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Characterization properties of biocarbon pellets for safe transportation and storage

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Abstract –Replacing the fossil carbon with biocarbon is a promising and effective way to reduce dependence of the metallurgical industry on the fossil carbon and increase sustainability as well. Densification is the process of compressing loose biocarbon into regularly shaped, dense products such as pellets and briquettes. Densification technology serves as a viable and efficient strategy to refine raw biocarbon into high-value forms such as pellets and briquettes, effectively improving its mechanical performance and boosting both mass density and energy density. Despite these improvements, densified biocarbon products remain susceptible to quality degradation when exposed to rainfall or high-humidity environments for short periods during transportation and storage. Systematic study on the thermal stability of densified biocarbon is important for safe transportation and storage of biocarbon, especially in large scale under different conditions. The objectives of this study are to evaluate the mechanical stability of biocarbon pellets upon water immersion treatment and investigate self-heating and self-ignition of biocarbon pellets through different measures. Water immersion and subsequent air-drying significantly degrade the durability of biocarbon pellets, with weight fluctuations returning to baseline but causing severe structural weakening after prolonged exposure. Thermal stability evaluation reveals that pellets undergo thermal runaway and smouldering combustion at temperatures above 145–160°C, accompanied by oxygen depletion and carbon oxide emissions. Consequently, a dual-monitoring approach combining temperature sensors with CO/CO_2 gas detection is recommended to manage self-heating and ignition risks during transport and storage.

1. INTRODUCTION

The global metallurgical industry has long relied mainly on fossil carbon feedstocks, predominantly metallurgical coal and coke. This heavy fossil dependence makes metal production one of the most carbon-intensive industrial sectors worldwide. To address growing global climate constraints, metallurgical facilities in Norway and across international markets are actively developing decarbonization strategies to renovate conventional production workflows and mitigate greenhouse gas (GHG) emissions (Werra, M., et al., 2021). For the short-to-medium term, the substitution of fossil-based metallurgical reductants with sustainably derived biocarbon represents the most technically and economically viable route toward low-carbon metallurgy. Produced via the pyrolysis of renewable biomass feedstocks, biocarbon qualifies as a biogenic, carbon-neutral material under mainstream carbon accounting frameworks (Makgobelele et al., 2021). The CO_2 released during biocarbon reduction is offset by the carbon previously sequestered by parental biomass during vegetative growth, enabling a closed carbon cycle for industrial metallurgical operations.

Despite its unique carbon-neutral advantage, the industrial-scale deployment of raw biocarbon is severely limited by scalability barriers and logistical constraints. Global metallurgical manufacturing consumes tens of millions of tons of coal and coke annually; even partial replacement of these fossil inputs requires a stable, high-volume supply chain that delivers biocarbon with consistent and controllable physicochemical properties (Wang and Skreiberg, 2023). Raw biocarbon typically pyrolyzed at 500–700 °C exhibits low bulk density, high porosity, and poor mechanical stability. Relative to conventional metallurgical coke, raw biocarbon readily fractures and collapses under mechanical stress, generating fine dust

particles during routine handling, transportation, and storage. This structural fragility causes substantial material loss and introduces critical operational safety hazards (Wang et al., 2018; Wang and Skreiberg, 2023). Mechanical densification of raw biochar into standardized pellets or briquettes provides an effective solution to these inherent deficiencies (Wang et al., 2018). This compaction process converts loose, low-density biocarbon into a high-performance energy and carbon carrier through three key improvements (Ngene et al., 2024). Densification drastically improves volumetric energy density of raw biocarbon, minimizing storage space requirements and reduces long-distance transportation costs (Riva et al., 2021). Densified biocarbon possesses enhanced mechanical durability, resisting physical abrasion and impact during transit and loading. This mechanical robustness effectively reduces material attrition, fine particle shedding, and associated spontaneous combustion risks (Riva et al., 2021). Even with these significant performance enhancements, densified biocarbon pellets remain vulnerable to structural degradation throughout logistical operations. Compressive force, surface abrasion, and high-energy impact—generated by material dropping from conveyors, chutes, and storage containers—progressively undermine the structural integrity of compacted biocarbon products (Ngene et al., 2024). Ambient environmental exposure further exacerbates pellet quality deterioration. Better water resistance is therefore an essential performance indicator that guarantees structural stability of biocarbon pellets under high-humidity conditions or intermittent rainfall during transportation and storage (García et al., 2021). Moisture infiltration not only lowers the calorific value of biocarbon pellets but also destroys internal bonding structures, leading to irreversible structural failure and performance degradation. Currently, there is a lack of systematic investigations into this moisture-induced degradation behaviour. Although Makgobelele et al. (2021) verified that increased binder content improves the water resistance of wood-derived charcoal briquettes, their evaluation was limited to a short-duration 2-hour immersion test. The long-term degradation kinetics and structural evolution of densified biocarbon under sustained moisture exposure remain poorly characterized.

The biocarbons with intrinsic properties such as high porosity and large specific surface area can pose substantial challenges for the large-scale handling, transportation and storage of biocarbon, owing to its high tendency toward self-heating and spontaneous ignition (Restuccia et al., 2019). Self-heating is a thermally hazardous phenomenon triggered by spontaneous exothermic reactions inside porous carbonaceous materials (Wang and Skreiberg, 2023). For biocarbon, this process is predominantly governed by surface oxygen chemisorption, during which gaseous oxygen reacts with active carbon sites to form stable carbon–oxygen surface complexes while continuously releasing thermal energy (Phounglamcheik et al., 2022). When internal heat generation surpasses the rate of ambient heat dissipation, accumulated thermal energy induces thermal runaway, potentially progressing into smouldering combustion or open flaming ignition. Existing studies have confirmed that low-temperature oxygen chemisorption serves as the dominant heat source responsible for the self-heating propensity of biocarbon materials (Restuccia et al., 2019). Beyond oxidative chemisorption, water vapor condensation represents a secondary exothermic mechanism that exacerbates biocarbon self-heating. The thermal interaction between biocarbon and moisture varies dynamically: water condensation releases heat, whereas water evaporation consumes thermal energy. Under humid storage conditions, biocarbon particles and fine residues readily adsorb atmospheric water vapor, and the subsequent condensation process generates instantaneous heat accumulation. This rapid thermal input elevates the baseline temperature of bulk biocarbon stockpiles, acting as a thermal precursor that reduces the energy barrier for intensified oxygen chemisorption and further accelerates self-heating progression. Additionally, humid environments facilitate microbial and fungal proliferation, triggering biological degradation of biocarbon during prolonged storage and transportation. This microbial activity also contributes to gradual temperature elevation and material performance

deterioration (Wang et al., 2017). Current experimental frameworks for evaluating biocarbon self-heating and autoignition risks primarily adopt oven-based assays and fixed-bed reactor systems. The oven basket method, established on the Frank-Kamenetskii critical thermal theory, is a standard static approach for determining the minimum ambient ignition temperature for a given biocarbon volume (Restuccia et al., 2019). Conventional safety assessments have heavily relied on this static testing strategy to define safe stacking and storage thresholds for bulk biocarbon (Van Blijderveen et al., 2013).
This study addresses these fundamental knowledge gaps by systematically investigating the water resistance and mechanical degradation behaviours of biocarbon pellets across various immersion timelines. Following water exposure, the pellets were evaluated for mechanical durability—a primary indicator of logistical viability and structural survival. The self-heating potential of the studied pellets are evaluated by conducting basket test and fixed bed tests. The insights gained from this work are critical for establishing reliable biocarbon value chains, preventing premature material degradation, and accelerating the widespread adoption of bio-based reductants in advanced metallurgical applications.

2. MATERIALS AND METHODS

2.1 Material

Biocarbon investigated in this study was manufactured from bamboo using a pilot-scale kiln reactor operated at approximately 600-650 °C. The as-produced biocarbon was ground into powder and subsequently densified into pellets.

2.2 Water immersion tests

Water immersion experiments were carried out by submerging individual biocarbon pellets in cold water. Two kinds of pellets were tested with different total immersion durations, including long pellets with length of 20-23 mm and short pellets with length of 10-12 mm. For water immersion test, each pellet was merged in cold water and retrieved for weighing at 15-minute intervals throughout the first hour. The same pellet was subsequently submerged for a further hour before undergoing another weight measurement and returned to the vessel for continued soaking. Following initial submersion, periodic weighing of the identical pellet was conducted at 12 h, 24 h and one week after the start of immersion. During every weighing procedure, each pellet was held above the vessel opening and shaken gently (fixed holding duration for 5 seconds and 5 of shakes) to remove surface water. Mass gain was calculated from the initial pellet mass and the measured mass recorded after each immersion interval. Structural evolution and physical integrity of each pellet were visually monitored continuously after submersion. Additionally, pellets subjected 1 week immersion test was further underwent ambient air-drying to characterise mass loss behaviour. A single saturated pellet was placed in a glass tube, with mass measurements collected at 10-minute intervals in the first hour, followed by subsequent measurements at 2 h, 12 h and 24 h. After that, the pellet was taken out the tube and place in a flat baker and dried one week. The weight of one pellet after each drying time scale was measured.

2.3 Durability of pellets

Mechanical durability (MD) measurements were performed using an ISO Tumbler 1000+ apparatus (Bioenergy Institute, Vienna, Austria) complying strictly with standard ISO 17831-1. These tests aimed to quantify how water immersion and subsequent air-drying alter the mechanical strength and structural integrity of biocarbon pellets. A defined initial mass of pellets (m_i) was introduced into the stainless-steel tumbling chamber. The chamber rotated continuously at 50 rpm over a 10 min testing period, corresponding to a total of 500 rotations to apply controlled mechanical abrasion and impact. Upon completion of tumbling, the

recovered material was sieved using a 3.15 mm round-hole sieve to isolate fine particles produced during the test. The residual mass of undamaged pellets (m_f) was then weighed, and this value was adopted to compute the mechanical durability index via the equation presented below

MD = 100x mf/ mi

Where:

- mi represents the initial pre-test sample mass.
- mf represents the final mass of the pellets retained on the sieve post-test.

2.4 Fixed bed test

Self-heating and autoignition tests were performed in a fixed-bed reactor employing biocarbon particles with sizes between 0.5–1 mm. For each measurement, pre-dried biocarbon (around 70 g) was filled into a 78 mm-diameter, 100 mm-tall cylindrical mesh basket positioned at the reactor tube mid-section. A central thermocouple embedded in the sample bed recorded temperature profiles continuously. Air flowed upward through the bed after entering the reactor base. The reactor was heated at 10 K min^{-1} to target temperatures (180, 190, 200, 250 °C) and maintained isothermally for defined periods. Produced gases passed through a condenser and dual filters to remove particles and tar vapour. The treated gas stream was metered and analysed via a Varian CP-4900 Micro-Gas Chromatograph to quantify CO, CO_2 and O_2. Once each experiment concluded, the basket was cautiously removed from the reactor, and the remaining solids were photographed and visually characterised.

2.5 Crossing-point self-heating test

All crossing-point tests were implemented based on the standard N.4 test procedure using a 1 dm^3 wire mesh basket. Major deviations from the standard protocol included the adoption of multiple testing temperatures (120, 140, 160, and 180 °C), upgraded thick-wire thermocouple probes, and the incorporation of an additional thermocouple embedded within the sample matrix. Except for the 140 °C test, which lasted continuously for 24 h, all other experimental runs were terminated within 3–16 h, which was sufficient to capture the characteristic crossing-point behaviour for self-heating assessment. Experiments were conducted using a Binder FD 53 laboratory oven equipped with a double-layer stainless steel mesh basket assembly. Temperature monitoring was achieved using three 1 mm-diameter Type K thermocouples complying with the Class 1 accuracy requirements specified in the IEC 60584:2013 (IEC 60584-1, 2013) standard. The thermocouple tolerance was defined as the greater value between ±0.5 °C and ±0.004 × T (T in °C), with a valid operational temperature range of 40–1000 °C. Temperature data were logged at a constant sampling frequency of 0.5 Hz using a calibrated data acquisition system that undergoes annual recalibration to ensure measurement accuracy and traceability. For spatial temperature arrangement, the first thermocouple (TC1) was positioned at the geometric centre of the cubic sample volume, whereas the second thermocouple (TC2) was placed 10 mm away from TC1 along a direction perpendicular to one lateral surface of the cubic sample assembly.

3. RESULTS AND DISCUSSIONS

Figure 1 shows weight gain of tested long and short biocarbon pellets after water immersion test at different time interval. Both long and short pellets had weight increase already after 15 minute and reached approximately 33-35% after 10,080-minute (7-day) period. Weights of long single pellets increased from about 1.3 to 1.8 gram, while weights of the short pellets increased from about 0.6 to 0.9 gram. It is interesting to see more weight increase of short pellets after same water immersion time, in comparison to the long pellets. The weight increase of one biocarbon pellet in the water involves filling of water in surface pores and wetting of the

pellet's exterior. The initially adsorbed water might transfer to interior of the pellets, which can be trapped within the internal micro-pores. As accumulation of the water in the interior structure of the pellets, an equilibrium might be established, and the water might not be easy to enter into or escape from the pellets. However, with longer water immersion time, already adsorbed water might movers further into the deeper micro-porous structure of the biocarbon through slow capillary action and diffusion. This might cause swelling of the biocarbon with fibrous structure and possible break down of internal cell walls. This can cause physical expansion and cracks of biocarbon pellets, opening up previously inaccessible internal volume and allowing the pellet to hold more water. This can partially explain increase of pellet weight upon prolonged water immersion test.

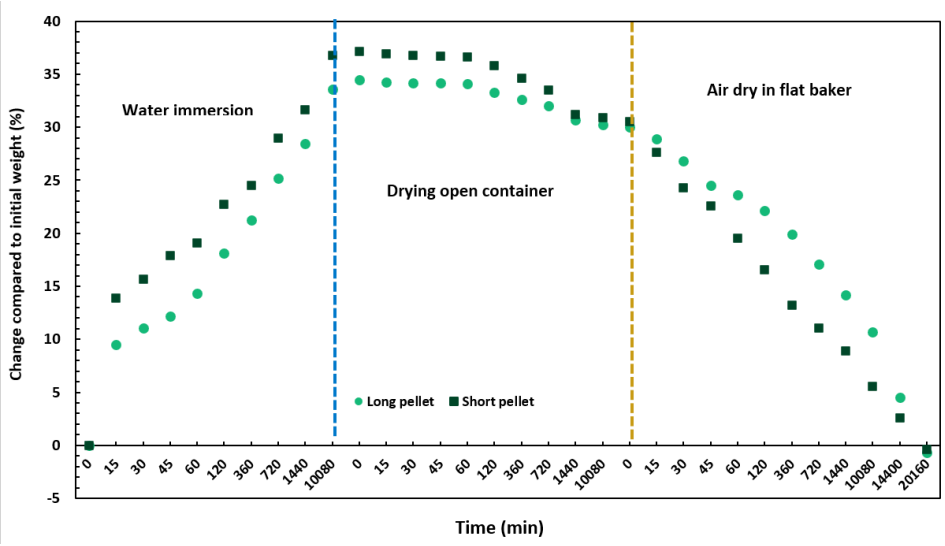

Figure 1: Weight gain of long and short biocarbon sample pellet after water immersion tests at different time interval

Figure 1 also shows different weight decrease behaviours of one test pellet as it was dried in a tube and a flat baker. The pellet was dried in a tube that has a diameter of 10 mm and length of 1 cm, which is placed on the bottom of the tube. It means there is almost no air flowing around of the pellet and adsorbed water is hardly evaporate. Therefore, only small weight losses were observed from the pellets as they were dried in the tube even after dried after 12 hours. However, as one pellet was taken out of the tube and place in a flat baker, it has more contact with surrounding air. Evident decrease of the pellet weight was monitored. During drying in open air in the flat baker, more weight loss was measured from the short pellet. The surface adsorbed water evaporates first, and internally trapped water will diffuse from internal structure. For the short pellets, the distance for water transferring from interior of pellet is shorter. It means more water can migrate and evaporate from the short pellets with given time.

Figure 2 shows that there were only slight decreases of durability of both long and short pellets after water immersion test with one week period. However, after two weeks water immersion test, more evident decreases of pellet durability were observed, indicating higher potential of formation of fines and reduction of mechanical properties of the pellet. During tumbling test, the pellets crush with internal surface of the tumbler, causing manifestation of pellet's surface and internal breaking down. Longer water immersion time leads to weaken binding force of the added binder that bonding biocarbon particle together. It causes reduction of binding forces, shredding of particles and production of fines from the pellet during tumbler test.

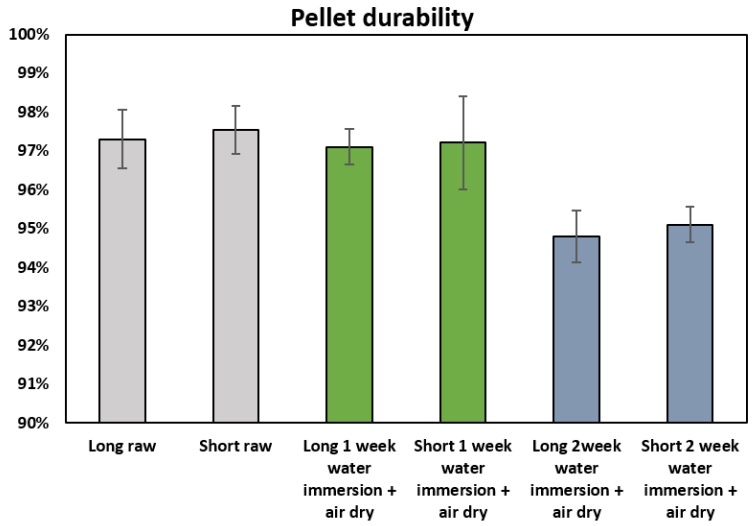

Figure 2: Durability of biocarbon pellet after water immersion test with different time periods and further air dry

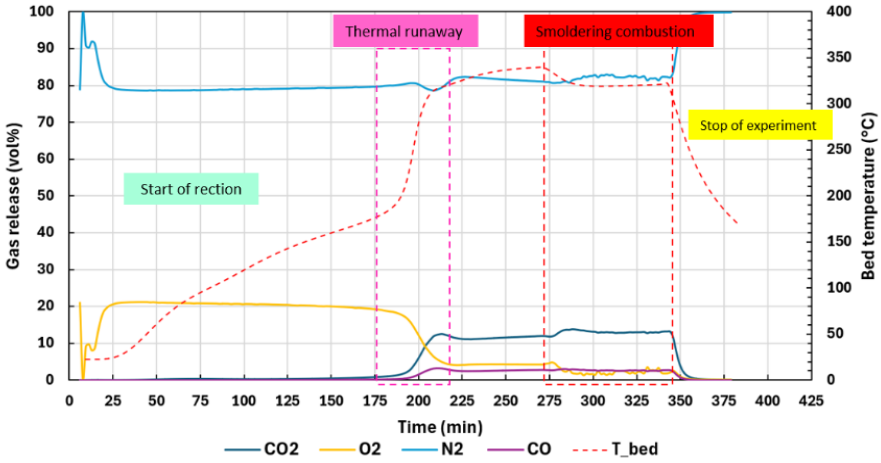

Figure 3: Temperature history of heating up the sample to 160°C with further holding time of 6 hours and change of supply of air

Figure 3 illustrates the temperature evolution and gas-release profiles measured during experiments conducted under a constant furnace set-point of 160 °C and a continuous air feed rate of 1 L/min. As sample temperature slowly reaches 160 °C, the outlet-gas O_2 concentration decreases marginally while CO_2 concentration increases. Once the sample attains 200 °C, CO and CO_2 emerge as indicator gases, denoting chemical-bond rupture and the transition from physical adsorption to active oxidation. After about 50 min of testing, sample temperature increases to 180 °C and then jumps steeply to nearly 330 °C within about 25 min. This temperature burst is accompanied by severe O_2 consumption, demonstrating intense internal reactions driven by high oxygen uptake of porous biocarbon. A major finding is that thermal runaway takes place at a furnace setting of 180 °C for biocarbon pellets. Post-runaway, sample temperature steadily rises and reaches 350 °C after 2 h. In this period, CO and CO_2 emissions stay at a high stable plateau, pointing to persistent smouldering combustion.

A total of five tests at temperatures from 120–160 °C were conducted using basket test. The recorded temperatures in the center of the sample are presented in Figure 4. As the preset temperature was 140 °C, there was a slight increase of temperature in the center of sample bed, which is over 150 °C. However, with further increase of testing time, the measured temperature decreased gradually and reached preset temperature 140 °C. The temperature measured from 140 °C indicates that there was heat accumulation in the center of the biocarbon

sample bed. However, the generated heat further dispatched with causing self-ignition of the sample. For basket tests conducted at temperature even at 145 °C, the measured temperature increase after the sample was loaded in the furnace after about 3.5 hours. After the temperature reached about 170 °C it increased sharply and reached 250 °C in about 20 minutes time, indicating combustion of the sample. With further increase of preset temperature of 150 °C and 160 °C, more evident increase of temperature took place in a shorter time, implying more intensive generation of heat.

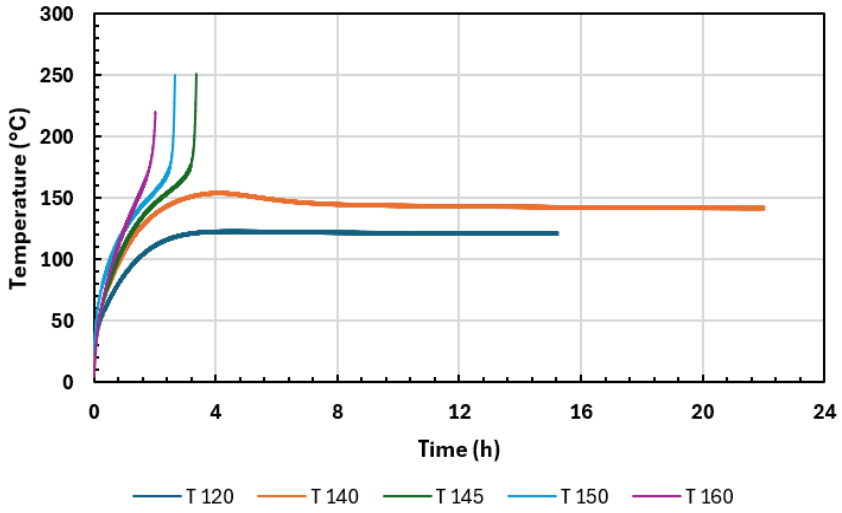

Figure 4: Recorded biocarbon sample bed centre temperatures at the different preset oven temperatures.

4. CONCLUSIONS

The comprehensive evaluation of biocarbon with different lengths reveals that moisture exposure and immersion duration are critical determinants of their structural integrity and logistical viability. Significant weight gains were monitored from the studied biocarbon pellets event after a short water immersion time. Prolonged immersion-extending to 7 days-results in substantial weight increases of approximately 33-35% for both short and long pellets. The further air-drying of water immersed pellets resulted in decline of weights, which eventually falls to their 'as received' state. However, the weight loss behaviours of pellets were considerably different as they dried in a semi open tube and a fully open flat baker. After water immersion and further air dry, the durability of pellets decreased, which are more evident after 2-week water immersion period compared to 1-week.

Self-heating and self-ignition behaviours of the studied biocarbon pellets were investigated by using fixed bed reactor and oven-basket test methods. The fixed bed reactor test results showed that at preset temperature of 160°C, the biocarbon become thermally unstable and further undergoes thermal runaway. This process was accompanied by reduction of O_2 and measurable appearance of CO_2 and CO in the gas exiting the furnace, indicating transition and occurring of biocarbon from self-heating to more intensive smouldering combustion. Oven-basket tests showed that thermal runaway of the studied biocarbon pellets took place as the oven temperature was preset at 145°C and a temperature higher than this value. The fixed bed and oven-basket test results indicate that a dual-monitoring approach - combining traditional temperature sensors with advanced gas detection for CO and CO_2 can be more sensitive and valuable to characterize properties of biocarbon related to self-heating and self-ignition during transportation and storage.

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