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MIKA PAHNILA

Development of biocarbon as a coke substitute for submerged arc furnace

UNIVERSITY OF OULU GRADUATE SCHOOL;
UNIVERSITY OF OULU,
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Abstract

Due to the rising cost of emission allowances and the EU's goal to achieve carbon neutrality at the beginning of 2050, there is strong pressure to reduce greenhouse gas emissions, especially carbon dioxide (CO_2) emissions. Globally, one of the largest sectors producing these emissions is the iron and steel industry, which is responsible of around 7–9% of global CO_2 emissions. This means that in this industry sector alone, there is a huge potential to reduce these emissions. One way to cut fossil-based emissions within the iron & steel industry is to use biocarbon to replace fossil-based carbon such as a coke to produce ferrochrome. This biocarbon could be made from different, currently non-utilized side streams, which would further promote the sustainability of biogenic carbon utilization in submerged arc furnaces.

In this doctoral thesis, the properties of biocarbon were modified to be closer to coke through multiple approaches: optimizing the selection of the raw materials, briquetting of the raw materials, optimizing the binder use and using different pyrolysis methods. The briquettes' suitability as a coke replacement was studied in conditions simulating the thermochemical stresses of a submerged arc furnace using a gas composition that contained 50% carbon dioxide and 50% carbon monoxide at 1100 °C. In these conditions, the degree of carbon conversion was determined. In addition, mechanical strength, porosity and electrical conductivity of the biocarbon briquettes were measured.

It was found that it would be possible to replace coke partially in a submerged arc furnace using a combination of three main actions: optimizing the selection of raw materials, optimizing the selection of the binder, and optimizing the pyrolysis process. The results show that lignin-based briquettes have the most coke-like properties such as gasification reactivity and mechanical strength. It was also found that dividing pyrolysis into multiple heating ramps and holding stages led to a higher biocarbon yield and more coke-like properties.

Keywords: binder, biocarbon, biomass, briquetting, properties, pyrolysis, submerged arc furnace

Pahnila, Mika, Biohiilen ominaisuuksien kehittäminen koksin korvaamiseksi uppokaariuunissa
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Tiivistelmä

Johtuen kasvavasta päästöoikeuksien hinnasta ja Euroopan Unionin tavoitteesta saavuttaa hiilineutraalisuus vuoteen 2050 mennessä, on olemassa kasvava paine vähentää kasvihuonepäästöjä, erityisesti hiilidioksidi (CO_2) päästöjä. Maailmanlaajuisesti yksi isoimmasta CO_2 päästöjen lähteestä on rauta & terästeollisuus, joka tuottaa arviolta 7–9 % maailman CO_2 päästöistä. Tämän takia yksinomaan tällä sektorilla on valtava potentiaali näiden päästöjen vähentämiseen. Yksi keino vähentää näitä päästöjä on käyttää biohiiltä fossiilisen hiilen, kuten koksin sijasta ferrokromin tuotannossa. Tämä biohiili voidaan valmistaa erilaisista, vielä hyödyntämättömistä sivuvirroista, joka tekee siitä vieläkin kestävämmän vaihtoehdon uppokaariuunien tarvitseman hiilen tuomiksesi prosessiin.

Tässä väitöskirjassa biohiilen ominaisuuksia muokattiin lähemmäksi koksia usein eri toimin: raaka-aineiden valinnan optimoinnilla, niiden briketöinnillä, sideaineiden käytön optimoinnilla ja pyrolyysiprosessin optimoinnilla. Brikettien soveltuvuus koksin korvaajaksi tutkittiin olosuhteissa, jotka jäljittelevät uppokaariuunissa vallitsevia olosuhteita, kaasukoostumuksen ollessa 50 % hiilidioksidia ja 50 % hiilimonoksidia lämpötilan ollessa 1100 °C. Hiilen konversio näissä olosuhteissa määriteltiin. Lisäksi brikettien muita ominaisuuksia kuten mekaanista lujuutta, huokoisuutta ja sähkönjohtavuutta tutkittiin.

Saadut tulokset osoittavat, että ligniinipohjaisilla briketeillä on eniten koksin kaltaisia ominaisuuksia, kuten kaasuuntumisreaktiivisuus ja mekaaninen lujuus. Mitä eri pyrolyysi menetelmiin tulee, pyrolyysin jakaminen useisiin eri lämmitysvaiheisiin ja useissa eri lämpötiloissa pitämiseen johtivat korkeampaan biohiilen saantoon ja enemmän koksin kaltaisiin ominaisuuksiin.

Asiasanat: biohiili, biomassa, briketöinti, ominaisuudet, pyrolyysi, sideaine, uppokaariuuni

It is our choices that show what we truly are far more than our abilities. Albus Dumbledore

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in our minds back then, but it has been a great honor to share this, over a decade long adventure with you.

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Oulu, 11.5.2026 Mika Pahnila

Symbols and abbreviations

σ	electrical conductivity [S/m]
ρ_e	envelope density [g/cm^3]
ρ_s	average skeletal density [g/cm^3]
ε	porosity
A	average cross-section area [m^2]
L	average height [m]
m	mass of the sample [g]
m.%.	mass percent
R	electrical resistance [Ω]
V	volume of the sample [cm^3]

Al	aluminum
Al_2O_3	aluminum oxide
Ar	argon
Ca	calcium
CO	carbon monoxide
CO_2	carbon dioxide
d.b.	dry basic
Fe	iron
Fe_2O_3	iron (III)oxide
FeCr	ferrochrome
FeMn	ferromanganese
FeNi	ferronickel
FeSi	ferrosilicon
GW	garden waste
He	helium
i.e.	id est
K	potassium
L	conventional pyrolysis
LIG1	lignin 1
LIG2	lignin 2
Mg	magnesium
Na	sodium
pp	percentage point
RQ	research question
S	segmented pyrolysis

SAF	submerged arc furnace
Si	silicon
SiO_2	silicon dioxide
SSA	specific surface area
T_L	temperature linear pyrolysis
T_S	temperature segmented pyrolysis
WW	demolition wood waste

List of original publications

This thesis is based on the following publications:

1. Pahnila, M., Koskela, A., Sulasalmi, P., & Fabritius, T. (2023). A review of pyrolysis technologies and the effect of process parameters on biocarbon properties. *Energies,16*(9), 6963. https://doi.org/10.3390/en16196936
2. Pahnila, M., Koskela, A., Sulasalmi, P., & Fabritius, T. (2024). Biocarbon production using three-staged pyrolysis and its preliminary suitability to the iron and steel industry. *Energies, 17*(13), 3131. https://doi.org/10.3390/en17133131
3. Pahnila, M., Koskela, A., Uusitalo, J., Hagström, A., Sulasalmi, P., & Fabritius, T. (2025). The effect of binders on the behavior of biocarbon briquettes under the stresses of a submerged arc furnace. *Journal of Sustainable Metallurgy, 12*(1), 839–852. https://doi.org/10.1007/s40831-025-01367-x
4. Pahnila, M., Koskela, A., Uusitalo, J., Vitikka, O., Sulasalmi, P., & Fabritius, T. (2025). The effect of biomass species and pyrolysis method on biocarbon briquettes suitability for submerged arc furnace. *Journal of Sustainable Metallurgy, 12*(1), 523–536. https://doi.org/10.1007/s40831-025-01343-5

The author of this thesis was the main author of all presented publications. The author was responsible for most of the publication work: conducting the literature reviews, planning and conducting the experiments, analyzing the results and writing the publications.

Contents

1 Introduction

The iron and steel industry is one of the largest producers of carbon dioxide (CO_2) emissions in the world. It is estimated that this sector contributes around 7–9% of the world's total anthropogenic CO_2 emissions (Ranzani Da Costa et al., 2022). On average, producing one ton of steel produces around 1.9 tons of carbon dioxide (CO_2) (World Steel Association, 2022). In Finland, producing one ton of stainless-steel releases around 1.7 tons of CO_2. This number represents the overall emissions intensity and includes the contribution of ferrochrome (FeCr) produced in submerged arc furnaces (SAF) (Menzel, 2023). A submerged arc furnace is a smelting furnace which uses electricity to generate heat and also uses coke for reduction and carbonization purposes. This heat is then used to melt the charged material. Typically, this furnace type is used to produce ferroalloys, although the process is energy intensive (Yu et al., 2023b). The main reason why this process is still used in ferroalloy production is that it offers high smelting efficiency and well-controlled reduction reactions (Yu et al., 2023a, 2023b).

Because SAF is an energy intensive reduction process and it produces a relatively high amount of CO_2 emissions, around 1.6 tons per one ton of FeCr, there is a strong need to cut these emissions down (Gyllenram & Wei, 2022). One way to cut fossil-based emissions is to use biocarbon to replace coke.

The main interest in replacing fossil carbon with biocarbon is that the biocarbon raw material is a renewable biomass. The biomass act as a carbon sink during its growth. When the biocarbon is used as a reductant, the released CO_2 is based on the same carbon that the plant has bound within it at the earlier stages of its lifecycle, thus the effect is neutral on the atmospheric carbon balance. The main reason why biocarbon is being considered as a substitute for coke is that it can be produced from renewable biomass sources, allowing it to replace carbon derived from nonrenewable sources (Suopajärvi, 2015).

This thesis focuses on evaluating different ways to produce biocarbon and modify its properties so that the produced biocarbon is suitable for use as a reductant in SAF as a replacement for fossil-based metallurgical coke. Fig. 1 summarizes the structure of this research to achieve this objective.

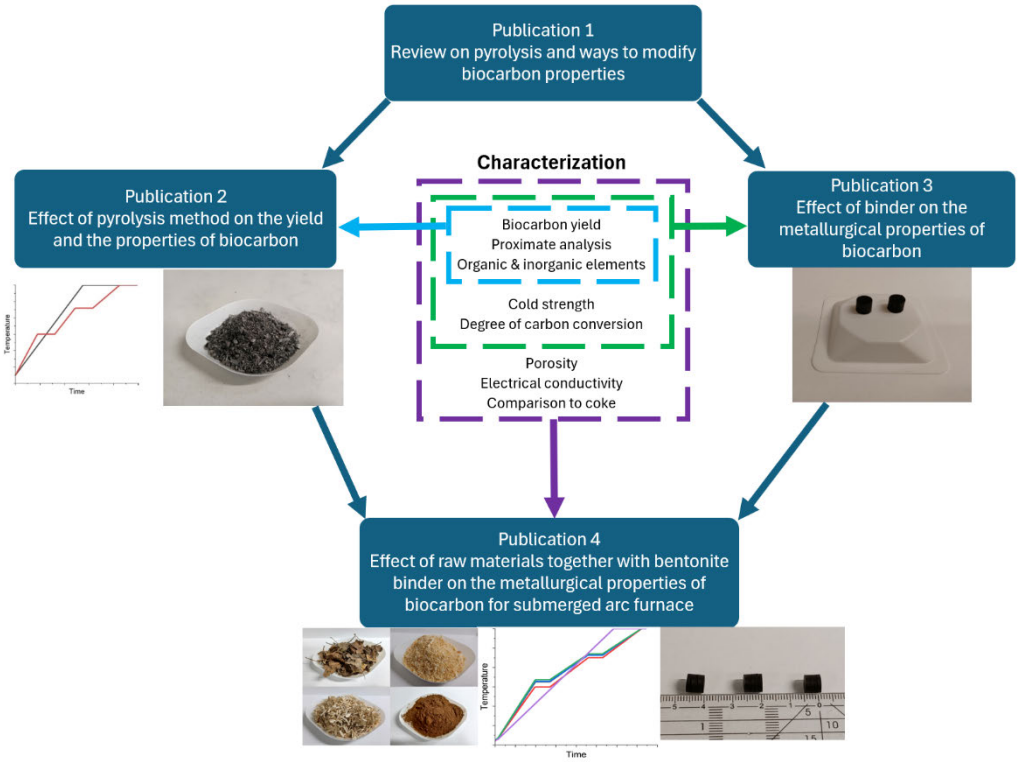


Fig. 1. Structure of the thesis.

The starting point of this thesis was to conduct a literature review (Publication 1) on ways to produce biocarbon and ways to affect produced biocarbon properties so it could be used as a replacement for coke in metallurgical processes. After the literature review the two most promising means of modifying the biocarbon properties were selected for further studies. These involved the optimization of the pyrolysis method (Publication 2) and the use of briquetting & binders (Publication 3). In Publication 4, the combined effect of the pyrolysis method, the use of binder in biocarbon briquettes and the use of different raw materials were studied. The objectives of this doctoral thesis are based on the topics considered in the publications. Therefore, the objectives of this thesis can be considered by using the following Research Questions (RQ) which were discussed in either one or more publications.

RQ1: How can biocarbon properties be affected so that the produced biocarbon is more suitable biocarbon for metallurgical use? (Publication 1)

RQ2: How does the use of segmented pyrolysis affect the biocarbon properties and biocarbon yield? (Publications 2 and 4)

RQ3: What is the most suitable binder type and binder amount, so that the produced biocarbon is suitable for submerged arc furnace usage? (Publication 3)

RQ4: What are the effects of different raw material sources and pyrolysis methods on the applicability of biocarbon is the SAF-process? (Publications 2–4)

2 Biocarbon

2.1 Raw materials

Biocarbon can be defined as a carbon rich material that is produced from a biomass-based feedstock using thermochemical conversion (Mohtasim & Das, 2025). In the past, biocarbon was typically produced from wood and used as fuel. Nowadays, the raw materials are more diverse. The raw materials include agricultural side streams, food waste, different wood species and various side streams from biorefineries (Chen & Pilla, 2022; Grojzdek et al., 2024; Hakala et al., 2020; Kane & Ryan, 2022; Saletnik et al., 2022).

Wood and plant-based by-products from agricultural and industrial operations are called lignocellulosic biomass (Chen & Pilla, 2022). The name originates from the main compounds of plants: lignin, cellulose and hemicellulose. The contents of these main components vary depending on the plant species and different parts of the plant. For example, stalks from wheat have a lignin content of around 5%, whereas stalks from giant reeds have been reported to contain 20% lignin. On the other hand, bark from loblolly pine has a lignin content around 44% (Chen & Pilla, 2022; Lourenço & Pereira, 2017).

Each of the main components have different main decomposition temperatures (Chen & Pilla, 2022). The decomposition of hemicellulose starts from 220 °C and ends at 315 °C. For cellulose, the thermal decomposition range is from 315 °C to 400 °C Lignin has the widest thermal decomposition range starting from 200 °C and ending approximately at 900 °C (H. Yang et al., 2007). In addition to the different decomposition temperatures of these main components, the biocarbon yield of the components varies. For example, when pyrolysis occurs at 850 °C, cellulose has the lowest yield (17.01%), followed by hemicellulose (20.67%) and lignin (41.40%). Therefore, the proportion of these components in a raw material directly influences the biocarbon yield (Ma et al., 2019).

2.2 Pyrolysis mechanisms

The pyrolysis of lignocellulosic biomass can be divided into three stages (Varma et al., 2018):

1. Evaporation of moisture. In this stage, the water from the feedstock evaporates. Typically, this stage starts when the temperature reaches 100 °C (Varma et al., 2018).
2. Decomposition phase. In this stage, the chemical bonds of biomass are broken, leading to the release of volatile compounds and rearrangement reactions. These reactions consist of the formation of char (temperatures below 500 °C), depolymerization of polymeric structures (from 250 °C to 500 °C) and fragmentation of the depolymerized compounds (temperatures over 600 °C). In the char formation stage, the biomass is converted into a solid residue because of the formation and rearrangement of benzene rings into a stable polycyclic structure. Simultaneously with rearrangement reactions, non-condensable gases are released. During the depolymerization, the polymer chains break into monomers, leading to a reduced degree of polymerization. This leads to the formation of volatile compounds. Often, the condensable volatiles are condensed into a liquid fraction. Typically, the depolymerization stage occurs in a temperature range from 250 °C to 500 °C. During the fragmentation stage, at temperatures over 600 °C, the monomer units undergo bond cleavage and are destroyed, leading primarily to the formation of non-condensable gases (Collard & Blin, 2014; Varma et al., 2018).
3. Secondary reactions. The volatile compounds generated in the decomposition or fragmentation stages are often unstable under the reactor conditions and may undergo further reactions. Non-condensable molecules go straight to the gas phase without any secondary reactions. Secondary reactions occur in the vapor phase, vapor-liquid interface or at the vapor-solid interface. They are generally classified as cracking or recombination reactions. During cracking, volatile compounds break down into smaller molecules. During recombination, volatile compounds react with higher molecular weight compounds such as polycyclic hydrocarbons. Furthermore, recombination occurring within the pores of solid residue can promote the formation of secondary char (Brennan Pecha et al., 2019; Collard & Blin, 2014; Varma et al., 2018).

2.3 The modification of biocarbon properties

2.3.1 Temperature

Temperature is the single most important process parameter that affects biocarbon yield during pyrolysis (Chen & Pilla, 2022; Varma et al., 2018). Generally, when the temperature rises, the solid biocarbon yield decreases (Varma et al., 2018). The main reason for the decreased biocarbon yield is that as the temperature increases, a greater proportion of volatile compounds are released into gas phase. These volatiles undergo secondary cracking reactions leading to the formation of both condensable and non-condensable gases. The non-condensable gases remain in the gas phase whereas the condensable fraction may undergo further reactions as described in Section 2.2 Pyrolysis mechanisms (Chen & Pilla, 2022; Collard & Blin, 2014; Varma et al., 2018; Yogalakshmi et al., 2022).

At the same time as the biocarbon yield decreases, the fixed carbon content of the samples increases. For example, it has been reported that when *Eucalyptus* spp. wood is pyrolyzed in a temperature range from 350 °C to 650 °C, the fixed carbon content increases from 64.5% to 93.3% respectively. This increase in the fixed carbon content is linked to the char formation stage, which occurs as described earlier in Section 2.2. (Oliveira et al., 2025).

2.3.2 Heating rate

The heating rate is also a significant factor affecting the product distribution during pyrolysis (Chen & Pilla, 2022). At high heating rates, depolymerization occurs rapidly and volatile compounds are released quickly which shortens their residence time and reduces the extent of secondary reactions. In contrast, at low heating rates, the prolonged exposure of volatiles to high temperatures combined with a prolonged residence time in the reactor favors secondary reactions such as cracking and recombination, leading to increased solid biocarbon formation (Chen & Pilla, 2022; Varma et al., 2018).

2.3.3 Residence time at the peak temperature

One of the key features of slow pyrolysis is the long retention time at the peak pyrolysis temperature (Sakhiya et al., 2020; Slezak et al., 2023). In general,

increasing the retention time leads to a decrease in the solid biocarbon yield. This occurs because the longer residence time allows more volatile matter to be released, thus increasing the carbon content of the produced biocarbon. The retention time affects also the specific surface area (SSA) of the biocarbon. According to (Chen & Pilla, 2022), as the retention time was increased, the SSA increased for biomass samples that were pyrolyzed in the temperature range of 300-700 °C (Chen & Pilla, 2022).

2.3.4 Briquetting

Briquetting is an agglomeration process where a loose feedstock is processed into a compact product (Yunusa et al., 2023). In this process, the feedstock is first mixed with a binder and then compressed under pressure. There are several ways to do that, with the most common being pellet mills, briquette presses and extruders. After applying pressure to the chosen raw material for a specific time, the raw material becomes compacted, thus having a higher density and better particle proximity than the untreated bulk raw material. This product is called briquette (Tumuluru et al., 2011; Yunusa et al., 2023). In addition to the increased density and better particle proximity, briquetting offers several other advantages, including a controlled particle size distribution, more efficient feeding into the target process, improved material handling during the storage and transportation phase and lesser generation of fines during the transportation phase (Kpalo et al., 2020; Surup et al., 2020).

The quality of briquettes depends on the conditions during the compaction phase (e.g. used pressure, temperature and time) and feedstock properties such as moisture content, particle size and its distribution, and composition. The effects of compaction pressure, moisture content and particle size are summarized below (Kpalo et al., 2020):

1. Compaction pressure. The feedstock material can be densified using low or high pressures. In general, when the applied pressure increases, the density of the briquettes increases. This is because the higher pressure enhances both: plastic and elastic deformation of the particles, thus reducing the voids between them (Kpalo et al., 2020). High compaction pressure also improves the briquettes mechanical strength (Granado et al., 2021).
2. Moisture content. During briquetting, the feedstock's natural water content works as a lubricant, reducing the friction between the particles. Water also works as a natural binder forming solid bridges between particles through van der Waal's forces. The optimal moisture content of the feedstock

depends on material, but typically it ranges from 8% to 20%. (Kaliyan & Vance Morey, 2009; Kpalo et al., 2020).

3. Particle size, shape and distribution. These parameters strongly influence both: the briquette quality and production costs. According to the literature, the most optimal particle size depends on the briquettes desired properties (Kpalo et al., 2020). Some studies have highlighted the use of smaller particle sizes (below 2mm) because of improved density and strength (Antwi-Boasiako & Acheampong, 2016; Kaliyan & Vance Morey, 2009). Meanwhile, the use of larger particle sizes has been found to improve the impact resistivity of the briquettes (Rahaman & Salam, 2017; Tumuluru et al., 2015). However, it seems that the most optimal particle size is a mixture of fine and coarse particles since smaller particles fill the voids between the larger ones, thus reducing the void volume and therefore improving the compaction density (Kpalo et al., 2020). Mixing various particle sizes improves the densification process by helping the finer particles to fill the voids between the larger particles (Yumak et al., 2010).

According to (Yunusa et al., 2023), the briquetting of biomass or biocarbon contains following process steps:

1. Collection of feedstock and the binder.
2. Characterization of feedstock. The physical and thermochemical properties of feedstock such as density, moisture and volatile content are characterized.
3. Pretreatment. To improve the quality of the final product, various pretreatment steps can be used including physical (e.g. screening and milling) and thermal (e.g. carbonization and torrefaction) treatments.
4. Material preparation. At this point, binder and water are added to the feedstock and they are mixed into feedstock manually or using mechanical mixers. The water and binder improve the particle bonding ability.
5. Densification. The material prepared in the previous step is compacted. This enhances the material properties such as density and offers improved materials handling during transportation. Densification can be done by using different machines such as extrudes, pellet mills and briquetting machines (Tumuluru et al., 2011; Yunusa et al., 2023).
6. Drying and cooling. After the densification, briquettes are dried in an oven for several hours to several days. This reduces the briquettes moisture content (Yunusa et al., 2023). To reduce the moisture content faster, the cooling could take place right after the briquetting in a separate chamber (Yunusa et al., 2023) or using the conveyor belt (Adzic & Savic, 2013). In

addition to these, rotary drying drums could be used to further speed up the drying process (Ståhl et al., 2004).

The densification step of the biomass-based materials described on the list above can be done using one of the following methods (Sanchez et al., 2022):

1. Pyrolyzed densification using a binder. In this method, the biomass is first pyrolyzed and then crushed. A binder is added into crushed biocarbon, mixed and then densified.
2. Direct densification with binders. In this method, the binder is added directly into pre-treated biomass and then mixed. After mixing, the densification process is carried out.
3. Binderless briquetting. There are two main processing methods to do this. The biomass is either directly densified, or it is first pyrolyzed and then densified without using binders. In both cases, a high pressure (over 160 MPa) is used. Using high pressure increases interlocking and adhesion/cohesion forces between the particles thus leading to the formation of intermolecular bonds in the contact area. For pyrolyzed biomass, this is quite a difficult method to carry out because briquettes made without any binders crack easily and their mechanical strength is low (Ranzi et al., 2018; Sanchez et al., 2022).

2.3.5 The use of binders

According to Ngene et al. (2024), binders are defined as: "*Chemical or biological compounds in liquid or solid state that facilitate compaction of materials acting as lubricants and plasticizers*". This is achieved via interactions between the binder and solid particles in the feedstock material (Ngene et al., 2024).

Binders are generally divided into three categories, namely organic, inorganic and compound binders. Each of these categories have their own advantages and disadvantages (G. Zhang et al., 2018). For example, organic binders typically have a low ash content, but their thermal stability is low. On the other hand, inorganic binders have good thermal stability, but the ash content is high (G. Zhang et al., 2018). Compound binders combine the advantages of different binders. One of the key advantages of using compound binders is that they can reduce the use of inorganic binders while improving briquettes properties such as mechanical strength (Borowski et al., 2022; G. Zhang et al., 2018). However, according to (G. Zhang et al., 2018), one key downside of compound binders is their high ash content (G. Zhang et al., 2018).

2.4 Biocarbon production

2.4.1 Traditionally used technologies

To produce biocarbon, biomass has to be thermally treated, i.e., pyrolyzed. Pyrolysis is described as "*a thermal decomposition of organic matter in the absence of oxygen*" (Al-Rumaihi et al., 2022). There are three main methods to achieve this: slow, fast or flash pyrolysis. The differences between the methods are the heating rates used and final pyrolysis temperatures, thus leading to different product distributions (Panchasara & Ashwath, 2021).

In slow pyrolysis, the main product is biocarbon. A typical feature of slow pyrolysis is the use of a low pyrolysis temperature (below 700 °C), as well as a long material residence time inside the reactor and a slow (0.1–0.8 °C/s) heating rate. In fast pyrolysis, high heating rate (>10 °C/s) combined with a mild (400–800 °C) pyrolysis temperature with low retention time (below 2 seconds) is being used. This leads to formation of bio-oil (Sakhiya et al., 2020). Flash pyrolysis typically involves ultra-high heating rates (>100 °C/s) combined with a very short residence time inside the reactor. The main product is pyrolysis gas (Al-Rumaihi et al., 2022). Table 1 presents the typically used process features linked to each of these techniques.

Table 1. Pyrolysis types and their main process parameters (Reprinted under CC BY 4.0 license from Publication 1 © 2023 Authors).

Parameter	Slow pyrolysis	Fast pyrolysis	Flash Pyrolysis
Temperature (°C)	300–700	400–800	800–1000
Heating rate (°C/s)	0.1–1	10–1200	>1000
Vapor residence time	5–30 min	<5 s	<0.5 s
Particle size (mm)	5-50	<1	<0.2
Products (%)			
Biocarbon	35	20	12
Pyrolysis oil	30	50	75
Pyrolysis gas	35	30	13

Conventionally, the pyrolysis temperature inside the pyrolysis reactor is increased in steps, i.e., the pyrolysis process can be divided into different stages each with individual pyrolysis temperatures. This leads to a heating rate profile that progresses in a logarithmic manner, i.e., the heating rate is at its highest at the beginning of the process and stabilizes towards the retention temperature

(Di Blasi, 2008; S. Wang et al., 2017; H. Yang et al., 2007). However, instead of a logarithmic or linear heating rate and one retention temperature, pyrolysis could be done using multiple heating rates and pyrolysis temperatures (Cheung et al., 2011; K. Han et al., 2016; Lam et al., 2010; Oyedun et al., 2012). The number of these stages could be two or more (K. Han et al., 2016; Lam et al., 2010). The stages could be as follows:

1. A first heating stage, followed by the adiabatic stage.
2. A second heating stage, followed by the second adiabatic stage.
3. A third heating stage, followed by the third adiabatic stage (Cheung et al., 2011; Lam et al., 2010).

The schematic illustration of these stages is shown in Fig. 2.

The idea of this method is to utilize the energy released by exothermic reactions and thus reducing the energy consumption of the pyrolysis process by up to 22.5% compared to conventional pyrolysis (Cheung et al., 2011). In addition to potential savings in energy consumption, the biocarbon properties are also different with segmented pyrolysis compared to conventional pyrolysis. Oyedun et al. (2012), carried out laboratory scale pyrolysis experiments using a segmented heating pattern. According to the obtained results, when segmented pyrolysis was used, the biocarbon yield was up to 3.87 percentage points (pp) higher compared to conventional pyrolysis and the yield of fixed carbon was around 1.29 pp higher. At the same time, it leads to lower volatile matter and fixed carbon content (Oyedun et al., 2012).

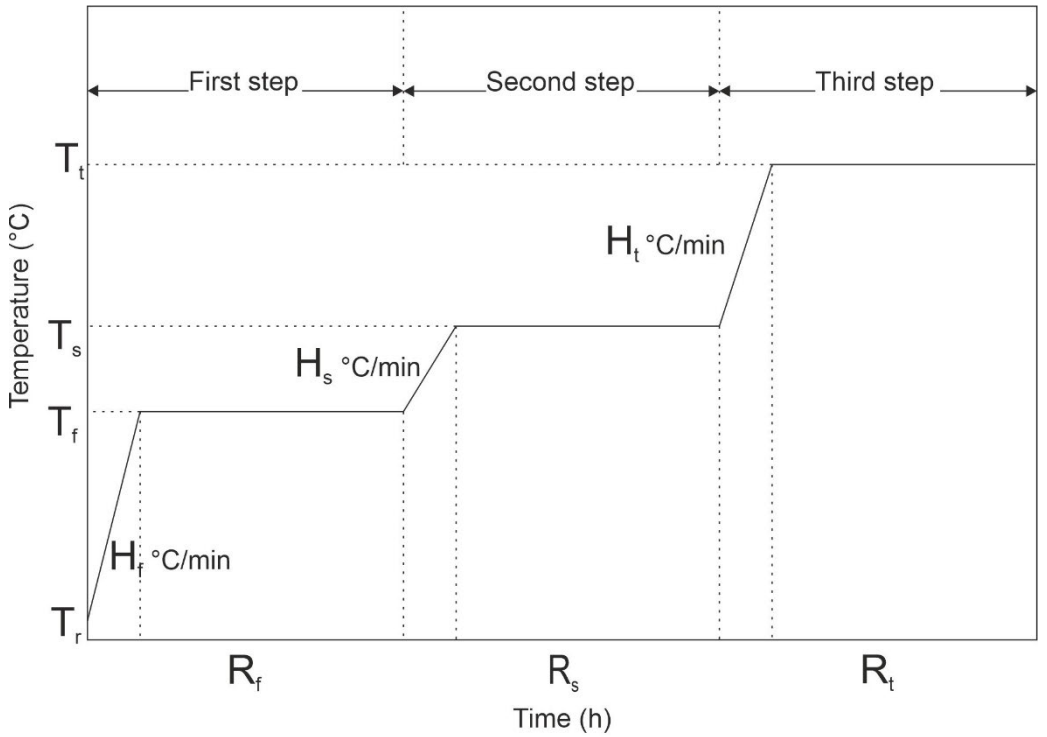


Fig. 2. A schematic illustration of a heating pattern for segmented pyrolysis (Reprinted under CC BY 4.0 license from Publication 2 © 2024 Authors).

2.4.2 New technologies

Microwave pyrolysis

As the name suggests, microwave assisted pyrolysis relays on the use of microwaves to pyrolyze the feedstock. The main difference compared to conventional methods is that the heat is generated within the sample whereas in conventional pyrolysis heat is generated outside of the sample from where it is transferred inside the sample (G. Wang et al., 2020). Because of this, microwave pyrolysis offers multiple advantages over conventional pyrolysis. Besides accelerating the carbonization, the process also becomes more efficient through the reduced processing time, and lower temperatures requirements for reaching a corresponding carbonization level compared to conventional pyrolysis (Ke et al., 2024). Microwave pyrolysis offers lower energy consumption and it does not require drying before pyrolysis. This is because water absorbs

the microwave radiation, thus enhancing the process efficiency (Ingole et al., 2016). Despite these multiple advantages, there are few downsides that make the utilization of this technology difficult. For example, the exact temperature inside the reactor is difficult to monitor, controlling the heating rate is difficult (S. Li et al., 2022; Luque et al., 2012).

Solar pyrolysis

Solar pyrolysis is quite a new technology for pyrolysis. It relies on using the energy from solar radiation, which is first collected and then concentrated into reactor. The temperature range is high, up to 2000 °C and heating rates from 5 °C/s to 450 °C/s can be achieved (G. Wang et al., 2020). One of the key advantages with solar assisted pyrolysis is that it could reduce the CO_2 emissions by up to 32% compared to conventional pyrolysis. This estimation is based on an experimental procedure, where all the energy needed in pyrolysis was produced using solar heaters. This means that there was no heating source from outside (Joardder et al., 2014; Rahman et al., 2021).

Despite the lower CO_2 emissions, globally the use of solar pyrolysis is quite limited because the amount of solar radiation depends highly on factors such as the weather (for example, a high wind speed causes greater heat loses during pyrolysis), time of the day, the season of the year and geographical location of the pyrolysis plant (Chintala, 2018). One proposed way to tackle these restrictions is the use of external heating (Rodat et al., 2020). In this concept, the feedstock inside of the reactor is heated using solar radiation when available. When there is not enough solar radiation to perform pyrolysis, the external heating source is used. External heating could be provided by using electricity or fuel-based burners. By adapting this kind of hybrid heating technique, the continuous operation of reactors could be possible (Rodat et al., 2020).

Plasma pyrolysis

Plasma pyrolysis uses plasma to pyrolyze the feedstock material. A typical feature of this technology is the use of high heating rates, up to 10^4–10^7 °C/s and temperatures, up to 9700 °C (Cheng et al., 2016; Tang et al., 2013; Wnukowski, 2023). The main product of plasma pyrolysis is pyrolysis gas, while the solid and liquid yields are low (Ciuta et al., 2017; Tang et al., 2013). Compared to the gasification of biomass, which is also used to produce pyrolysis gases, there are a few differences. For example, the used gas atmospheres are different, the gas

production in gasification is faster and the overall energy consumption of plasma pyrolysis is higher (Pettinau et al., 2024).

Although plasma pyrolysis leads to relatively high gas yield, over 60% according to Fasihi et al. (2024), the process consumes a lot of energy in comparison to conventional pyrolysis technologies. The heat losses during the gasification are high and because of that, the overall process efficiency is reduced (Soria-Verdugo, 2019).

2.5 Metallurgical biocarbon

According to the Bioenergy Association, metallurgical biocarbon is a carbon rich material obtained from biomass through pyrolysis. Metallurgical biocarbon can be used as a reducing agent or as a substitute for coke in applications where a high carbon content is needed (Bioenergy Association of New Zealand, 2021). A high carbon content generally means that the fixed carbon content of the biocarbon should be over 85% (Surup et al., 2020).

Until the beginning of the 20th century, biocarbon was widely used in the iron & steel industry, before coal and coke replaced biocarbon as the main carbon source. The last blast furnace operating with biocarbon was closed in the USA as late as 1945. The main reason behind this was that coal and coke had higher energy content compared to biocarbon and the production of biocarbon was the biggest expense when producing iron and steel. Moreover, there were quality problems with the produced biocarbon, thus causing operating problems in steel making processes. Finally, due to the rising production volumes in iron & steel industry, the needed amount of biocarbon increased so much that the woody biomass could not support its production (Davis & Lundin, 2021; Straka, 2017).

Historically, biocarbon used for metallurgical purposes was produced from locally available resources such as wood (Davis & Lundin, 2021). In addition to wood, agricultural side streams have also been used (Chen & Pilla, 2022). In recent years, the suitability of other raw materials such as rice & wood residues (Anand et al., 2023), hydrolysis lignin (Koskela et al., 2021), and different wood types such as spruce and birch (L. Wang et al., 2023) have been investigated These studies have highlighted the potential of using these materials as a replacement for coke. For example, hydrolysis lignin-based briquettes have a higher density compared to metallurgical coke, which could help them penetrate the melt in metallurgical applications where the carbon material is injected (Koskela et al., 2021). Wood residues showed a high (over 85%) fixed carbon

content when pyrolyzed at temperatures over 600 °C. This means that they can be used in different metallurgical applications (Anand et al., 2023).

However, despite the potential that biocarbon has to partially replace coke in the iron and steel industry, there remain some technical challenges that need to be solved before biocarbon can replace coke partially in industrial scale operations. Biocarbon generally has a higher gasification rate compared to coke (Mousa et al., 2016), the mechanical strength is lower (Y. Han & Tangstad, 2024; Surup et al., 2020), and the apparent density is lower (Suopajärvi et al., 2013). In addition to these technical challenges, biocarbon demand is higher compared to its production, the biocarbon supply chains are complex, the process for permits for the appropriate facilities is time consuming and the final price of biocarbon is high compared to fossil carbon (Kivijakola et al., 2025). The final price of biocarbon is affected by the cost of original feedstock, the cost of pyrolysis process itself and the transportation cost both in and out of the pyrolysis plant (Kivijakola et al., 2025). According to Kivijakola et al. (2025), the key ways to increase biocarbon use in the iron and steel industry is to find a balance between the biocarbon price, its production and demand. Solving both technical and economic problems could increase the usability of biocarbon in the iron and steel industry.

3 Biocarbon utilization in submerged arc furnaces

3.1 Process overview

Submerged arc furnaces are widely used in the ferroalloy industry to produce ferroalloys such as ferronickel (FeNi), ferrochrome, ferromanganese (FeMn) and ferrosilicon (FeSi) (Degel et al., 2015; Y. Yang et al., 2004; Yu et al., 2021). The principle of SAF is as follows: a feedstock consisting of ore and a carbon reductant is fed to the furnace from the top (Kadkhodabeigi, 2011). The material is then heated by electrodes which convert electrical energy into heat. These electrodes provide the thermal energy required to melt the charge inside the furnace and enable the necessary reduction reactions to take place (Friedrich et al., 2018).

There are three main types of submerged arc furnaces: open, semi closed and closed (Wei et al., 2023). When an open furnace is used, carbon monoxide (CO) is ignited above the charge. This produces extra heat (Wojtaszek-Kalaitzidi et al., 2025). In contrast, closed furnaces offer lower power consumption and higher productivity compared to open furnaces (Eissa et al., 2012).

Regardless of the furnace type, the temperature and the gas composition inside the reactor vary. According to Y. Yang et al. (2004), the SAF can be divided into five distinct zones based on these gradients:

1. The gas region. This is located in the upper part of the furnace. The gas composition in this area consist of approximately 90% CO. Temperatures vary from 800 °C to 1000 °C (Heikkilä et al., 2017; Y. Yang et al., 2004).
2. The packed bed region. In this zone, the chromite is heated and starts to reduce in a solid state. The temperature in this zone is over 1200 °C (Hayes, 2004).
3. The smelting region. This zone consists of the region around the electrode tips. The temperature is from 2000 °C to 3000 °C (Y. Yang et al., 2004).
4. The molten slag layer region. This is located above molten alloy zone. This zone consists of oxides and flux that forms slag. Unreduced chromite may also dissolve into the slag. The temperature in this zone is from 1650 °C to 1700 °C (Y. Yang et al., 2004).

5. The molten alloy zone. This zone is found at the bottom part of the furnace. This zone consists of molten alloy, and the temperature is around 1600 °C (Y. Yang et al., 2004).

A schematic illustration of submerged arc furnace is presented in Fig. 3.

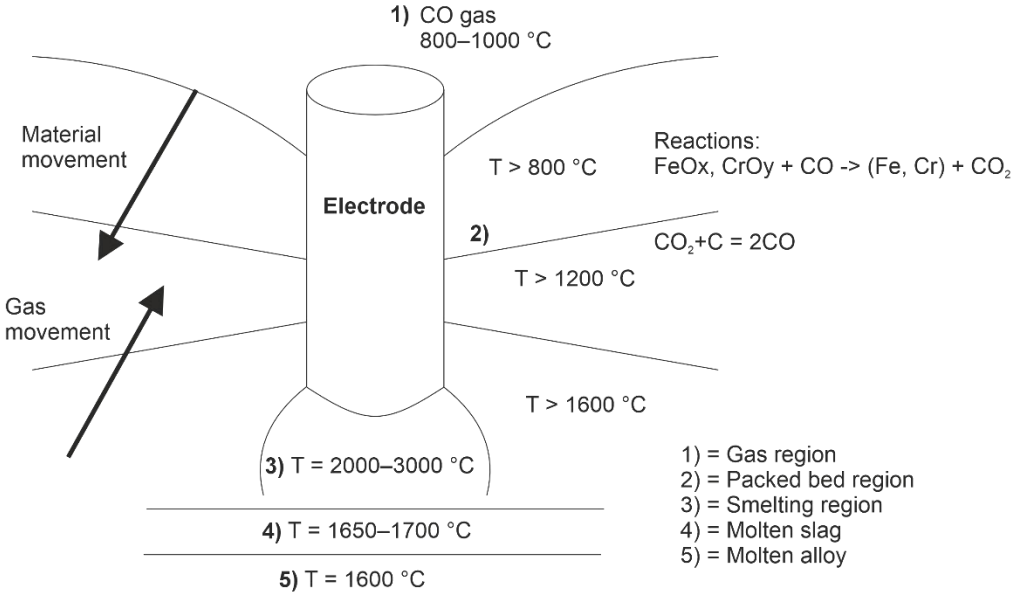


Fig. 3. A schematic illustration of a submerged arc furnace. Based on information given by Hayes (2004); Heikkilä et al. (2017); and Y. Yang et al. (2004).

3.2 Required properties of carbon reductant in SAF

In terms of replacing metallurgical coke in SAF with metallurgical biocarbon without compromising the operability or changing the configuration of the existing process, certain properties must be comparable to coke. These include the carbon gasification reactivity, mechanical strength, density, electrical conductivity and the fixed carbon content (Y. Han & Tangstad, 2024; Surup et al., 2020). In this section, the carbon gasification reactivity, electrical conductivity and mechanical strength are discussed in more detail.

3.2.1 Carbon reactivity

The reactivity of carbon reductants is an important factor in the SAF process. If the carbon reductant is too reactive, it results in increased consumption of both carbon material and electricity (Surup et al., 2020). In general, biocarbon has higher reactivity than coke (Monsen et al., 2007; L. Wang et al., 2023). The reasons behind this could be that biocarbon has higher porosity and higher surface area compared to coke (Y. Han & Tangstad, 2024). In addition to the higher porosity and surface area, it is suggested that the proportion of catalytic elements such as potassium (K), magnesium (Mg) and sodium (Na) increase the reactivity. In contrast, silicon (Si) and aluminum (Al) acts as an inhibiting elements thus lowering the reactivity (Phounglamcheik et al., 2021).

One way to directly reduce the gasification reactivity of biocarbon is briquetting of biocarbon. According to (Kaffash et al., 2021), densification decreases reactivity of biocarbon compared to non-briquetted material. This occurs because the densification reduces porosity. Lower porosity further leads to decreased surface area. The combined effect of these two is as follows: the porosity and the surface area make the gas penetration into biocarbon more difficult, thus slowing down the rate of gasification reaction (Kaffash et al., 2021).

One established method to measure the reactivity of coke can be found in the American Society for Testing and Materials (ASTM) Standard D5341-19. The test temperature in the standard is 1100 °C and the gas composition is 100% CO_2. The samples are held at this temperature for 120 minutes (ASTM International, 2019). It is reported that in these conditions, the biocarbon reactivity is 30 to 40 times higher compared to coke (Monsen et al., 2004). According to Surup et al. (2020), the higher reactivity is the reason that different temperatures and CO_2 concentrations have been used in experiments. In experiments, different researchers have applied temperatures between 800 °C and 1100 °C and gas atmospheres from pure CO_2 to mixtures containing 25% CO_2 and 75% CO (Kaffash et al., 2021; Mianowski et al., 2016; Ranzi et al., 2018; L. Wang et al., 2017, 2023).

3.2.2 Electrical conductivity

In the SAF process, one important factor is the electrical conductivity of the charge material. During smelting, the electrical current flows through the coke bed (Y. Han & Tangstad, 2024). In general, the electrical conductivity of the biocarbons tends to increase as the pyrolysis temperature rises (Antal & Grønli,

2003). For example, MacFarlane et al. (2025) reported that the electrical conductivity of biocarbons from hemp increased from 1.63×10^{-3} S/m to 1576.69 $\times 10^{-3}$ S/m when the pyrolysis temperature increased from 400 °C to 900 °C. Moreover, the electrical conductivity depends on the used raw material. Antal & Grønli, reported that the electrical conductivity of two different biocarbons from Babacu nut and Eucalyptus lignin carbon produced at 900 °C varied from 80.65 S/m to 526.32 S/m, respectively (Antal & Grønli, 2003). Because the used raw material and pyrolysis temperature have a significant effect on the electrical conductivity of the produced biocarbon, it is important to investigate the electrical conductivity of every new charge material.

The electrical conductivity of the carbon material inside the SAF is affected by many factors, such as the furnace operating temperature, degree of carbonization and particle size of the carbon materials (Baumgartner et al., 2024; Surup et al., 2020; Tangstad & Ringdalen, 2025). Therefore, these must be considered when evaluating biocarbon. According to Tangstad & Ringdalen (2025), when the electrical conductivity of biocarbon and coke were tested using an experimental test procedure in a temperature range from 1000 °C to 1600 °C, the biocarbon showed similar electrical conductivity to metallurgical coke especially when the temperature reached over 1500 °C. (Tangstad & Ringdalen, 2025).

The electrical conductivity of the charge affects the electrode tip positioning. A sufficiently high biocarbon conductivity is required to optimize the electrode placement and improve the heat distribution in the lower parts of furnace (Surup et al., 2020; Tangstad & Ringdalen, 2025).

3.2.3 Mechanical strength

The mechanical strength of raw materials is one of the key properties that needs to be considered before feeding material into the process. The generation of fines could cause harm not only during the transportation phase, but also when the material is fed into the process. If biocarbon is not briquetted before transportation, it could generate as much as 20% fines compared to its original mass (Y. Han & Tangstad, 2024; Surup et al., 2020). The reason behind the fractal nature of biocarbon is that compared to coke its porosity is usually higher and the degree of graphitization is lower (Surup et al., 2020). To reduce the fines generation and to improve the mechanical properties of the feedstock material, briquetting is used.

Briquettes' mechanical strength directly influences the suitability of biocarbon briquettes in SAF. In short, briquettes need to be strong enough to withstand stresses before charging in the furnace and need to also endure the stresses inside the furnace (Surup et al., 2021). According to the literature, metallurgical coke used in SAF generally requires a compressive strength greater than 15 MPa (Kaffash & Tangstad, 2021; Surup et al., 2020).

The briquettes' mechanical strength and composition affect their suitability for SAF by affecting the carbon reactivity and the gasification behavior of carbon (Makhambetov et al., 2024). Especially, mechanical strength is an important factor because it affects the generation of fine particles which affects the permeability (Surup et al., 2020). Fine generation can lead to insufficient operation of the furnace thus increasing the energy consumption of the furnace (Y. Han & Tangstad, 2024). If the briquettes break down easily during the process thus generating the fine particles, the gasification of carbon is faster due to higher surface area (Surup et al., 2021). Studies have shown that the particle size influences the carbon gasification reactivity behavior (Eidem et al., 2010). Furthermore, cold strength and reducibility in high temperatures are the key properties when it comes to briquettes properties. If these are not good enough, it will lead to insufficient use of reductants (Patra et al., 2025). Consequently, the insufficient strength of the briquettes could lead to carbon consumption through gasification occurring too early thus leaving a too low amount of carbon for sufficient chromite reduction.

3.3 The current state of biocarbon use in SAF

In recent years, there have been several successful trials on the use of biocarbon in SAF. These trials have been carried out in silicon, ferrosilicon (FeSi) and ferrochrome (FeCr) production (Associação Brasileira dos Produtores de Ferro-Liga e Silício Metálico (ABRAFE), 2024; Correa Ramos, 2018; Mousa et al., 2025; Surup et al., 2021; Tata Steel, 2024; Wojtaszek-Kalaitzidi et al., 2025).

Tata Steel performed successful industrial trials in 2024. In the trials, 5% of coke was replaced by biocarbon in FeCr production. This replacement led to a 6% reduction of CO_2 emissions in the ferrochrome plant (Tata Steel, 2024).

In the project "Developing Bio-briquettes for Ferrochrome Production In Submerged Arc Furnace (Bio4SAF)" the objective was to increase the biocarbon use in SAF. According to project's final report, industrial trials of biocarbon use were successfully performed, with a total of 350 tons of biocarbon-chromite

briquettes. The results from these tests show that by optimizing the composition of the biocarbon-chromite briquettes (moisture content, binder, biocarbon addition), up to 10% of biocarbon could be added to chromite briquettes without compromising the quality of the final product. Furthermore, the report suggests that in given test conditions, coke could potentially be replaced at even higher levels, around 21.8%, which corresponds to an estimated 25% reduction in CO_2 emissions (Mousa et al., 2025). For future work, they suggested the investigation of different biomasses as a raw materials for the biocarbon and further optimizing the briquetting process itself. Moreover, optimizing the SAF-process itself (temperature, charge composition and smelting time) would further increase the biocarbon use (Mousa et al., 2025).

In the production of silicon and ferrosilicon, ELKEM AS was able to replace 20% of coke by biocarbon in Norway (Correa Ramos, 2018). This is a similar level to that suggested in a study by Wojtaszek-Kalaitzidi et al. (2025) for the production of ferromanganese.

In Paraguay, ELKEM has already replaced coke completely in ferrosilicon production (Surup et al., 2021). In Brazil, biocarbon is already widely used in the silicon and ferrosilicon production. Reports indicate that metallurgical coke has been replaced by biocarbon at levels exceeding 50% of the total carbon use, although the exact numbers are not public. Moreover, the use of biocarbon in these production processes has been steadily increasing (Associação Brasileira dos Produtores de Ferro-Liga e Silício Metálico (ABRAFE), 2024; Correa Ramos, 2018).

4 Materials and methods

The experimental work in this thesis was carried out using different biomass-based raw materials which were then pyrolyzed. The raw materials were either in powder form or further processed to briquettes. The main properties of the produced biocarbons were studied.

4.1 Materials

A total of six different biomass-based raw materials were used in the research work of this thesis. The raw materials were spruce, two different types of hydrolysis lignins (LIG1 & LIG2) from industrial stakeholders, demolition wood waste (WW), garden waste (GW) and fiber hemp (hemp). In addition to this, coke was used as reference material to further evaluate the briquettes' suitability in SAF.

The raw materials were chosen based on their potential future availability in Finland. According to the literature, the future availability of hydrolysis lignin will be 165000 tons, around 248000 tons of demolition wood waste will be available and the garden waste availability is 220000 tons, annually. In view of the availability of hemp, the literature does not provide an estimation of its future availability but it is a potential raw material in future biocarbon production because of its fast growth (Karppinen et al., 2024; NordFuel, 2024; Saini et al., 2020; Statistics Finland, 2024).

For the agglomeration of the biomasses, three binders were used: bentonite (CAS No. 1302-78-9), starch from wheat ($(C_6H_{10}O_5)n_5$) and glycerol ($C_3H_8O_3$). The percentage of bentonite in the blend varied from 2 m.% to 8 m.%, whereas the amount of binder varied from 1 m.% to 7 m.% when starch and glycerol were used as binders. In Publication 4, only bentonite was used as a binder with the amount of 8 m.%. The used raw materials as well as the utilized binders are listed in Table 2.

Table 2. The used raw materials and binders in this thesis.

Material	Publication 2	Publication 3	Publication 4
Spruce	X		
Lignin 1		X	X

Material	Publication 2	Publication 3	Publication 4
Lignin 2		X	
Garden waste			X
Hemp			X
Demolition wood waste			X
Coke			X
Bentonite		X	X
Glycerol		X	
Starch		X	

The characterization of the used biomass raw materials is shown in Table 3. One of the main differences between the used biomasses is the volatile matter content, which varied from 59.00 m.% to 80.77 m.% between the materials. Additionally, the fixed carbon content of the raw materials varied from 14.45 m.%. (spruce) to 38.76 m.%. (LIG1). Another difference is the percentages of the main elements, carbon (C), hydrogen (H), nitrogen (N), sulfur (S) and oxygen (O). For example, both lignins had the highest carbon content and at the same time, the oxygen content of the samples was the lowest. Furthermore, in earlier work, the content of these elements has varied between biomasses (Vassilev et al., 2010).

Table 3. Raw material characterization (m.%. = mass percent, n.m. = not measured).

Property	Unit	Spruce	Lignin 1	Lignin 2	Garden waste	Hemp	Demolition wood waste
Volatile matter	m.%,	80.77	59.00	64.89	67.72	73.31	80.00
Fixed carbon	m.%	16.45	38.76	32.61	22.93	22.82	18.42
Ash content	m.%	2.78	2.24	2.42	9.35	3.87	1.52
Organic elements							
C	m.%.	n.m.	61.64	54.30	47.34	47.29	50.67
H	m.%.	n.m.	5.92	5.69	5.74	5.96	6.37
N	m.%.	n.m.	0.59	0.50	1.54	0.44	0.00
O	m.%.	n.m.	14.19	15.13	30.01	37.21	38.77
S	m.%.	n.m.	0.05	0.23	0.15	0.05	0.04

4.2 Methods

4.2.1 Sample preparation

The raw materials used in this thesis were received with varying moisture contents ranging from 1% up to 50%. Therefore, some of the materials needed to be dried before further processing. Spruce, LIG2, GW, hemp and WW were dried at 40 °C, until there was no detectable mass loss, i.e., moisture release from the sample. This took approximately 9 days of drying. Once the drying was completed, the moisture content of these materials was around 1%. LIG1 had a moisture content of approximately 1% when received, so no further drying was needed.

After drying, the biomasses were milled to a < 0.5 mm size fraction with a Retsch ZM200 ultra centrifugal mill (Retsch GmbH, Haan, Germany). For spruce (Publication 2) and LIG1 (Publications 3 and 4) no milling was done. For the spruce the material was not briquetted before pyrolysis and for LIG1 the particle size was already below 0.5 mm.

After milling, the binder was added, with the amounts described earlier in section 4.1. Deionized water was added to the mixtures to increase the moisture content either to 10% (LIG1, GW, WW, hemp) or to 15% (LIG2). The water was added to improve the particles' bonding ability and to reduce the friction during the agglomeration. The reason for the higher water addition with LIG2 was the higher moisture absorption capability of LIG2 in comparison to LIG1. This was noted at an early stage of agglomeration as the LIG2 based briquettes had the tendency to fracture after briquetting with a 10% water addition.

When the briquettes were made, a hydraulic press was used. In Publication 3 when LIG1 and LIG2 were used, a manually operated hydraulic press was used. This was changed to an automatic hydraulic press (Tablet Press, AZYP-20TS, Xiamen, China) in Publication 4 when LIG1, WW, GW and hemp were used as raw materials. This was done to improve the quality of the briquettes by more accurate control of the applied force and holding time during the compression of the briquettes.

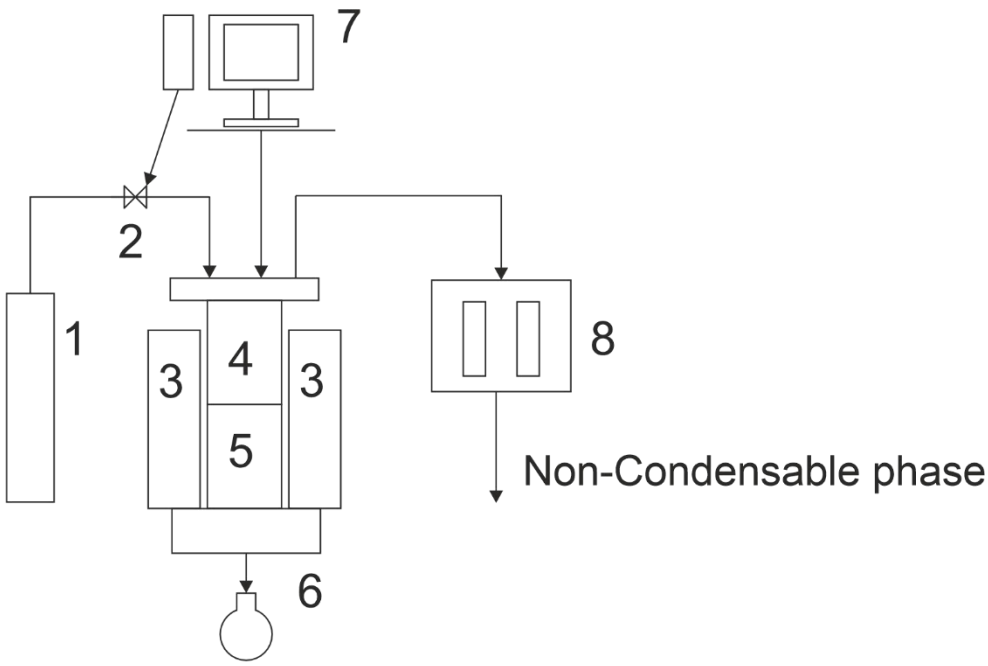
During the briquetting phase an 8 mm mold was used, and an internal pressure of around 160 MPa was applied. The holding time of the compression was 2 minutes and led to briquettes with an average height varying from 7 mm to 8 mm.

4.2.2 Pyrolysis experiments

Pyrolysis

To perform pyrolysis experiments, two furnaces were used. For smaller batches of biomass in Publications 2–4, a Nabertherm HT08/18 chamber furnace was used (Nabertherm GmbH, Lilienthal, Germany). When this furnace was utilized, the samples were put inside a graphite crucible, which was then placed inside a corundum crucible. The empty space between these were filled with synthetic graphite powder and sealed with a corundum cover. A similar experimental set up has been earlier used by Koskela et al. (2021).

For the larger batches (Publication 2), a custom-made batch reactor together with a gradient furnace (Entech ETF 75/17V) was used. The reactor was made of stainless steel and had a volume of 10 liters. Nitrogen, with a flow rate of 2 liters/min, was used as an inert gas throughout all experiments. The same device has been used earlier by Farrokh et al. (2018). A schematic illustration of this furnace is presented in Fig. 4.



1. Nitrogen sylinder
2. Flow control valve
3. Chamber furnace
4. Pyrolysis reactor
5. Biomass sample
6. Tar collecting
7. Computer
8. Condensation unit

Fig. 4. A schematic illustration of laboratory scale pyrolysis device (Reprinted under CC BY 4.0 license from Publication 2 © 2024 Authors).

The pyrolysis experiments carried out in this thesis were performed using two different pyrolysis methods: conventional (linear pyrolysis, L) and segmented (S) pyrolysis. Conventional pyrolysis was used for all raw materials. Segmented pyrolysis was used also for all raw materials except LIG2.

In the segmented pyrolysis, the target temperatures were the same as in conventional pyrolysis. The main difference between segmented and conventional pyrolysis are the different heating patterns. In segmented pyrolysis, the process was divided into three stages, all with different heating rates, which varied between the used raw materials. The heating rates were calculated so

that the total heating time was the same as in conventional pyrolysis. In addition to that, the process time was the same as in conventional pyrolysis. This meant, that the samples were kept for each stages target temperature for 160 minutes. The illustration of used heating and the target temperatures when the segmented pyrolysis was used are shown in Tables 4 and 5.

Table 4. The used heating patterns in Publication 2.

Material	Starting temperature, (°C)	Heating rate, (°C/min)	Target temperature, (°C)	Heating rate, (°C/min)	Target temperature, (°C)	Heating rate, (°C/min)	Target temperature, (°C)
Spruce	T_{room}	7.0	150	4.8	230	3.2	300
Spruce	T_{room}	6.7	240	2.8	330	5.2	500
Spruce	T_{room}	6.1	300	1.3	360	7.4	700
Spruce	T_{room}	5.9	360	2.6	510	6.8	900

Table 5. The used heating patterns in Publication 4.

Material	Starting temperature[1]	Heating rate[2]	Target temperature[1]	Heating rate[2]	Target temperature[1]	Heating rate[2]	Target temperature[1]
Hemp	T_{room}	7.4	299	4.0	459	3.9	600
Garden waste	T_{room}	7.9	326	3.7	465	3.6	600
Lignin	T_{room}	8.0	328	3.6	463	3.6	600
Demolition wood waste	T_{room}	8.2	337	3.5	470	3.4	600

[1] °C
[2] °C/min

Schematic illustrations of the heating patterns used in Publications 2 and 4 are presented in Fig. 5 and Fig. 6. However, when the spruce was used as a raw material, the used pyrolysis device set some restrictions related to the heating rates. The device used allowed heating rates below 8 °C/min so it was not possible to set the staged temperatures to be as ideal as possible. Based on data from the pyrolysis of spruce, the ramps were set more ideally when LIG1, hemp, WW and GW were later used as raw materials.

TGA-data on the thermal degradation of different raw materials was used as the basis for the design of the different pyrolysis stages for the different raw materials. For the ramp in the first stage, the decomposition temperature of the

raw material needed to be taken into account thus taking the full advantage of the decomposition phenomenon that occurs. The second stage was then set up between the first and the third pyrolysis temperature. This was used to ensure a uniform temperature inside the furnace.

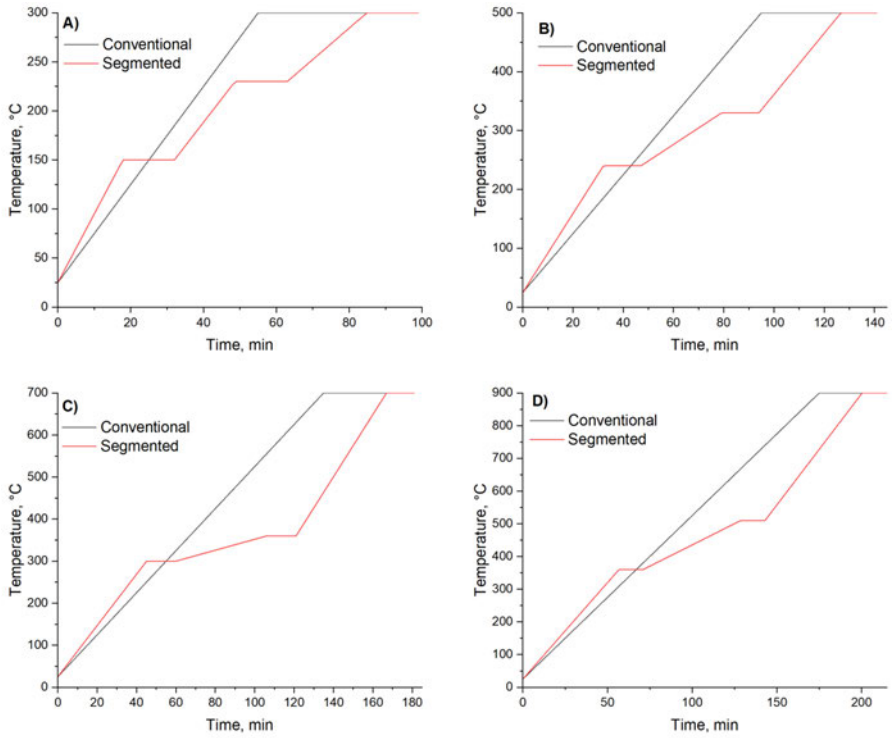


Fig. 5. A schematic illustration of the used heating patterns in pyrolysis of spruce on a temperature range from 300 °C to 900 °C (ramp durations shortened for clarity). A) = Final temperature 300 °C, B) = Final temperature 500 °C, C) = Final temperature 700 °C, D) = Final Temperature 900 °C (Data adapted under CC BY 4.0 license from Publication 2 © 2024 Authors).

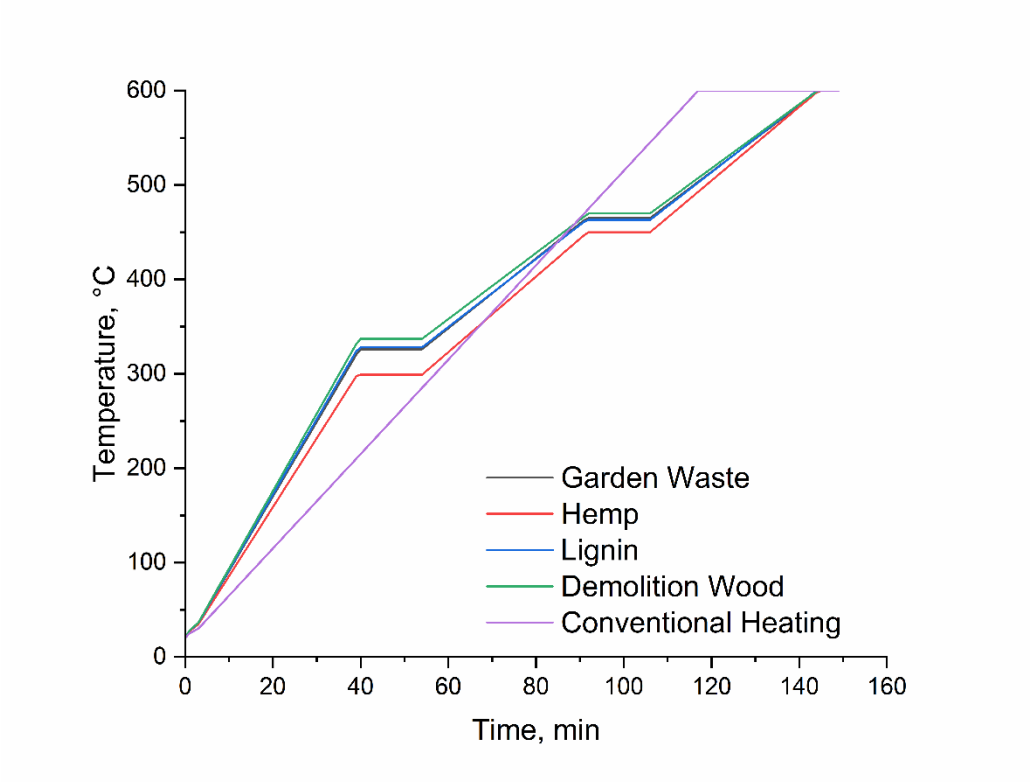


Fig. 6. A schematic illustration of the heating patterns used in Publication 4 (Reprinted under CC BY 4.0 license from Publication 4 © 2025 Authors).

Thermal analysis of pyrolysis

To analyze thermal behavior of spruce, a Netzsch STA 449 F3 Jupiter TGA device (Netzsch-Gerätebau GmBH, Selb, Germany), was used. The program used for these tests was similar to one presented in Table 4. Only the holding times at different stages varied from the programs presented in Table 4. The samples were kept at their final pyrolysis temperature for 15 minutes under conventional pyrolysis and for segmented pyrolysis the samples were kept in each of the stages for 5 minutes. This change was made in order to speed up the analyses.

4.2.3 Yield of fixed carbon

To compare the biocarbons produced at different temperatures, the yield of fixed carbon needs to be considered. The yield of fixed carbon takes into account not only the biocarbon yield but also the fixed carbon content of the samples and the ash content of the original feedstock (Oyedun et al., 2012). The yield of fixed carbon is defined as follows

$$Yield\ of\ fixed\ carbon\ (\%) = \left[Biocarbon\ yield\ \times \left(\frac{Fixed\ carbon}{100 \times feed\ ash}\right)\right] \times 100. \qquad (1)$$

4.2.4 Cold strength tests

The compressive strength of the produced briquettes was determined using a Gleeble 3800 thermomechanical simulator by Dynamic Systems Inc. (Austin, Texas, United States of America). The test procedure was based on the program reported by (Koskela et al., 2023). The experiments were carried out at room temperature. In the experiments, the compression speed was 0.1 mm/s. This resulted in the breaking of the samples during the 30 second compression cycle. To increase the reliability of the results, the experiments were done for 10 randomly selected briquettes of each mixture.

4.2.5 Carbon reactivity tests

The gasification reactivity of the produced biocarbon briquettes (Publications 3 and 4) was measured using a Netzsch STA 449 F3 Jupiter thermogravimetric analyzer (Netzsch-Gerätebau GmBH, Selb, Germany). These gasification experiments were carried out in conditions that simulated the thermochemical stresses of a submerged arc furnace. The experiments were based on the experimental program reported by (L. Wang et al., 2023).

In this procedure, the samples were first dried at 105 °C to reduce the moisture content of the samples. After this, the dried samples were heated starting from room temperature at a heating rate of 10 °C/min. At this point, argon was used as an inert gas. When the temperature reached 1100 °C, the sample was kept at that temperature for an additional 15 minutes to stabilize the temperature. After that, the gas was changed to 2.5% argon (Ar), 48.75% CO and 48.75 CO_2 %. For LIG1 and LIG2, the gasification time was 60 minutes, while for the GW, hemp, LIG and WW samples, the reaction time was 15 min. When the target

time was completed, the gas flows were changed back to 100% argon, and the samples were cooled to room temperature at a cooling rate of 40 °C/min. The cooling was carried out to stop gasification reactions occurring and thus preserving the samples for further possible studies.

Based on the mass loss during the gasification and the original carbon content of the samples, the degree of carbon conversion could be calculated. To increase the reliability of the results, each of the samples were tested twice, and the average carbon conversion of the samples was determined. A schematic illustration of the experimental procedure for the longer gasification experiment (Publication 3), is shown in Fig. 7.

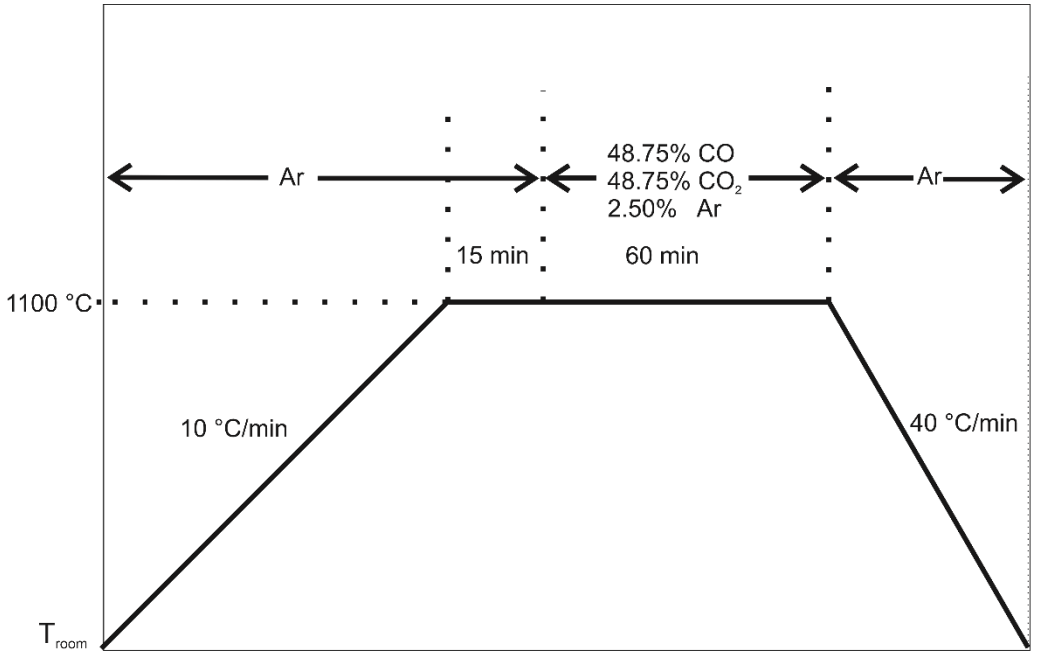


Fig. 7. The heating pattern for the gasification test (Reprinted with permission from Publication 3 © 2025 The Minerals, Metals & Materials Society).

4.2.6 Porosity

To evaluate the briquettes' porosity, an AccuPyc II 1340 gas displacement gas pycnometer (Micrometrics Instrument Corporation, Norcross, Georgia, United States of America) was used. This method is based on the use of helium gas (He) and its penetration into open pores of the pre-weighted sample. This allows the skeletal density (ρ_s) to be determined. During one measurement cycle, the

device takes five different measurements of the skeletal density. Besides the skeletal density, the determination of the porosity of the sample also requires the determination of the envelope density (ρ_e). The envelope density is determined by measuring the mass and volume of the sample and inserting the values into Equation 2

$$\rho_e = \frac{m}{V}, \tag{2}$$

where ρ_e is the envelope density (g/cm^3), m is the mass of the sample (g) and V is the volume of the sample (cm^3).

Once the envelope and the skeletal density is known, the porosity of the samples can be calculated using Equation 3

$$\varepsilon = \frac{\rho_s - \rho_e}{\rho_s}, \tag{3}$$

where ε is the porosity, ρ_s is the average skeletal density (g/cm^3) and ρ_e is the envelope density (g/cm^3).

4.2.7 Electrical conductivity

The electrical conductivity of the briquettes was measured using a GW Insteak LCR-817. The schematic illustration of this device is presented in Fig. 8. In the test procedure, the samples were put between two copper plates, and the electrical resistance (R) was measured. Based on the electrical resistance, the cross-section area and height of the briquettes, the conductivity (σ) was calculated as follows

$$\sigma = \frac{L}{RA}, \tag{4}$$

where: σ is the electrical conductivity (S/m), L is the average length (m), A is the average cross-section area (m^2) and R is the electrical resistance (Ω).

During the experiments, a total of 10 measurements per briquette were taken. For each sample type, 10 briquettes were randomly selected. Based on these 100 measurements, the average electrical conductivity for each mixture was calculated.

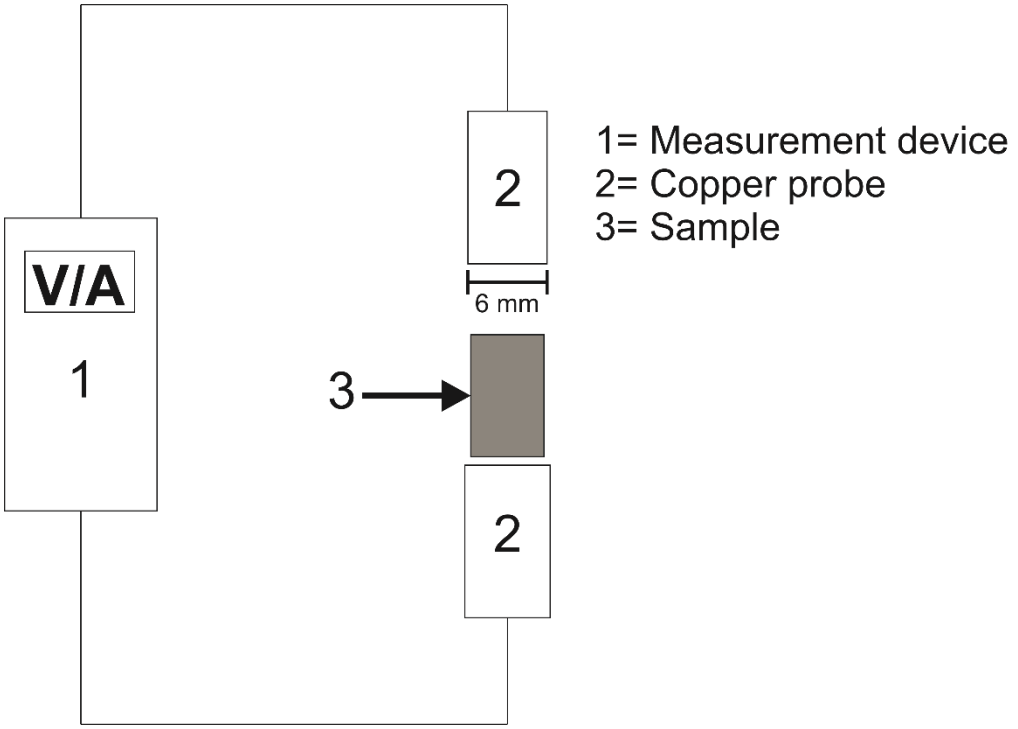


Fig. 8. A schematic illustration of the device used to measure the electrical conductivity (Reprinted under CC BY 4.0 license from Publication 4 © 2025 Authors).

5 Results and discussion

5.1 The effect of pyrolysis methods on biocarbon properties

5.1.1 Biocarbon yield

The effect of conventional and segmented pyrolysis on the biocarbon solid yield at four different pyrolysis temperatures is shown in Fig. 9. According to the results, increasing the pyrolysis temperature from 300 °C to 900 °C, reduced the biocarbon yield from 42.3% to 24.7% in the case of segmented pyrolysis. Similarly, in conventional pyrolysis, the biocarbon yield decreased from 36.9% to 24.5%. The difference in the biocarbon yield between pyrolysis methods was at it highest 5.4 pp, when pyrolysis took place at 300 °C. According to the literature, the decrease in the biocarbon yield when the pyrolysis temperature rises is caused by the reduced volatile matter content of the produced biocarbon and the depolymerization of the biomass-based feedstock during the heating (Varsally et al., 2023).

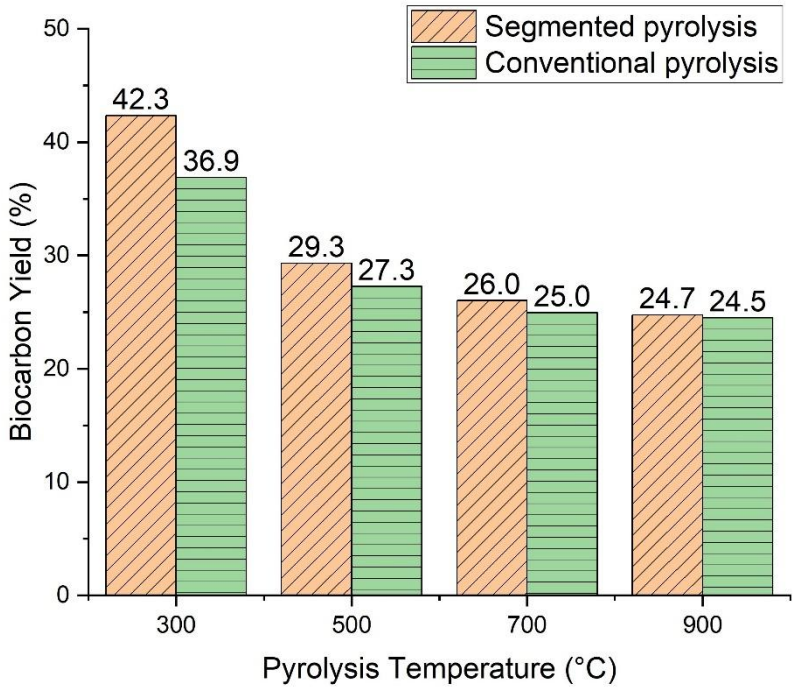


Fig. 9. The biocarbon yield of spruce when different pyrolysis methods were applied (Reprinted under CC BY 4.0 license from Publication 2 © 2024 Authors).

5.1.2 Physicochemical changes during pyrolysis

To understand how the pyrolysis temperature influences biocarbon properties such as the moisture, ash, volatile matter and fixed carbon content, a proximate analysis was carried out. These analyses were performed on the biocarbons produced using both pyrolysis methods at all investigated temperatures. The results are presented in Fig. 10.

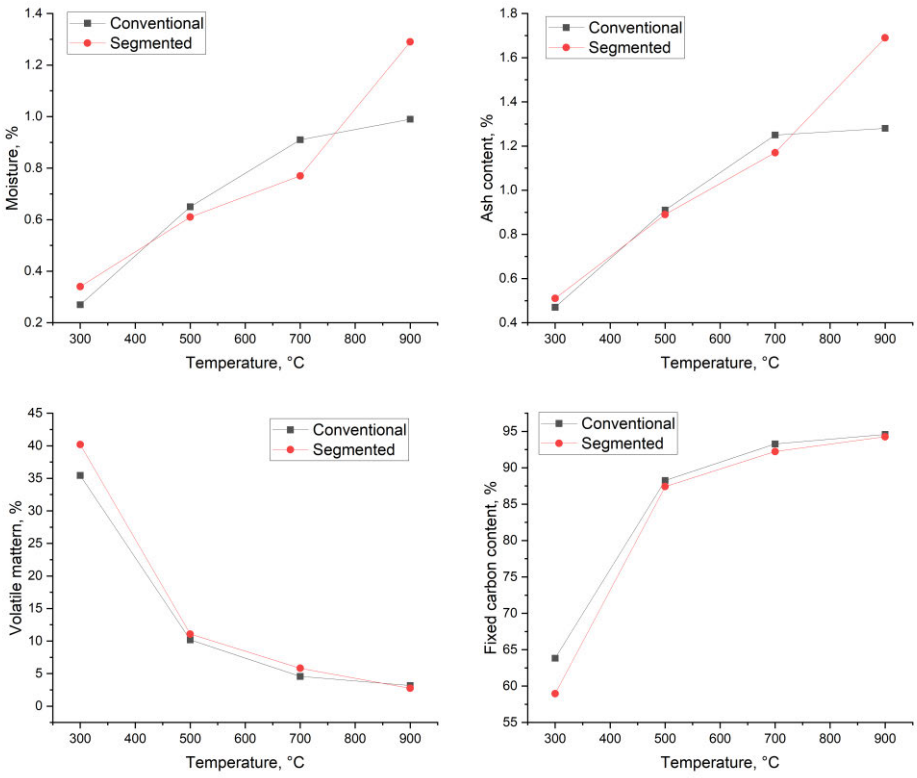


Fig. 10. Results from the proximate analysis (Reprinted under CC BY 4.0 license from Publication 2 © 2024 Authors).

According to proximate analyses, when the pyrolysis temperature was increased from 300 °C to 900 °C, the moisture content of the samples increased from 0.27% to 0.99% when conventional pyrolysis was used. For biocarbon produced using segmented pyrolysis, these values were 0.34% and 1.17%, respectively. This could be attributed to the biocarbons being ground before the proximate analysis took place. This grinding combined with the increased pyrolysis temperature increases the number of pores, which increases the sample surface area. Therefore, the samples' capability to adsorb water is increased (Tomczyk et al., 2020; P. Zhang et al., 2025).

Regarding ash content, the increase was from 0.41% to 1.28% in conventional pyrolysis and from 0.51% to 1.17% in segmented pyrolysis. Interestingly, in segmented pyrolysis, the highest amount of ash was observed at a pyrolysis

temperature of 700 °C. The reason behind the increased ash content at higher pyrolysis temperatures is that when the pyrolysis temperature increases it leads to the cracking of organic compounds into gaseous and liquid products. At the same time, most inorganic components does not devolatilize, thus leading to increased ash contents (Dhar et al., 2020; Puri et al., 2024; Tomczyk et al., 2020).

When the pyrolysis temperature was increased from 300 °C to 900 °C, the volatile matter content decreased from 35.44% to 3.17% during the conventional pyrolysis and from 40.20% to 2.75% during the segmented pyrolysis. When the final pyrolysis temperature was between 300 °C and 700 °C, segmented pyrolysis resulted in a slightly higher volatile matter content compared to conventional pyrolysis. In general, the decrease in the volatile matter content with increasing temperature is attributed to the progressive carbonization of the biomass, which promotes devolatilization and reduces the proportion of volatile compounds (Babinszki et al., 2021).

The fixed carbon content of the samples increased as the pyrolysis temperature increased. In conventional pyrolysis the increase was from 63.82% (300 °C) to 94.58% (900 °C) and in segmented pyrolysis it was from 58.95% (300 °C) to 94.68% (900 °C). Interestingly, segmented pyrolysis produced slightly lower fixed carbon contents in the temperature range of 300–700 °C, being from 0.2 pp (700 °C) to 4.9 pp (300 °C) lower compared to conventional pyrolysis. Generally, the increase in the fixed carbon content is inversely related to the decrease of volatile matter content, as a higher degree of carbonization results in a greater proportion of fixed carbon (Babinszki et al., 2021).

The development of the yield of fixed carbon of the produced biocarbons is shown in Fig. 11. The results indicate that the yield of fixed carbon is highest at lower temperatures. In both methods, the maximum value is achieved at 500 °C: 24.76% for conventional pyrolysis and 26.34% for segmented pyrolysis. The difference between yield of fixed carbon at this temperature between these two methods is 1.6 pp. At temperatures above 500 °C, the yield of fixed carbon decreases. This result is in line with the results reported earlier in the literature (Elyounssi et al., 2010; Oyedun et al., 2012).

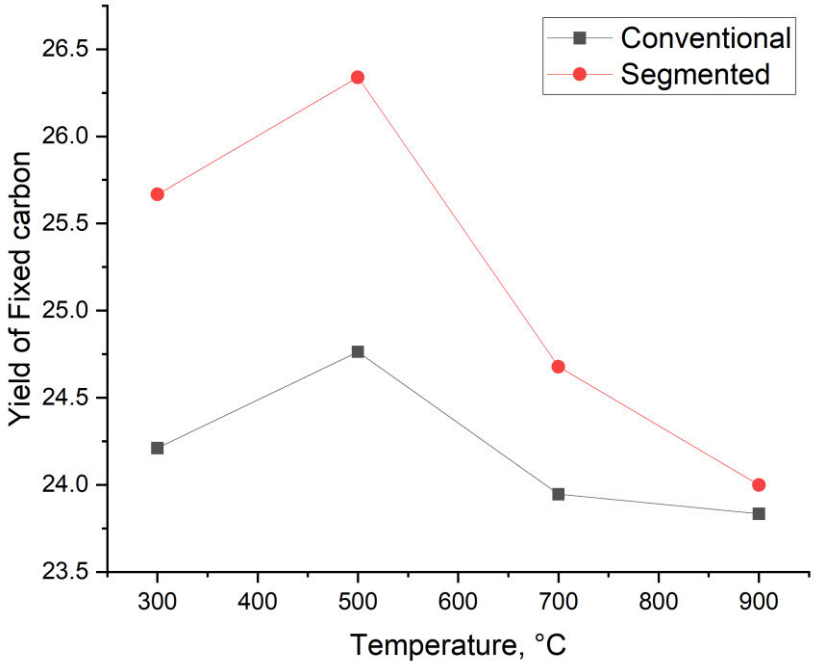


Fig. 11. Yield of fixed carbon (Reprinted under CC BY 4.0 license from Publication 2 © 2024 Authors).

5.1.3 Chemical changes during the pyrolysis

Table 6 summarizes the chemical composition of the produced biocarbons. As expected, the carbon content of the samples increases as the pyrolysis temperature rises. The highest carbon content is achieved when the pyrolysis temperature is 900 °C. This is linked to the higher carbonization degree. Moreover, the oxygen and hydrogen contents of the samples decrease when the temperature is increased due to the removal of hydrogen and oxygen containing groups of biomass (Zou et al., 2024).

Table 6. The results from the ultimate analysis for the produced biocarbon, (Reprinted under CC BY 4.0 license from Publication 2 © 2024 Authors).

Sample	Organic elements[1]						
	O	N	C	H	S	H/C	O/C
300L	19.91	0.00	74.79	3.59	0.25	0.48	0.27
300S	21.61	0.00	72.69	4.38	0.00	0.60	0.30
500L	6.07	0.00	90.08	2.47	0.00	0.27	0.07
500S	6.65	0.00	89.61	2.65	0.00	0.30	0.07
700L	2.65	0.00	94.72	0.73	0.00	0.08	0.03
700S	2.65	0.00	94.55	0.89	0.00	0.09	0.03
900L	2.00	0.00	95.25	0.10	0.00	0.01	0.02
900S	1.95	0.00	95.49	0.18	0.00	0.02	0.02

[1]Mass percent

The use of segmented pyrolysis improves the oxygen to carbon (O/C) and hydrogen to carbon (H/C) ratios of the biocarbons. The calculated ratios are shown in a Van Krevelen diagram in Fig. 12. As seen in the diagram, the segmented pyrolysis improves the hydrogen to carbon and oxygen to carbon ratio significantly. When the biocarbons are produced at lower temperatures, these ratios are similar to lignite when segmented pyrolysis is used. When the temperature rises, these ratios become more similar to anthracite (at a pyrolysis temperature of 700 °C) and finally when the pyrolysis temperature reaches 900 °C, these ratios are outside of the range of anthracite. This means that in terms of degree of carbonization, biocarbons produced at 700 °C and 900 °C are suitable for the replacement of anthracite in different metallurgical applications.

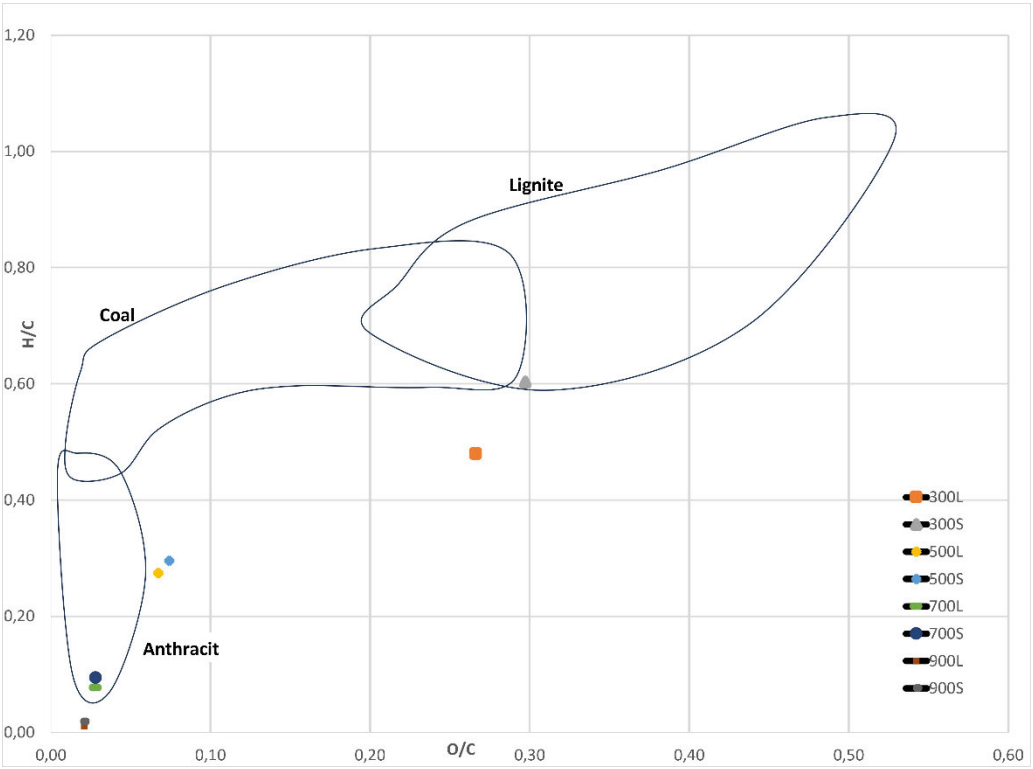


Fig. 12. Van Krevelen diagram and the calculated ratios from the produced biocarbons (Reprinted under CC BY 4.0 license from Publication 2 © 2024 Authors).

5.1.4 Thermal analysis of pyrolysis

To evaluate the efficiency of the applied pyrolysis methods and to evaluate how well each of the stages was set in the segmented pyrolysis, a thermal analysis of the pyrolysis was conducted. The results from the thermal analysis are shown in Fig. 13.

The thermal analysis of the pyrolysis reveals that when the pyrolysis took place at 300 °C, the decomposition of hemicellulose already occurred.

For segmented pyrolysis, two main things could be noticed: the temperature for the first stage was not high enough for decomposition reactions to occur, rather it served as a drying stage for moisture release. Secondly, a similar hemicellulose decomposition peak of occurred as in conventional pyrolysis.

In conventional pyrolysis at 500 °C (Fig. 13. C & D), the main decomposition of spruce occurred at a temperature of around 360 °C, indicating that most of the decomposition reactions took place at this temperature. When segmented pyrolysis was implemented, the decomposition of hemicellulose peaked during the first stage (around 240 °C) igniting the char formation. The peak was instantly followed by a holding stage and slower heating rate compared to conventional pyrolysis which enabled more char formation to occur before the thermal degradation peak of cellulose. This further led to a higher solid yield at the end of pyrolysis.

For final pyrolysis temperatures of 700 °C & 900 °C (Fig. 13. E–H), the decomposition profiles are quite similar at both temperatures for conventional pyrolysis. For segmented pyrolysis at 700 °C, the temperature for the first stage appears to be close to the main decomposition temperature of spruce. Between the first and second stage, there is an additional peak, which is most likely related to the decomposition of cellulose. This peak was not as intensive as in conventional pyrolysis, mainly because of the lower heating rate of segmented pyrolysis. A small decomposition peak occurred after the second stage, when segmented pyrolysis took place. This peak most likely contributed to the decomposition of lignin.

With the final pyrolysis temperature of 900 °C (Fig. 13 G & H), both methods showed quite similar total mass losses in the pyrolysis. The main difference between the observed mass loss behaviors is attributed mainly to variations in decomposition rates. For segmented pyrolysis, the higher heating rates compared to conventional pyrolysis accelerated the decomposition process, resulting in earlier and more intensive initial mass loss peaks than in conventional pyrolysis. When viewing the second stage in segmented pyrolysis, the decomposition phenomena were mainly completed. Therefore, this stage was unnecessary in terms of enhancing the solid yield of the biocarbon.

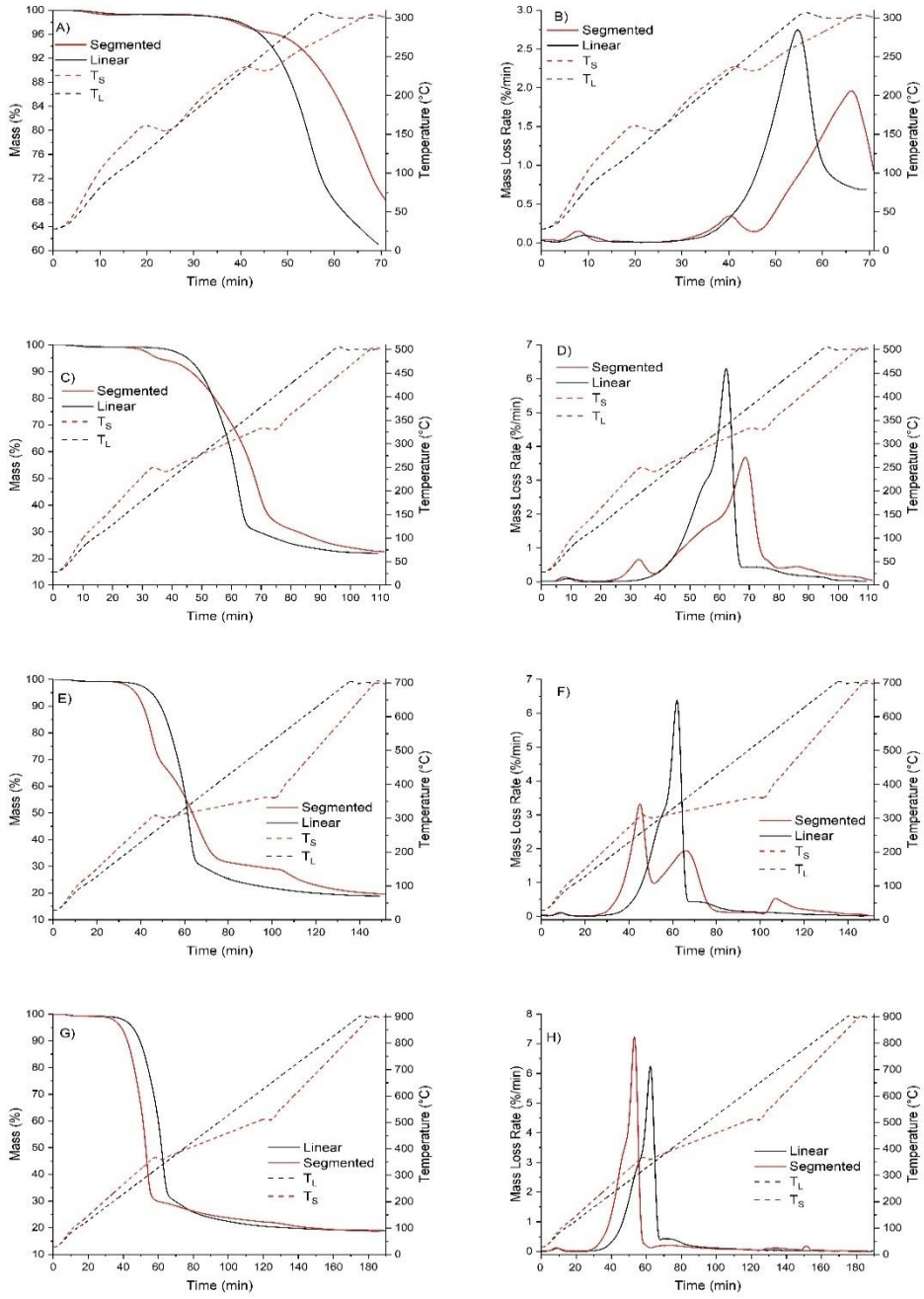


Fig. 13. Thermal analysis of pyrolysis (T_L = Temperature linear pyrolysis, T_s = temperature segmented pyrolysis), (Reprinted under CC BY 4.0 license from Publication 2 © 2024 Authors).

Based on thermal analysis the following conclusions can be drawn related to setting the heating protocol:

1. Optimizing the first stage. The temperature for the first stage should be as close as possible to the main decomposition temperature of the original feedstock where most of the decomposition occurs. For spruce, this temperature is around 360 °C.
2. Optimizing the second stage temperature. The temperature of the second holding stage should be in the midpoint of the temperatures of the first holding stage and final pyrolysis temperature. As observed in Fig. 13, most of the decomposition has already occurred before the temperature reaches 400 °C. Setting the second stage temperature in this way helps to achieve a uniform temperature across the feedstock bed, thus potentially reducing the energy consumption of the pyrolysis. This could also allow the use of higher heating rates when the sample is heated from the second stage to its final pyrolysis temperature thus making segmented pyrolysis faster compared to conventional pyrolysis.

5.2 The effect of binders on biocarbon briquettes

5.2.1 The effect of binders on the biocarbon yield

The effect of different binders on binder free biocarbon yield is shown in Fig. 14. These results are normalized into binder free content. According to the results, adding bentonite and starch increases the biocarbon yield, whereas glycerol tends to decrease the biocarbon yield with both lignin types. For the studied binders, bentonite increases the biocarbon yield the most, by 9.95% for LIG1 and 9.35% for LIG2. In contrast, the results indicate that the biocarbon yield tends to decrease when the amount of glycerol is increased in the blend. This decrease in the biocarbon yield was 1.18% (LIG1) and 1.39% (LIG2). When starch was used as a binder, the increase on the biocarbon yield was 4.42% (LIG1) and 2.19% (LIG2). The results do not show a clear correlation between the increased binder content and biocarbon yield when starch and glycerol are used as a binder, i.e., the highest biocarbon yield was achieved when the starch was added at 3–5 m.% and the addition of glycerol was 3 m.%.

The differences between the obtained biocarbon yields may originate from different mechanisms in how the binders affect the formation of biocarbon during pyrolysis. Bentonites' ability to increase the biocarbon yield is attributed to its ability to promote secondary reactions during pyrolysis. These reactions occur via gas-solid interactions, facilitating dehydration, condensation and repolymerization of gaseous compounds into secondary char (Collard & Blin, 2014; Dou & Goldfarb, 2017; Mohan et al., 2006). In the case of glycerol, it is reported that glycerol favors the formation of pyrolysis gases, thus reducing the solid biocarbon yield (Bartocci et al., 2018). Starch's ability to increase the biocarbon yield is most likely based on its ability to promote thermal dehydration and cross-linking reactions, thus promoting char formation before the main decomposition stage of spruce (M. Li et al., 2019).

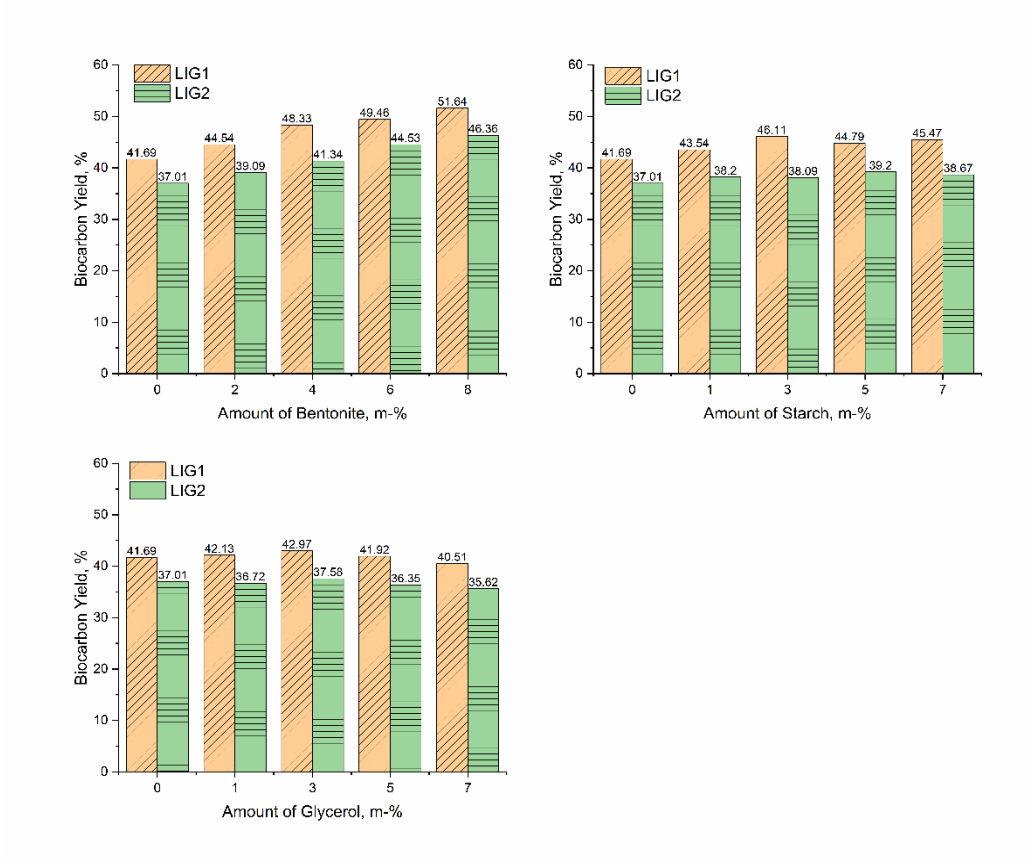


Fig. 14. The biocarbon yield of different binders and their doses (Reprinted with permission from Publication 3 © 2025 The Minerals, Metals & Materials Society).

5.2.2 The chemical composition of biocarbon briquettes

Tables 7 and 8 show the main composition of the produced pyrolyzed briquettes. According to the results, the content of inorganic elements varies. In general, the content of inorganic elements of LIG2-based biocarbons is higher than that of LIG1-based biocarbons. The main reason behind this is the higher content of these elements in LIG2, as presented in Table 3 in Section 4.1.

When bentonite is used as a binder, the silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and iron(III)oxide (Fe_2O_3) content is increased compared to binder less samples. The main reason behind this is that the content of these oxides is high in bentonite.

Table 7. Inorganic elements of the produced briquettes (mass percent, n.d. = not detected), (Reprinted with permission from Publication 3 © 2025 The Minerals, Metals & Materials Society).

Element	LIG1 B0	LIG1 B8	LIG1 S7	LIG1 G7	LIG2 B0	LIG2 B8	LIG2 S7	LIG2 G7	Bentonite
Na_2O	0.68	0.71	0.15	0.61	2.50	1.29	2.24	2.38	2.19
MgO	0.07	0.40	0.40	0.09	0.12	0.35	0.10	0.11	1.75
Al_2O_3	0.03	2.64	n.d.	0.03	0.12	2.22	0.11	0.12	12.04
SiO_2	0.05	9.07	0.03	0.05	0.39	7.98	0.36	0.39	38.25
P_2O_5	0.66	0.93	0.66	0.65	0.96	1.16	0.98	1.00	1.03
SO_3	0.31	0.33	0.08	0.31	2.80	2.29	2.59	2.60	0.14
Cl	0.04	0.06	0.05	0.04	0.04	0.06	0.04	0.04	0.27
K_2O	0.10	0.40	0.03	0.09	0.52	0.51	0.48	0.50	0.92
CaO	0.96	1.11	0.26	0.89	1.45	1.30	1.38	1.48	1.36
TiO_2	n.d.	0.66	n.d.	n.d.	0.04	0.65	0.04	0.04	1.29
Cr_2O_3	0.02	0.02	n.d.	0.02	0.05	0.03	0.04	0.05	0.02
MnO	0.16	0.07	n.d.	0.14	0.09	0.06	0.09	0.09	0.02
Fe_2O_3	0.45	6.80	0.01	0.44	0.69	7.24	0.65	0.77	10.79
Co_3O_4	n.d.	n.d.	n.d.	n.d.	n.d.	0.02	n.d.	n.d.	0.02
NiO	0.03	0.02	0.01	0.03	0.03	0.03	0.03	0.03	0.01
CuO	0.02	0.02	0.01	0.03	0.02	0.02	0.02	0.03	0.02
ZnO	0.04	0.04	n.d.	0.03	0.04	0.05	0.03	0.04	0.02
Rb_2O	n.d.	n.d.	n.d.	n.d.	n.d.	0.01	n.d.	n.d.	0.01

The calculated oxygen to carbon (O/C) and hydrogen to carbon (H/C) ratios shows that there is a small difference between these values. For LIG1, this value varied from 0.05 to 0.09 and for LIG2 these values were either 0.008 or 0.09. When viewing the H/C ratios these variations were between 0.01 and 0.02 for both lignin types. When these values are viewed in a Van Krevelen diagram (Fig. 12), you can see that the values are quite close to anthracite.

According to the results, bentonite containing mixtures have less carbon than the other samples. The main reason behind this is that samples containing bentonite have a higher ash content compared to the other samples.

Table 8. The organic element composition for selected briquettes (Reprinted with permission from Publication 3 © 2025 The Minerals, Metals & Materials Society).

Property	LIG1 B0	LIG1 B8	LIG1 S7	LIG1 G7	LIG2 B0	LIG2 B8	LIG2 S7	LIG2 G7
Ultimate analysis[1]								
Nitrogen	0.83	0.69	0.80	0.83	0.61	0.49	0.62	0.63
Carbon	93.22	76.9	92.95	93.13	87.30	72.69	89.05	89.44
Hydrogen	1.36	1.29	1.37	1.35	1.16	1.11	1.17	1.18
Sulphur	0.00	0.00	0.00	0.00	0.20	0.14	0.15	0.19
Oxygen	4.58	6.90	5.42	4.44	6.62	6.81	6.91	8.17
O/C	0.05	0.09	0.06	0.05	0.08	0.09	0.08	0.09
H/C	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.01
Proximate analysis								
Moisture[2]	0.71	0.77	0.75	0.81	1.03	0.59	1.09	1.06
Volatile matter[1]	6.39	8.26	6.39	7.20	9.22	7.88	7.97	7.51
Fixed carbon[1]	92.39	74.93	91.32	90.74	86.11	71.04	86.95	86.62
Ash[1]	0.69	16.14	1.54	1.26	3.58	20.50	3.98	4.80

1Mass percent, dry basic

[2] Mass percent

The amount of ash varied a lot between the samples. The lowest amount of ash was obtained when no binder was used. The amount of ash depended on the lignin type when starch and glycerol were used as binders. The highest amount of ash was obtained when bentonite was used as a binder. The reason behind the high ash content of bentonite-containing briquettes is related to bentonite's

inorganic nature. As seen in the inorganic element composition, bentonite has a lot of inorganic elements which concentrate in the ash after the material is burned. On the other hand, starch and glycerol, are both organic materials with low amounts of inorganic elements. Because of that, the ash content of starch- and glycerol-containing biocarbons is lower.

5.2.3 The evaluation of biocarbon briquette strength

The biocarbon briquettes' cold strength is shown in Fig. 15. According to the results, the cold strength depends on the used binder and the amount of binder being used. In addition, the results show that there was a small difference between the used lignin types, with LIG1 briquettes having a lower compression strength compared to LIG2. The compression strength of LIG1-based briquettes without the addition of binder was 35.3 MPa, while with an addition of 8% bentonite the compression strength was 22.8 MPa. The strength of LIG2-based briquettes varied from 51.7 MPa (no binder) to 49.6 MPa (8% bentonite).

The reasons why LIG1 had a higher drop in its strength are discussed next. The first reason is an overly low water content (10%) in the blend, which may have not enabled proper particle bonding (i.e. durable bonds) during the briquetting stage. Secondly, during the compaction phase, the force of the compression may have been too high thus leading to microfractures in the briquettes that weakened the structure. This indicates that the briquetting conditions need to be further optimized when LIG1 is used as a raw material.

In view of other used binders, starch increased the strength of the briquettes from 28.0 MPa to 33.0 MPa for LIG1, while this increase was from 37.8 MPa to 42.8 MPa for LIG2. The main reason behind the increased strength of the briquettes with a starch addition is starch's ability to enhance the attraction forces between the particles (Akbar et al., 2021). Finally, glycerol had a decreasing effect on the briquette's density. The strength of LIG1-based briquettes decreased from 36.2 (1% of glycerol) to 35.8% (7% glycerol). Similarly, the decrease was from 43.6 MPa (1% of glycerol) to 35.6 MPa (7% glycerol) in the case of LIG2.

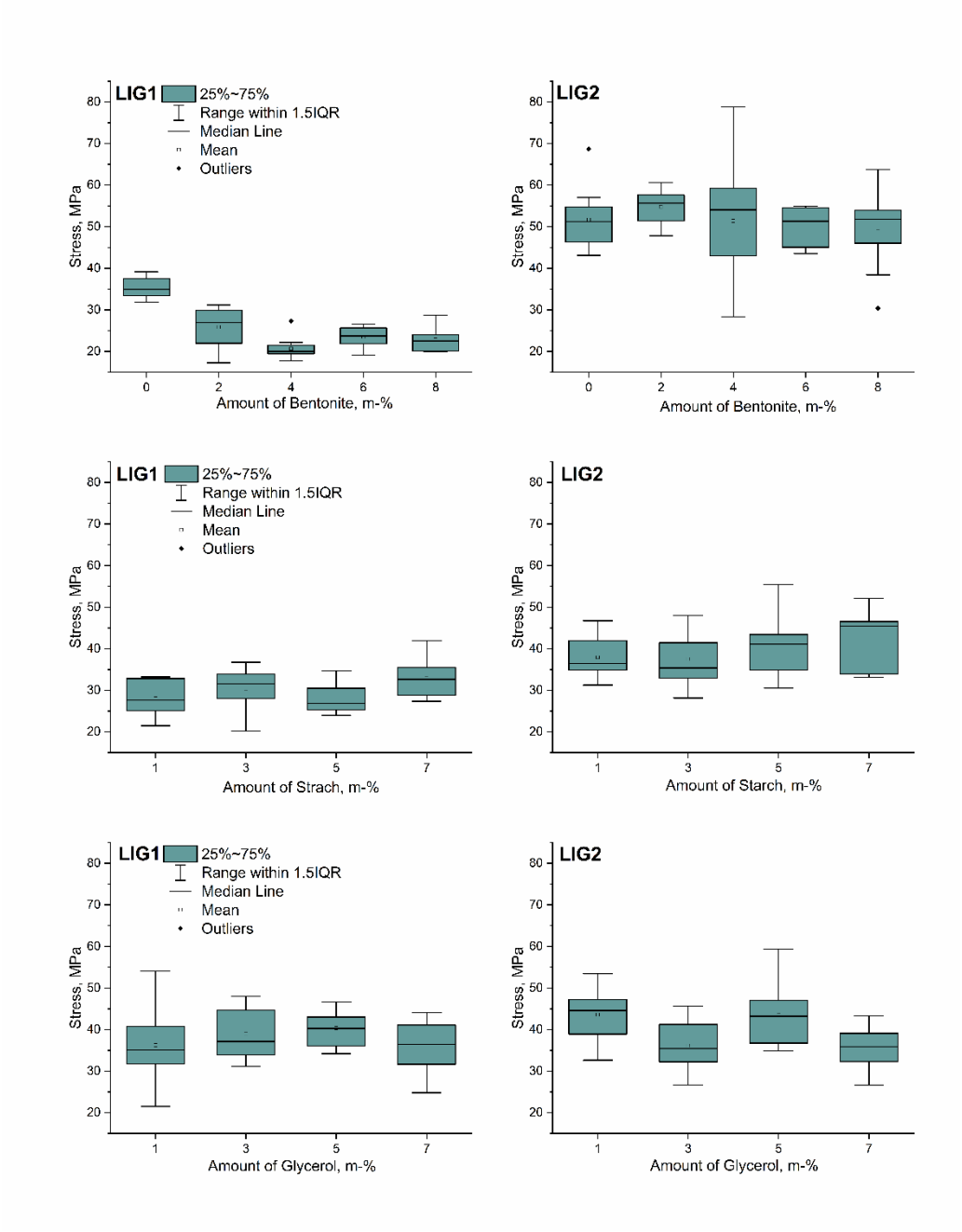


Fig. 15. Compressive strength of the lignin briquettes (Reprinted with permission from Publication 3 © 2025 The Minerals, Metals & Materials Society).

5.2.4 The effect of binders on degree of carbon conversion

A total of eight different biocarbon briquettes were used in the gasification tests. These tests simulated the stresses of the submerged arc furnace. For these tests, briquettes without added binder, the briquettes containing 8 m.% bentonite (B8), the briquettes containing 7 m.% starch (S7) and the briquettes containing 7 m.% glycerol (G7), were selected. Fig. 16 shows the carbon conversion of these samples during the gasification.

According to the results, the degree of carbon conversion depended on the used lignin type and the used binder. For example, in the gasification of the LIG1 sample without binder addition, full carbon conversion was achieved after 58 minutes from the initiation of the reaction stage of the experiment. For LIG2, this was already achieved after 45 minutes from the initiation of the gasification phase of the experimental program. The faster reaction rate of LIG2 may be linked to the higher carbon content of the LIG1 samples compared to LIG2, as seen in Table 8 presented in Section 5.2.2.

When starch and glycerol are used as a binder, full carbon conversion is achieved faster compared to binder-free samples or bentonite-doped samples. For example, in the case of LIG1 G7, full carbon conversion was achieved after a reaction time of 55 minutes. At the same time, the degree of carbon conversion for LIG1 B8 was around 72% after 55 minutes. The same pattern also applies to LIG2: in LIG2 G7, the full carbon conversion was achieved around 40 minutes from start of the program. For sample LIG2 B8, the degree of carbon conversion was at the same time around 70%.

The hindering effect of bentonite on the gasification reactivity of biocarbon briquettes may be linked to the briquettes' higher ash content. This higher ash contents limit the interaction between the gas and solid phases (Trubetskaya, 2022; Wu et al., 2023).

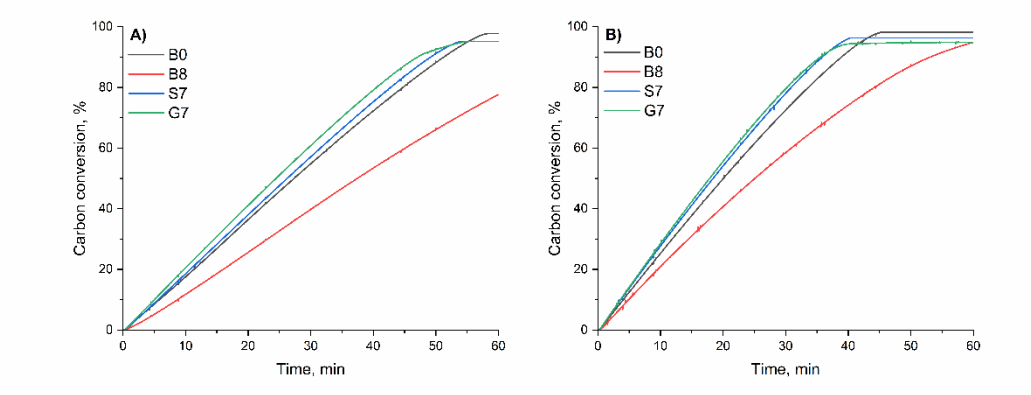


Fig. 16. The degree of the carbon conversion of lignin briquettes in a CO/CO_2 atmosphere. A) = LIG1, B) = LIG2 (Reprinted with permission from Publication 3 © 2025 The Minerals, Metals & Materials Society).

5.3 The effect of different raw materials and pyrolysis methods on biocarbon conversion in SAF conditions

5.3.1 Biocarbon yield

Fig. 17 shows the biocarbon yield from the studied biomasses (GW, WW, hemp & LIG) which were produced using conventional (L) and segmented (S) pyrolysis. These biocarbon yields are normalized in a binder free mass to enable a comparison of the solid yield of biomass-based carbon between the samples.

According to results, the use of lignin as a raw material led to the highest biocarbon yield (52.4%) when segmented pyrolysis was applied. This is followed by GW (42.0%), hemp (35.0%) and WW (32.7%). With conventional pyrolysis the solid biocarbon yields were 44.5% (LIG), 40.4% (GW), 33.7% (hemp) and 31.0% (WW). This means that the segmented pyrolysis increased the biocarbon yield for all the used raw materials, with the improvements varying from 1.3 pp to 7.9 pp compared to conventional pyrolysis. The largest improvement was found when lignin was used as a raw material (7.9 pp), and a small but constant improvement was found for hemp, GW and WW. These results are in line with a previous study, demonstrating the yield enhancing effect of segmented pyrolysis (Oyedun et al., 2012).

This means that segmented pyrolysis increases the biocarbon yield from 1.3 pp to 7.9 pp, confirming the earlier results presented in the literature on the increasing effect of segmented pyrolysis on the biocarbon yield.

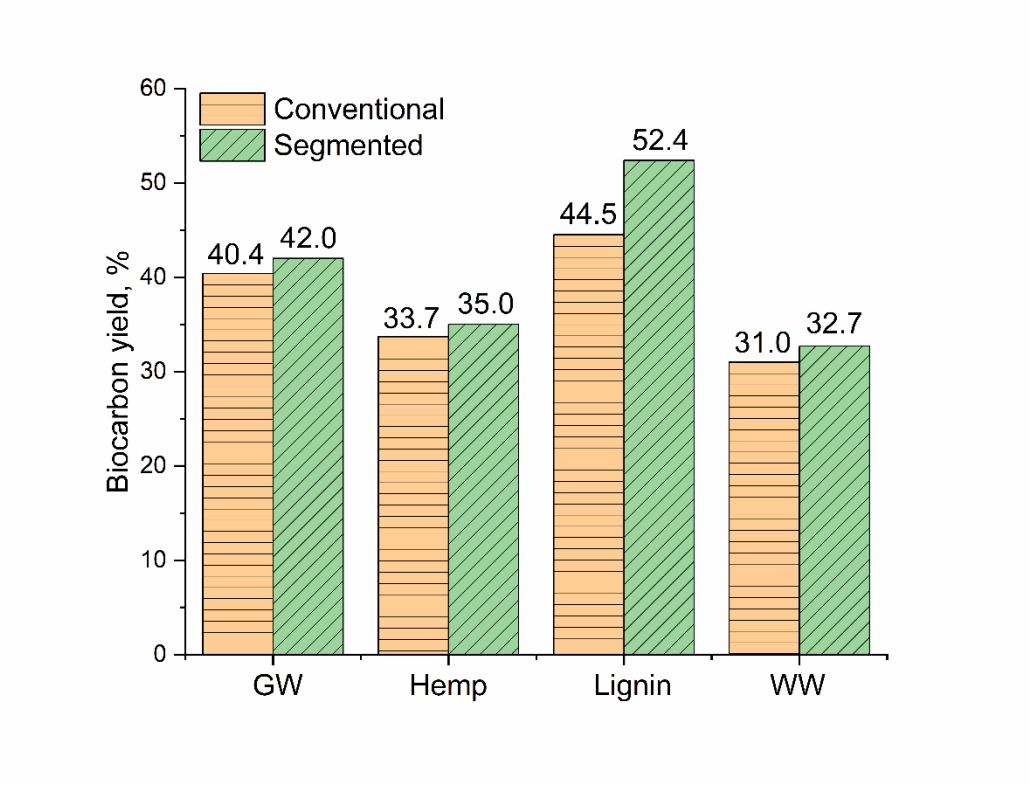


Fig. 17. The biocarbon yield of different raw materials (Reprinted under CC BY 4.0 license from Publication 4 © 2025 Authors).

5.3.2 The characterization of biocarbon briquettes

Table 9 shows the chemical characteristics of the produced biocarbon briquettes and metallurgical coke sample which was used as a reference material in the experiments. According to the results, the fixed carbon content of the biocarbon briquettes was significantly lower compared to coke used in SAF, which had a fixed carbon content of 88.19%. As seen in Table 9, none of the biocarbon briquettes matched this. The highest fixed carbon content was measured from LIG briquettes followed by WW-, hemp- and GW-containing biocarbons. Moreover, the volatile matter content of the studied biocarbon briquettes was higher than that of coke. When viewing the ash content, it can be noticed that

coke had the lowest ash content (9.27%). Out of the biocarbon briquettes, the lowest ash content was found from the L briquettes, followed by WW-, hemp- and GW-based biocarbons. The amount and composition of ash are important parameters, because they may affect the quality of final product and have an effect on the energy consumption in SAF (Surup et al., 2020).

Table 9. The chemical composition of the produced briquettes (n.d. = not detected), (Reprinted under CC BY 4.0 license from Publication 4 © 2025 Authors).

Property	GW L	GW S	Hemp L	Hemp S	Lignin L	Lignin S	WW L	WW S	Coke
Proximate analysis									
Moisture[1]	1.36	0.90	1.05	0.82	0.61	0.64	0.82	0.70	0.47
Volatile matter[2]	13.73	13.35	10.01	11.17	7.14	9.79	13.42	9.82	2.07
Fixed Carbon[2]	50.45	47.45	58.95	61.25	74.69	74.43	62.02	68.63	88.19
Ash[2]	34.46	38.3	29.99	26.76	17.56	15.14	23.74	20.85	9.27
Ultimate analysis[2]									
C	47.13	50.32	65.96	58.96	75.99	75.71	74.68	76.01	86.23
H	0.89	1.10	0.89	1.03	1.33	1.57	1.12	1.49	0.45
N	1.37	1.48	0.51	0.48	0.64	0.64	n.d.	n.d.	1.15
S	0.03	0.04	0.04	0.11	n.d.	n.d.	n.d.	n.d.	0.65
O	6.46	6.84	3.97	4.39	3.46	3.54	4.06	4.47	0.85
H/C	0.02	0.02	1.01	0.02	0.02	0.02	0.02	0.02	0.01
O/C	0.14	0.14	0.06	0.07	0.05	0.05	0.06	0.06	0.01
Trace elements[2]									
Na	0.61	0.61	0.42	0.49	0.27	0.28	0.49	0.81	n.d.
Mg	0.63	0.63	0.66	0.34	0.35	0.14	0.15	0.34	0.46
Al	1.89	2.23	1.00	1.03	0.71	0.74	2.74	2.58	0.70
Si	5.95	6.85	2.90	2.84	1.99	2.07	4.41	6.25	1.31
P	0.61	0.59	0.46	0.47	0.16	0.15	0.18	0.19	0.13
S	0.12	0.13	0.08	0.07	0.02	0.03	0.01	0.02	0.62
Cl	0.07	0.07	0.54	0.56	0.02	0.02	0.03	0.02	0.02
K	0.81	0.92	2.96	2.87	0.12	0.12	0.25	0.32	0.06
Ca	4.63	4.29	1.54	1.05	0.26	0.26	0.41	0.41	0.18
Ti	0.24	0.26	0.16	0.15	0.12	0.12	0.17	0.21	0.08

Property	GW L	GW S	Hemp L	Hemp S	Lignin L	Lignin S	WW L	WW S	Coke
Cr	0.03	0.03	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Mn	0.14	0.13	0.01	0.01	0.02	0.10	0.02	0.02	n.d.
Fe	2.46	2.52	1.44	1.48	1.41	1.25	1.43	1.62	0.49
Zn	0.10	0.09	0.01	0.01	0.01	0.01	n.d.	n.d.	n.d.

[1]Mass percent

[2] Mass percent, dry basic

5.3.3 The effect of pyrolysis on biocarbon briquette density

The envelope densities of biocarbon samples before and after pyrolysis as well as the mass loss during the pyrolysis is shown in Table 10. The envelope density of the reference coke is also listed in Table 10.

Table 10. Briquette densities (Reprinted under CC BY 4.0 license from Publication 4 © 2025 Authors).

Density	GW L	GW S	Hemp L	Hemp S	Lig L	Lig S	WW L	WW S	Coke
Before[1]	1204	1204	1108	1108	1236	1236	1109	1109	875
After[1]	659	630	674	654	1030	1110	615	546	
Difference[1]	545	574	434	454	206	126	494	563	
Mass change[2]	45.3	47.7	39.2	41.0	16.7	10.2	44.5	50.8	

[1] kg/m^3

[2] Percent

According to the results, the obtained briquette densities before pyrolysis are well beyond the density of coke. Before pyrolysis, the densities of the briquettes varied from 1108 kg/m3 (hemp) to 1236 kg/m3 (Lignin). After pyrolysis, the variation between the densities was much higher. The lowest density was obtained from WW biocarbon that was pyrolyzed using segmented pyrolysis (563 kg/m^3). Only lignin-based biocarbons consisted similar or higher density than coke. Most likely, the reason behind the lignin-based briquettes' higher density is the lignin's complex polyaromatic structure that forms a backbone for the formation of the carbon structure during the pyrolysis. This combined with the lowest amount of volatile matter makes the briquettes denser.

5.3.4 Porosity

The porosity values of the briquettes are shown in Table 11. The results show that the average porosity of the briquettes varied from 60.48% (Lig S) to 88.09% (hemp L). Coke had a porosity of 57.90%, which means that lignin-based biocarbon briquettes had the most coke-like porosity. Interestingly, the used pyrolysis method caused some differences between the porosities: the application of segmented pyrolysis tended to decrease the porosity of the briquettes except for the WW-briquettes. According to the literature, lower porosity is one of the key characteristics of lower gasification reactivity compared to materials that have higher porosity (Kaffash & Tangstad, 2022).

Table 11. The average porosities of the briquettes after pyrolysis (Reprinted under CC BY 4.0 license from Publication 4 © 2025 Authors).

	GW L	GW S	Hemp L	Hemp S	Lignin L	Lignin S	WW L	WW S	Coke
Measurement 1[1]	87.23	86.94	87.74	86.20	69.19	63.73	87.11	88.97	52.90
Measurement 2[1]	88.24	86.51	88.44	84.96	67.48	57.22	90.87	89.46	62.30
Average porosity[1]	87.74	86.73	88.09	85.58	68.34	60.48	88.99	89.21	57.90

[1]Percent

5.3.5 Electrical conductivity

The results from the electrical conductivity (S/m) measurements are shown in Fig. 18. According to results, all the produced biocarbons are electrically non-conductive materials, with the highest measured electrical conductivity being around 0.002 S/m. This was measured from the hemp L sample. The used pyrolysis method was found to affect the electrical conductivity of biocarbons, as segmented pyrolysis produced biocarbons with lower electrical conductivity compared to biocarbon produced in conventional pyrolysis. The electrical conductivity of coke was at the level of 257.458 S/m. This is over 1,000 times higher compared to biocarbon briquettes. Because of lower electrical conductivity of biocarbons, the replacement of coke by biocarbon in SAF may cause some problems, such as lowered process efficiency (Heikkilä et al., 2017).

One reason behind the low electrical conductivity is the relatively low pyrolysis temperature (600 °C) which leads to a low degree of graphitization for the biocarbons. One simple way to increase the graphitization degree is to increase the pyrolysis temperature (Gabhi et al., 2020).

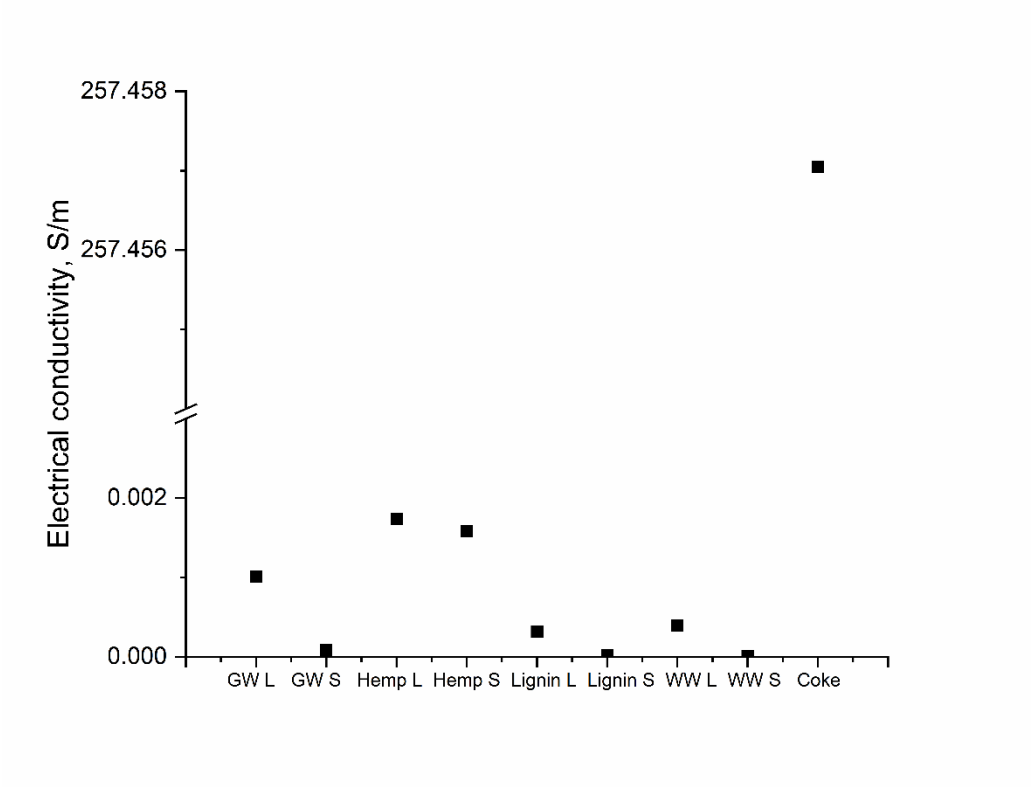


Fig. 18. Electrical conductivity (Reprinted under CC BY 4.0 license from Publication 4 © 2025 Authors).

5.3.6 Compressive strength

The results from these tests are shown in Fig. 19. According to results, the average compressive strength varied from 12.9 MPa (GW L) to 31.1 MPa (Lig S). After Lignin, the second highest strength was measured from hemp based biocarbon, followed by WW- and GW-based biocarbons. Compared to the compression strength of coke (17.9 MPa), lignin briquettes showed a significantly higher compression strength, while all of the other biocarbon briquettes showed a similar strength to coke. The results also show that the standard deviation between the briquettes' strength was quite close, except in the case of lignin-based biocarbon briquettes.

The used pyrolysis method seems to also affect the mechanical strength of biocarbon briquettes. According to results, segmented pyrolysis had a reduction effect on the strength of hemp- and WW-based biocarbon briquettes, while for Lignin- and GW biocarbon briquettes, it seems that this pyrolysis method increased mechanical strength.

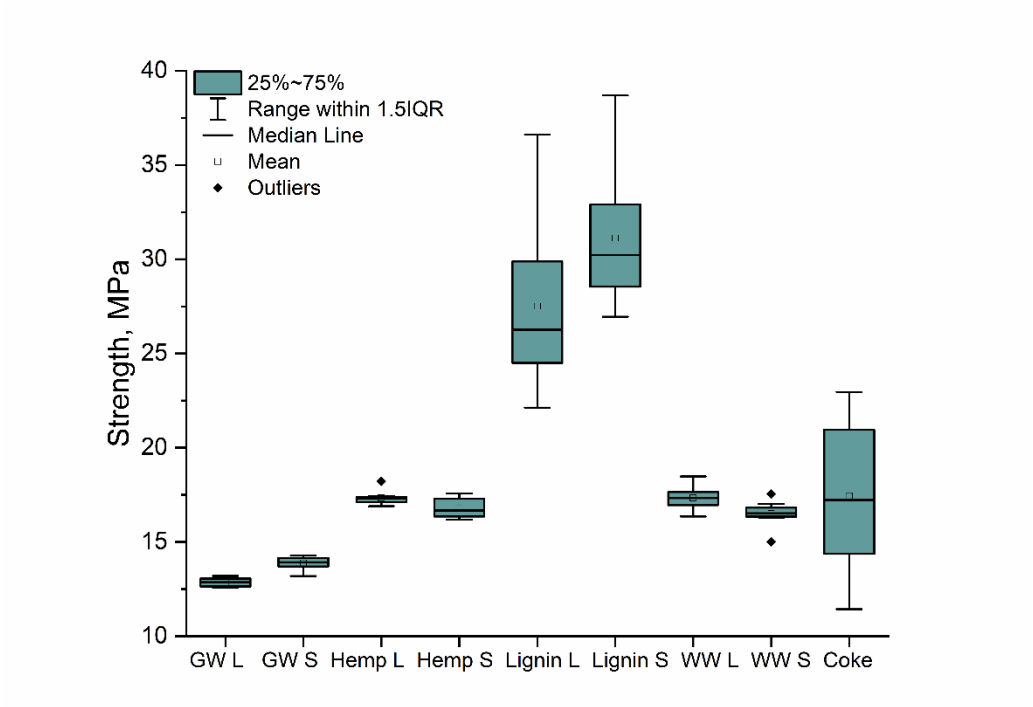


Fig. 19. Briquette strength (Reprinted under CC BY 4.0 license from Publication 4 © 2025 Authors).

5.3.7 Degree of carbon conversion

The carbon conversion of the biocarbon briquettes is depicted in Fig. 20. According to the carbon conversion, the most coke-like behavior was achieved when lignin was used as a raw material, with the degree of carbon conversion being 21.7%. This was followed by WW-, GW- and hemp-based biocarbon briquettes. The biocarbon from segmented pyrolysis showed lower degree of carbon conversion with all the studied briquettes type. The difference was around 2% for lignin briquettes and at the highest around 5% for hemp and WW briquttes. These findings indicate that the degree of carbon conversion depends on the used raw materials and the pyrolysis method.

In the literature, there are several factors that affects the degree of carbon conversion, for example the concentration of catalytic elements such as potassium (K), calcium (Ca) and magnesium (Mg). On the other hand, elements like silicon (Si) and aluminum (Al) have an inhibiting effect on carbon conversion (Czerski et al., 2021). As the elemental analysis (Table 9) shows, the amount of these elements does not fully correlate with the carbon conversions with all the samples. Therefore, it can be stated that not only the gasification inhibiting elements affect the gasification behavior of the samples, but there are also structural characteristics such as porosity and density affecting the carbon conversion behavior (Chan et al., 1999; P. Wang et al., 2023).

Although earlier studies suggest that the density, oxygen content and porosity influence the degree of carbon conversion (Chan et al., 1999; P. Wang et al., 2023), the presented data does not support this trend. A comparison of the oxygen content (Table 9), density (Table 10) and porosity (Table 11) with the measured degrees of carbon conversion revealed no consistent or explanatory relationship.

Based on the literature and obtained results on the relationships between these factors, it can be concluded that there is no single factor that explains the obtained pattern that segmented pyrolysis leads to less reactive biocarbon. Rather the lower degree of carbon conversion is a consequence of multiple factors. One possible explanation will be explored here. If the porosity is high and the pores are mainly long micropores, these increase the gasification reactivity, because these pores have a high surface area compared to their volume (Czerski et al., 2021; Mishra et al., 2018). When this is combined with catalytic inorganic elements, the gasification reactivity is promoted even more.

The similar degree of carbon conversion to coke of the lignin-based briquettes was achieved by limiting the reaction pathway through following steps: 1) choice of the raw material, 2) choice of pyrolysis method, and 3) choice of the binder/dope for the biocarbon.

– When the hydrolysis lignin is pyrolyzed, the backbone of carbon formation is a highly aromatic lignin structure which has a polyaromatic 4x4 c-c- fused ring structure that may already form when the hydrolysis lignin is pyrolyzed at 600 °C (Lu & Gu, 2022).
– When the lignin is pyrolyzed in segmented pyrolysis, the carbon structure has time to form during the first holding stage by linking the polyaromatic structures, thus forming a tight carbon structure (Lu & Gu, 2022). Because of the tight carbon structure, the biocarbon is less prone to absorbing the

reactive gas into carbon structure. At the same time, the surface area of the biocarbon remains relatively low (Sharma et al., 2023).

– When the elements that are either neutral or inhibitive material are added to the raw material blend, and they are inside the carbon matrix, they form an ash layer during the gasification due to the consumption of the surface carbon. This ash layer will inhibit the reaction rate from increasing, thus working as a controlling mechanism during the gasification (Trubetskaya, 2022).

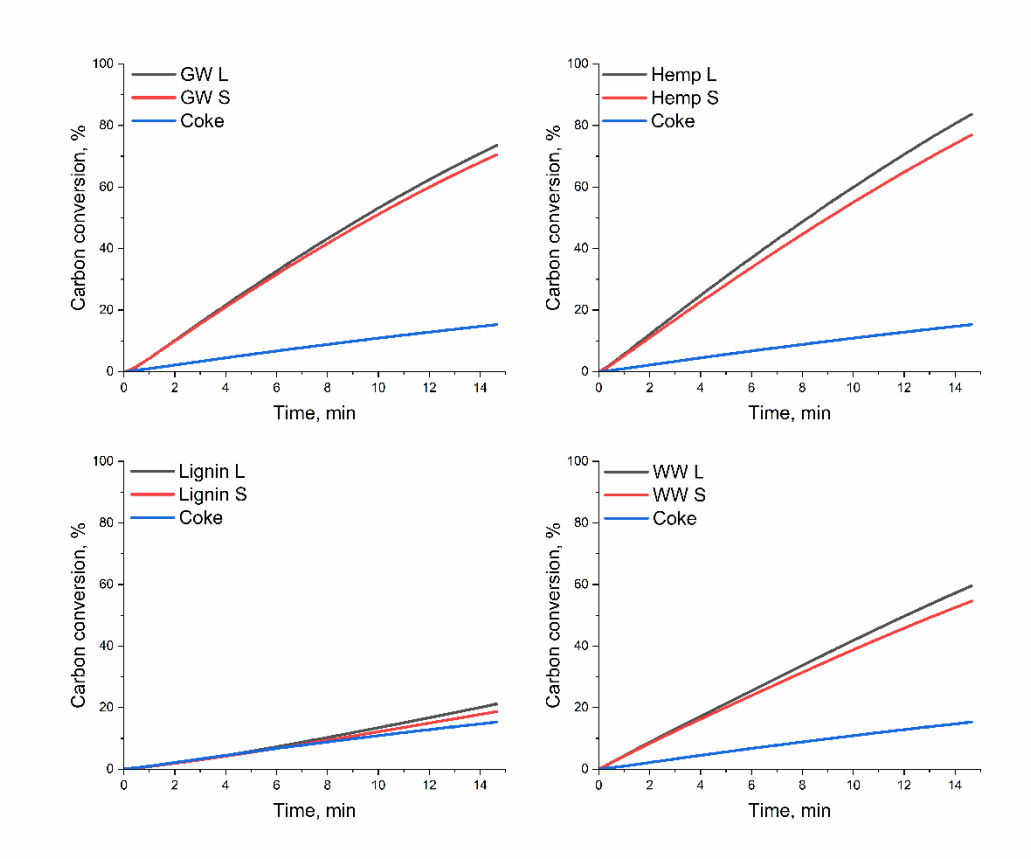


Fig. 20. Degree of carbon conversion (Reprinted under CC BY 4.0 license from Publication 4 © 2025 Authors).

5.3.8 A comparison of the main properties of the briquettes

To highlight the overall performance of the produced biocarbon briquettes and to compare how well they actually performed compared to coke, the evaluation of the main properties of the briquettes is shown in Table 12. A mark "+" indicates that the briquettes did not come close to matching coke, "++" indicates that they did not match very well, "+++" means that they were quite close to coke and "++++" means that they performed at a similar level or even better than coke.

Table 12. Comparison the main properties of the produced briquettes (Reprinted under CC BY 4.0 license from Publication 4 © 2025 Authors).

Property	Unit	Coke	GW L	GW S	Hemp L	Hemp S	Lignin L	Lignin S	WW L	WW S
Fixed carbon	m.%, d.b.	88.19	+	+	++	++	+++	+++	+++	+++
Volatiles	m.%, d.b.	2.07	+	+	+++	++	+++	+++	+	+++
Ash	m.%, d.b.	9.27	+	+	+	++	+++	+++	++	++
Density, after pyrolysis	kg/m^3	874.42	+++	+++	+++	+++	++++	++++	+	+
Strength	MPa	17.43	++	++	+++	+++	++++	++++	+++	+++
Porosity	%	57.9	+	+	+	+	+++	++++	+	+
Conductivity	S/m	257.46	+	+	+	+	+	+	+	+
Carbon Conversion	%	15.33	++	++	+	+	++++	++++	+++	+++
Total			12	12	15	15	25	26	15	17

As seen in Table 12, the lignin-based briquettes achieved the most coke-like properties. This was followed by WW- and hemp-based biocarbon briquettes, whose characteristics were identical. GW showed least coke-like properties. When viewing the porosities and the strength of the briquettes, lignin-based briquettes showed similar values to coke. Additionally, when viewing the degrees of carbon conversion, ash content, fixed carbon and volatile matter content, the lignin-based briquettes performed the best. Some of these properties (cold strength, density) were even better than those of coke, some were similar level (degree of carbon conversion) and some were worse (ash content, electrical conductivity). When viewing the used pyrolysis method, the segmented pyrolysis led to slightly better biocarbon briquette properties compared to conventional pyrolysis, highlighting this method's potential. Based on these results, in the future lignin-based biocarbon has the potential to replace

coke partially in SAF when producing ferrochrome. This replacement potential could be up to 50% when taking into account all of the properties of the briquettes and the current state of use of biocarbon in iron & steel production. The limited availability of hydrolysis lignin on the other hand sets restrictions that could affect the use of lignin as a substitute for coke in the SAF-process.

6 Conclusions and future work

6.1 Conclusions

This doctoral thesis had the following main target: to develop biocarbon properties so that biocarbon could be used more efficiently in submerged arc furnace to replace coke. The reason a submerged arc furnace was selected was the CO_2 reduction potential that biocarbon has in this application. The biocarbon for this application was produced using multiple different binders, binder dosages, raw materials and pyrolysis methods. The biocarbon properties were then compared to coke, to see how well they met the required physical and chemical properties of the coke.

The work related to this thesis consists of four scientific publications, in which Publication 1 focused on a literature review to determine ways that could be used to modify biocarbon properties. Publication 2 focused on modifying biocarbon properties using different pyrolysis methods. In Publications 3 and 4 the focus was on the effect of different binders and their dosages (Publication 3), as well as different raw materials and pyrolysis methods (Publications 3 and 4). In Publications 3 and 4, biocarbon briquettes were studied under the stresses of the submerged arc furnace to gain information about the gasification reactivity, mechanical strength and structural characteristics of the produced biocarbons. Finally, in Publication 4, these measured biocarbon properties were compared to coke to determine the most coke-like biocarbon briquette.

The most important conclusions of the work can be drawn from the research questions set at the beginning of this work as follows:

RQ1: How can biocarbon properties be affected so that the produced biocarbon is more suitable for metallurgical use? (Publication 1)

– The key ways to affect biocarbon properties are following: pyrolysis temperature, heating rate, briquetting, use of binders, use of different pyrolysis methods and the selection of raw material.
– The fixed carbon content of the samples increased from 64.5% to 93.3% as the pyrolysis temperature rises from 350 °C to 650 °C.
– Binding the materials improves the mechanical strength of the material and offers improved materials handling

– In segmented pyrolysis the yield of fixed carbon is 2.9pp (at 400 °C) higher compared to conventional pyrolysis, although the overall carbon content of the material is slightly lower.

RQ2: How does the use of segmented pyrolysis affect the biocarbon properties and biocarbon yield? (Publications 2 and 4)

– According to results, the use of segmented pyrolysis increases the biocarbon yield by 5.4 pp (at 300 °C) to 0.2 pp (900 °C).
– When pyrolysis takes place at temperatures from 300 °C to 900 °C, the yield of fixed carbon is increased by a maximum of 1.6 pp when the segmented pyrolysis is used. At the same time, the fixed carbon content in a given temperature range is from 4.9 pp lower to 0.1 pp higher compared to conventional pyrolysis.
– When the pyrolysis takes place at 500 °C and onwards, the fixed carbon content is over 85%, which is mentioned in the literature to be high enough for metallurgical purposes.
– Adjusting the segmented pyrolysis stages is very important. According to the results, the first holding stage should be close to the actual decomposition temperature of the original feedstock. The second stage should then be set at the midpoint between the first-stage temperature and the final-stage temperature.

RQ3: What is the most suitable binder type and binder amount, so that the produced biocarbon is suitable for submerged arc furnace usage? (Publication 3)

– According to the results, using bentonite or starch individually as binders increases the biocarbon yield by 9.9 pp (at 8 m.% bentonite) and 3.8 pp (at 7 m.% starch), respectively. In contrast, using glycerol as a binder decreases the biocarbon yield by 1.4 pp at a dosage of 7 m.%
– Adding 8 m.% bentonite lowers the fixed carbon content of the briquettes up to 16.4% compared to starch (7 m.%) and glycerol (7 m.%). The fixed carbon content of the 8 m.% bentonite-containing briquettes is lower than 85% which is needed in metallurgical applications.
– All of the briquettes showed a compressive strength over 20 MPa, which is similar level compared to metallurgical coke values reported in the literature.
– In view of gasification reactivity, when the LIG1 sample was used as a raw material, adding 8 m.% bentonite reduced the degree of carbon conversion by over 20% compared to starch- and glycerol-containing samples.

– Based on the results, bentonite with the addition of 8% was the most suitable binder for hydrolysis lignin-based biocarbons in terms of replacing metallurgical coke in a submerged arc furnace, although the amount of bentonite addition has to be further optimized to reduce the ash content and increase the fixed carbon content of biocarbon.

RQ4: What are the effects of different raw material sources and pyrolysis methods on the applicability of biocarbon in SAF process? (Publications 2–4)

– The biocarbon briquette quality depends on the used raw materials as well as the used pyrolysis method
– The selection of raw material affects the biocarbon yield during pyrolysis (the difference between materials is up to 7.9 pp). The strength of the briquettes varied between materials from 13.1 MPa (garden waste) to 31 MPa (Lignin). These strengths are quite similar to the coke used as reference material, which had a compression strength of 17 MPa.
– The fixed carbon content of the samples depended on the used raw material. The lowest fixed carbon was 47.5% (garden waste S) and the highest was 75.7% (Lignin L). These contents were much lower than the fixed carbon content of coke, which was 88%.
– The selection of raw materials also affects the gasification reactivity of biocarbons. Lignin based briquettes showed the most coke-like carbon conversion behavior, with just a 2% to 4% higher carbon conversion degree compared to coke during a 15 min reaction time.
– Because segmented pyrolysis resulted from 2–5% of lower degree of carbon conversion, it represents a viable alternative for producing biocarbon for use in a submerged arc furnace.
– The results indicate, that it is possible to replace coke partially in SAF by using lignin-based, bentonite-doped biocarbon briquettes. This material showed similar properties compared to metallurgical coke, such as mechanical strength, porosity and fixed carbon content. When taking into account all of the briquettes properties, the replacement ratio could be 50%.

6.2 Future work

This thesis showed that it is possible to replace coke partially in submerged arc furnaces by using lignin-based based briquettes and other biomass-based raw materials. This was achieved with the use of binders and different pyrolysis

methods. Despite this, there is still room to improve the properties of the biocarbon briquettes.

One way to continue this research would be to bring down the inorganic content of the biocarbon briquettes. As the results showed, the tested biocarbon briquettes had much higher ash contents compared to coke. Minimizing the amount of ash would not only bring the amount of this closer to coke but also help improve the process efficiency.

The second way to continue the research would be to optimize the use of binders. In this research, compound binders were not used. In industrial processes typically multiple binders are used as a mixture to enhance the briquette properties. Developing the binder mixtures may help to bring the amount of inorganic elements closer to those of coke, thus reducing the amount of ash.

Finally, the effect of other pyrolysis methods on the suitability of biocarbon briquettes needs to be evaluated further. As the results show, segmented pyrolysis leads to decreased carbon conversion. This is achieved by the lowered porosity and denser structure compared to briquettes made under conventional pyrolysis. Studying the effect of increased pyrolysis temperature on the briquette properties would help to make them even better.

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Original publications

1. Pahnila, M., Koskela, A., Sulasalmi, P., & Fabritius, T. (2023). A review of pyrolysis technologies and the effect of process parameters on biocarbon properties. *Energies, 16*(9), 6963. https://doi.org/10.3390/en16196936

1. Pahnila, M., Koskela, A., Sulasalmi, P., & Fabritius, T. (2024). Biocarbon production using three-staged pyrolysis and its preliminary suitability to the iron and steel industry. *Energies, 17*(13), 3131. https://doi.org/10.3390/en17133131

2. Pahnila, M., Koskela, A., Uusitalo, J., Hagström, A., Sulasalmi, P., & Fabritius, T. (2025). The effect of binders on the behavior of biocarbon briquettes under the stresses of a submerged arc furnace. *Journal of Sustainable Metallurgy, 12*(1), 839–852. https://doi.org/10.1007/s40831-025-01367-x

3. Pahnila, M., Koskela, A., Uusitalo, J., Vitikka, O., Sulasalmi, P., & Fabritius, T. (2025). The effect of biomass species and pyrolysis method on biocarbon briquettes suitability for submerged arc furnace. *Journal of Sustainable Metallurgy, 12*(1), 523–536. https://doi.org/10.1007/s40831-025-01343-5

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