity of ash in the fuel not to exceed 0.7, 1.5, and 3% for classes A1, A2, and B, respectively. The thresholds for groups I, II, and III within the IWPB are 1, 1.5, and 3%, respectively. HydroMask#1 and HydroMask#3 would resist deformation and release energy as effectively as premium-grade solid fuels; however, they would allow for achieving only regular categories by these independent certification schemes. Thermal pretreatment removed volatile N-containing and S-containing compounds from blends, reducing the quantity of ash in hydrochars. However, it could not be technically sufficient for developing premium-grade fuels, supporting the significance of screening low-ash biogenic raw materials for co-pelletization with SFM. Importantly, all blends met the stricter requirements of N and S; hence, their burning would emit neither NO\(_x\) nor SO\(_2\) above toxicant levels [48].

ENPlus and IWPB predict optimal neither tensile strength nor hygroscopicity for commercially available solid biofuels. Therefore, we measured them to provide further knowledge of the ability of blends to resist elongating force and attract water from surroundings through either absorption or adsorption. HydroMask#1 broke down at 1.2 MPa and thus outstripped HydroMask#2 (1.1 MPa) and HydroMask#3 (1 MPa) in developing mechanical resistivity, supporting particular synergies between SFM and agricultural residues. Lignin can strengthen material through either depolymerization or fragmentation of polar functional groups [49]. Covalent bonds and weaker dipole–dipole interactions between its polymeric subunits can aggregate particles effectively, allowing the fuel to resist pulling force or compressive load firmly [50]. Cellulose can develop intermolecular bonding forces through electrostatic attraction between –OH and either C or O at glycosidic rings [51]. Densification intensifies such mechanisms and thus increases the mechanical resistivity of a material [51]. The positive impact of hemicellulose on tensile strength occurs through its toughening as the temperature and pressure rise in the system for frictional compression [51]. The acetylation of active O-containing and H-containing centers in its monomeric units strengthens the fuel upon cooling and thermosetting [51]. The HTC removed volatile O-containing and H-containing compounds from blends, whereby decreasing available active binder centers in hydrochars for compaction. In addition, it reduced their fractions of cellulose and hemicellulose, further contributing to a loss of bonding functionality. However, composite fuels resisted more elongation than HydroRef (0.9 MPa). Therefore, the SFM provided bonding mechanisms for co-pelletization through interactions of TPPs.
Forest residues generally offer more suitable materials for compaction than agricultural residues. They contain xylans and thus reduce the backpressure on the presser machine, allowing for the development of high-density solid fuels [50]. HydroRef was denser and resisted more abrasion than all models for CPFF, supporting the ability of pinewood sawdust to develop a greater grindability over the peanut shell, sugarcane bagasse, and corncob. However, co-pelletizing such agricultural residues and SFM allowed for the development of higher energy efficiency and compressive resistance on composite pellets. In addition, the plastic component increased the resistance of blends to attract water from surroundings onto their structures through either absorption or adsorption microscopically, thereby improving hydrophobicity. For instance, HydroMask#2 brought less isothermally available environmental vapor from a wet source onto itself and thus developed the lowest hydrophobicity at 5.1%. The most hygroscopic CPFF was HydroMask#3 (6.8%), while HydroMask#1 (5.65%) reabsorbed water from the chamber moderately. All blends were more hydrophobic than HydroRef (8.35%). Therefore, SFM acted as a waterproofing agent for blends through the ability of PP, PE, and nylon to repulse hydration. It also improved the smoothness and degree of shining on the surface of products (Fig. 1), which are significant features of visual quality for commercialization. The HTC contributed to hydrophobicity by removing O-containing and H-containing functional groups from blends, such as –OH in water and R–COOH in volatile compounds [23].

3.3 Kinetics of combustion of composite plastic-fiber fuels

We proved the technical viability of the conversion of SFM to CPFF. The product can offer the industry an alternative high-quality solid fuel. To characterize the CPFF effectively, we conducted a thermogravimetric experiment. Biogenic raw materials (Fig. 2A) and fuel blends (Fig. 2B) burned out effectively. They produced heat until the thermo-oxidative degradation of combustible matter leveled off. The stages of combustion were (I) vaporization of water or dewatering, (II) devolatilization, and (III) carbonization.

Biogenic raw materials burned out analogously. Hence, their thermograms were strictly similar, making it challenging to distinguish them graphically (Fig. 2A and B). However, we could identify a slightly sharper exothermic peak of devolatilization in the thermogram on pinewood sawdust (Fig. 2A). Pinewood sawdust released more heat from 350 to 425 °C since it contained more cellulose (44.25%) and hemicellulose (34.1%) than agricultural biomass, irrespective of

Fig. 2 Production of heat and thermal degradation of biogenic raw materials and composite plastic-fiber fuels. HydroMask#1, composite fuel of surgical face mask plus peanut shell; HydroMask#2, composite fuel of surgical face mask plus sugarcane bagasse; HydroMask#3, composite fuel of surgical face mask plus corncob; HydroRef, reference wood biofuel. The northern hemisphere of the panel provides the flow of heat from agricultural feedstocks (A) and products (B). The southern hemisphere of the panel provides the thermal decomposition of agricultural feedstocks (C) and products (D).
origination (Table S5, Supplementary material). As the temperature rose from 25 to 350 °C, it intensified the thermal decomposition of volatile matter, thereby driving it out of the material. Between 350 and 425 °C, the thermal conversion of organic matter generated a carbon-dense solid residue [1].

Amongst agricultural by-products, the peanut shell (27.8%) developed a sharper exothermic peak of carbonization since it contained more hemicellulose than corn-cob (24.6%) and sugarcane bagasse (20.65%). In addition, although corn-cob (36.5%) and peanut shell (34.5%) contained more cellulose than sugarcane bagasse (41.95%), they produced comparable exothermic peaks of devolatilization. Their endothermic peaks of dewatering also were similar. Agricultural residues, especially the peanut shell, were less responsive to oxidation than pine wood sawdust. They added ash to the combustion excessively, decelerating the thermal decomposition of matter. Ash is inert and does not burn, negatively impacting the conversion of matter to energy. While pine wood sawdust released heat up to 970 °C, agricultural residues burned out effectively up to 600 °C (Fig. 2A).

We expected lower efficiency on burning blends since agricultural residues contained ash excessively. However, combining them with the SFM allowed for balancing the proximate composition of products, thereby improving their combustion (Fig. 2B and D). HydroMask#2 (266.5 mW g⁻¹) outperformed HydroMask#1 (143.15 mW g⁻¹) and HydroMask#3 (135.95 mW g⁻¹) in the release of heat at 365 °C. It also produced more energy than HydroRef (146.6 mW g⁻¹). The sugarcane bagasse brings alcohol (OH) and carboxylic acid (COOH) from industrial processing into its chemical composition. These functional groups reduce energy potential by increasing the proportion of oxygen in the material [52]. However, thermo-oxidative decomposition of hydrocarbons in SFM can allow for the development of composite fuel with higher thermogravimetric performance. Thermoplastic compounds, such as PP, deform rapidly as the temperature increases [53]. As covalent bonds in their polymeric subunits break to heat, they develop a higher calorific value, thereby enabling the production of energy-dense fuels [54].

HydroMask#2 also contained more cellulose than HydroMask#1 and HydroMask#3 (Table S5, Supplementary material); hence, it provided more substrate to the system for combustion, thereby developing the sharpest exothermic peak of devolatilization. However, as the thermal process converted organic matter to carbon (Fig. 2D), the content of hemicellulose decreased from 11.5 to 0.1% (Fig. 3); thereby, the release of heat from HydroMask#2 decreased to 84.9 mW g⁻¹ at 442.75 °C (Fig. 2B). As opposed to HydroMask#2, HydroMask#1 (220.5 mW g⁻¹) and HydroMask#3 (218.25 mW g⁻¹) produced more heat as the temperature rose from 365 to 430–445 °C. Therefore, both outstripped HydroMask#2 while releasing energy as intensively as HydroRef (235.1 mW g⁻¹) at temperatures above 400 °C. Lignin decomposes slower and over a broader range of temperatures than cellulose and hemicellulose [55]. An endothermic peak occurs at 100–180 °C, corresponding to dewatering and devolatilization [56]. Exothermal peaks also arise in its DTG curve between 280 and 390 °C and around 420 °C. Above 500–600 °C, the thermal degradation of lignin yields a wide and flat tailing section, making it distinctive from cellulose and hemicellulose [57]. These polymers are more reactive to heat; hence, they derive sharper breakthrough curves while their proportions in the sample decrease significantly. As lignin decomposes slowly (<0.15% °C⁻¹), it loses 40% of its initial mass below 700 °C. Even though the rate increases to 0.3% °C⁻¹ above 750 °C, the loss of matter at 870 °C is only 67% of the total [55]; hence, its content in the char increases proportionally to the decrease of cellulose and hemicellulose (Fig. 3).
All blends cumulated more heat than the reference biofuel throughout the thermogravimetric experiment. However, they developed particular features of combustion. For instance, HydroMask\#2 burned out more vigorously, releasing energy rapidly for the system up to 365 °C. Therefore, it would offer a reliable fuel for industrial-scale burning systems, such as boilers in coal-fired power plants or gas-fired stations. HydroMask\#1 and HydroMask\#3 burned out more gradually while extending combustion up to 500 °C. Therefore, they would offer benefits to residential-scale systems, such as household wood-burning stoves and downdraft gasifiers. However, their utilization could demand caution to avoid technical and operational problems. They generated more residual solid matter (Table 3) than HydroRef as the quantity of ash increased for the burning system, further supporting incomplete combustion. The occurrence of black carbon (char), soot, or tar in the boiler reduces technical performance and lifespan\[58\]. It promotes cooler zones within the furnace and corrodes exchanging surfaces. It also increases the need for soot-blowing and cleaning activities, making the operation costly\[59\].

The SFM increased the responsiveness of fuels to heat, yielding higher thermogravimetric indexes (Table 3). HydroMask\#2 ignited earliest and burned out most intensively; hence, it developed the highest estimates of $DTG_c$, $DTG_i$, $DTG_f$, and $DTG_t$. Compared to HydroRef, HydroMask\#2 increased the $DTG_c$ by eightfold. The increases from HydroMask\#1 and HydroMask\#3 were fivefold and fourfold, respectively. Therefore, HydroMask\#2 maximized the combustibility. However, it generated more residual solid matter than HydroMask\#1 (1.85%) and HydroMask\#3 (1.9%). Sugarcane bagasse (3.7%) produced a higher quantity of solid residues than corncob (2.7%) and peanut shell (1.3%), thereby increasing the formation of ash and heavy tar from the burning of HydroMask\#2 (2.3%). HydroMask\#1 and HydroMask\#3 also developed lower flammability and ignitability. Therefore, they would offer product-level solutions for controlling smoky combustion, toxic emission, and hazardous self-heating during transportation and storage\[58\].

The SFM improved combustion. It increased the release of energy through the thermal decomposition of PP, PE, and nylon. However, it could intensify the generation of ash and tar through the incomplete combustion of the nose frame or band. For instance, while the peanut shell generated 1.3% of residual solid matter, the production from HydroMask\#1 was 1.85%; hence, it supported the propensity of the SFM to increase the formation and deposition of inorganics in the boiler. The nose bridge strip can produce a solid residue of approximately 24% of the total mass\[2\]. Temperatures between 435 and 500 °C can intensify the process\[38\], driving the need to adjust operating conditions on the equipment for thermal conversion.

### Table 3 Thermogravimetric indicators of thermal quality of raw materials and composite plastic-fiber fuels

| Material                  | $T_i$ [°C] | $T_p$ [°C] | $T_b$ [°C] | $R_p$ [% min$^{-1}$] | $R_v$ [% min$^{-1}$] | $DTG_c$ [$x 10^{-8}$] | $DTG_i$ [$x 10^{-6}$] | $DTG_f$ [$x 10^{-5}$] | $DTG_t$ [$x 10^6$] | Residual matter [%] |
|---------------------------|------------|------------|------------|----------------------|----------------------|-----------------------|-----------------------|-----------------------|-----------------------|---------------------|
| HydroMask\#1              | 326.4      | 403.3      | 567.55     | 5.1                  | 3.75                 | 4.1                   | 4.65                  | 4.75                  | 1.85                  |                     |
| HydroMask\#2              | 325.4      | 406.45     | 567.5      | 5.6                  | 3.75                 | 4.65                  | 4.75                  | 2.3                   | 2.3                   |                     |
| HydroMask\#3              | 326.8      | 420.55     | 567.6      | 5.5                  | 3.75                 | 4.65                  | 4.75                  | 2.3                   | 2.3                   |                     |
| HydroRef                  | 327.4      | 407.7      | 587.6      | 4.75                 | 3.75                 | 4.75                  | 2.3                   | 2.3                   | 0.95                  | 0.95                |
| Peanut shell              | 327.4      | 405.3      | 481.6      | 3.45                 | 3.75                 | 3.75                  | 3.75                  | 2.7                   | 0.7                   | 1.3                 |
| Sugarcane bagasse         | 326.8      | 406.45     | 567.6      | 5.1                  | 4.75                 | 4.75                  | 4.75                  | 2.7                   | 0.95                  | 0.95                |
| Corncob                   | 327.4      | 407.7      | 587.6      | 4.75                 | 3.75                 | 4.75                  | 2.3                   | 2.3                   | 0.95                  | 0.95                |
| Pinewood sawdust          | 327.55     | 420.05     | 749.8      | 4.1                  | 1.45                 | 0.5                   | 0.7                   | 1.3                   | 0.5                   | 1.3                 |
3.4 Profile of metal oxides and the propensity of composite plastic-fiber fuels to slag and foul

We performed EDXRF spectroscopy to quantify metal oxides in biogenic raw materials and fuel blends and thus determine their potential formation of slagging and fouling in the boiler. Peanut shell (28.3%) and sugarcane bagasse (27.7%) brought more CaO into the mineral phase of biomass than corncob (25.5%) (Fig. 4A), supporting the extrinsic inorganic contamination. Calcium oxide (quicklime) can reduce sintering and fouling by increasing the melting temperature of ash [60]. When dry, CaO is not corrosive to steel. However, it can react with water to form Ca(OH)₂. Calcium hydroxide (slaked lime) can manifest as excessively corrosive to steel; hence, such an inorganic compound can increase slagging and fouling while causing thermal equipment to wear [61]. Its combination with components in ash, such as MgO, can yield sludge [62]. Such a sedimentary deposit can manifest as excessively corrosive as slaked lime to steel, and its abrasive nature can cause boilers to overheat and prematurely fail [62].

Corncob (12.95%) also contained less Fe₂O₃ than sugarcane bagasse (14%) and peanut shell (14.25%). However, its proportion of K₂O was the highest at 57.95%. The values for sugarcane bagasse and peanut shell were 53.95 and 54.5%, respectively. Therefore, although sugarcane bagasse and peanut shell generated more ash than corncob, they developed higher ratios of CaO/K₂O of approximately 0.5. Increasing the proportion of Ca-containing oxides and silicates in the material can reduce its propensity for slagging and fouling since they contribute to the formation of heavily meltable ash [60]. As opposed to CaO, K₂O allows these physical deposits to accumulate rapidly in the boiler by lowering the melting temperature of ash [34]. Not only K₂O but also SO₃ reduces the melting point of ash [34]. Sugarcane bagasse (4.35%), corncob (3.4%), and peanut shell (2.95%)
concentrated more such a metal oxide in their profiles than pinewood sawdust (2.35%). Therefore, they would make it easier for products to deposit and accumulate slag in the boiler at lower operating temperatures.

Sugarcane bagasse contained the highest relative quantity of SO$_3$; hence, its fuel blend developed the highest FRI of approximately 1.1 (Fig. 4B), supporting the role of such a metal oxide in producing low-meltable ash. The SO$_3$ represented 4.2% of the profile of metal oxides of HydroMask#2. Although such a product developed the highest FRI, it would not form and accumulate physical deposits on conducting surfaces as rapidly as HydroMask#1 and HydroMask#3 since its SRI was lower. The values for the SRI of HydroMask#1 and HydroMask#2 were 0.035 and 0.0295, respectively; hence, both would produce slag more intensively than HydroRef. The SRI and FRI for the reference wood fuel were 0.7 and 0.0275, respectively, further supporting the role of agro-residual biomass in increasing fouling and slagging, especially sugarcane bagasse. The SFM also contributed to fouling and slagging by introducing Fe into blends through the nose frame or band.

Slagging and fouling stand as physical deposits in boilers. Slagging will occur in areas directly exposed to flame radiation, such as furnace walls and pendant superheaters. Fouling will form deposits in areas not directly exposed to flame radiation, such as conducting tubes [34]. An index below 0.6 denotes a low propensity to either foul or slag. An FRI between 0.6 and 40 and SRI between are typical of fuel with a moderate deposit, while high fouling and slagging will occur above 40 and 2, respectively [34]. Therefore, all fuel blends would develop moderate slagging and low fouling. Indices allowed for estimating the propensity of materials and products to slag and foul. Industrial-scale research must focus on modeling their mechanisms of formation. The knowledge of the distribution and size of minerals in blends and workflows through the boiler will be necessary for accurate simulation of the dynamics of the boiler.

Low-meltable ash deforms between 1000 and 1200 °C. Therefore, the ENPlus demands stakeholders not to operate boilers above 1100 °C to avoid fouling, slagging, and sintering. All models for CPFF would develop moderate slag and low foul at 1000 °C. Therefore, they would require reducing the temperature for a non-problematic utilization for residential and industrial customers. For instance, HydroMask#2 would release heat most effectively while not severely generating solid residual matter at 365 °C. The optimum range for HydroMask#1 and HydroMask#3 would be 350–500 °C. However, further thermogravimetric experiments are necessary for validating these technical specifications since our study is still at an early stage of development.

### 3.5 Spectral fingerprinting of raw materials and composite plastic-fiber fuels

![Fig. 5](image)

We performed FTIR spectroscopy to measure the absorption of IR (infrared) energy from samples and thus provide knowledge of their constituents and functions at an atomistic level. By analyzing the Fourier-transform spectrograms on SFM (Fig. 5), we recognized the ability of its layers to absorb IR energy intensively at 3000–2800 cm$^{-1}$ and 1400–800 cm$^{-1}$ due to the vibrational stretching of PP and isotactic PP. The inner layer for inhibition of ultra-fine particles provided the sharpest spectral peak at 2920 cm$^{-1}$, exposing the medium-frequency absorption of IR energy due to the vibrational stretching of –OH in PP occurring in nonwoven cloth. Layer#1 provided another sharp characteristic absorptive peak of PP at 2850 cm$^{-1}$ due to the anti-symmetrical vibration of CH$_3$ in the structure of such a polymer. Although layer#3 consists of nonwoven cloth and thus functions analogously to layer#1 by
filtering fine particles from degrading harmful substances [7], it absorbed more IR energy at 2920 and 2850 cm$^{-1}$. As opposed to layer#1 and layer#3, layer#2 transmitted the IR energy between 2920 and 2850 cm$^{-1}$ in the spectrum of layer#2, despite PP occurring in the arrangement of meltblown cloth for electrostatic micro-filtration and isolation of fine particles from droplets and aerosols [7].

The layers also transmitted the IR energy between 2800 and 1400 cm$^{-1}$. Such a region in their spectra was amorphous rather than crystalline and, therefore, not insightful for characterization and interpretation. However, layer#3 outstripped layer#2 and layer#1 in the absorption of IR energy due to the anti-symmetrical bending of C–CH$_3$ in PP at a lower electromagnetic frequency of 1385 cm$^{-1}$. The outer layer also absorbed more IR energy due to the in-plane bending or rocking of C–CH$_2$ in PP at 795 cm$^{-1}$.

Spectroscopic studies on the SFM are available in the literature. They can support the trends in our instrumental analysis. For instance, Yousef et al. [1] demonstrated the high-intensity absorption of IR energy from samples at 3000 cm$^{-1}$. The authors assigned the peak for the vibrational stretching of –OH in PP. Nam et al. [63] identified significant spectral peaks at 2900 and 1115 cm$^{-1}$ due to atom-to-atom vibrations of C–H from CH$_3$OH in the meltblown cloth and C–O in PP in the nonwoven filter, respectively. Ali et al. [2] described the absorption of IR energy at 1160 and 975 cm$^{-1}$ as the wagging and rocking for C–C and CH$_3$ in the molecular structure of PP, respectively. Tao et al. [64] characterized the absorption of IR energy between 1250 and 800 cm$^{-1}$ as vibration of isotactic PP. Therefore, functional groups vibrate at specific frequencies of IR radiation, allowing for the development of reliable spectral fingerprinting of layers of SFM. Infrared spectra of absorption for such material can assure its technical specifications for the production of CPFF. In addition, they can offer insights for stakeholders in checking for the quality and authenticity of the product, which is significant to traceability.

Biogenic raw materials (Fig. 6A) absorbed more IR energy than fuel blends (Fig. 6B). Therefore, lower-intensity peaks of thermoreactive natural polymers in the spectra of products validated the role of HTC in treating feedstocks for co-pelletization. In addition, they highlighted the interactions between SFM and agricultural residues in determining the molecular features of the models for CPFF. For instance, at 1700–1650 cm$^{-1}$, the peanut shell, sugarcane bagasse, and corn cob absorbed 43.4, 57.4, and 38.95% of the IR radiation, respectively. The values for the absorbance of HydroMask#1, HydroMask#2, and HydroMask#3 were 31.25, 34.1, and 21.85%, respectively. Therefore, thermal pretreatment reduced the ability of products to absorb IR energy effectively by degrading either C=O in aromatic rings of lignocellulose [65] or PP in SFM [2]. The carbonyl group absorbs IR energy intensively between 1800 and 1600 cm$^{-1}$.

However, thermal decomposition reduces its skeletal vibration in the sample for spectroscopy [65].

Corn cob developed the highest absorption of IR energy amongst biogenic raw materials at 1000 cm$^{-1}$. Therefore, it outstripped sugarcane bagasse and peanut shell in the vibrational stretching of C–O–C (ether) in cellulose and hemicellulose. As ether is highly sensitive to heat, we could not identify a characteristic peak from spectra of fuel blends (Fig. 6B), further supporting the role of HTC in removing volatile compounds from feedstocks. In addition, sugarcane bagasse brought the sharpest peak into spectra of absorption of IR energy for agricultural residues at 980 cm$^{-1}$ (Fig. 6A).

Therefore, its highest quantity of N intensified the anti-symmetrical vibrational stretching of C–O from N–CO–C. Such a pattern also existed in spectra of fuel blends between 1445 and 915 cm$^{-1}$, validating the co-occurrence of biomass and nylon and their roles in forming N-containing functional groups and emitting NO$_x$, CO, and volatile hydrocarbons [66].

Only pinewood sawdust (Fig. 6A) and HydroRef (Fig. 6B) absorbed IR energy at 2920 cm$^{-1}$ due to the vibrational stretching of C–H in glucomannan and arabinoxylolacatan [67]. Such polysaccharides manifest in woody biomass. Therefore, we could not identify a characteristic peak from spectra of agricultural residues and fuel blends, validating the accuracy of FTIR spectroscopy in distinguishing raw materials and products. Such an instrumental technique performs a Fourier transform on interferograms to obtain fingerprints of samples. Frequencies are specific to the functional groups and generally become visible above 1500 cm$^{-1}$. As for fingerprinting bands, they are characteristic of the molecules and atoms, making them reliable for identification below 1500 cm$^{-1}$. Although fingerprinting region is less reliable for identifying functional groups, the absence of a band can be more indicative than its presence, as we demonstrated on constituents of SFM, biogenic feedstocks, and composite plastic-fiber fuels. Therefore, FTIR spectroscopy would offer a quality-controlling and troubleshooting chemometric approach for stakeholders in industries and research centers.

### 3.6 Generation of permanent gasses and non-methane volatile organic compounds from composite plastic-fiber fuels

We quantified the generation of permanent gasses and NMVOCs from fuels to address the implications of burning them for occupational safety and environmental protection. For instance, HydroMask#2 emitted 694.75 mg m$^{-3}$ of permanent gasses, making it the highest-emission blend (Table 4). Of the total, carbon dioxide represented 34.6%, making it the predominant fraction, while CO and SO$_2$ contributed less to the profile by representing 17.9 and 16.1%, respectively. In addition, the representativeness
Fig. 6 Fourier-transform spectra of absorption of infrared energy by biogenic raw materials (A) and composite plastic-fiber fuels (B). HydroMask#1, composite fuel of surgical face mask plus peanut shell; HydroMask#2, composite fuel of surgical face mask plus sugarcane bagasse; HydroMask#3, composite fuel of surgical face mask plus corncob; HydroRef, reference wood biofuel.

Table 4 Profile of emissions of composite plastic-fiber fuels

| Substance [mg m⁻³, STP, db, 10 vol% O₂] | HydroMask#1 | HydroMask#2 | HydroMask#3 | HydroRef |
|----------------------------------------|-------------|-------------|-------------|----------|
| CO                                     | 107.25 [21.8%] | 124.2 [17.9%] | 106.1 [17.75%] | 56.2 [13.7%] |
| CO₂                                    | 147.5 [29.9%] | 240.5 [34.6%] | 187.5 [31.4%] | 169.5 [41.3%] |
| NOₗ                                  | 152.8 [31%] | 218.3 [31.4%] | 195.65 [32.75%] | 138.6 [33.8%] |
| SO₂                                   | 85.2 [17.3%] | 111.75 [16.1%] | 108.2 [18.1%] | 46.15 [11.2%] |
| Total permanent gasses                 | 492.75      | 694.75      | 597.45      | 410.5    |
| Aldehydes                              | 11.15 [20.45%] | 23.9 [35.8%] | 18.35 [28.75%] | 10.5 [18.3%] |
| Furans                                 | 19.3 [35.4%] | 17.6 [26.4%] | 17.1 [26.8%] | 13.2 [22.95%] |
| Naphthalenes                           | 6.75 [12.4%] | 12.75 [19.1%] | 18.2 [28.5%] | 27.5 [47.8%] |
| Terpenes                               | 17.35 [30.75%] | 12.5 [18.7%] | 10.2 [15.95%] | 6.3 [10.95%] |
| Total non-methane VOCs                 | 54.55       | 66.75       | 63.85       | 57.5     |

The number between brackets denotes the proportion of the substance in the total emission.

HydroMask#1, composite fuel of surgical face mask plus peanut shell; HydroMask#2, composite fuel of surgical face mask plus sugarcane bagasse; HydroMask#3, composite fuel of surgical face mask plus corncob; HydroRef, reference wood biofuel.
of CO was intermediate since it contributed 31.4%. Comparatively, HydroMask#2 generated more NOx or SO2 than HydroMask#1 (492.75 mg m⁻³) and HydroMask#3 (597.45 mg m⁻³). Therefore, the extrinsic inorganic contamination brought by sugarcane bagasse to its composition increased the release of airborne fast-acting toxic chemicals.

HydroMask#2 also most emitted NMVOCs. Of its total 66.75 mg m⁻³, aldehydes and furans represented 35.8 and 26.4%, respectively; hence, they were the predominant fractions of the profile. In contrast, such a blend emitted naphthalenes and terpenes in lower proportions of 19.1 and 18.7%, respectively. The total emission of NMVOCs from HydroMask#3 was 63.85 mg m⁻³. Therefore, it could be technically comparable to HydroMask#2 by quantity; however, by quality, it released aldehydes and naphthalenes at lower proportions of 28.75 and 15.95%, respectively.

HydroMask#1 emitted lower quantities of permanent gases and NMVOCs (54.55 mg m⁻³) than HydroMask#2 and HydroMask#3. Therefore, such a combination developed the lowest-emission composite fuel. Most importantly, it could be competitive with HydroRef (57.5 mg m⁻³) by the total generation of aldehydes, furans, naphthalenes, and terpenes, which are sources of sensory irritation and discomfort to stakeholders. Although HTC removed O-containing, N-containing, and S-containing functional groups from hydrochars, it could not be technically sufficient to develop composite plastic-fiber fuels capable of lower emissions than the reference. Therefore, excessive minerals in agro-residual biomass and incomplete combustion of polymers in the SFM could increase the generation of hazardous gasses from blends.

The SFM brought 0.2% of N into its ultimate composition, thereby increasing the specific emission of NOx from blends. Sugarcane bagasse provided the highest-N biogenic raw material for the production of CPFF; hence, its combination with SFM developed the composite fuel with the highest emission of NOx. The study by Brillard et al. [39] on the combustion of SFM can support the role of agro-residual biomass in the emission of NOx. The authors quantified 170 ppm of NOx and more than 12,000 ppm of CO and CO2. Therefore, NOx represented less than 1% of the total generation, while we calculated proportions of 31, 31.4, and 32.75% for HydroMask#1, HydroMask#2, and HydroMask#3, respectively. In addition, as the content of S in SFM was below the LOQ of the CHNS/O elemental analyzer, only biomass could contribute effectively to the specific emission of SO2. Therefore, the choice of biogenic material and the definition of its proportion in the blend with SFM were significant to the successful production of CPFF. They must be subjects of further in-depth studies for optimization to scale.

The SFM also impacted the specific emission of CO. Thermal degradation of PP and PE can produce such a gas between 60 and 170 °C [68]. However, their combination with natural polymers can generate CO from 50 to 500 °C [69], supporting the emissions from all blends. Although SFM increased the exhaustion of CO from the boiler, its products would not offer a problematic utilization for consumers. The DIN EN 303–5 sets the specific emissions of CO and NOx not to exceed 200 and 500 mg m⁻³, respectively. Therefore, all models for CPFF emitted these gases below their critical toxic limits, which is significant for developing occupational safety and environmental protection [70].

### 3.7 Insights into the conceptual and technical ramifications of composite plastic-fiber fuel

We applied PCA to summarize information on models for CPFF. Such a multivariate technique reduced the dimensionality of experimental data, thereby allowing the identification of the best discriminant features of technical performance. The subsets, namely, PCI, PCII, PCIII, PCIV, and PCV, spanned 30, 20.65, 18.15, 11.6, and 9% of the total variance, respectively (Table S6, Supplementary material). A cumulative variance of 89.4% would ensure a model of insightful statistics for stakeholders to decide on the manufacturing line for CPFF effectively; hence, they would not spend resources investigating meaningless and duplicative variables.

The analytical space of PC1 provided the best graphical representation of the impact of physicochemical properties on the thermo-oxidative decomposition of the material. We calculated positive correlations between such an explanatory component and the eigenvectors, namely, volatile matter (\( r = 0.9; \) \( p \) value < 0.01), moisture (\( r = 0.8; \) \( p \) value < 0.05), H (\( r = 0.75; \) \( p \) value < 0.05), O (\( r = 0.95; \) \( p \) value < 0.01), cellulose (\( r = 0.8; \) \( p \) value < 0.05), hemicellulose (\( r = 0.9; \) \( p \) value < 0.01), and hygroscopicity (\( r = 0.95; \) \( p \) value < 0.01), whereas its loadings with solid carbon (\( r = -0.9; \) \( p \) value < 0.01), calorific value (\( r = 0.95; \) \( p \) value < 0.01), and lignin (\( r = -0.9; \) \( p \) value < 0.01) were positive. Blends, irrespective of biogenic feature, moved forward in the first dimension of the multifactorial map (Fig. 7), while HydroMask#2 and HydroMask#3 moved backward. In addition, HydroMask#1 provided the closest eigenvalue to the origin of the multifactorial map, thereby not representing the role of composition in accelerating the thermal conversion of matter to energy as effectively as HydroMask#2. The PCI supported the effectiveness of HTC in transforming SFM and agro-residual biomass into blends for high-quality copelletization by developing higher calorific value and hygroscopicity. The thermal pretreatment removed water and volatile matter from the starting material through dehydration, decarboxylation, and demethylation, thereby concentrating carbon in the hybrid hydrochar for co-densification.
The PC$_{II}$ and the eigenvectors, namely, bulk density ($r = 0.75; p$ value < 0.05), DTG$_i$ ($r = 0.9; p$ value < 0.01), DTG$_c$ ($r = 0.9; p$ value < 0.01), Fe$_2$O$_3$ ($r = 0.75; p$ value < 0.05), and ZnO ($r = 0.7; p$ value < 0.05), brought positive correlations into the multifactorial map. In addition, its linear relationships with $T_b$ ($r = -0.8; p$ value < 0.05), $R_v$ ($r = -0.75; p$ value < 0.05), DTG$_t$ ($r = -0.8; p$ value < 0.05), and residual matter ($r = -0.9; p$ value < 0.01) were negative, making it the explanatory component of transportation of heat from fuel to the system. Therefore, the denser the material, the easier the heat flows between and within particles. In contrast, empty spaces make it harder for the heat to transfer, even if Fe$^{3+}$ and Zn$^{2+}$ are present in the fuel. These metal ions are products of the decomposition of Fe$_2$O$_3$ and ZnO, which occur in the inorganic phase of SFM and biomass. They allow electrons to transfer between particles effectively, thereby acting as conductors of heat to fuel. Increasing the release of energy from fuel to the system improves comprehensive combustion. We can demonstrate such a synergy on HydroMask#2 and HydroMask#3. These eigenvalues moved upward in the second dimension of the multifactorial map as the reference fuel. However, they burned out more intensively and produced a higher quantity of residual matter, decreasing their expressiveness in the analytical space of PC$_{II}$. While they provided closer eigenvalues to the origin of the multifactorial map, the HydroRef provided the farthest eigenvector. The reference fuel burned out slowly and generated a lower quantity of residual matter, thereby characterizing the gradual transportation of heat most effectively graphically.

In addition to Fe$_2$O$_3$ and ZnO, we identified other insightful metal oxides for the multivariate mapping of variables to samples. For instance, the coefficients of the linear combination of the PC$_{III}$ and Al$_2$O$_3$ ($r = -0.9, p$ value < 0.01) and SiO$_2$ ($r = -0.95, p$ value < 0.01) were strongly positive. In contrast, it had weaker positive correlations with K$_2$O ($r = 0.75; p$ value < 0.05) and SrO ($r = 0.7; p$ value < 0.05). Therefore, the third dimension of the multifactorial map highlighted the role of inorganic compounds in forming physical deposits in the boiler. The Al$_2$O$_3$ and SiO$_2$ moved downward in the analytical space of PC$_{III}$, hence, they provided the best discriminants of fuels with a lower propensity to produce fouling and slagging. The K$_2$O moved upward in the analytical space of PC$_{III}$, making it the strictest indicator of heavier physical deposits. In addition, the positive correlation between PC$_{III}$ and fouling ($r = 0.7, p$ value < 0.05) indicated the predominant deposit and accumulation of ash on conducting surfaces, such as superheaters and reheaters. Therefore, slagging would not excessively occur when ash sticks to the walls of the boiler. Understanding the dynamics of slagging and fouling is key to successfully operating the burning of solid fuels, as it determines the type and severity of physical deposit and how to address its removal, for instance, by blowing, dispersing an insulation material, or lowering the outlet temperature.

A positive correlation of 0.7 ($p$ value < 0.05) occurred between Ti and PC$_{IV}$, making it the explanatory component of the material's reactivity. All blends and models for CPFF moved upward in the analytical space of PCIV, while pine-wood sawdust and reference fuel moved downward, supporting the role of SFM in accelerating ignition. The PP, PE, and nylon acted as highly volatile thermoplastic hydrocarbons to blends, reducing their resistance to oxidative degradation. In addition, TiO$_2$ from the earloop and biomass provided the best insight into thermal conductivity. The correlation between such an eigenvector and PCV was positive ($r = 0.8, p$ value < 0.05). Therefore, a material will conduct heat more effectively when TiO$_2$ or its oxidation state...
3.8 Implications, trade-offs, and challenges for converting the SFM to composite plastic-fiber fuel

Integrating the SFM and biomass into a blend for co-pelletization allows the development of high-quality hybrid solid fuel for generating heat and electricity. For instance, such a plastic material and sugarcane bagasse work well together to improve combustion comprehensively. Physical and chemical synergies between them can increase the quantity of isothermally available energy in the form of heat for the system. While sugarcane bagasse excessively brings N and S into the inorganic phase of its composition, the composite fuel meets the limit value for ash and, in addition, the stricter specifications of the European standard for these compounds, thereby not critically emitting NOx (<500 mg m\(^{-3}\)), SO\(_2\), and CO (<200 mg m\(^{-3}\)). Decreasing the specific generation of CO, which eventually manifests as severely poisonous and asphyxiant to stakeholders during offloading ocean-ongoing cargoes or upon entering rooms for unstuffing and inspection, can enable the implementation of occupational safety in indoor facilities. Cleanly and safely producing energy can certify fine-scale manufacturing systems to guarantee the non-problematic utilization of the product for customers, which is crucial to developing responsive and thriving residential and industrial markets.

China’s ban on imports of foreign waste, including recyclable polymers, entails infrastructural, logistical, and technological challenges in developing global-scale zero-plastic or circular plastic economy action plans. While the integrative carbonization-pelletization framework can effectively convert the SFM to hybrid fuel at the experimental scale, its delivery at full scale would offer the global bioeconomy a way to address the high-rate management of such a disposable material. It would work better in regions where these techniques approach commercialization, such as in European Union and North America. However, stakeholders of the global energy security system, such as the scientific community, policymakers, and civil society, must cooperate to elaborate on ways to address emerging countries in the developmental process for equity. For instance, Brazil would offer a hotspot in South America to incorporate the composite plastic-fiber fuel into the bioeconomy through the biomass and bioenergy sector. Sugarcane bagasse, peanut shell, and corncob stand as abundant, available, and accessible bioresources of Brazilian agriculture, highlighting the role of such a country in our quest to develop co-pelletization as a sustainable WTE platform to convert the SFM to solid fuel for circular economy and environmental protection.

The SFM typically manifests as hazardous to human health; hence, its handling may not be safe for professional staff and ordinary people. We were not allowed to employ WSFM from hospitals or public places in the laboratory. Then we acquired clean material from a pharmacy. Therefore, further in-depth research must focus on collecting the SFM from medical facilities and public areas to resemble realistic conditions and overcome this limitation of our study. Introducing disinfection into the manufacturing line at a step backward from blending would be timely to protect workers against viral particles staying active on the mixture until the thermal pretreatment. In addition, manufacturing managers must instruct staff on properly wearing PPEs to implement a higher level of occupational safety in the facility.

We planned not to unfold the SFM while handling it for blending to address a resource-efficiency methodology. We proved the pre-production to be feasible at an experimental scale. However, large-scale producers must focus on implementing automation to balance operational cost-effectiveness and occupational safety while improving the fuel’s quality. For instance, removing metal components from the SFM, such as the nose frame or band, either automatically or semi-automatically under the control of an assistant operator, could reduce the generation of oxides during combustion. Even though Ti from the nose frame can work as effectively as a thermal conductor to fuel, thereby improving its release of heat to the system, Fe, Ca, or Mn can restrict its role in combustion through their oxidation to Fe\(_2\)O\(_3\), CaO, and MnO\(_2\), respectively. These oxides, especially CaO, cause the boiler to wear, overheat, and fail. In addition, they create cooler regions in the equipment through the formation of slagging and fouling on conducting surfaces, thereby decreasing techno-economic performance.

Researchers know how to recover eco-friendlier energy from COVID-waste streams, including the SFM, via pyrolysis, torrefaction, and gasification. Therefore, our integrative framework can offer a new waste-to-energy platform to convert such residue into a fuel-flexible blend cleanly and safely.
Broadly analyzing its techno-economic and environmental ramifications must be the priority for further industrial-scale studies in applicable destinations, such as coal-fired power plants, gas-fired stations, and homemade wood-burning stoves.

4 Conclusion

We recovered cleaner and safer energy from the surgical face mask through the co-pelletization of its hydrochar with agro-residual biomass. The integrative framework yields high-quality solid fuel for generating heat and electricity in stricter residential (ENPlus’ class A2) and industrial (IWPB’s industrial group II) energy niches. Therefore, it can offer industries and research centers opportunities to implement high-throughput manufacturing lines for mechanically recycling waste while generating eco-friendlier energy for circular economy and sustainable development. The hybrid product enables us to address trade-offs and synergies between disposable medical plastic residue from the COVID-19 pandemic and biogenic raw materials available in the agriculture sector; hence, it represents a triumph of the waste-to-energy nexus. However, it is still at an early stage of development, driving the need to determine its economic performance and environmental footprint to upscale and position it in the real world through zero-waste energy supply chains.

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Data availability Experimental data and materials will be available from the corresponding author upon reasonable request.

Declarations

Ethics approval Not applicable.

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