Energimyndighetens titel på projektet – svenska Utveckling av bio-briketter för ferrokromproduktion i nedsänkt bågugn (Bio4SAF)	
Energimyndighetens titel på projektet – engelska Developing bio-briquettes for ferrochrome production in Submerged Arc Furnace (Bio4SAF)	
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Nyckelord: 5-7 st Biocarbon, Fossil CO_2 emission, Chromite briquettes, Ferrochrome production, SAF, Sustainability, Circular economy	

The project "Developing Bio-briquettes for Ferrochrome Production in Submerged Arc Furnace (Bio4SAF)" is part of the Industrial life "Industriklivet" program, Area 1- Process industry emissions of greenhouse gases and is financed by the Swedish Energy Agency. The project consortium consists of Swerim AB, Vargön Alloys AB, and Envigas AB.

The project started on 1st April 2022 and ended on 30 November 2024.

Preface

The project has a total original budget of 13,990,126 SEK, which is divided among several sources of financing as shown in the following table.

Partners	Total kostnad	Energimyndigheten Sökt stöd	Vargön stöd till Swerim & Envigas	Egen instas	Stöd, % av stödgrundande kostnader
Swerim	3 021 264 kr	1 591 558 kr	1 429 706 kr	0 kr	53%
Envigas	1 112 000 kr	505 900 kr	272 500 kr	333 600 kr	45%
Vargön Alloys AB	9 856 862 kr	2 464 216 kr	0 kr	7 392 647 kr	25%
Total	**13 990 126 kr**	**4 561 674 kr**	**1 702 206 kr**	**7 726 247 kr**	**33%**

Sammanfattning

Ferrokromindustrin är starkt beroende av fossilt koks som en kritisk komponent vid smältningsreduktion av kromitmalm i nedsänkta ljusbågsugnar (SAF). Detta beroende har lett till omfattande utsläpp av fossilt CO_2, vilket utgör en stor utmaning för branschens långsiktiga hållbarhet. För att möta denna utmaning och främja en mer hållbar framtid är det avgörande att utveckla både kortsiktiga och långsiktiga strategier för att minska de fossila utsläppen.

I detta sammanhang utgör Bio4SAF-projektet ett strategiskt och framåtblickande tillvägagångssätt för att minska fossila CO_2-utsläpp från SAF genom att ersätta fossilt koks med förnybara kolkällor. Projektet har fokuserat på flera tekniska framsteg, inklusive produktion av högkvalitativt biokol av Envigas, särskilt anpassat för FeCr-produktion. Dessutom innefattade projektet receptutvecklingen av biokol-kromitbriketter utförd av Swerim, där en vibropress används.

En iterativ process genomfördes för att utveckla självreducerande kromitbriketter med upp till **10 % biokol**, utan att kompromissa med briketternas hållfasthet. Projektet inkluderade även briketteringsförsök i pilotförsöks skala vid Vargöns briketteringsanläggning för att optimera produktionen inför storskalig tillverkning, vilket resulterade i framställningen av **350 ton** biokol-kromitbriketter. Dessa briketter chargerades därefter i ugn nr 10 hos Vargön, där en utvärdering av processtabilitet, utsläpp och produktkvalitet genomfördes. Resultaten gav värdefulla insikter om briketternas hållfasthet och effektivitet.

Den framgångsrika Bio4SAF-kampanjen visade att det var möjligt att ersätta **21,8 %** av det fossila kokset med biokol, vilket resulterade i en minskning av **fossila CO_2-utsläpp med 25 %** och en reducering av fossil energiförbrukning med **118 GWh**. Dessutom möjliggjorde de utvecklade briketterna återvinning av **1 %** av den genererade filterstoft, vilket bidrog till en förbättrad resurseffektivitet.

Baserat på dessa framsteg belönades Bio4SAF-projektet med Hållbarhetspriset av International Chrome Development Association (ICDA) i Hongkong 2024, vilket understryker dess betydande påverkan och innovation. Projektet finansieras av Energimyndigheten, vilket betonar engagemanget och stödet för hållbara energiinitiativ.

Genom denna innovativa och samarbetsbaserade forskningsinsats strävar Bio4SAF-projektet efter att bana väg för en hållbar FeCr-produktion genom att minska industrins beroende av fossilt koks och reducera de relaterade fossila CO_2-utsläppen. Projektets resultat bidrar inte bara till miljömässig hållbarhet utan skapar också en plattform för framtida framsteg inom FeCr-industrin.

Energimyndigheten

Summary

The ferrochrome (FeCr) industry is heavily reliant on fossil coke as a critical component for the smelting reduction of chromite ore within submerged arc furnaces (SAFs). This dependence has led to significant fossil CO_2 emissions, posing a considerable challenge to the long-term sustainability of the sector. To address this issue and foster a sustainable future, it is essential to develop both short-term and long-term strategies aimed at reducing these emissions.

In this context, the **Bio4SAF project** represents a strategic and progressive approach to mitigating fossil CO_2 emissions from SAFs by substituting fossil coke with renewable carbon sources. The project has focused on several technical advancements, including the production of high-quality biocarbon by Envigas specifically tailored for FeCr production. Additionally, the project involved the design and optimization of biocarbon-chromite briquettes using a vibro press machine developed by Swerim.

An iterative process was undertaken on a technical scale to create self-reduced chromite briquettes containing up to **10% biocarbon** without compromising quality. The project also conducted pre-industrial scale briquetting trials at the Vargön briquetting plant to optimize large-scale production, culminating in the production of **350 tons** of biocarbon-chromite briquettes. These briquettes were implemented in SAF number 10 at Vargön, where an assessment of process stability, emissions, and product quality was performed, providing critical insights into the viability and effectiveness of the briquettes.

The successful Bio4SAF campaign demonstrated the potential to replace **21.8%** of fossil coke with biocarbon, resulting in a **25% reduction** in fossil CO_2 emissions and a decrease in fossil energy consumption by **118 GWh**. Additionally, the developed briquettes facilitated the recycling of **1%** of generated flue dust, contributing to improved resource efficiency.

Based on these achievements, the Bio4SAF project was honored with the **Sustainability Award** by the International Chrome Development Association (ICDA) in Hong Kong in **2024**, highlighting its significant impact and innovation. The project is financed by the **Swedish Energy Agency**, emphasizing the commitment and support for sustainable energy initiatives.

Through this innovative and collaborative research endeavor, the Bio4SAF project aims to pave the way for sustainable FeCr production, reducing the industry's reliance on fossil coke and mitigating the associated fossil CO_2 emissions. The outcomes of this project not only contribute to environmental sustainability but also establish a framework for future advancements in the FeCr industry.

1. Introduction

The European ferroalloy industry possesses a central role in modern everyday life and has a major strategic role in the value chain for the European economy to be fossil-free by 2050 [1]. Modern-day low-carbon energy production heavily relies on ferrochrome, as alternative materials lack the durability required for such applications. Despite the substantial efforts to enhance production efficiency and environmental practices in the FeCr industry, fossil coke is still required to achieve the reduction of metal oxides, endangering sustainability amid strict EU climate measures. Average CO_2 emissions are 1.6 t CO_2/t FeCr, corresponding to 19-25 Mt CO_2 emissions annually [2]. Hence, in pursuit of the EU's environmental objectives, metallurgical sectors are continuously striving to meet the outlined climate plan [3]. Although significant investments are directed towards attaining CO_2 targets within the steel industry via H_2-based technology [4,5], it remains thermodynamically unfeasible to replace carbon with hydrogen in FeCr alloy production.

Biocarbon, being a promising solution to diminish fossil CO_2 emissions and attain carbon neutrality within the ferroalloy industry, is particularly abundant in Nordic nations with vast opportunities to obtain forest biomass. Integrating biocarbon into residual product briquettes or creating pure biocarbon briquettes offer flexible options. Incorporating biocarbon into residual briquettes is a straightforward process that requires minimal investments in the system and can be easily implemented compared to developing pure biocarbon briquettes for top charging. Previous advancements from the BioAgglomerate project [6] indicated that the addition of ~2% torrefied sawdust to blast furnace briquettes (approximately 64kg/tonHM) could reduce coke consumption by 9-11 kg/tonHM, which corresponds to 33-40 kg/tonHM in fossil CO_2 emissions. Through careful optimization of briquette composition and biocarbon quality, 5 wt.% addition of biocarbon to the briquettes is feasible without compromising the mechanical strength of the final briquettes [7].

In Submerged Arc Furnace (SAF), besides its contribution to reduction and melting, coke aids in the conversion of electrical energy to heat and ensures the permeability of the load for CO gas ascent emphasizing the need for biocarbon with specific properties and quality tailored to SAF requirements [8]. Another challenge faced by the FeCr industry is the variability in the quality of chromite ore. The production of FeCr in SAF necessitates hard lumpy chromite ore with a smaller proportion of fine-grained material to enhance process efficiency, minimise dust generation, and reduce energy consumption [9]. The gradual depletion of rich and hard lumpy chromite ore deposits forces FeCr producers to make use of lower-quality ores. The usage of low-grade ore increases the production of fines and reduces material efficiency in the FeCr industry. In other words, variations in ore quality significantly affect the reduction of chromite ore in the furnace,

thereby escalating energy consumption and diminishing process efficiency. Currently, the majority of fines (0-16 mm) generated from ore screening in the FeCr industry are recycled back to SAF through agglomeration in the form of hexagonal briquettes. Briquetting enhances fines and residue circulation thereby mitigating dust formation from SAF.
Biocarbon-containing briquettes offer the most direct route to reduce fossil CO_2 emissions from the FeCr industry without significant alterations to the current process. The self-reduced biocarbon-chromite ore briquettes can potentially improve the efficiency of carbothermic reduction in SAF, thereby reducing coke consumption and fossil CO_2 emissions. Additionally, the developed briquettes will aid in the recirculation of fines/residual material back to the production system, improving resource efficiency and reducing the environmental impact of landfilling. Therefore, this study aims to optimize briquetting parameters to achieve the highest biocarbon addition to the briquettes without compromising mechanical strength. Furthermore, this study provides a unique opportunity for higher biocarbon utilization to maximize coke replacement and reduce fossil CO_2 emissions.

2. Goal and Objectives

The main goal of Bio4SAF project is to reduce the fossil CO_2 emissions from the FeCr industry by replacing up to 20% of fossil coke by developing biocarbon-chromite ore briquettes. This enables an annual reduction of more than 30,000 tons of fossil CO_2 emissions from the Swedish FeCr industry and more than 4.0 Mton from global FeCr production. The project encompassed the evaluation of process parameters, monitoring of dust emission, gas generation, and product quality, and comprehensive assessment of overall efficiency to effectively reduce fossil CO_2 emissions. The project focuses on 2 aspects the first one is to introduce the biocarbon to the SAF for replacing the fossil coke and the second is to maximize the resource efficiency by recycling the FeCr dust from SAF. A simplified flowchart of Bio4SAF concept is shown in **Figure 1**.

The proposal's core innovative components centered around the following key areas:

1) Processing of appropriate biomass feedstock to produce biochar with quality meets the FeCr production.
2) Assessment of materials eligible for briquetting, recycling, and exploitation with FeCr plant.
3) Design and optimization of biocarbon-chromite ore briquettes specifically tailored for SAF processes.
4) Production of biocarbon-chromite briquette on an industrial scale with quality fulfil SAF implementation.
5) Generation of advanced knowledge through full-scale trials that incorporate the utilization of biocarbon in SAF.

6) Evaluation of the industrial campaign to figure out the effect of the developed biocarbon-chromite briquette on the process efficiency and product quality.
7) Evaluation of the environmental impacts of using renewable carbon instead of fossil coke by LCA.

The outcomes of this project will significantly contribute to the transition from fossil-based to bio-based practices within the FeCr and ferroalloys sector which can be used as a milestone towards achieving 100% replacement of fossil coke in SAF. By fostering the greater adoption of bioenergy and promoting a sustainable bioeconomy, this initiative will facilitate the transformation of the FeCr production sector towards a more environmentally conscious and resource-efficient future.

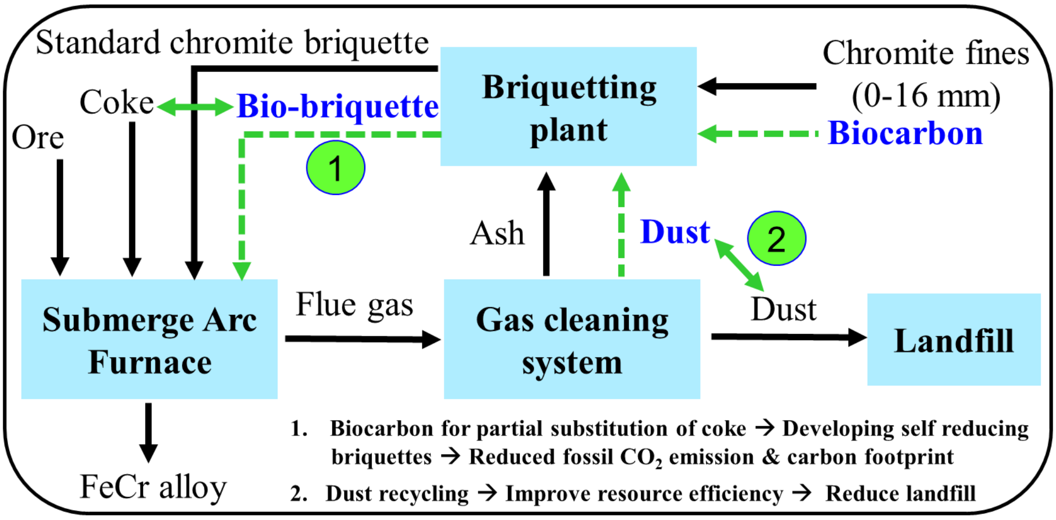


Figure 1: Simplified flowchart for Bio4SAF project

3. Project Partners and the Project Work

The Bio4SAF project is coordinated by Swerim AB and the project partners are Vargön Alloys, and Envigas. The project provides an outstanding opportunity for the integration of biocarbon producers with ferroalloys production for green FeCr production. Envigas worked to optimize and adapt the biocarbon quality to fulfill the requirements needed for production of FeCr in SAF. Swerim worked on developing a technical scale biocarbon-chromite ore briquette with maximizing the biocarbon addition without deteriorating the mechanical strength and/or the briquettes quality. The key parameters for briquetting were optimized and identified. The optimum recipes from technical scale were selected for pre-briquetting industrial trials in larger batches (2-3 tons/each) at Vargön to verify the briquette quality before going to the industrial production. An industrial campaign was successfully executed at Vargön SAF and the process was monitored and several parameters such metal composition, slag composition, dust generation and composition, coke consumption, energy consumption were evaluated to understand the effect of developed biocarbon-chromite briquettes on the process stability and FeCr product quality. The industrial campaign was managed by Vargön, and in close collaboration with Swerim who has monitored the dust generation and off-gases analysis during the campaign. Environmental assessments were conducted in view of the industrial campaign at Vargön comparing the reference case with biocarbon case.

The project work packages (WP) can be described as follows:

WP1. State-of-the-art

In this work package complementary review of raw materials, slag, dust, and waste materials in FeCr was assembled. A flowchart was created showing the materials to the landfill and that are eligible for briquetting, recycling, and exploitation. An overview of ongoing research, development, and demonstration efforts in the FeCr sector were conducted and evaluated. Swerim in close collaboration with Vargön worked on this WP which included:

1.1 Developing process flowsheet for materials and energy flow in FeCr plant
1.2 Complementary analysis of chromite ore, dust and FeCr residues

WP2. Characterization and optimization of biocarbon

The existing pilot facility at Envigas worked on the production of biocarbon for testing on both laboratory- and technical scale. In parallel with WP3, WP4 and WP5, where new knowledge regarding the biocarbon characteristics and how these affect the optimal conditions of briquettes, the pilot facilities process parameters were adapted for large-scale production of approximately 40-45 tons of biocarbon for the pre-briquetting trials and the main industrial campaign at Vargön. The biocarbon were characterized in terms of the physical (e.g., particle size, porosity, density, etc.) and chemical properties (e.g. carbon content, volatile matter, ash content, impurities, etc.). Envigas led this WP in close collaboration with Swerim and Vargön and the activities included:

2.1 Identification of ferro industries requirements specification of biocarbon
2.2 Selection of raw biomass and optimization of the process parameters
2.3 Production of biocarbon for technical and industrial-scale briquetting

WP.3 Technical scale briquetting and characterization

Swerim intensively worked on the development of technical-scale biocarbon-chromite briquette to meet the quality needed for FeCr production in SAF. Recipes were stepwisely designed and evaluated to identify the impact of different parameters such as moisture, biocarbon additions, flue dust addition, and the binder type and ratio on the mechanical strength of the briquettes. The technical scale vibro-press at Swerim has been used for the production of biocarbon-chromite briquettes under conditions simulated the industrial scale briquetting plant at Vargön. Swerim led this WP in close collaboration with Vargön and Envigas and the activities included:

3.1 Reference briquette production and optimization
3.2 Design and optimization of recipes for biocarbon-chromite ore briquettes
3.3 Maximization the biocarbon addition to chromite ore briquette

WP.4 Evaluation of biocarbon-chromite briquettes from technical scale

This work package focused on evaluating the quality of the briquettes prepared in WP3. The mechanical strength was evaluated using standard tumbler index in conjunction with the drop test. Drying behaviour, density, cold and hot mechanical strength were evaluated. The activities included:
4.1 Evaluation of the effect of binder types, binder ratio, biocarbon content on the quality of biocarbon-chromite briquette.
4.2 Evaluation the mechanical strength of technical scale biocarbon-chromite ore briquette
4.3 Evaluating the cold and hot mechanical strength of industrial-scale briquettes

WP.5 Implementation and verification in industrial scale

Conducting trials on industrial scale is vital for evaluating the quality and feasibility of developed biocarbon-chromite ores briquette implementation in SAF. Briquettes for the industrial trial were manufactured at Vargön briquetting plant in view of the optimal briquette recipe developed in WP3/WP4. During the industrial campaign, different charging rate of biocarbon-chromite ore briquettes were implemented to partially replace the fossil coke. The process was monitored and several parameters such as off gas, iso-kinetic dust measurement in addition to follow up of coke consumption, FeCr quality and slag generation to understand the effect of developed briquettes on process stability and product quality. Evaluation of process stability, data for energy efficiency and emissions are evaluated through mass- and heat balance by Swerim, also recommendations regarding implementation. Vargön led this WP in close collaboration with Swerim AB and Envigas. This WP included:
5.1 Manufacturing and evaluation of biocarbon-chromite ore briquette in batch industrial scale
5.2 Manufacturing and evaluation of biocarbon-chromite briquette for industrial campaign
5.3 Industrial campaign using biocarbon-chromite ore briquette in SAF
5.4 Collection of operational data and evaluation of trial

WP.6 Process and sustainability analysis

The environmental consequences of using renewable carbon sources has been implemented through LCA (life cycle assessment). LCA was based on the data retrieved throughout the project, which leads to a comparison between the reference case and case with 10% biocarbon addition in chromite ore briquettes.
6.1 Literature study on life cycle aspect of briquettes and biocarbon briquettes.
6.2 LCI, lifecycle inventory – data gathering and documentation
6.3 LCA – assessment of environmental consequences of study system and reporting

WP.7 Project management & reporting

In this work package, the overall activities of the applied project were coordinated, documented, and shared with the project group and reported to the Swedish Energy Agency. The achieved results were presented and discussed in the project meetings and shared within the project group. The overall results of the project were evaluated and discussed in the present final report and attached deliverables. Throughout the project, all partners had close collaboration, and the research activities were discussed and planned within the project team to ensure efficient utilization of knowledge and expertise within the group. Regular meetings were held to discuss the technical and scientific aspects of the project. Dissemination of the results to companies and institutes in the ferroalloy sector and biocarbon producers was highly considered during the project. The important findings of the project results were published in several conferences and seminars. Based on the successful results, the project won the Global Sustainability Award provided by iCDA for the year 2024. The dissemination of the project results will be discussed later. Swerim led this WP and took the responsibility for preparing the meeting agenda, meeting invitation for the project partners, documentation of meeting minutes, and reporting according to the guidelines of Energimyndigheten.

4. Developing and Evaluation of Biocarbon-Chromite Briquette on Technical Scale

4.1 Materials and characteristics

4.1.1 Chromite ores

As a preliminary step, a complementary analysis of the supplied chromite ore types, dust and residue material have been done. This includes chemical analysis (see **Figure 2**), particle size distribution (see **Figure 3**). Moreover, a crushability test (see **Table 1**) under standard condition was executed on different types of chromite ores which are used at Vargön.

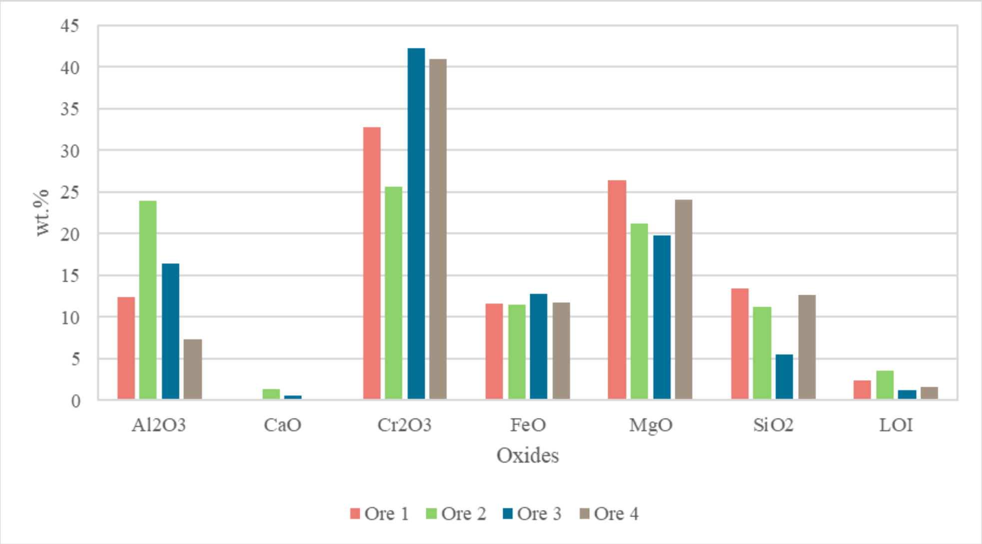


Figure 2: Chemical analysis of chromite ores

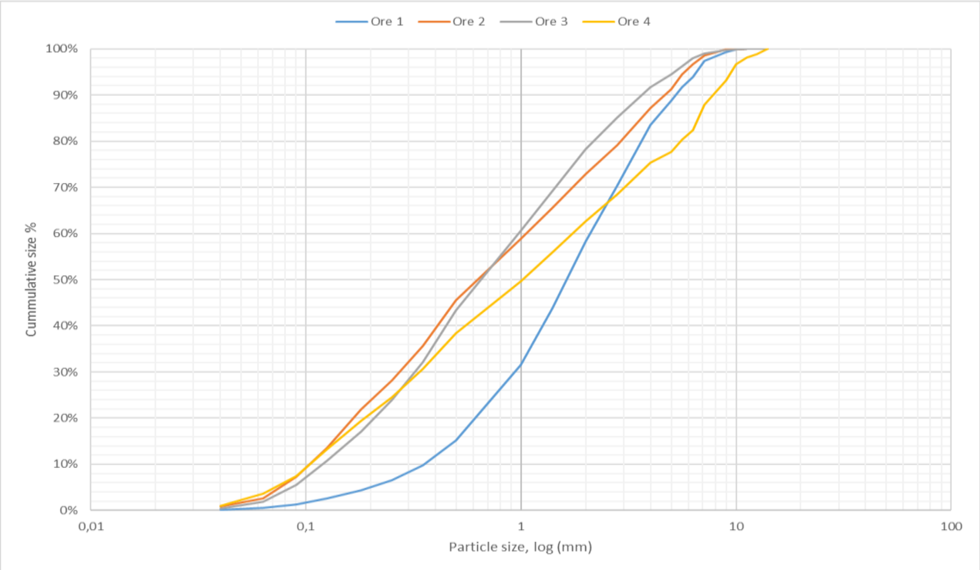


Figure 3: Particle size distribution of chromite ores

Table 1: Crushability test of chromite ores

Chromite Ores	**Impact strength, N**	**Tested Work Index (WI)**	**Abrasion Index (AI)**	**Specific gravity, ton/m^3**
Ore 1	511	6.9±1	0.21	3.61
Ore 2	604	7.8±1.4	0.07	3.76
Ore 3	486	5.8±0.9	0.25	4.08
Ore 4	412	6.1±1.5	0.11	3.3

4.1.2 Additives

Other additives in the briquetting mixture, which are residues generated during FeCr production at Vargön, were analyzed. These include FeCr dust and FeCr ash, with the results of the chemical analysis presented in **Table 2**. Additionally, Vargön employs another additive known as "Monofil" in the briquetting mixture, which has also been analyzed and is included in the table. The analysis of these additives is crucial for understanding their properties and potential use for partial replacement of Portland cement (see analysis in table 2) and evaluating the impact on the briquetting process.

Table 2: Chemical analysis of additives

Additives	**CaO**	**SiO2**	**Al2O3**	**MgO**	**Fe2O3**	**Cr2O3**	**Na2O**	**K2O**	**S**	**Others**
Flue dust	1	20.9	6.6	41.2	4.55	9.5	1.3	1.4	1.08	12.47
Monofil	39.2	35.9	10.7	10.1	0.36	NA	0.37	0.87	1.6	0.9
Portland cement	63	19.5	5.1	1.2	3	NA	0.15	1.3	1.5	5.25

4.1.3 Biocarbon

The biocarbon was produced and supplied by Envigas. Several pyrolysis campaigns were conducted at Envigas pilot plant in Bureå to produce biochar from with quality meet the desired characteristics for the project application. The pyrolysis process of biomass was conducted in an electrically heated screw reactor, with a pyrolysis temperature ranging from 550 to 650 ^{o}C, as depicted schematically in **Figure 4**. The yield of biochar, or biocarbon, was determined directly from the process by measuring the weights of the input feedstock and the resulting biochar. The proximate analysis of biocarbon was conducted by a certified external lab (Eurofins) and given in **Table 3**. It shows that the biocarbon has low volatile matter (VM), ash, sulfur and P content which meet the requirements for FeCr production and sulfur content compared to the metallurgical coke while the VM was higher in biocarbon, and C-fix was identical. The bulk density was 0.37 g/cm^3 for biocarbon as -received. The moisture content was 1.2% while the calorific value was 34.1 MJ/kg. The particle size distribution of biocarbon as received is given in **Figure 5**. Part of the biocarbon was milled to fractions under 1 mm to be tested for briquetting. **Figure 6** shows the comparison of chemical analysis between coke and biocarbon. The biocarbon has lower moisture and ash content compared to the coke while has higher carbon content.

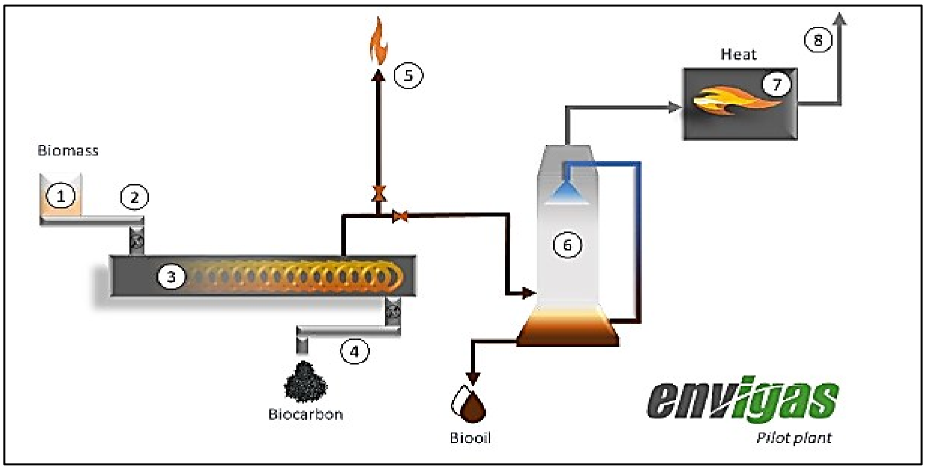


Figure 4: Envigas pilot plant used for the pyrolysis of biomass and biocarbon production: (1) Biomass storage, (2) dosing screw, (3) electrically heated pyrolysis screw, (4) biochar cooling screw, (5) emergency flare, (6) condenser, (7) off-gas burner, and (8) exhaust pipe

Table 3: Chemical analysis of Envigas biocarbon

C-total, wt.% (db)	VM, wt.% (db)	Ash, wt.% (db)	S, wt.% (db)	P, wt.% (db)	HHV, Mg/kg	Moisture, wt.%	ρ-bulk kg/m^3
94.8	2.2	1.1	0.06	<0.001	34.1	1.2	368

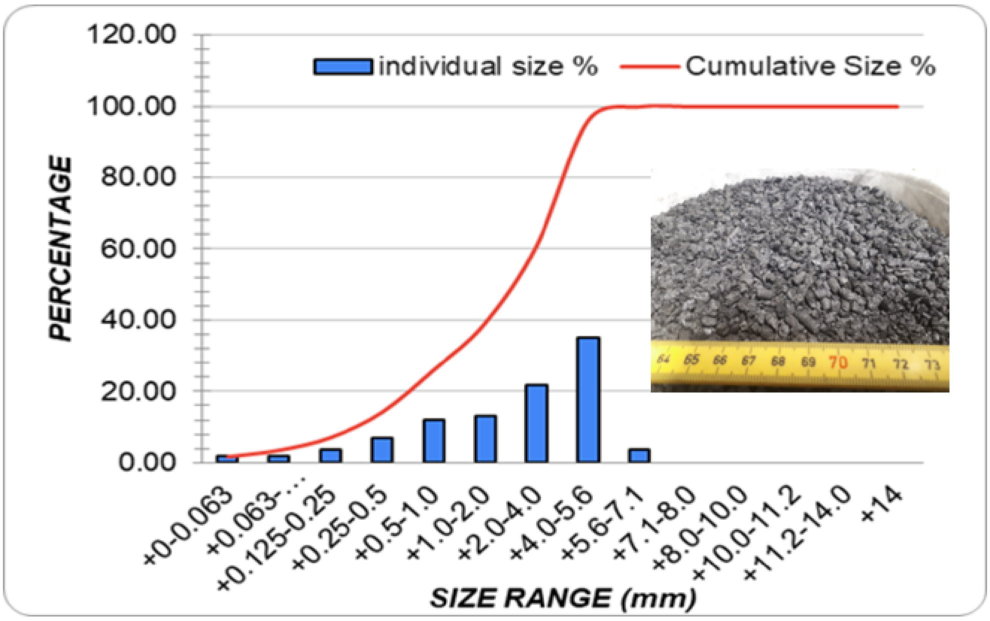
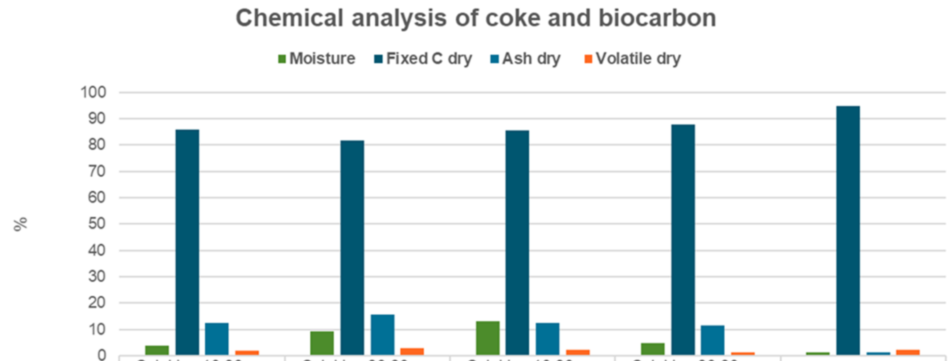


Figure 5: Particle size distribution of biocarbon as-received



	Colobian 10-30mm Pile 7971	Colobian 30-60mm Pile 7972	Colobian 10-30mm Pile 7973	Colobian 30-60mm Pile 7968	Biocarbon - Envigas
Moisture	3.85	9.16	12.94	4.73	1.2
Fixed C dry	85.93	81.73	85.5	87.6	C_tot 94.8
Ash dry	12.33	15.53	12.3	11.3	1.1
Volatile dry	1.79	2.72	2.14	1.16	2.2

Figure 6: chemical analysis of coke vs biocarbon

4.2 Methodology

The briquettes were manufactured using a vibro-press (Teksam VU600/6) briquetting machine shown in **Figure 7**. The machine consisted of a hydraulic station and a press capable of exerting pressures ranging from 100-120 bars. The briquetting process commenced with the accurate weighing of materials and adjusting their proportions based on the recipes. Each recipe yielded a batch weighing approximately 25 kg. The materials were thoroughly mixed using an Eirch mixer, gradually adding water until achieving a homogeneous mixture. Next, the prepared mixture was introduced into steel molds featuring 16 hexagonal-shaped holes within the briquetting machine. After filling the molds, the materials underwent 20 seconds of vibration and mechanical pressing force to facilitate briquette ejection. The resulting briquettes, approximately 7.0 cm in height and 3.3 cm in edge length with a hexagonal shape, were placed on a wooden pallet and subjected to a 24-hour curing period in a humidified atmosphere. Following curing, the briquettes were air-dried at ambient temperature for one week as shown in **Figure 8**. To assess the initial mechanical strength, a drop test was conducted. Each briquette was dropped from a height of 1.0 m onto a metal plate. The test continued until either 50 drops were reached or the briquette had diminished to nearly half of its original height. In addition, the mechanical strength was evaluated based on compression strength as shown in **Figure 9a**. Based on the drop test results, specific recipes were selected for measuring the Tumbler index (TI) as shown in **Figure 9b** by the Swedish standard SS-ISO 3271:2007. Approximately 15 kg of briquettes from each recipe were loaded into a rotating drum tumbler with a diameter of 100 cm, rotating at a speed of 25 rpm. The tumbling duration was fixed at 8 minutes (200 revolutions). After tumbling, the fraction larger than 6.3 mm was weighed and expressed as a percentage of the initial weight of the charged briquettes.

Figure 7: Teksam vibro press machine

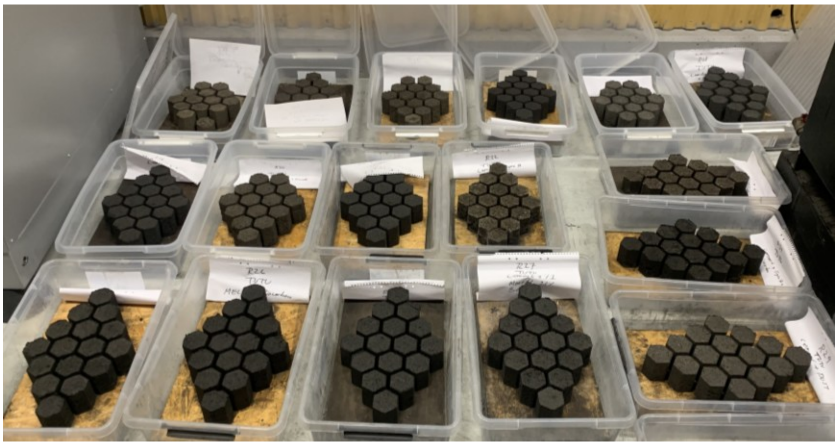


Figure 8: Technical scale briquetting left for air drying

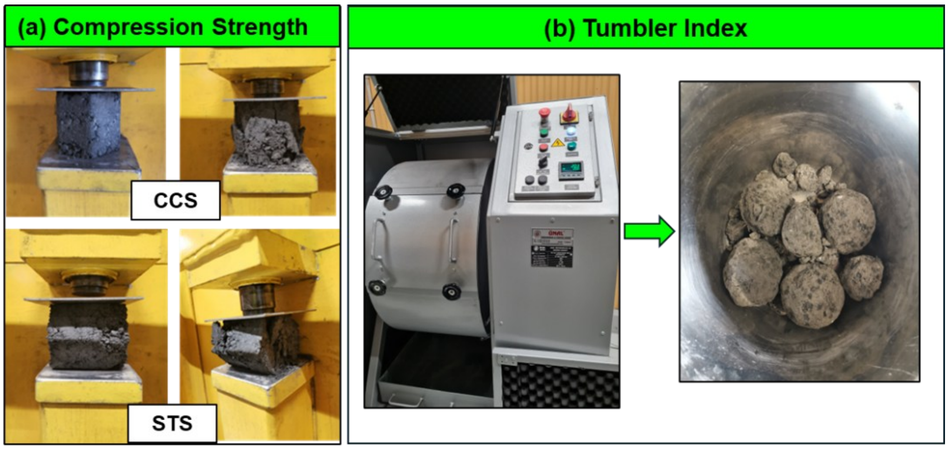


Figure 9: Testing the mechanical strength of the briquettes using:
(a) Compression strength (b) Tumbler device

Selected recipes from the pre-briquetting industrial scale trials were subjected to test the hot strength. **Figure 10** shows the set-up of the furnace used for testing the hot strength. The test programme can be summarized as follow:

1. The briquettes are prepared to one qual height (70 mm) and dried at a temperature of 105°C for a period of 24 hours.
2. The weight of the briquette is measured and recorded.
3. The briquette is then placed inside a furnace and a load of 25 kg is applied on top of the briquette.
4. N_2 gas is introduced into the furnace as the carrier gas, with a flow rate of 5 l/min.
5. The furnace is gradually heated at a rate of 5°C per minute until it reaches a temperature of 1000°C. This temperature is maintained for a duration of 1 hour as shown in **Figure 11**.
6. After the heating process is complete, the heating is stopped, and the cooling process is initiated by circulating N_2 gas over the briquettes overnight.
7. Once the briquettes have cooled down, it is extracted from the furnace and re-weighed.
8. The weight loss of the briquette is calculated.
9. The strength of the briquettes is measured and compared to their initial strength.

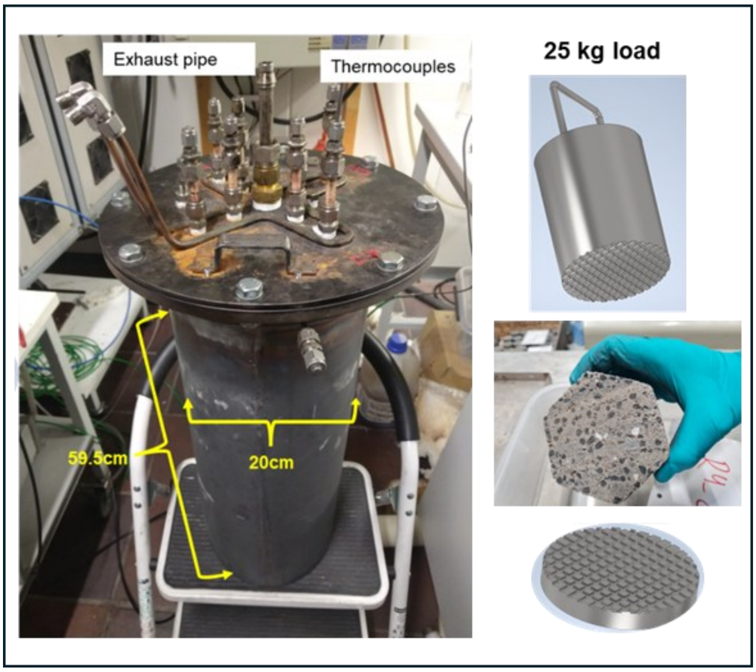


Figure 10: Set-up for measuring the hot strength of the briquettes

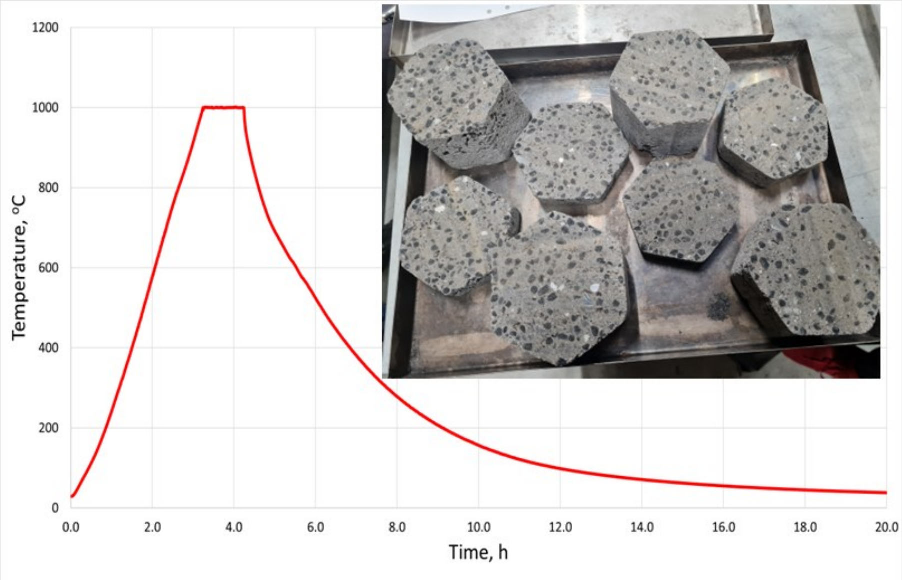


Figure 11: Temperature profile implemented for hot strength of the briquettes

4.3. Technical scale briquetting recipe design and evaluation

4.3.1. Designing biocarbon-chromite briquette on technical scale

The technical scale briquetting was developed and optimized over five different stages, spanning from August 2022 to June 2023. **Figure 12** illustrates a systematic approach to refining briquetting recipes, incorporating various binders and adjustments to improve product quality, and it can be summarized as follows:

1. Stage 1 (August 2022): Started off with testing the industrial scale briquettes produced by Vargön Alloys. Tumbler index for all of the supplied three different recipes (recipe C 1-3, A 1-3, and T 1-3) were evaluated to foresee what ore type worked well during industrial scale production.
2. Stage 2 (September 2022): Technical scale production of briquettes started with a focus on evaluating moisture content of different ores and its effects on reference briquette simulating the supplied Vargön reference recipe in the first stage.
3. Stage 3 (November 2022): Involved the addition of biocarbon (5-10% concentration) to the briquetting recipes, assessing its impact on the final briquetting strength. Continued the evaluation of monofil addition and further refining of the cement ratio in the recipes.
4. Stage 4 (April 2023): This stage prioritized identifying the best recipes based on a calculated tumbler index (TI) for the briquettes, incorporating new binders with various biocarbon. Focused on producing reference briquettes using a specific binder and

incorporating additional biocarbon variations. Investigated the effects of varying cement ratios on the briquettes, including the replacement of some cement with different additives.

5. Stage 5 (June 2023): Emphasized the selection of polymer types, adjusting content from 0.25% to 0.5% for optimal recipe formulation. Effect of sieving and other types of biocarbon were evaluated finally selecting the best recipe from the technical scale production.

Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Industrial Scale production at Vargön Alloys	Technical scale briquetting at Swerim			
•Test industrial scale briquettes produced by Vargön Alloys. •Tumbler index for the supplied recipes were evaluated to foresee what ore type worked well during industrial scale production.	•Reference case •Moisture evaluation •Technical scale drop test comparison of industrial scale briquettes from Vargön Alloys	•Evaluation of cement ratio •Addition of 5-10% of grinded and as-received biocarbon •Minor binder replacement with monofil	•Addition of 10% of sieved, grinded and as-received biocarbon •Replacement of binders with dust •Testing new binders (Flue dust, Cemfree, Cemfree conc., molass, Lignin A: Tech D947, Lignin B: Tech DP4229)	•Effect of sieving and other types of biocarbon were evaluated •Variation of Floform content is evaluated •Selection of best recipes from the technical scale trials

Figure 12: Stages of developing the briquettes

4.3.1.1 Testing Industrial Scale Briquettes from Vargön (stage 1)

In WP3, 3 recipes with different mixes of ores (Ore 1+ Ore 2, Ore 3, and Ore 4) of standard chromite briquettes were delivered from Vargön to Swerim for testing the mechanical strength. The mechanical strength was evaluated based on drop test and correlated to theoretically calculated tumbler index. Mixture of Ore 1 and Ore 2 is called ind_ref_C1-3 (industrial reference recipe C), Ore 3 containing recipe as ind_ref_A1-3, and Ore 4 containing recipe as ind_ref_T1-3. The mechanical strength was in order of Ind_ref_recipe_T > Ind_ref_recipe_C > Ind_ref_recipe_A as shown in **Figure 13**, followed by **Figure 14** showing few supplied briquettes from Vargön Alloys.

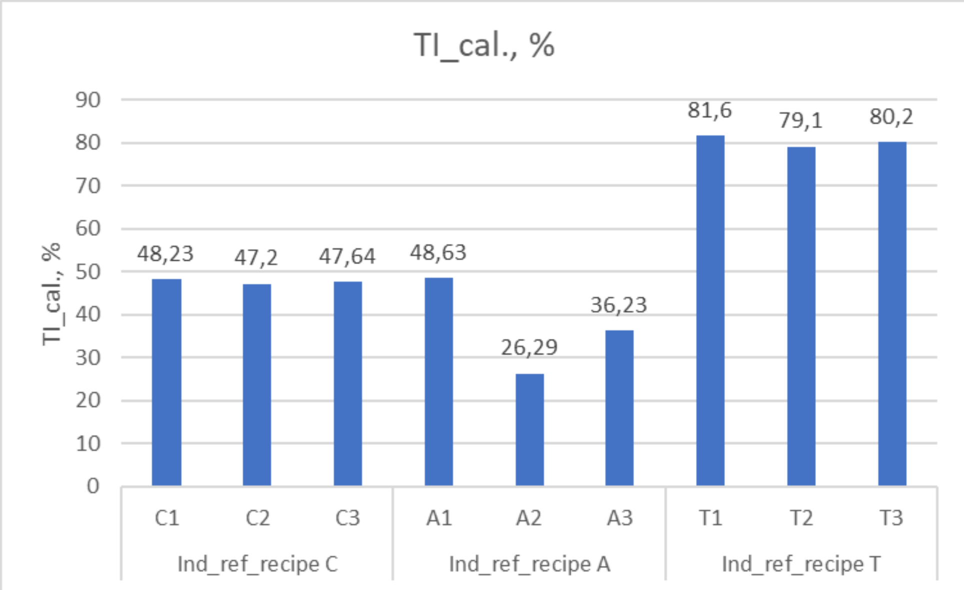


Figure 13: Calculated tumbler index for 3 types of standard briquette produced at Vargön


Figure 14: Briquettes supplied from Vargön

4.3.1.2 Technical scale production of reference recipes at Swerim (Stage 2)

A total of 10 recipes (B1-B10) were designed on technical scale at Swerim to test and develop reference briquettes before adding the biocarbon as given in **Table 4**. The briquette mixtures are adjusted to simulate the standard recipes (mix of Ore 1+Ore 2, Ore 3, and Ore 4) at Vargön in a technical scale production at Swerim. The moisture content was optimized to get proper mixtures for compaction in technical Vibro-press at Swerim.

Table 4: Recipes designed for technical scale reference briquette

Recipe	Cement	Monofil	Ore 1	Ore 2	Ore 3	Ore 4	Moisture content	CCS, bar (after 3 weeks)
B1	4.2	3.1	46.3	46.3			5	29
B2	4.2	3.1	46.3	46.3			6.5	94
B3	4.2	3.1	46.3	46.3			7.8	94
B4	4.2	3.1			92.6		5.7	129
B5	4.2	3.1			92.6		7	157
B6	4.2	3.1			92.6		7.7	160
B7	4.2	3.1				92.6	4.5	100
B8	4.2	3.1				92.6	8	114
B9	4.2	3.1				92.6	4	112
B10 (dry basis)	4.2	3.1	46.3	46.3			8.1	121

4.3.1.3 Technical Scale production of briquettes a Swerim (Stages 3, 4 and 5)

Since Ind_ref_recipe_T and Tec_ref_recipe_T which is made of Ore 3 outperformed all other ore types, the major interest is to proceed with the technical scale briquetting by concentrating mainly on the TUTU recipe. Entire technical scale briquetting can be split up into the following 3 stages.

Stage 3: **Table 5** explains the recipes produced during stage 3. Initially, addition of cement/monofil to Ore 1+Ore 2 (R1 and R2), Ore 4 (R3 and R4) and Ore 3 (R5A and R6A) recipes were explored. Subsequently, addition of biocarbon (5-10%) were added to the TUTU recipes by varying water content according to the biocarbon addition (R7-R10). Furthermore, partial replacement of cement (R11 and R12) with ash/dust were also explored as a conclusion to this stage.

Table.5: Recipes produced during stage 3

Recipe	Cement	Monofil	Ore 1	Ore 2	Ore 3	Ore 4	Ash	Dust	Biocarbon as-received	Biocarbon grinded	Moisture content	CCS, bar, (after 3 weeks)
R1	7.4		46.3	46.3							8.6	158
R2	5.3	3.1	45.8	45.8							8.5	149
R3	7.4					92.6					8.4	116
R4	5.3	3.1				91.6					8.3	119
R5A	7.4				92.6						8.2	162
R5B	7.4				92.6						6.9	163
R5C	7.4				92.6						4.6	163
R6A	5.3	3.1			91.6						8.2	162
R6B	5.3	3.1			91.6						5.5	163
R6C	5.3	3.1			91.6						6	140
R7	4.3	3.1			87.6				5		9.9	76
R8	4.3	3.1			82.6				10		11.5	47
R9A	4.3	3.1			87.6					5	10.4	61
R9B	4.3	3.1			87.6					5	10.5	75
R10	4.3	3.1			82.6					10	12.7	42
R11	4.3	3.1			87.6		5				8.2	153
R12	4.3	3.1			87.6			5			8.2	163

Stage 4: **Table 6** depicts the recipes produced during stage 4 of this project. During this stage, 27 recipes with different compositions were tried out so as to reduce the cement content. Parallelly, with an intention to increase the biocarbon content to 10% without major loss in mechanical strength.

Table.6: Produced recipes during stage 4

Recipe	Cement	Monofil	Dust	Ore 3	Lignin A	Lignin B	Molasses	Cemfree	Cemfree Conc.	Biocarbon as received	Biocarbon grinded	Biocarbon sieved <2.8mm
R13				92,6					7,4			
R14				92,6				7,4				
R15		3,1		92,6				4,3				
R16				91,6				8,4			10	
R17			7	92,6					0,4			
R18			7	82,6					0,4		10	
R19	7,4			82,6							10	
R19A	7,4			82,6						10		
R19B	7,4			82,6								10
R20		7		82,6					0,4			
R21		7		82,6					0,4		10	

R22	4,3			92,6	3,1							
R23	4,3			92,6		3,1						
R24	4,3			82,6	3,1						10	
R24A	4,3			82,6	3,1							10
R24B	4,3		1,1	82,6	2							10
R25	4,3			82,6		3,1					10	
R25A	4,3			82,6		3,1						10
R25B	4,3		1,1	82,6		2						10
R26	4,3			82,6			3,1				10	
R27	5,3	3,1		81,6							10	
R27A	5,3	3,1		81,6								10
R28	8,4			81,6							10	
R28A	8,4			81,6								10
R29	4,3		3,1	92,6								
R30	4,3		3,1	82,6							10	
R30A	4,3		3,1	82,6								10

Stage 5: **Table 7** depicts the recipes produced during stage 5 of the project, with comparatively higher cement content, so as to increase the tumbler index of the resultant vibro-pressed briquettes. Effect on increasing the addition of biocarbon (R31A to R32B and R32A to R31B) is explored along with the effect of sieving of the biocarbon (R31A to R31B and R32A to R32B). Additionally, effect of addition of another type of biocarbon addition to the chromite fines briquettes were explored and compared to the reference (R33 to R32A and R32B). After obtaining decent value for tumbler index, reduction of cement from 10% to 7% (R34 to R37) was carried out as last few tests during this stage.

Table.7: Recipes produced during stage 5

Recipe	Cement	Dust	Ore 3	Floform	Sodium silicate	Bentonite	Biocarbon as-received	Biocarbon grinded	Biocarbon sieved <2.8mm	Other grinded biocarbon	Moisture content
R31A	10		85				5				9,8
R31B	10		85						5		11,3
R32A	10		80						10		14,5
R32B	10		80				10				9,9
R33	10		80							10	17,3
R34	7	3	80				10				9,6
R35	7		80		3		10				12,1
R36	7	2	80	1			10				11
R36A	7	2	80,5	0,5			10				11,4
R36B	7	2	80,8	0,2			10				11,4
R37	7		80			3	10				11,6

4.3.2 Evaluation of biocarbon-chromite briquette from technical scale

The drying behavior, density and mechanical strength of the technical scale reference briquettes were measured and evaluated. The mechanical strength was measured based on the calculated tumbler index but also the cold compression strength as given in **Figures 15 and 16**, respectively. The technical scale briquettes (produced in stage 2) showed similar trend to that produced at the industrial scale (tested in stage 1) and it was in order Ore 3 > Ore1+Ore2 > Ore 4.

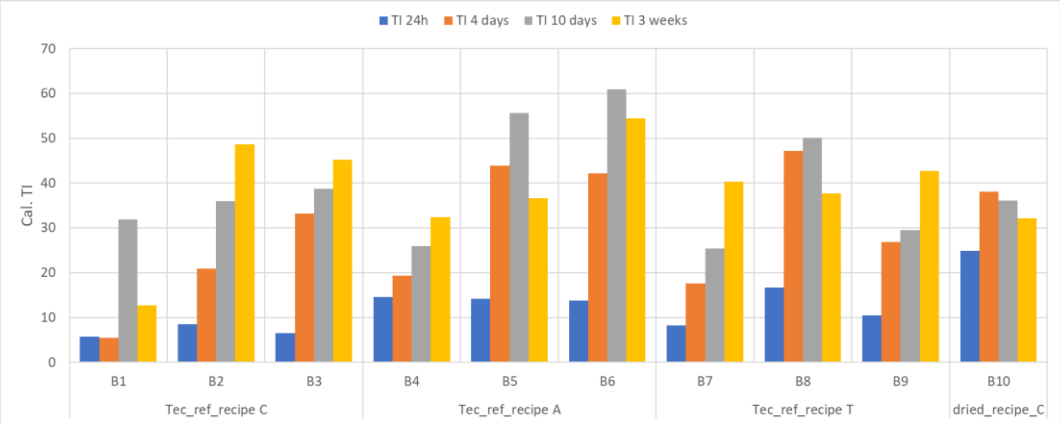


Figure 15: Calculated tumbler index for technical scale reference briquette

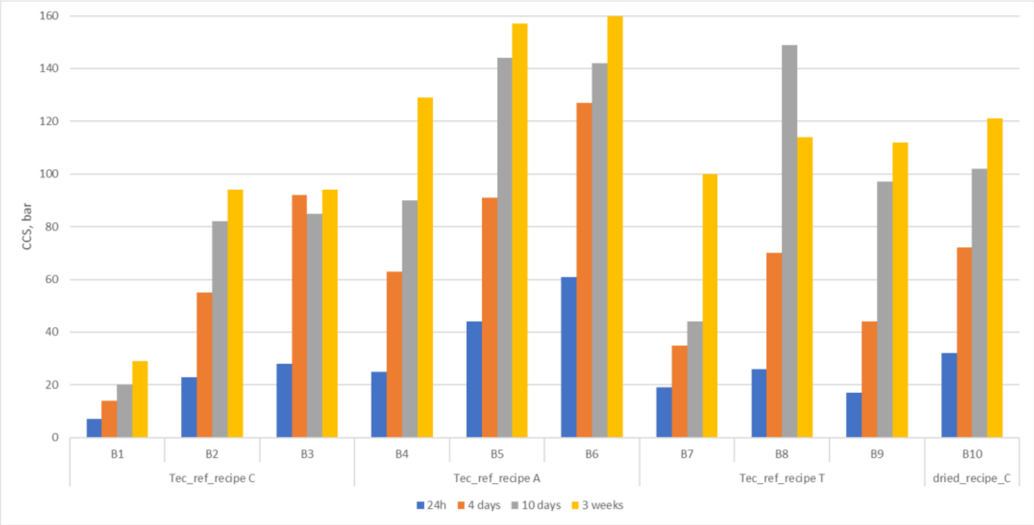


Figure 16: CCS of reference briquettes

From the obtained results, Ore 3 recipes were given primary consideration for further technical scale briquetting. For the afore-mentioned three runs throughout the project, variation in density, moisture content, Cold Compressive Strength (CCS), and tumbler index were determined. Additionally, for few recipes, drop test was also carried out to examine disintegration percentages of certain recipes.

Stage 3: **Figure 17, 18, and 19** depicts the tumbler index plots, briquettes after tumbling and strength variation plot of the vibro-pressed briquettes produced during the stage 3, respectively. This run proved that the reduction of water content decreased strength and tumbler index of the vibro-pressed briquettes significantly. Partial replacement of cement with monofil produced briquettes with low mechanical properties. Increasing the biocarbon addition from 5% to 10% have reduced the strength of vibro-pressed briquettes. Furthermore, the recipes produced with grinded biocarbon performed better than as received biocarbon. Finally, on comparing recipes produced with dust and ash, recipes containing dust outperformed recipes containing ash.

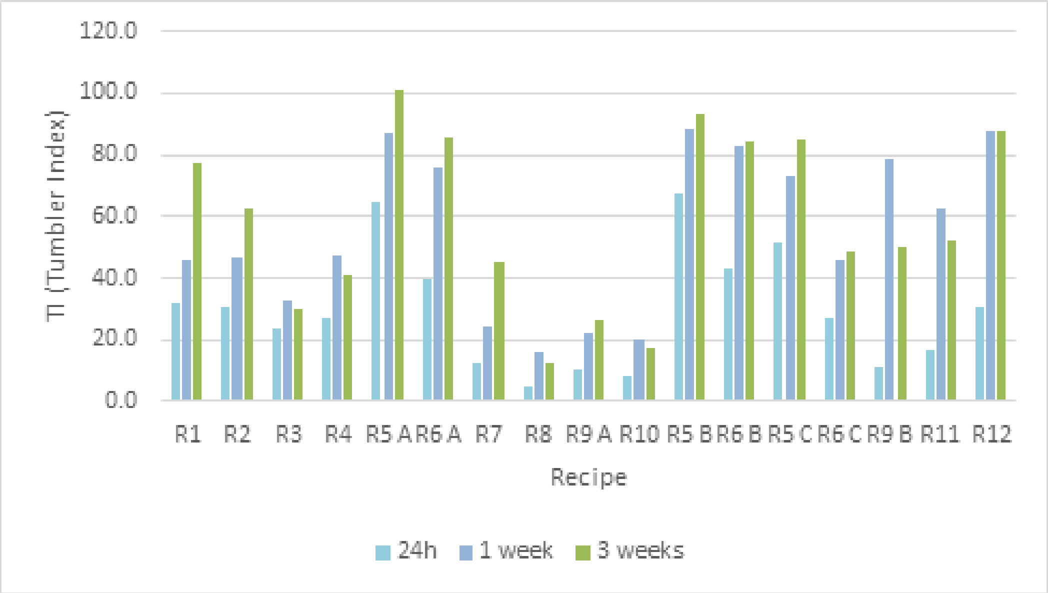


Figure 17: Tumbler index variation of the recipes for stage 3

Figure 18: Tumbler index measurement

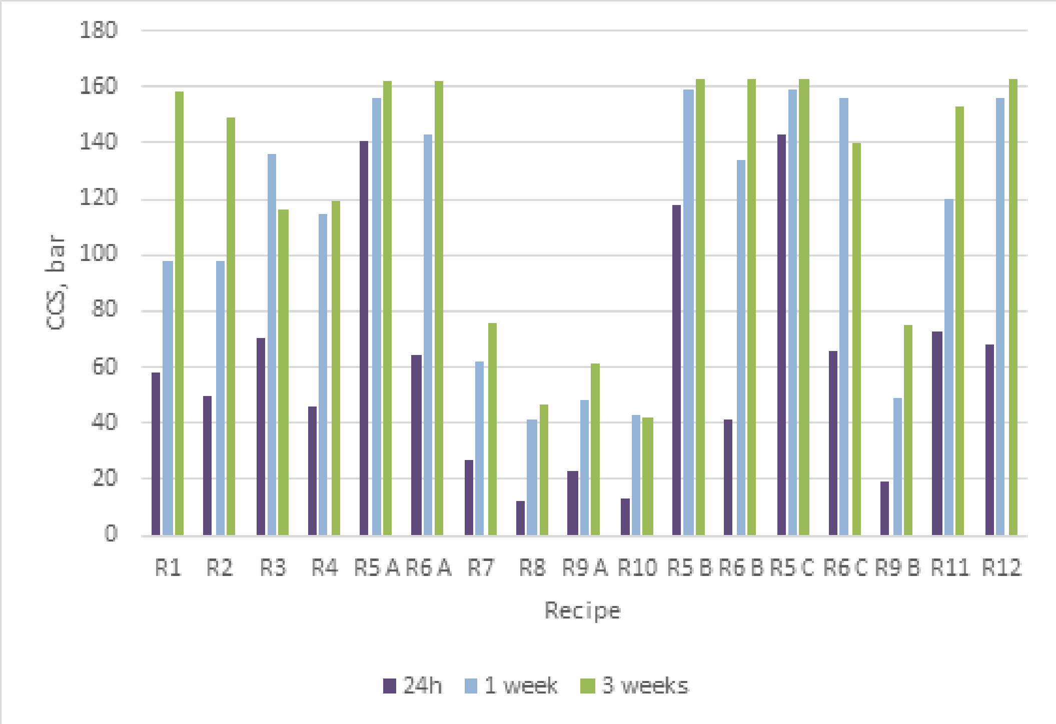


Figure 19: Strength (CCS) variation of the recipes for stage 3

Stage 4: **Figure 20 and 21** represent the tumbler index and CCS variation of the produced recipes during this run. Results proved that addition of 1% cement to dust/monofil ratio resulted in stronger briquettes. Therefore, dust has the possibility of replacing monofil as a binder. Recipes produced with lignin A and lignin B, as a binder, performed well in terms of strength and tumbler index. Whereas usage of cemfree or cemfree concentrate showcased very low strength, making them incapable to use as a binder during vibro-press briquetting of chromite fines. Generally, tumbler index for the developed briquettes were low when in comparison with the reference briquettes, as supplied from Vargön alloys. Hence, during the next run, cement content in the briquettes will be increased so as to result in higher quality vibro-pressed briquettes.

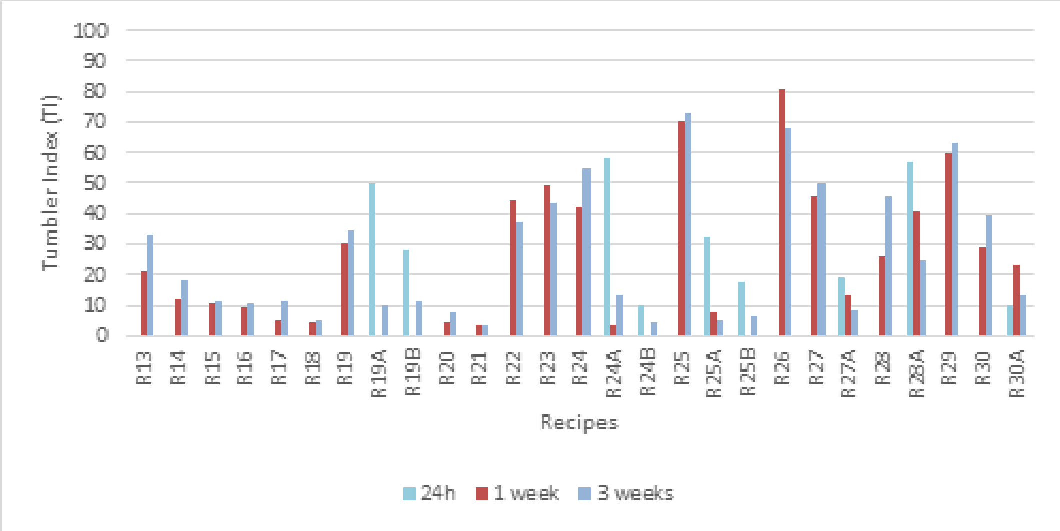


Figure 20: TI variation for the produced recipes during stage 4

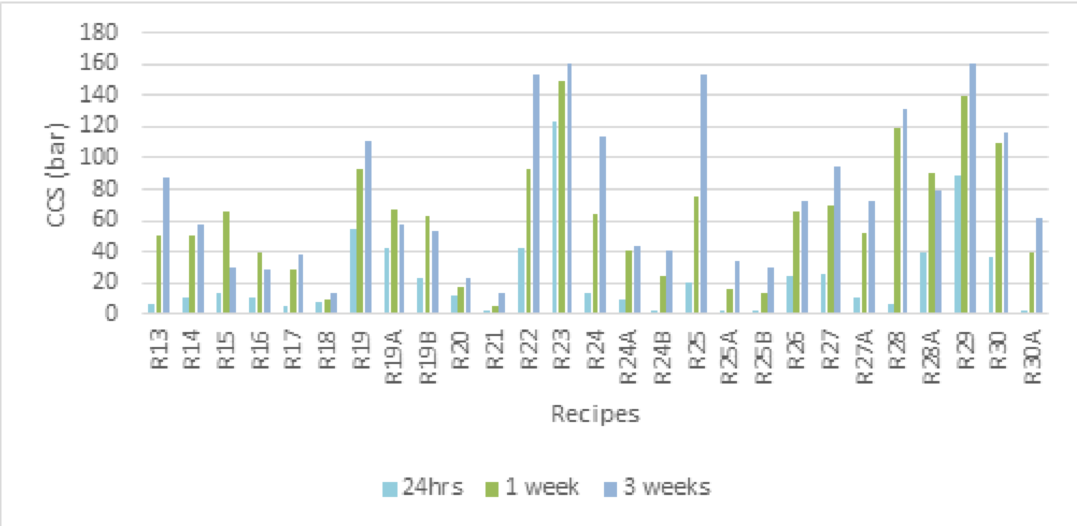


Figure 21: CCS variation for the produced recipes during stage 4

Stage 5: **Figure 22 and 23** represents the tumbler index and CCS variation for the produced recipes under stage 5. Usage of sieved biocarbon have increased the strength and tumbler index of the vibro-pressed briquettes significantly but also lowered the mechanical properties while increasing the biocarbon content from 5% to 10%. While the addition of other type of biocarbon showed very low improvement in the mechanical properties of the vibro-pressed briquettes. As the last part, replacement of 3% cement with 2% dust and 1% floform was the best combination to proceed with when in comparison with other combinations. Moreover, reduction of 1% floform content to 0.5 or 0.2% will further reduce the mechanical properties of the vibro-pressed briquettes.

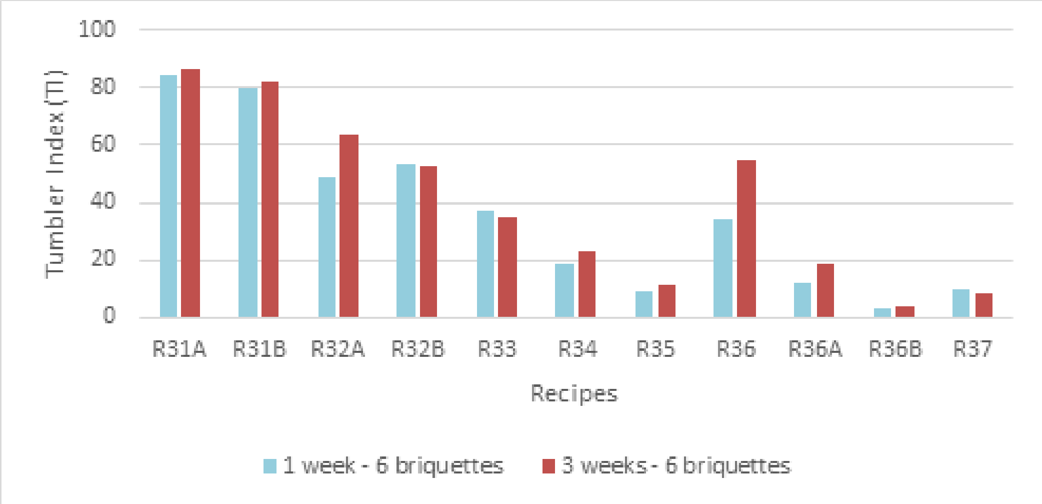


Figure 22: Tumbler index variation for the developed recipes during stage 5

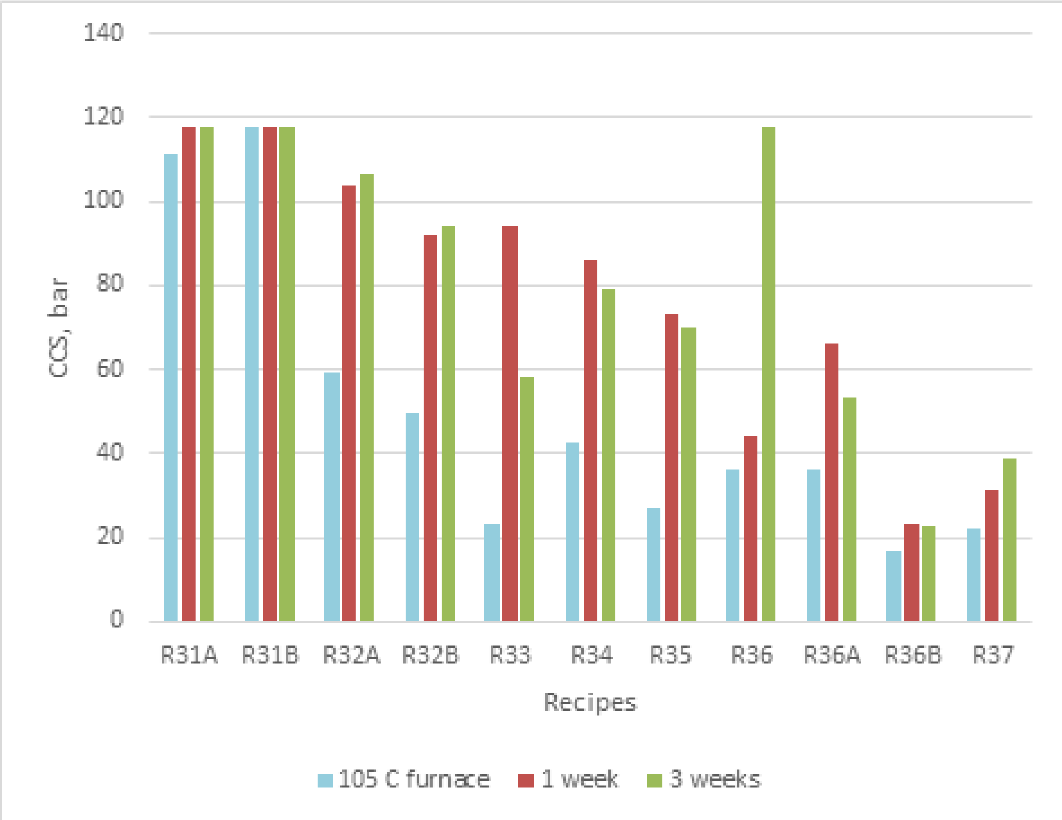


Figure 23: Strength (CCS) variation of the developed recipes during stage 5

Among the developed recipes on a technical scale during stage 5 (last stage), shown in **Table 8**, two recipes (R32B and R36) showed promising results in terms of mechanical strength as shown in **Figure 24**. These two recipes were recommended to proceed to the pre-industrial scale in larger batches.

Table 8: Highlighted recipes on a technical scale for upscaling

Recipe	Cement	Dust	Ore 3	Polymer FS	Sodium silicate	Bentonite	Biocarbon as-received	Biocarbon sieved <2.8mm	Other grinded biocarbon	Moisture content
R31A	10		85				5			9,8
R31B	10		85					5		11,3
R32A	10		80					10		14,5
R32B	10		80				10			9,9
R33	10		80						10	17,3
R34	7	3	80				10			9,6
R35	7		80		3		10			12,1
R36	7	2	80	1			10			11
R36A	7	2	80,5	0,5			10			11,4
R36B	7	2	80,8	0,2			10			11,4
R37	7		80			3	10			11,6

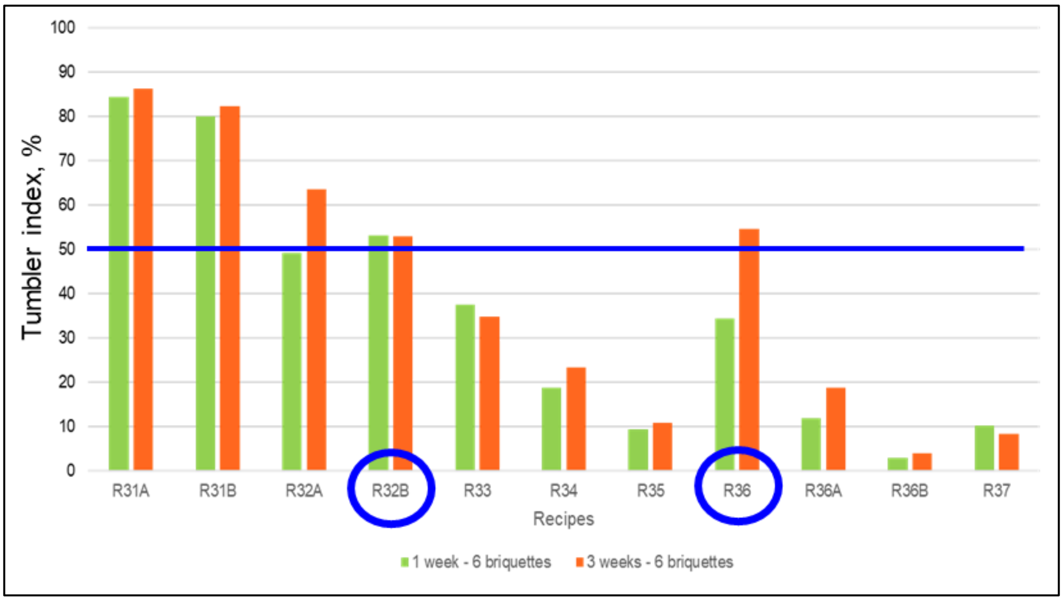


Figure 24: TI of technical scale and highlights of selected recipes for upscaling

5. Industrial Scale Briquetting

Before scaling up to large-scale industrial production, small batches (approximately 1,5 tons each) were tested, evaluated, and optimized, as described in the following sub-sections. In addition, risk assessments were conducted to ensure the safety of handling the biocarbon in the briquetting plant.

5.1. Pre-industrial scale Briquetting

5.1.1 Material handling for pre-industrial scale trials

For pre-industrial scale trials, a set-up was arranged for material handling as shown in **Figure 25**. Special tools were designed to open the biocarbon bag from the bottom before discharging to the material house at position 2. The chromite ore was placed positions 1 and 3 in material house. Two silos were arranged for cement and monofil while flue dust was charged manually to the mixer.

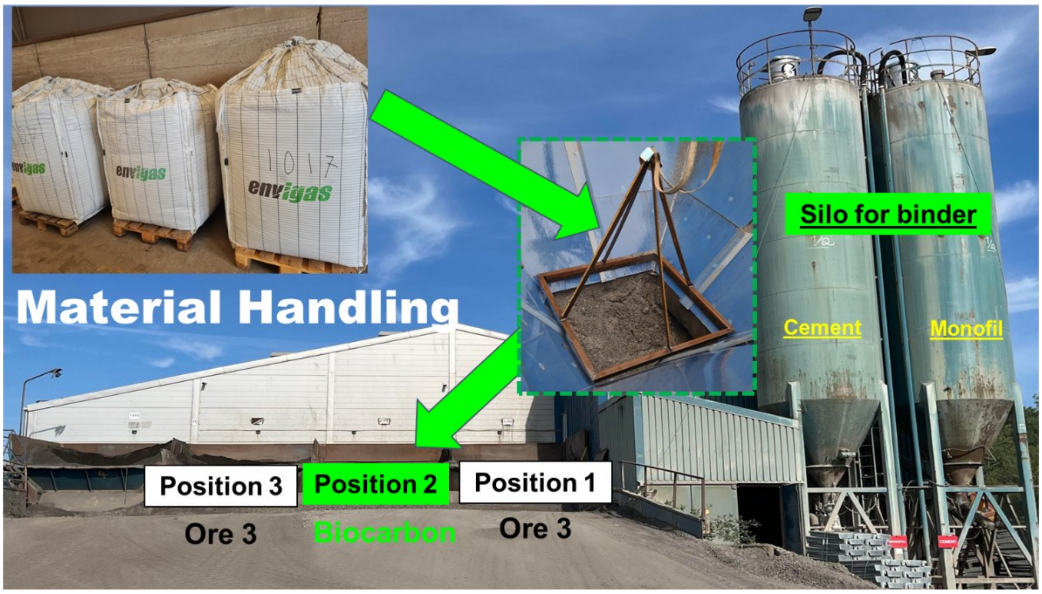


Figure 25: Material handling for pre-industrial trials

5.1.2 Designing the recipes for pre-industrial scale

Considering the outcomes of the technical-scale briquetting outlined in the previous section which were done at Swerim, a total of 16 recipes were formulated and assessed on a pre-industrial scale at Vargön, as detailed in **Table 9**. Among these recipes, one (REF) served as a reference and did not include any biocarbon, while the remaining recipes incorporated a 10% biocarbon addition. In the pre-trials, all biocarbon utilized was in its as-received form. Moisture content is a critical parameter in the agglomeration process. Consequently, certain recipes were replicated with varying moisture content to determine the optimal moisture level. This resulted in the production of 25 distinct batches, each with its specific moisture content, aimed at identifying the moisture content that yielded the best outcomes in terms of briquette quality and performance.

The briquetting procedure is illustrated in **Figure 26**. It begins by weighing the materials according to the specified recipe, with each batch totaling approximately 1,5 tons. The materials are mixed in an industrial-scale mixer, and water is added during mixing to achieve the desired moisture level. After 40 seconds of mixing, an agglomeration test was conducted to get a feeling of the batch. Done by compacting a small portion of material by hand. If it felt dry and didn't compact well, it indicated the need for additional water. If additional water was required, it was added to the batch by weighing it in buckets and then carefully incorporating it into the batch. Once a homogeneous mixture is obtained, the briquetting mix is transferred via a belt to the charging container that feeds the vibro press. The feeder fills the vibro press mold and adjusts the material level within it. The press operates under vibration for 2.5 seconds and the counter pressure is 55 bar, producing 98 hexagonal-shaped briquettes per batch. Under normal conditions the vibro press can produce 500-700 tons of briquettes per day. The green briquettes are then delivered to a curing chamber. The curing chamber consists of 6 compartments and each compartment has 36 trays which can cure about 296,000 briquettes per day. The green briquettes are cured for approximately 24 hours before being moved to the storage yard for further drying as shown in **Figure 27**, which can take up to 3 weeks. Each trial day ends with a batch of reference briquettes to ensure that biocarbon briquettes are pushed out from the curing chamber after 24h.

Table 9: Recipes designed for pre-industrial scale trials.

Recipe	REF	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15
Cement (%)	4.3	10	9	8	7	5	4.5	4.5	6	6	5.5	5.5	4.3	4.3	4.5	4,5
Monofil (%)	3.1	0	0	0	0	0	0	0	0	0	0	0	0	3.1	2.3	0
Polymer FS(%)	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0.2	0.5
Dust (%)	0	0	0	0	0	2	2.5	2.3	1	0	0	1	3.1	0	0	2
Biocarbon (%)	0	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Ore 3 (%)	92.6	80	81	82	83	83	83	83	83	84	84.5	83.5	82.6	82.6	83	83
Tota, (%)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

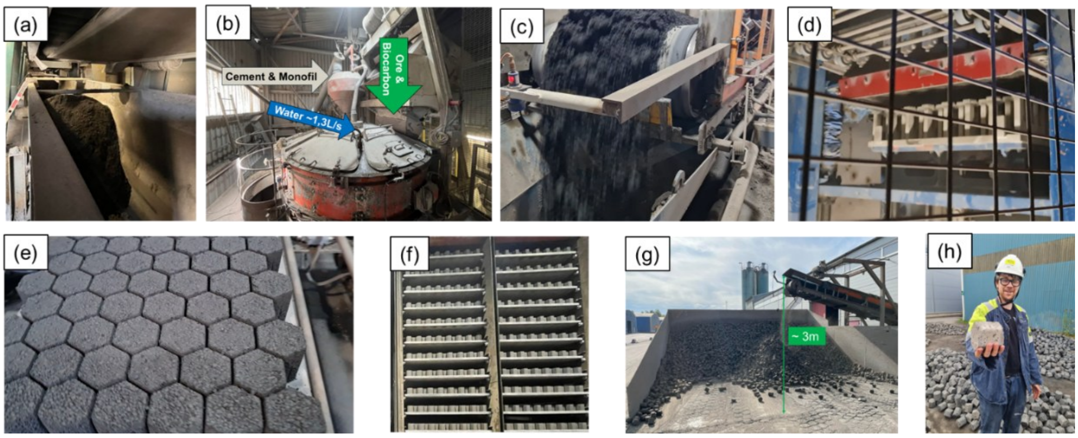


Figure 26: Briquetting procedures on pre-industrial scale:
(a) Weighing the materials, (b) Mixing and adding binder and water, (c) Belt for delivering the mixture to vibro press, (d) Vibro press briquetting machine, (e) Green briquettes after production, (f) Briquettes in curing chamber (g) Briquettes delivery to storage after curing (h) Briquettes after drying.

Figure 27: Pre-industrial scale briquetting at Vargön

5.1.3 Moisture optimization

When incorporating biocarbon into the briquetting mixture, it is essential to adjust the moisture content to produce high-quality briquettes. Several batches were produced for each recipe and the moisture content were measured in the mixture before press, after press, after 24h curing and after 1 week of drying as shown in **Figure 28**. An optimal moisture level facilitates the binding of materials, ensuring that the briquettes are formed effectively. This can be clearly shown in REF, R2-Batch 3, and R15-batch 1. However, if the moisture content is excessively high, the mixture may adhere to the mould, which can lead to reduced compaction force during the briquette formation process. This, in turn, compromises the overall quality and integrity of the briquettes. The optimum moisture content represents a balance where the mixture retains sufficient moisture without becoming overly wet. This balance can be identified in cases where the difference in moisture content before and after pressing is minimal. After a curing period of one week, all batches demonstrated satisfactory drying levels, with moisture content falling below 5 wt.%. This outcome indicates that the briquettes underwent adequate drying during the curing process, which is crucial for enhancing their quality and stability. Maintaining low moisture levels contributes to the briquettes' durability, making them more resilient to handling and transportation.

In this context, careful management of moisture content is given to optimize the biocarbon-chromite briquette quality. The findings underscore the importance of monitoring moisture levels throughout the briquetting process, from mixing to curing, to ensure the production of high-quality briquettes that meet performance standards.

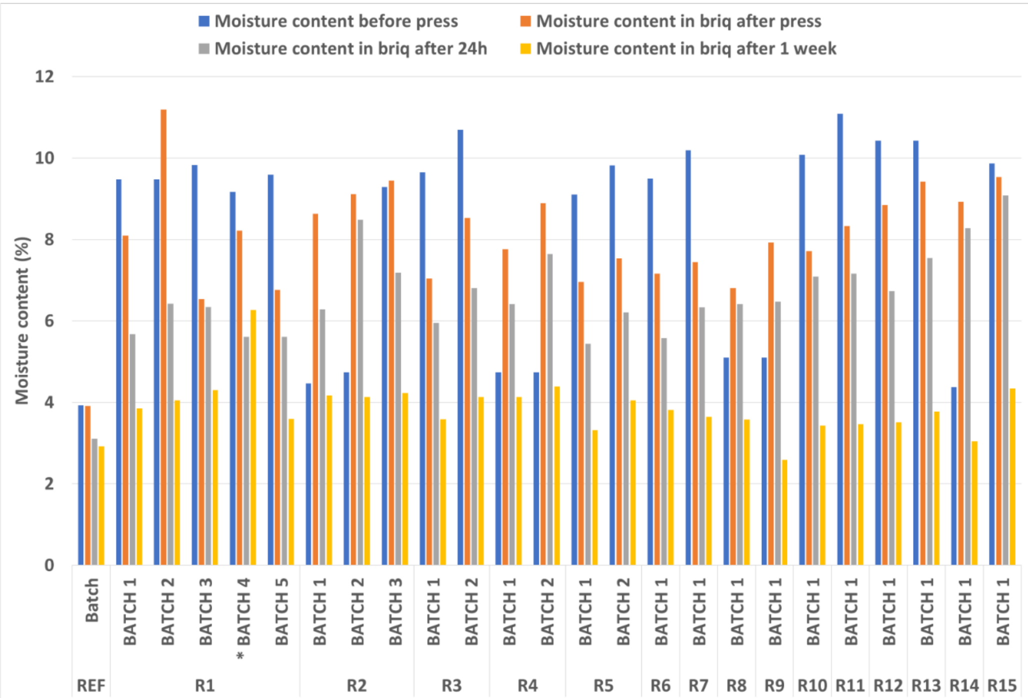


Figure 28: Moisture content of the recipes during the pre-industrial trials

5.1.4 Evaluation of cold mechanical strength

The mechanical strength of the briquettes was evaluated using the standard Tumbler Index (TI), with the results illustrated in **Figure 29**. The cement content in the briquettes significantly influences their mechanical strength. Higher levels of cement (>7%) in recipes R1-R4 can counteract the potential weakening effects of biocarbon compared to recipes R5-R15, which were produced with lower cement content (<7%). The density of most biocarbon-containing briquettes ranged from 2.5 to 2.8 g/cm³, slightly lower than the reference briquettes without biocarbon, which had a density of about 3.3 g/cm³. The higher density and strength of recipe R1-Batch 4 were attributed to uncertainties regarding the amount of biocarbon added to this batch.

The most promising recipes in terms of mechanical strength were R3-Batch 2 (containing 9% cement), R4-Batch 4 (7% cement), and R11-Batch 1 (5.5% cement and 1% flue dust). From an environmental perspective, relying excessively on cement in biocarbon briquetting is counterproductive, as it negates the advantages of incorporating biocarbon. Therefore, R11 exhibited the most promising results, featuring a cement content that was

1.5 wt.% higher than the reference case while notably excluding 3.1% monofil. Remarkably, R11 achieved comparable mechanical strength to the reference sample, indicating an effective balance between cement utilization, recycling of flue dust, and adequate mechanical strength. This suggests that R11 optimized the use of biocarbon while minimizing excessive reliance on cement.

For further assessment of high-temperature strength, the recipes selected for analysis included REF, R3-Batch 2, R4-Batch 2, and R11. These samples were chosen based on their performance metrics and qualities observed during initial evaluations, making them suitable candidates for examining structural integrity under elevated temperatures.

This comprehensive analysis underscores the importance of finding an optimal balance between biocarbon and cement in briquette formulation, aiming to enhance mechanical strength while maintaining environmental sustainability. Future studies could explore additional additives or alternative formulations to further improve the performance of biocarbon briquettes without compromising their ecological benefits.

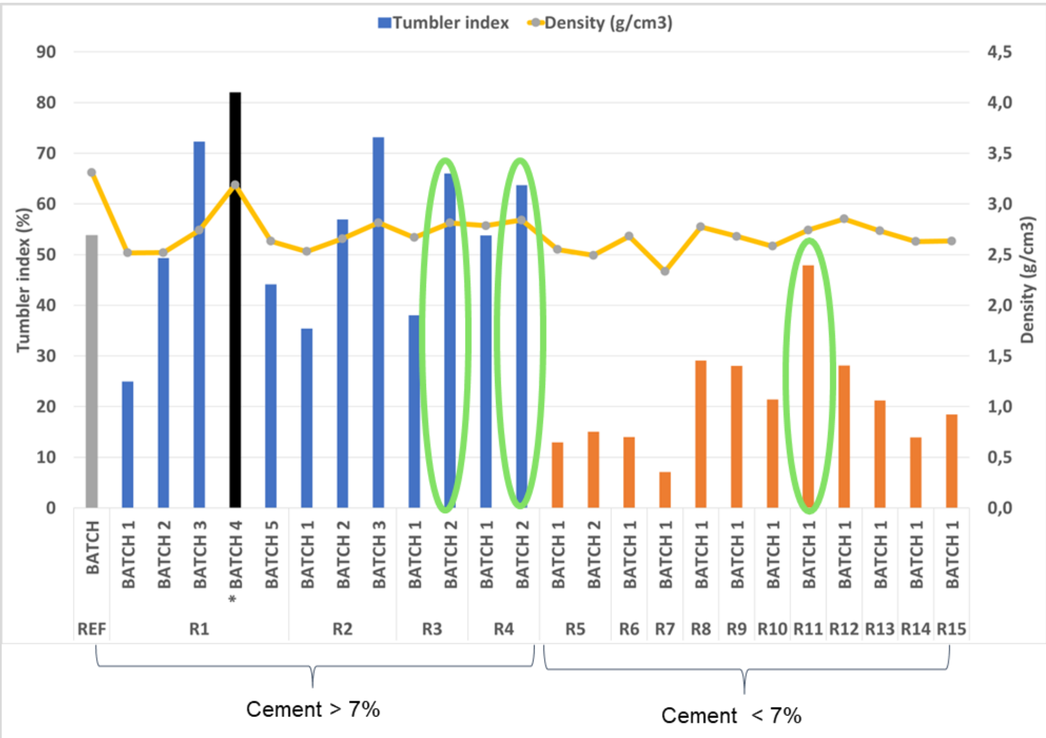


Figure 29: Tumbler index of the recipes produced during the pre-industrial vs moisture

5.1.5 Evaluation of hot mechanical strength

The recipes were subjected to hot strength testing. Detailed procedures for assessing hot strength were provided in the previous methodology section. The hot strength testing of the selected recipes was executed at 1000°C under a load of 25 kg per briquette for 1 hour. Although the biocarbon-containing recipes initially exhibited cold mechanical strength comparable to the reference, a noticeable decrease in mechanical strength was observed after conducting the hot strength test, as shown in **Figure 30**. This reduction in strength corresponded with an increased mass loss, which directly resulted from the briquettes being subjected to high temperatures.

At 1000°C, the embedded biocarbon facilitated the reduction of FeO in the ore, making it an effective component for this process. Post-trial analysis of the carbon content in the briquettes indicated an average carbon loss of only 23% of the initial amount. The calculated mass loss, based on an oxygen balance assumption for complete FeO reduction, averaged 3.7 wt.%. In contrast, the measured average mass loss was 6.6 wt.%. This discrepancy can be attributed to the removal of volatiles and chemically bonded water released during cement hydration.

Notably, R11 exhibited the lowest cement content among the biocarbon recipes while still maintaining acceptable cold and hot mechanical strength. This characteristic makes it a strong candidate for larger-scale production of the briquettes. Selecting R11 is crucial to ensure that the biocarbon-chromite briquettes can effectively reach the reduction zone of the Submerged Arc Furnace (SAF) without significant disintegration, thereby maximizing the efficiency of the reduction process.

In this context, while the hot strength evaluation highlighted challenges in maintaining mechanical integrity at elevated temperatures, R11's optimal balance of biocarbon and cement positions it as a viable option for industrial applications.

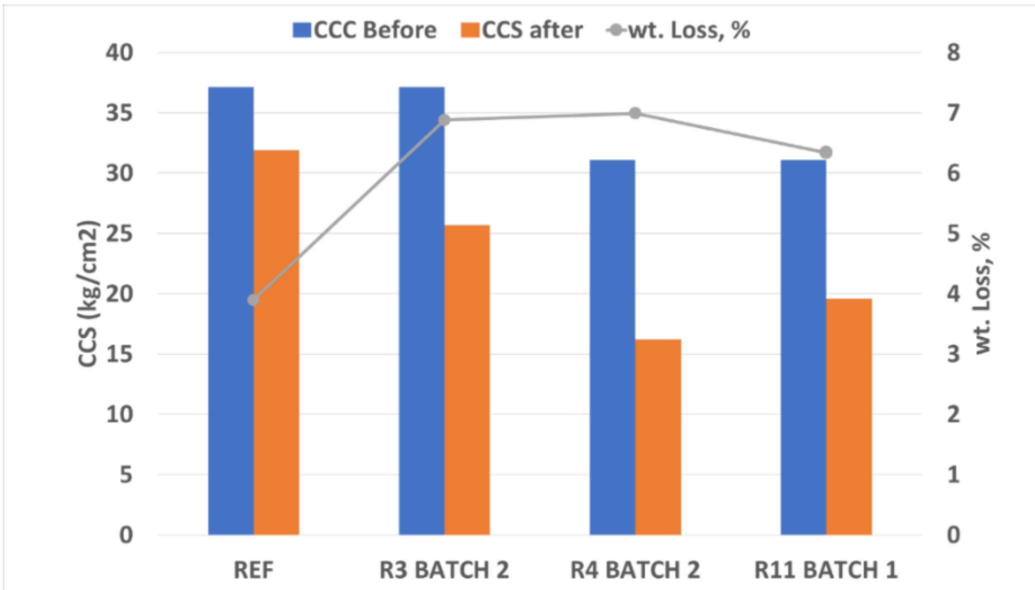


Figure 30 CCS before and after hot strength vs mass loss of each briquette

The main outcomes from the pre-industrial trials can be summarized as follows:

- A total of 36 tons of biocarbon briquettes were produced during an 8-day test period.
- The initial evaluation of the briquettes indicates that a higher cement content leads to significantly stronger briquettes. Specifically, recipes with cement content above 7% performed as well as or better than the reference briquettes in drop tests.
- Flue dust used as a binder demonstrated promising results; with just 1% flue dust, the cement content could be reduced to 5% while maintaining performance comparable to the reference briquettes in drop tests.
- Among the produced briquettes, those using polymer as a binder required a curing time of over 24 hours. However, this extended curing did not enhance mechanical strength, resulting in the lowest performance in drop tests.
- Hot strength testing showed good stability of the briquettes after heating up to 1000 ºC under load in inert N_2 gas. By measuring the carbon content before and after heating, it indicates that 66-100% of the initial carbon in REF briquettes was consumed compared to only 20-25% of the initial carbon in the biocarbon-chromite briquettes.
- Recipe R11, containing 5.5% cement and 1% flue dust, was selected for the industrial trial.

5.2 Full industrial-scale briquetting

For the full-scale industrial briquetting campaign, the materials were organized similarly to the pre-industrial trials (see **Figure 25**). However, instead of manual feeding, the silo originally used for monofil was repurposed to feed flue dust, as there was no need to include monofil in Recipe R11. This change streamlined the process and optimized efficiency.

A total of six batches were produced to ensure reproducibility of the briquettes. During this phase, the moisture content was meticulously measured, as illustrated in **Figure 31**. Initially, the moisture content of the mixture ranged from 8-9%, but this decreased to 6-7% after one week of curing.

The mechanical strength of the briquettes was assessed using the tumbler index, shown in **Figure 32**. Remarkably, the mechanical strength of briquettes produced at the full scale was approximately 27%, compared to 47.7% from the pre-trials. This difference highlights the challenges faced during large-scale production due to weathering conditions. The average moisture content of the full-scale briquettes was around 4.7%, slightly higher than the 4.2% observed in the pre-trial briquettes.

Figure 33 illustrates the physical condition of the briquettes before and after the tumbler index test. It is evident that the full-scale production generated more fines compared to the pre-trials. The reduced strength of the full-scale briquettes can primarily be attributed to adverse weather conditions, including snow and poor weathering, which affected the production process.

Despite the lower mechanical strength compared to the pre-trials, the full-scale briquettes still exhibited adequate strength for charging into the SAF. In total, approximately 350 tons of biocarbon-chromite briquettes from Recipe R11 were successfully produced and stored, as depicted in **Figure 34**, ensuring readiness for the upcoming industrial smelting campaign.

This comprehensive approach to scaling up the briquetting process not only underscores the importance of material management but also highlights the adaptability required to overcome environmental challenges in industrial production.

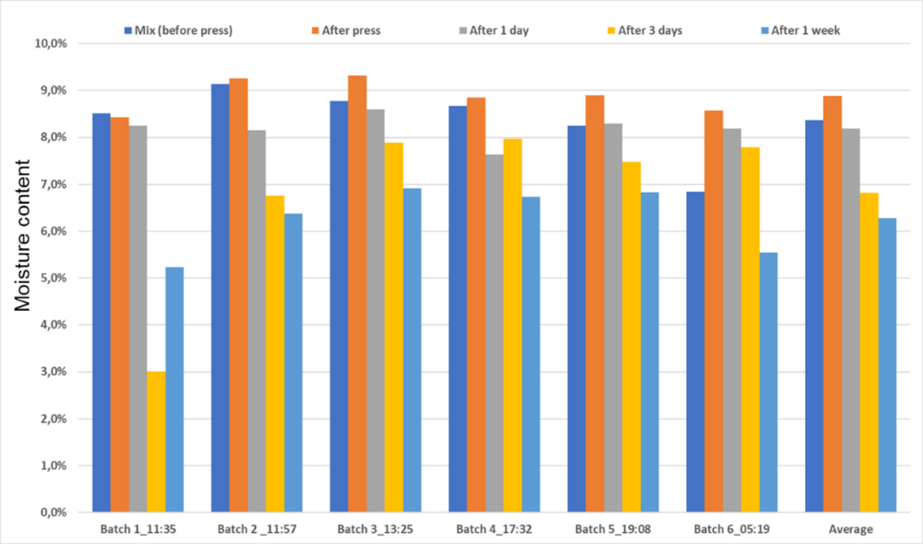


Figure 31 Moisture content for 6 batches from R11

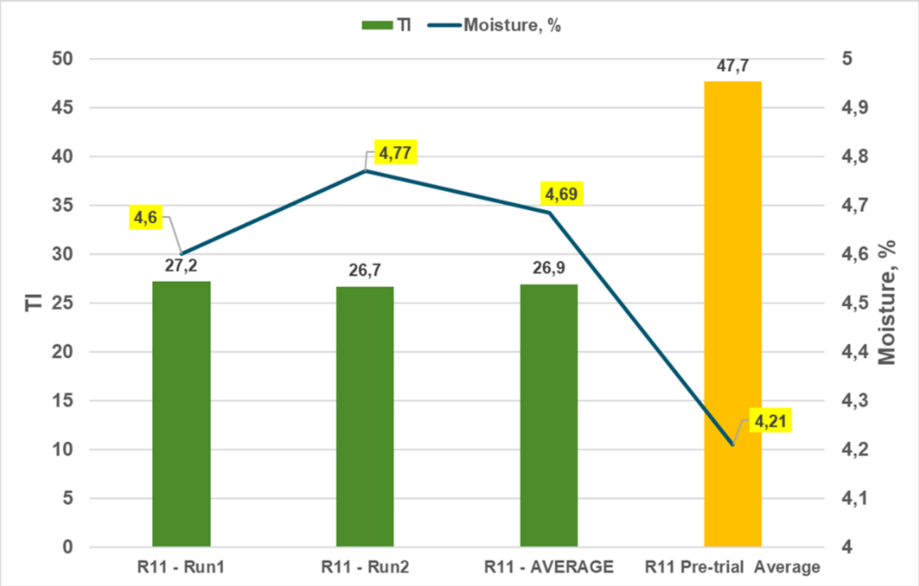


Figure 32 Tumbler index vs moisture content of the briquettes

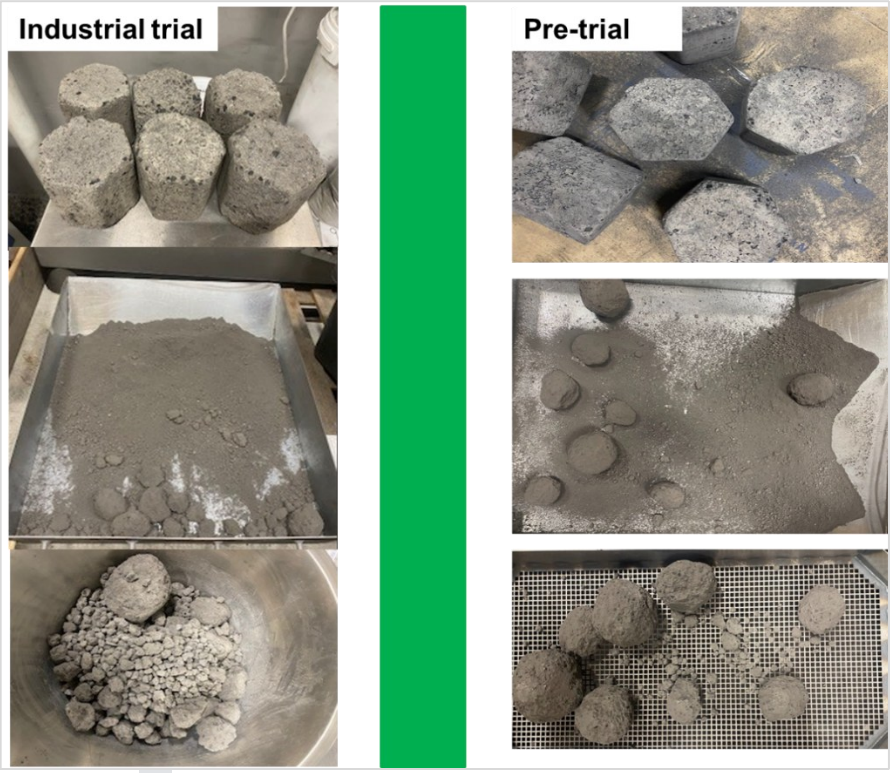


Figure 33 Photos of briquettes before and after tumbler index

Figure 34 Biocarbon-chromite briquettes from full scale briquetting

6. Industrial Campaign at Vargön SAF

6.1 Design of industrial campaign

The campaign aims to implement biocarbon as a reductant for HC FeCr production, via self-reducing biocarbon-chromite briquettes, replacing fossil coke with a green carbon source. Process data was collected throughout the campaign in order to conduct a complete mass and energy balance over the system. Therefore, metal and slag samples were taken from each tapping, while dust samples were collected via Swerim gas measuring equipment. In addition, gas analyzer was connected to the off gas system to monitor the off-gas composition. The campaign was conducted at SAF No. 10 at Vargön. The trials started with reference (REF) briquettes then switched to the developed biocarbon-chromite briquettes (R11). The recipes of reference and developed biocarbon is given in **Table 10.**

The primary objective of this campaign was to explore the feasibility of partially replacing top-charged coke with biocarbon in the briquettes.

The Campaign Timeline is shown in Table 11 and can be described as follow:

- **REF Period:** The campaign commenced on Wednesday week 5, 2024, utilizing reference briquettes (REF). The charging rate of REF briquettes was gradually increased from 10% to 30% by Friday. On Saturday, the charging rate reverted back to 10% before switching to biocarbon briquette.
- **Transition to Biocarbon:** Starting Sunday, the campaign shifted focus by transitioning from 10% REF briquettes to 10% biocarbon-chromite briquettes (R11). By Monday of Week 6, the usage exclusively comprised 10% R11 briquettes.
- **Increased Use of Biocarbon:** From Tuesday to Friday of Week 6, the biocarbon-chromite briquettes' charging rate was increased to 30%.
- **Return to Reference Briquettes:** The weekend of Week 6 saw a return to reference briquettes at a 30% charging rate. This pattern continued into Week 7, where the furnace operated solely with REF briquettes.

This structured approach allows for a comprehensive comparison of performance metrics between the biocarbon-infused and traditional briquettes throughout the campaign.

The SAF campaign aims to evaluate the operational efficiency and performance implications of substituting conventional materials with biocarbon, thereby promoting more sustainable practices in the SAF operations.

Table 10: REF and R11 recipes used during the industrial campaign

Briq recipe	Ore	Cement	Monofil	Filter dust	Biocarbon
REF	92,6%	4,3%	3,1%	0%	0%
R11	83,5%	5,5%	0%	1%	10%

Table 11: Bio4SAF Campiagn timeline

			REF →				Biocarbon →					REF →		
Per charge (%)	W5 We	W5 Thu	W5 Fri	W5 Sat	W5 Sun	W6 Mon	W5 Tus	W5 We	W5 Thu	W5 Fri	W5 Sat	W5 Sun	W7 Mon	W7 Tus
Briq, REF	10	30	30/ 10	10	10						30	30	30	30
Briq, R11					10	10	30	30	30	30				

Figure 35 illustrates the data collection points during the campaign at SAF No. 10 at Vargön. It highlights three key monitoring and measurement locations, each contributing to the overall evaluation of the operation:

1. **SAF Monitoring:** This section focuses on the input charging burden and output products, including FeCr and slag. Continuous monitoring at this point ensures that the production processes are optimized and that the FeCr meets the required quality.
2. **Metal Recovery Plant:** During tapping, three ladles are arranged for each heat: one for metal, one for a mix of metal and slag, and the last for slag. The slag recovery plant operates on the separation of metal from the slag to produce metal-rich and metal-poor slag. The metal-rich slag undergoes further physical treatment for chromium metal separation, while the metal-poor slag is sent to the storage slag yard.
3. **Filter System:** This system is crucial for monitoring of dust generation. An iso-kinetic dust measuring probe was installed during the campaign to assess the rate of dust generation and conducts off-gas analysis using a Swerim gas analyzer. By analyzing dust and monitor the off-gas generation, the data helps in evaluating the efficiency of biocarbon utilization during the campaign.

The interconnectedness of these components, as depicted in the figure, emphasizes a comprehensive approach to monitoring and optimizing the entire process at SAF No. 10. The data collected from these points will inform operational adjustments and enhance both productivity and environmental stewardship at Vargön Alloys AB.

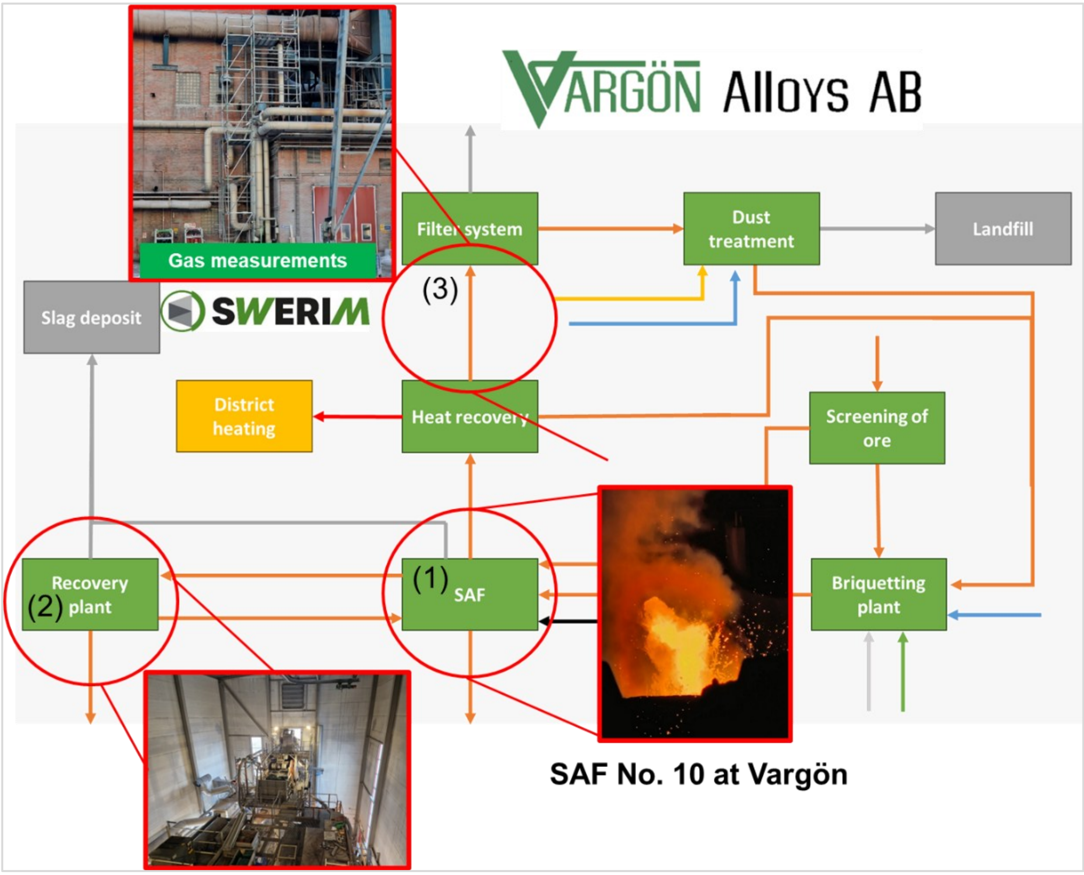


Figure 35 Data collection points during the campaign

6.2 Evaluation of the SAF campaign

6.2.1 Coke replacement

Vargöns metallurgical process is a semi-batch process where raw material is continuously fed to the semi-closed SAF via charging machines. Metal and slag are tapped in intervals after a certain amount of power has been introduced to the furnace via the electrodes. The coke amount charged to the furnace is determined by mass- and heat balance calculations based on the chemical composition of the ore charge, consisting of ore/s, briquettes, and limestone. The coke replacement with biocarbon was based on the initial amount of coke ($Coke_{initial}$) per ore charge. Three factors determined the replacement ratio:

- Amount of biocarbon in the briquettes
- Briquette charge rate
- Ratio between biocarbon and fossil carbon

The first step was determining how much biocarbon there was in the ore charge. Calculated by multiplying the charge rate of briquettes by the percentage of biocarbon in the briquettes

$$Charge_{biocarbon} = Briquette\ charge\ rate * \%\ biocarbon\ in\ briquetters \quad \text{(Eq.1)}$$

The second step was to determine the ratio between biocarbon ($C_{Biocarbon}$) and fossil carbon (C_{Fossil})

$$C_{ratio} = \frac{C_{Biocarbon}}{C_{Fossil}} \quad \text{(Eq.2)}$$

It was then possible to determine how much coke to remove from the coke charge by converting the amount of biocarbon charged from the briquettes to coke by multiplying Eq.3 with Eq.4 and dividing it with the fossil coke's C-fix value

$$Coke_{biocarbon} = \left(\frac{(Charge_{biocarbon} * C_{ratio})}{Coke_{Cfix}}\right) \quad \text{(Eq.3)}$$

From there, the new coke charge was calculated by subtracting the converted biocarbon to coke from the initial coke charge

$$Coke_{new} = Coke_{initial} - Coke_{biocarbon} \quad \text{(Eq.4)}$$

The coke replacement ratio was then determined by dividing the new coke charge by the initial coke charge

$$Coke\ replacment\ ratio = \frac{Coke_{new}}{Coke_{initial}} \quad \text{(Eq.5)}$$

Figure 36 illustrates the carbon replacement during the charging process to the SAF, specifically highlighting the substitution of coke with biocarbon in the briquettes. The blue columns represent the biocarbon-to-coke replacement ratio, which approximately reaches 1.0, indicating a balanced substitution. The line tracks the percentage of coke removed throughout the campaign. It can be seen that, when 10% biocarbon-chromite briquettes (R11) are charged, approximately 5.5% of the coke is removed. As the biocarbon-chromite briquettes increase to 30% in the burden, the amount of removed coke rises significantly to 21.8%.

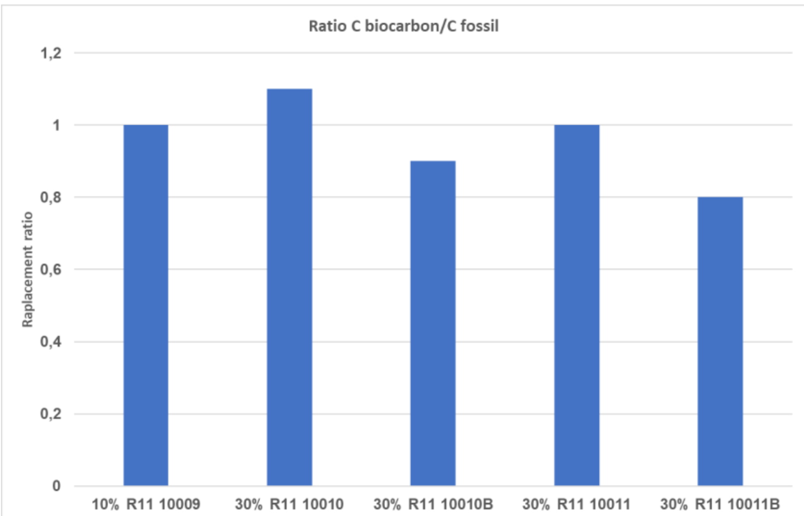


Figure 36 Coke replacement in the charge

6.2.2 Carbon and Silicon in Metal

Figure 37 illustrates the variations in carbon, silicon, and sulfur levels throughout the campaign. Initially, during the reference period with 10% briquettes, the carbon content in the metal increased from approximately 7% to around 8%, stabilizing at this level during the subsequent charging of biocarbon briquettes. During the 30% biocarbon period, we aimed to increase the replacement ratio of coke with biocarbon to over 1 (see **Figure 36**), which could potentially lead to a coke shortage in the lower part of the furnace. This situation might cause a decrease in Si content in the melt and an increase in S concentration, as illustrated in **Figure 37**. To address the sulfur issue, we enhanced the basicity of the slag, which helped lower the temperature and reduced sulfur solubility. Throughout the remainder of the biocarbon period, we successfully maintained sulfur concentrations within acceptable levels.

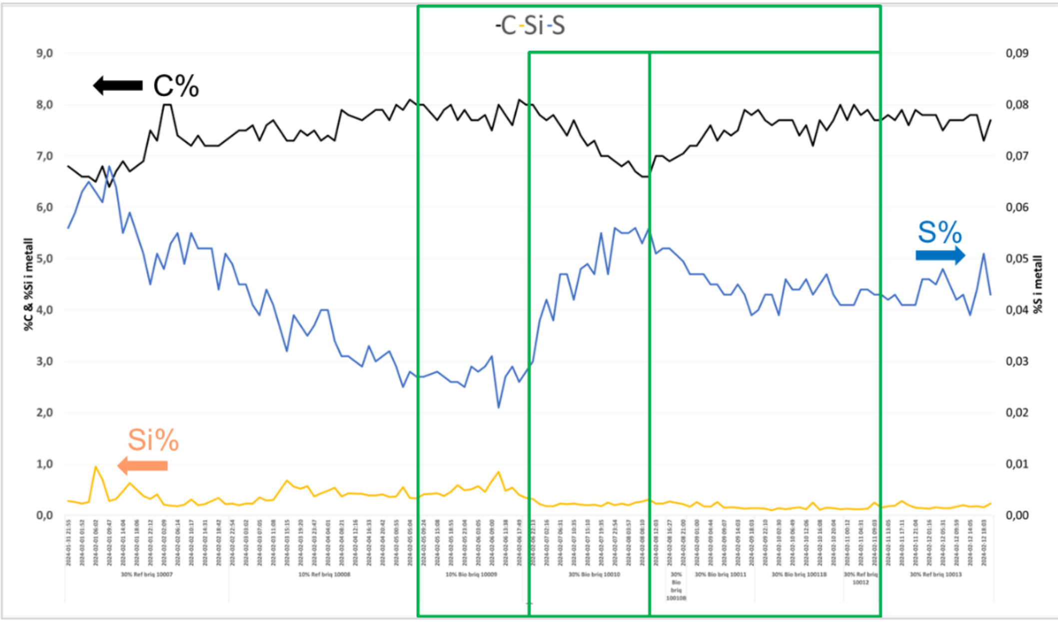


Figure 37 Concentration of C, Si, and S in the FeCr during the campaign

6.2.3 Phosphorus-Sulfur in Metal

The variations in P and S levels throughout the campaign are illustrated in **Figure 38**. Initially, sulfur levels exhibited a downward trend, fluctuating around 0.06% before reaching a low point (0.02-0.03%). Following this, there was a slight increase during the period of charging 30% biocarbon briquettes, stabilizing in the range of 0.04%. This level is lower than what was achieved with 30% reference briquettes at the beginning of the campaign. This reduction can be attributed to the relatively higher sulfur content (1.6%) in the monofil used in the reference briquettes, compared to the biocarbon briquettes manufactured without monofil. Additionally, the lower sulfur content in biocarbon compared to top-charged coke likely contributed to this decrease, indicating effective sulfur removal processes influenced by the input sulfur in the biocarbon-chromite briquettes.

In contrast, phosphorus levels remained relatively stable around 0.008% but began to increase to 0.01% with the charging of 30% biocarbon-chromite briquettes. Interestingly, phosphorus stabilized around 0.01% until the end of the biocarbon charging phase, after which it started to drop back to 0.008% when returning to the reference briquettes.

In general, it can be concluded that, while sulfur is being effectively reduced during biocarbon period, the gradual increase in phosphorus warrants further investigation to understand its implications for the quality of the final product. Overall, these figures underscore the importance of monitoring elemental concentrations to optimize metallurgical operations and enhance product quality.

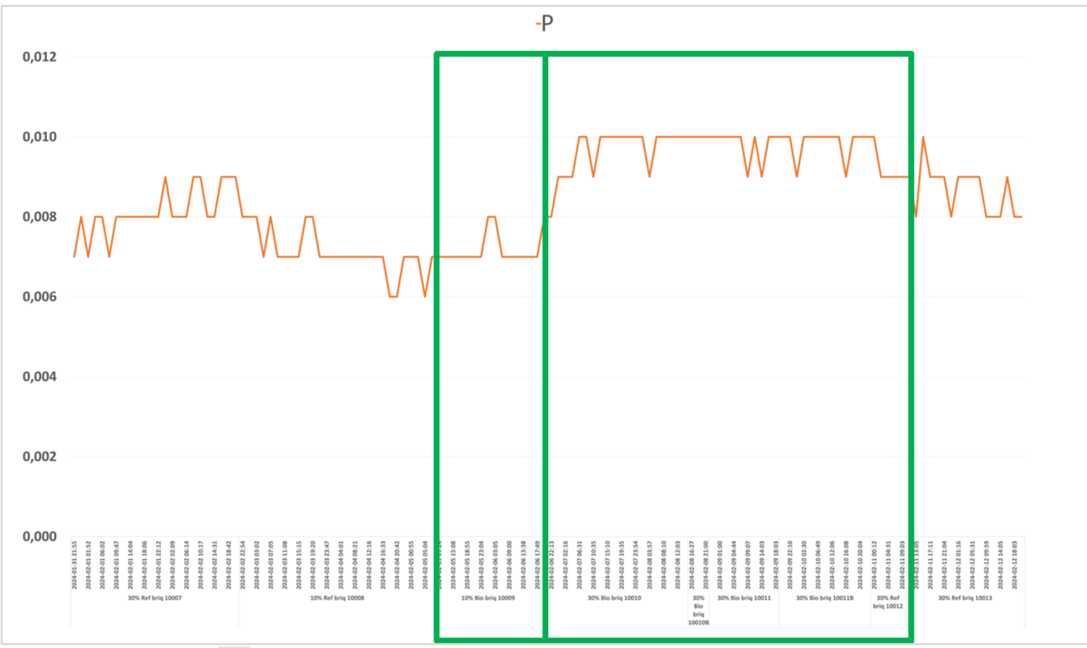


Figure 38 Concentration of P in the FeCr during the campaign

6.2.4 Energy and electrode consumption

The energy consumption during the campaign is illustrated in **Figure 39**. Throughout the campaign, energy consumption exhibited fluctuations, with notable peaks and troughs. During the period with 30% REF briquettes, energy usage averaged around 16 MWh, reflecting the established operational parameters and the energy requirements associated with fossil coke utilization. Charging 10% biocarbon briquettes resulted in a slight decrease in energy consumption, averaging just below that of the REF period. When the biocarbon briquette charging rate was increased to 30%, energy consumption increased slightly, approaching the levels recorded with 10% REF but still remaining lower than those observed with 30% REF. This reduction can be attributed to the lower energy requirements of self-reduced biocarbon-chromite briquettes compared to traditional fossil fuels, potentially enhancing overall energy efficiency in the metallurgical process. In addition, the stability in energy consumption during the biocarbon period, in contrast to the more variable consumption seen with reference briquettes, suggests that biocarbon may provide a more consistent energy profile. However, drawing definitive conclusions from such a short campaign is challenging; a longer campaign is recommended to obtain more validated data for a comprehensive analysis of energy consumption and efficiency.

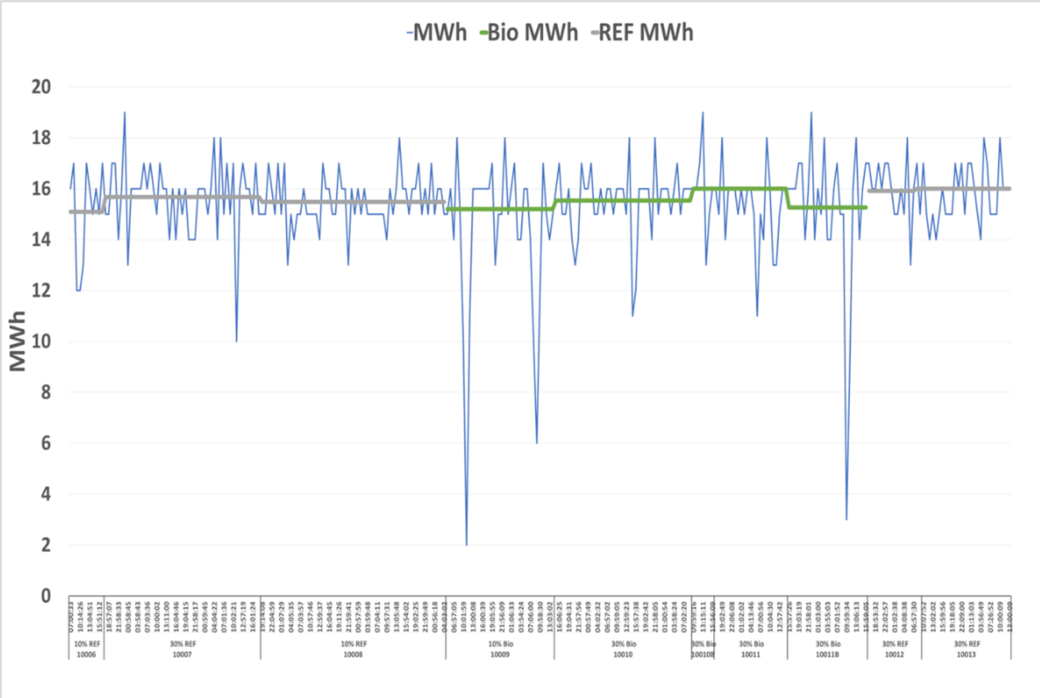


Figure 39 Energy consumption during the campaign

6.2.3 Metal recovery from slag

Figure 40 illustrates the comparison of metal recovery from slag during the REF and Biocarbon periods. The data indicates that metal recovery rates are relatively similar between the two periods, but there are notable differences in specific categories. For instance, the recovery rate of metals from the middling fraction sized 1-8 mm was higher during the biocarbon period compared to the REF period. Conversely, the recovery rate for the middling fraction sized 8-32 mm was higher during the REF period, highlighting a contrasting performance based on particle size. Overall, while the metal recovery from slag during both periods remains close, there are no significant changes in overall recovery rates between REF and biocarbon periods. This suggests that both materials have comparable efficiencies, although variations exist depending on the size of the material being processed.

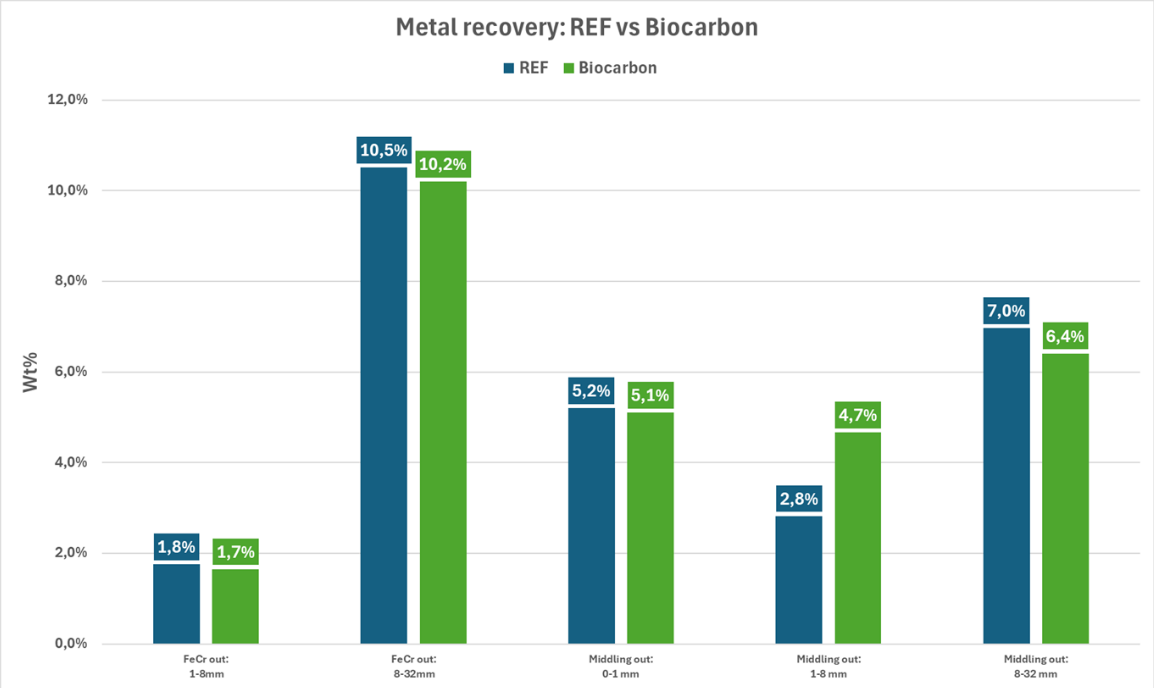


Figure 40 Metal recovery from slag

6.3 Iso-kinetic dust and off-gases measurements

6.3.1 Measuring points

The measuring positions are shown in **Figure 41**, the off-gas flow coming from the SAF passes the dust measuring position number 1 and a short distance later the gas flow probe and temperature probe are positioned, position number 2. Further a distance position 3 was placed where the gas analysis probe was mounted just before the gas cleaning filter. The gas- and dust analysers were placed below the roof inside the workshop. The back-purging- and control units, also temperature and gas flow data acquisition unit were placed on the roof above the workshop close to the gas cleaning filter. Calibration of the analysers was done before the measurements started and control of the analysers after the measurements were completed. Pressurised air was used for automatically back-purging the gas probe and manually back-purging the gas flow probe.

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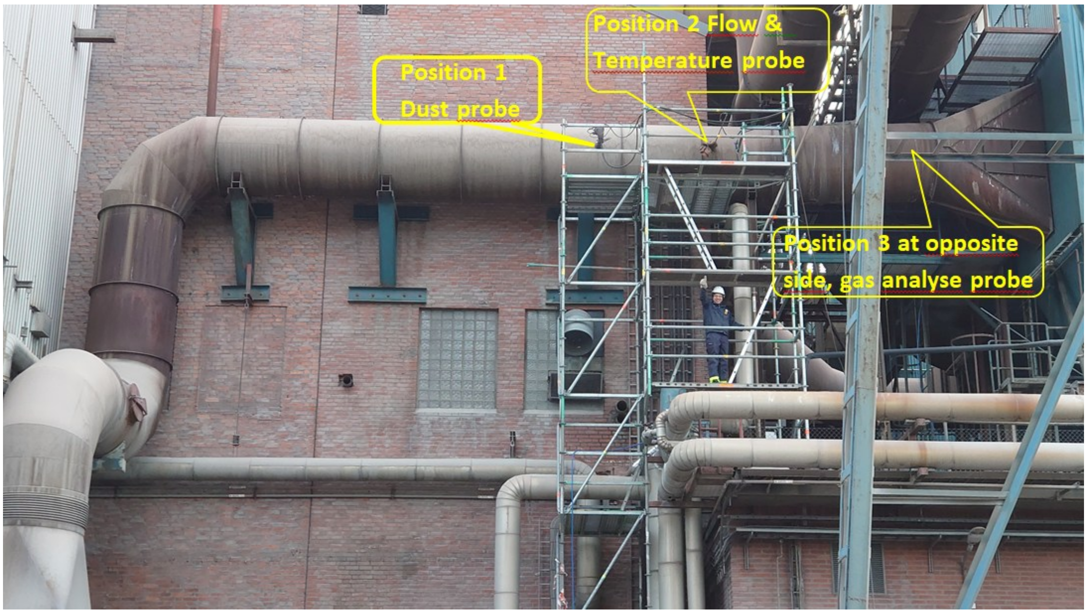

Figure 41- Measurement positions in the gas duct, dust, gas flow, temperature and gas analyses.

6.3.2 Gas analysis

The gas analysis was conducted on the off-gas using the gas probe located at Position 3, where the key gas components analyzed included CO, CO2, O2, H2, NOx, and SO2. The instruments utilized for this analysis were gas analyzers from SICK, employing infrared and paramagnetic techniques. Additionally, temperature measurements were taken at the gas flow sampling point using thermocouples. The setup for the gas duct involved several components: a heated probe with a filter was inserted at the measuring point, connected by a heated hose to the gas preparation system, which consisted of a filter, cooler, and pump. A hose then directed the gas to the analyzers. To prevent clogging in the gas probe, a PLC-controlled N_2 back-purging system was also integrated into the setup. All signals from the analyzers were routed to a data acquisition unit and a computer for further analysis.

Table 12 presents the average gas analysis data collected during the campaign, highlighting the concentrations of various gas components at different time points of REF and biocarbon period. The gas analysis was conducted consistently throughout the campaign, however some interruptions occurred due to issues with back-purging the probe and instances of water from condensate freezing in the gas hose, which obstructed the off-gas flow to the analyzers. These interruptions, which are not depicted in the figures, likely influenced the overall results.

The trends in gas analysis indicate relatively consistent levels of off-gas components across the measured periods. It can be seen that, an increase

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in CO_2 levels was observed when using bio briquettes, specifically at the 10% and 30% blends, although the effect may have been more pronounced if the process had operated without disruptions. On February 8 and 9 2024, there was a decrease in production at the furnace, leading to lower CO_2 levels than anticipated. This decline is reflected in the O_2 levels, which were higher during the same period. Consequently, the average values for O_2 and CO_2 on these dates may be misleading, as they do not accurately represent the expected gas concentrations under optimal operating conditions.

Table 12: Average off-gas analysis

		10% Ref	30% Ref		10% Bio		30% Bio		
Gas analyse		**31-jan**	**01-feb**	**02-feb**	**05-feb**	**06-feb**	**07-feb**	**08-feb**	**09-feb**
Average									
CO	[%]	0,096	0,099	0,101	0,105	0,107	0,101	0,110	0,111
CO2	[%]	3,23	3,62	3,76	3,71	4,14	3,57	2,96	3,56
H2	[%]	0,23	0,24	0,24	0,26	0,26	0,25	0,27	0,27
NOx	[ppm]	19	20	20	28	25	39	16	20
SO2	[ppm]	30	38	40	49	48	35	37	38
O2	[%]	18,15	17,90	17,80	17,79	17,51	17,18	18,30	17,89

6.3.3 Dust measurement and analysis

The flue dust sampler consists of two principal components: the duct station and the ground station. The duct station features a heated probe with a zero-pressure nozzle and a filter holder, while the ground station includes a vacuum pump, condensate bottle, regulating valve, and gas volume meter, as shown in **Figure 42**. Dust concentration in the gas flow is determined by sampling with a probe inserted into the gas stream, with sampling time adjusted based on the dust concentration level. Dust collected on a filter allows for the measurement of gas volume, enabling the concentration to be calculated from the filter's weight increase and the gas sample volume. The sampler also measures pressure differences at the probe inlet using a pitot static tube, facilitating isokinetic dust sampling, which ensures that the gas sample flow matches the off-gas flow velocity in the duct. This is crucial for accurate analysis of dust composition and particle size distribution.

Figure 42 – Ground station of dust measurement equipment.

The dust generation rate (g/Nm³ of dry gas) is illustrated in **Figure 43**, which includes data from 41 selected samples collected during the campaign. The figure reveals notable fluctuations in the dust generation rate, with several samples surpassing the average level of approximately 2.5 g/Nm³ of dry gas, particularly during the periods when biocarbon briquettes were used. However, it is important to note that interruptions in the process, caused by issues such as equipment malfunctions and condensate freezing, may have affected the data collected. **Table 13** provides the average dust amounts for each scenario, clearly indicating an increase in dust emissions associated with the use of biocarbon briquettes. Specifically, the dust levels measured during these periods were roughly 1 g/Nm³ of dry gas higher than those recorded in the reference cases.

These findings suggest that the use of biocarbon briquettes may lead to higher dust generation compared to traditional briquettes. To achieve a more comprehensive evaluation of the results, a longer campaign with fewer interruptions would be necessary. This would allow for a clearer understanding of the relationship between biocarbon utilization and dust emissions, highlighting the need for effective dust management strategies during operations.

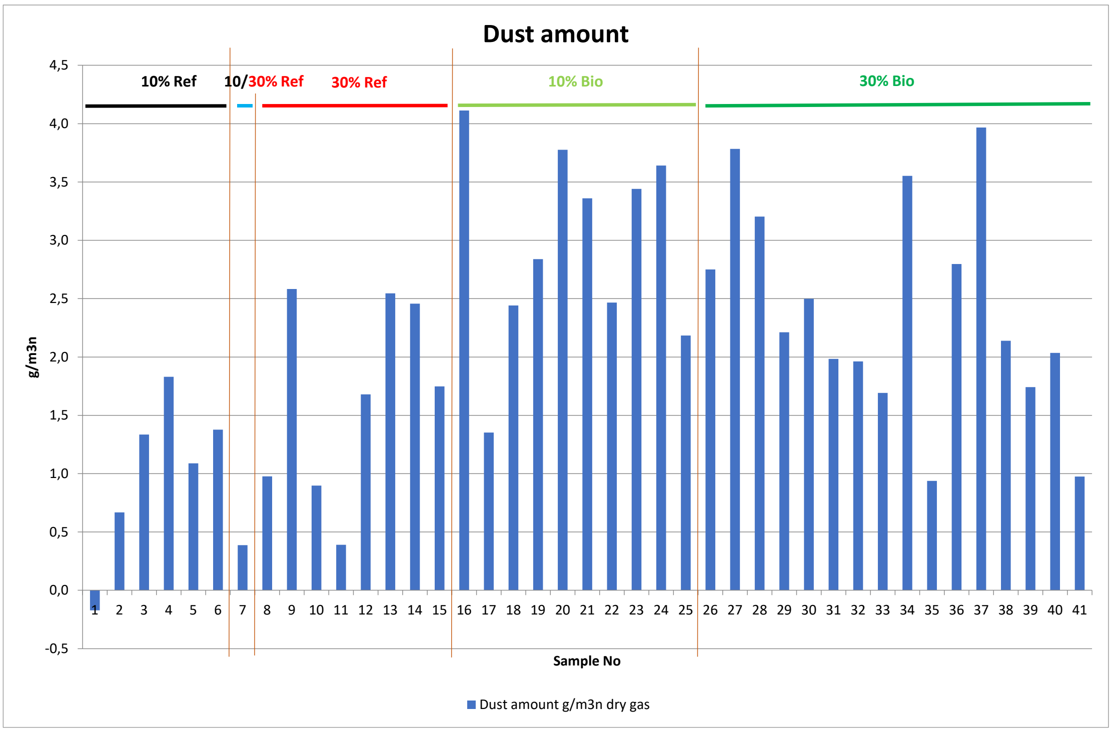

Figure 43 – Dust amount in off-gas before gas cleaning

Table 13 – Average dust amount for all cases

	10% Ref	30% Ref	10% Bio	30% Bio
Average g/m3n dg	1,3	1,5	2,8	2,4

6.4 Evaluation of Campaign using HSC Chemistry

The HSC Chemistry mass and heat balance model was employed to analyze process data collected during the Bio4SAF campaign. The material flow during the REF and bio-briquette charging simulation are given in **Figures 44 and 45**, respectively.

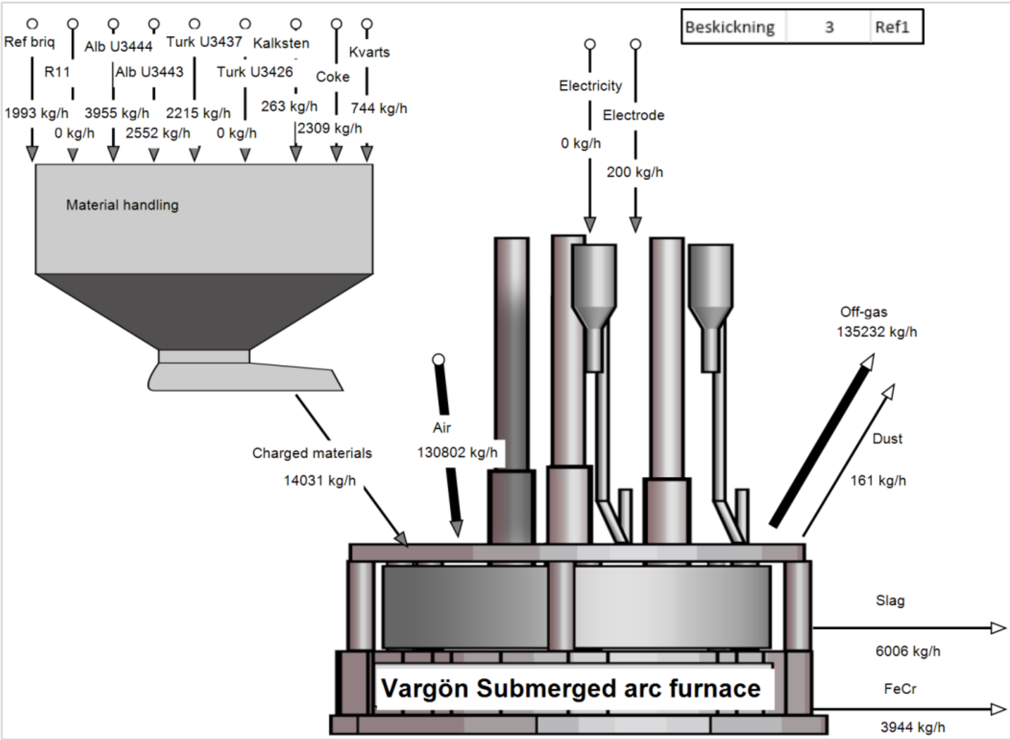

Figure 44 Overview of reference period simulation in HSC Chemistry

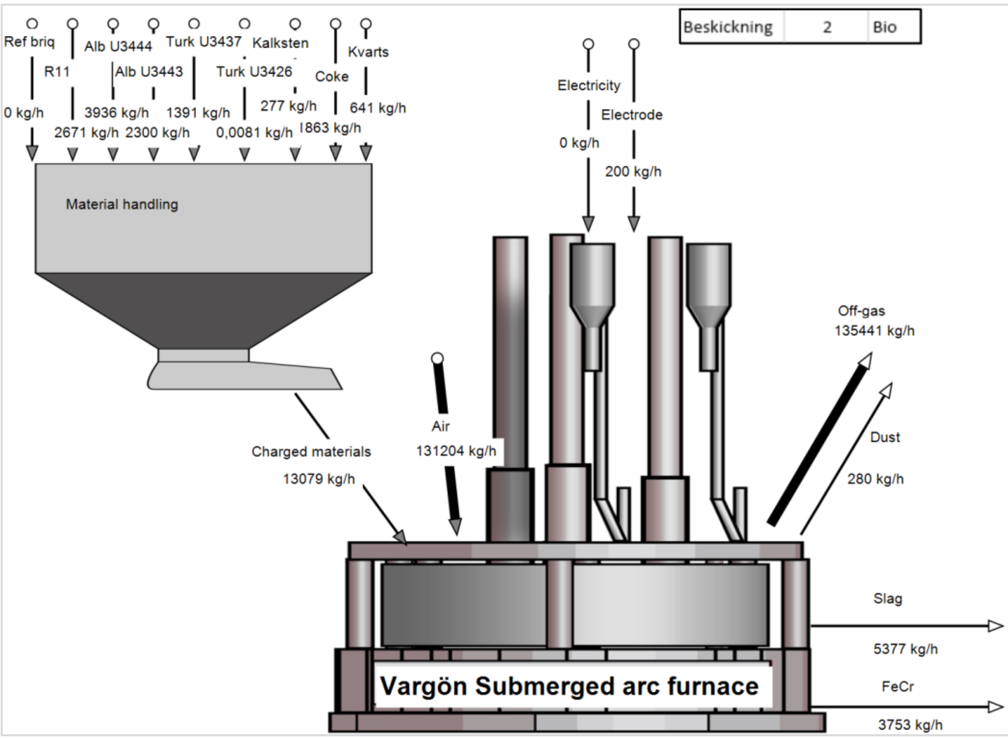

Figure 45 Overview of biocarbon period simulation in HSC Chemistry

Selected data comparing both practically measured and calculated values is presented in **Table 14**. The analysis reveals that while the calculated slag composition aligns closely with the measured values, there are notable discrepancies regarding the production of FeCr. Specifically, the calculated production rate of FeCr is 1 ton per hour higher than reported measurements. Additionally, the carbon content in the off-gas shows significant differences, with calculated values indicating 310 kg/h and 369 kg/h less carbon than the measured figures. These discrepancies can largely be attributed to inconsistencies in the data collected during the metal/slag separation process and the off-gas analysis. Interruptions in the production process may have affected the reliability of the measurements, leading to variations in reported data. To enhance the reliability of future assessments, it is crucial to address these inconsistencies and ensure continuous monitoring during trials. This will help provide a clearer understanding of the system's performance and improve the accuracy of both calculated and measured data.

Table 14 Calculated data compared with process data

		Simulation		Process data	
		Ref1	**Bio**	**Ref**	**Bio**
Slag	ton/h	6.01	5.38	5.36	5.62
FeCr	ton/h	3.94	3.75	2.92	2.71
Slag/FeCr	ton/ton	1.52	1.43	1.84	2.05
%SiO2 slag	%	30.50	29.95	33.3	32.2
%CaO slag	%	4.08	4.81	4.45	5.05
%MgO	%	36.99	37.79	39.2	38.5
%Al2O3 slag	%	20.40	20.79	21.8	21.7
%TiO2 slag	%	0.27	0.26	0.36	0.36
% MnO slag	%	0.13	0.09	0.13	0.13
%S slag	%	0.27	0.24	0.22	0.22
C Off-gas	kg/h	1710	1606	2021	1974

Table 15 presents the carbon balance for both the reference period and the bio period. During the reference period, the carbon input to the SAF per hour is slightly higher, although the specific carbon flow per ton of FeCr remains comparable at 508 kg/ton for the reference period and 501 kg/ton for the bio period. The percentage of incoming carbon that is converted into FeCr is similar for both periods, at 14.6% for the reference period and 14.3% for the bio period. This indicates that the utilization efficiency of bio-carbon is comparable to that of fossil carbon. However, a notable difference arises in the carbon balances between the two trial periods: a higher percentage of carbon is found in the dust during the bio period, with 0.3% of the incoming carbon ending up in dust compared to just 0.1% in the reference period.

However, the findings reveal that the integration of bio-briquettes into the production process could potentially reduce reliance on fossil resources.

Table 15 Carbon balance according to simulation

		Ref1	Bio
IN			
C in total	**kg/h**	**2005**	**1880**
C in Bio	kg/h	0	219
C in fossil	kg/h	2005	1661
C Coke	kg/h	1766	1425
C Bio-briquette	kg/h	0	219
C Other	kg/h	238	235
OUT			
C out	kg/h	**2005**	**1880**
C FeCr	kg/h	292	268
C Off-gas	kg/h	1710	1606
C dust	kg/h	2.2	6.4

In terms of CO2 emission, the trials demonstrate a comparable utilization of bio-based carbon and fossil carbon within the SAF, with 85% of the incoming carbon ultimately released into the off-gas. The direct specific CO_2 emissions measured were 1589 kg/ton of FeCr during the reference period and 1567 kg/ton during the bio period. There are significant discrepancies between the mass balance calculations and the actual process data regarding the slag-to-FeCr production ratio. Due to this uncertainty in the calculated FeCr production, the estimates for CO_2 emission reductions and fossil energy savings rely primarily on coke consumption figures, rather than on the FeCr production rate.

Table 16 presents the annual consumption and emissions associated with coke and biocarbon, comparing a reference case with a scenario where 21.8% of metallurgical coke is replaced by biocarbon briquettes, as achieved in the Bio4SAF campaign. The calculations are based on an annual coke consumption of 60,000 tons, with 85% carbon content in coke and 90% in biocarbon. The analysis assumes a 1:1 replacement ratio of carbon in coke and biocarbon, with 85% of the carbon resulting in direct emissions in the off-gas, and an energy content of 9 kWh/kg for both materials. By replacing 13,080 tons of coke with 12,353 tons of biocarbon, the trials indicate a reduction of 34,628 tons in direct fossil CO_2 emissions from the SAFs, alongside a decrease in fossil energy consumption of 118 GWh. This highlights the potential environmental benefits of incorporating bio-based materials into the production process, emphasizing the importance of transitioning toward more sustainable energy sources.

Table 16 Yearly consumptions and emissions pertaining to coke and biocarbon

	Unit	Reference	Biocarbon
Coke replacement with biocarbon	%	0	21.8
Coke consumption	ton	60 000	46 920
Biocarbon consumption	ton	0	12 353
Direct fossil CO_2 emissions	ton	158 843	124 215
Fossil energy consumption	GWh	540	422
Bio energy consumption	GWh	0	111
Reduction of direct fossil CO_2	ton	-	34 628
Reduction of fossil energy	GWh	-	118

6.5 Main Outcomes from the Bio4SAF Campaign

The results from the Bio4SAF campaign indicate that the introduction of biocarbon through chromite briquettes is an effective method for integrating biocarbon into the SAF. The main finding can be summarized in the following points:

1. **Phosphorus Levels**: There was no significant issue regarding P content; a minor increase in P was observed when the proportion of biocarbon briquettes was raised from **10%** to **30%**.
2. **Dust Generation**: The trials revealed a higher generation of dust during the biocarbon period, with the carbon content in the dust increasing by nearly **70%**. However, the developed biocarbon-chromite briquettes facilitated the recycling of **1%** of the generated flue dust.
3. **Reduction Rate and CO Gas**: A higher reduction rate was noted in the upper part of the furnace, leading to increased CO gas production. If oxygen levels are insufficient for complete combustion of CO, this can result in soot formation within the dust.
4. **Soot Formation**: Increased flow rates of CO gas, coupled with shorter residence times, may lead to the condensation of CO into soot within the dust. This could be attributed to hydrocarbon or volatile cracking occurring in the upper section of the furnace.
5. **Impact of Increased Charging Rate**: The elevated charging rate of biocarbon briquettes may have contributed to a greater generation of fines. These fine, carbon-rich particles could be entrained in the off-gas and subsequently collected in the filter dust.
6. **Gas-Solid Separation**: Insufficient gas-solid separation may have occurred due to the lighter and smaller fraction of biocarbon. This could

result in lower levels of CO and CO_2 in the off-gases while leading to higher carbon content in the filter dust.

7. **Energy Saving, CO_2 emissions:** Compared to reference periods, the energy consumption for the biocarbon period was 8.6% lower, and with 21,9% less coke per ton FeCr, it resulted in a reduction of 24.9% fossil CO_2.

7. Life Cycle Analysis (LCA)

The primary objective of this LCA study is to evaluate the environmental impacts, particularly CO2 emissions and Global Warming Potential (GWP), associated with using biocarbon in place of coke in FeCr production. This comparison seeks to identify the more sustainable option and provide recommendations for reducing the environmental footprint of FeCr manufacturing. OpenLCA software is used to perform this study followed by sensitivity and inventory analysis.

The system boundaries for this study adopt a cradle-to-gate approach, encompassing all processes from raw material extraction—specifically biomass for biocarbon and coal for coke—to the production of one ton of FeCr, as illustrated in **Figure 46**. This includes upstream processes such as raw material sourcing, briquetting, smelting in the SAF, and operations at the recovery plant. By considering all these stages, the assessment captures both direct and indirect environmental impacts, ensuring a comprehensive evaluation of resource utilization, energy consumption, and emissions throughout the FeCr production process.

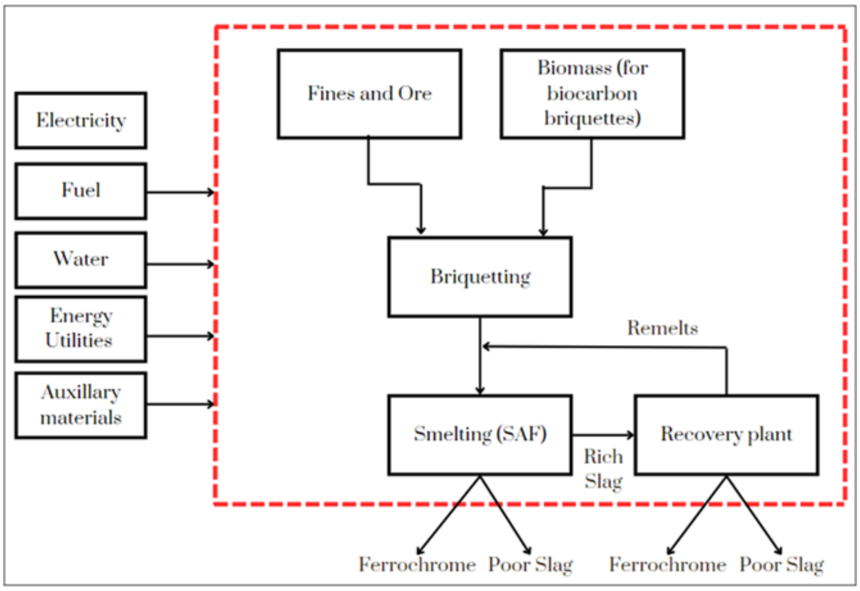

Figure 46 Boundaries of LCA system

The key metric utilized in this study is the GWP over a 100-year horizon (GWP100), expressed in kilograms of CO_2 equivalent, following the IPCC 2021 impact assessment method. **Table 17** illustrates the environmental benefits of incorporating briquettes composed of 10% biocarbon-chromite, which constitute 25% of the total ore charged into the SAF during FeCr production.

The introduction of these briquettes corresponds with a 21.8% reduction in coke consumption, decreasing from 660 kg coke/ton FeCr in the reference case to 516 kg coke/ton FeCr when using the 10% biocarbon-chromite briquettes**.** This change leads to a significant drop in GWP, from **1336.06** kg CO_2-eq to 1066.36 kg CO_2-eq, reflecting a reduction in CO_2 emissions of over **20%**. This demonstrates the environmental advantages of partially replacing traditional coke with biocarbon in mitigating greenhouse gas emissions during FeCr production.

Furthermore, the use of 10% biocarbon briquettes has been associated with a decrease in emissions during both the recovery plant and SAF phases when considering GWP impacts. For instance, the GWP for the SAF process using only coke is 1331.16 kg CO_2-eq, while the introduction of 10% biocarbon briquettes reduces this figure to 1061.61 kg CO_2-eq**.** Similarly, emissions from the recovery plant decline from 4.90 kg CO_2-eq to 4.75 kg CO_2-eq. **Table 18** further illustrates the emission reductions achieved in each process.

Table 17: GWP100 Comparison

Case	**GWP100**	**Unit**
Reference: without biocarbon	1336.06	kg CO_2-eq
10% biocarbon-chromite, 25% briquettes per charge	1066.36	kg CO_2-eq

Table 18: Emission Comparison for SAF and Recovery Plant

Case	**SAF**	**Recovery Plant**	**Unit**
Reference: without biocarbon	1331.16	4.90	kg CO_2-eq
10% biocarbon briquettes	1061.61	4.75	kg CO_2-eq

The incorporation of 10% biocarbon briquettes significantly influences various environmental categories during the production process. **Table 19** summarizes the impacts observed, demonstrating reductions in key areas such as acidification, ecotoxicity, and resource utilization, as assessed using the ReCiPe 2016 impact assessment framework. This data underscores that even a modest substitution of coke with biocarbon can lead to meaningful decreases in environmental impacts across multiple categories.

Table 19: Impact Category Comparison

Impact Category	Reference: without biocarbon	10% Biocarbon-Chromite, 25% Briquettes	Unit
Acidification: terrestrial	6.23	3.40	kg SO_2-eq
Ecotoxicity: freshwater	847.37	786.89	kg 1,4-DB-Eq
Ecotoxicity: marine	42.31	39.64	kg 1,4-DB-Eq
Eutrophication: freshwater	2.54	2.28	kg N-eq
Human toxicity: carcinogenic	1.79	1.61	kg C4H6O3-eq
Land use: non-renewable	0.12	0.10	kBq CO_2-eq
Material resources: metals/minerals	10.54	9.55	kg CFC-11-eq
Particulate matter formation	50.51	21.89	m^3
Photochemical oxidant formation	2.78	2.12	m^3

The LCA analysis indicates that substituting biocarbon for traditional coke in FeCr production can significantly mitigate environmental impacts. Even a **10%** substitution of coke with biocarbon results in notable reductions in carbon emissions, aligning with the industry's push for greener and more sustainable manufacturing practices.

GWP reductions improve with each increase in biocarbon and briquette proportions. For instance, raising biocarbon content from **15%** to **20%** at **10%** briquette proportions yields an additional GWP decrease of about **1.3%**. Similarly, increasing briquette proportions from **10%** to **30%** while keeping biocarbon content constant results in an approximate **6%** reduction. The most significant benefits are observed when both biocarbon content and briquette proportions are maximized concurrently, leading to a cumulative GWP decrease of around **14%** compared to lower substitution levels. These trends consistently demonstrate that increasing biocarbon content and briquette proportions yields environmental benefits.

The sensitivity analysis reveals that greater biocarbon use enhances environmental advantages. However, the relationship is not strictly linear; there may be an optimal range for biocarbon substitution that balances environmental benefits with practical and economic considerations. Diminishing returns and potential operational challenges warrant further exploration, as identifying optimal substitution levels is crucial. While many environmental metrics improved with biocarbon usage, certain areas, such as ionizing radiation and land use, showed minimal change.

The study also emphasizes biocarbon's potential to facilitate the FeCr industry's transition to a circular economy. By utilizing biomass residues, the sector can reduce its reliance on fossil fuels while generating value from waste products. This aligns with broader environmental goals and may offer economic advantages in regions where biomass is readily available.

The findings of this LCA study underscore the environmental benefits of incorporating biocarbon into FeCr production. Even partial coke substitution with biocarbon leads to reductions in greenhouse gas emissions, particularly in GWP100, while improving other environmental categories such as acidification, ecotoxicity, and fossil energy use. For example, replacing **10%** of coke with biocarbon in chromite briquettes resulted in a GWP100 reduction of over **20%**, highlighting biocarbon's potential to lower the carbon footprint of FeCr production. This approach offers a promising pathway toward achieving sustainability targets and reducing the overall carbon footprint of energy-intensive industrial processes. Additionally, using renewable biomass as a feedstock provides an opportunity to transition from fossil fuel dependency to a more circular and resource-efficient production model.

The sensitivity analysis further confirmed that increasing biocarbon content and briquette proportions enhance these benefits. The most effective scenario involved **20%** biocarbon and **30%** briquettes per charge, yielding a GWP100 decrease of **723.63 kg CO_2-eq** alongside significant reductions in acidification and resource energy use. This underscores the advantages of optimizing both biocarbon content and briquette utilization.

To fully realize biocarbon's potential, additional research is necessary to determine the optimal substitution levels that maximize environmental benefits while preserving the quality of FeCr produced. Future studies should also address operational challenges, such as biocarbon handling and furnace stability. Tackling these issues will be essential for increasing biocarbon adoption in FeCr manufacturing and ensuring widespread acceptance within the industry.

8. Conclusions

The **Bio4SAF project** has successfully advanced the development and implementation of biocarbon-chromite briquettes for ferrochrome production in submerged arc furnaces (SAFs).

Key findings from the project can be summarized as follows:

1. **Biocarbon Production**: High-quality biocarbon was produced by Envigas, utilizing raw feedstock sourced from residues of the forestry and wood industries. The feedstock underwent controlled pyrolysis, resulting in biocarbon with high carbon content, low volatile matter, and low ash content, making it suitable for FeCr production.
2. **Briquette Development**: Biocarbon-chromite briquettes containing **10% biocarbon** were developed and optimized using the technical scale vibro press machine at Swerim. This was followed by successful pre-industrial-scale testing at Vargön, marking a significant milestone in the project.
3. **Production Feasibility of Biocarbon Briquettes**: Through systematic research and iterative optimization at both technical and pre-industrial scales, approximately **350 tons** of biocarbon-chromite briquettes were produced at the full-scale briquetting plant at Vargön. This demonstrated the feasibility and effectiveness of integrating renewable carbon sources into the existing briquetting system without the need for significant new infrastructure investments.
4. **Successful SAF Campaign**: A successful campaign was executed at SAF No. 10 at Vargön. Notable outcomes included the replacement of **21.8%** of fossil coke with renewable biocarbon, leading to a **25% reduction** in fossil CO_2 emissions and a decrease in fossil energy consumption by **118 GWh**.
5. **Phosphorus and Dust Management**: The trials indicated no significant issues regarding phosphorus content in the melt, with only a minor increase observed when the proportion of biocarbon briquettes was raised from **10%** to **30%**. Although a higher generation of dust was noted during the biocarbon period, the briquettes enabled the recycling of **1%** of the generated flue dust.
6. **Heat-Mass Balance**: The **HSC Chemistry model** was employed to analyze the process data, confirming the consistency of calculated slag compositions with measured values. While discrepancies in FeCr production rates were noted, the model provided valuable insights into energy flows and material balances, reinforcing the project's outcomes related to efficiency and resource utilization.
7. **Life Cycle Analysis (LCA)**: The LCA study demonstrated that integrating biocarbon into the briquettes significantly mitigates the environmental impacts associated with ferrochrome production. By substituting fossil coke with biocarbon, the project achieved a reduction

in greenhouse gas emissions, aligning with broader sustainability goals within the ferroalloy industry.

8. **Need for Extended Campaign**: Although the initial campaign within Bio4SAF yielded promising results, it is highly recommended to conduct longer-term trials to validate these findings comprehensively and ensuring that the benefits observed during the campaign are sustainable over time.

In summary, the Bio4SAF project not only demonstrated the technical and operational viability of biocarbon-chromite briquettes but also set a precedent for future innovations in the ferrochrome industry. The successful outcomes highlight the critical role of renewable carbon sources in reducing dependency on fossil fuels, paving the way for a more sustainable and efficient metallurgical sector. As we move forward, these findings lay a solid foundation for ongoing research and development efforts aimed at achieving greater sustainability and decarbonization in the industry.

9. Future Work

Building on these results from the Bio4SAF project, future work should focus on several key areas:

1. **Maximizing Biocarbon Replacement**: Investigate alternative briquetting techniques to further increase the proportion of biocarbon replacing fossil coke. This could involve exploring different biomass sources and optimizing the briquetting process to enhance the mechanical properties of the briquettes.
2. **Extended Campaign Testing**: Conduct longer-term trials to validate the performance and efficiency of the biocarbon-chromite briquettes in operational settings. This will help assess the long-term stability of product quality and process efficiency over extended production cycles.
3. **Process Optimization**: Analyze the operational parameters in the SAF to identify opportunities for optimizing the melting process when using higher percentages of biocarbon. This could include adjustments in temperature, charge composition, and smelting time to further enhance efficiency.
4. **Environmental Impact Assessment**: Perform comprehensive LCA to quantify the environmental benefits of the new briquettes in comparison to traditional methods. This will provide a clearer understanding of the overall sustainability of the approach.
5. **Collaboration with Industry Partners**: Engage with industry stakeholders from other ferroalloys sectors such as FeMn, FeSi and SiMn to facilitate the adoption of these innovations on a larger scale. Collaborative efforts can help in scaling up production and integrating these practices into existing operations, thereby accelerating the transition to greener practices.

By focusing on these areas, the future work stemming from the Bio4SAF project can significantly advance the decarbonization efforts in the FeCr industry, paving the way for more sustainable practices and reduced environmental impacts.

10. Results dissemination

The results from Bio4SAF project have been presented and discussed in several events as follows:

1) Elsayed Mousa, Annelie Papadopoulos: Lowering direct emissions in FeCr production with biochar, HES Committee Meeting, 08-09 November 2022, Paris, France.
2) Elsayed Mousa, Ludvig Ånnhagen, Greger Hauri, Nizar Tiraani, Karthik Manu, Towards Sustainable FeCr Industry: Developing Biocarbon-Chromite Briquette for Submerged Arc Furnace, Chromium ESG Technical Summit, Luleå, Sweden, 18-19 October 2023.
3) Elsayed Mousa: New trends in agglomeration for sustainable iron and steel making, Nordic Sustainable Day, 31st January-1st February 2023, Oulu, Finland.
4) Elsayed Mousa, Biomass for sustainable metal industry, Svenska Bergsmannaföreningen (SBF), Online, 29th November 2023.
5) Annelie Papadopoulos, Bio4SAF project ”Towards sustainable FeCr Production”, SWERIM Day, 23 October 2024, Stockholm, Sweden.
6) Elsayed Mousa: Biocarbon for metal industry, Ferroalloy Producers Research Association (FFF), 22 August 2023, Luleå, Sweden.
7) Elsayed Mousa: From Waste to Worth: Elevating biogenic residues in iron and steel production, Green Steel Summit 2024, 25-26 July 2024, Raipur, India.
8) Elsayed Mousa, Ludvig Ånnhagen, Karthik Manu, Lars-Erik From, Annelie Papadopoulos, Staffan Rahmn, Greger Hauri, Nizar Tiraani, Mikael Jansson, Tobias Brink: Development of Biocarbon-Chromite Briquettes for Ferrochrome Production in Submerged Arc Furnace, INFACON XVII, 18-21 September 2024, Beijing, China.
9) Ludvig Ånnhagen: The road towards greener ferrochrome - the use of biocarbon in an industrial scale, 19-20 March 2025, LTU, Luleå, Sweden, forthcoming.
10) Elsayed Mousa: Advancing Sustainability in Metallurgical Sectors through Innovative Agglomeration and Biocarbon Utilization, TMS 2025, 154th Annual Meeting & Exhibition, 23-27 March 2025, Las Vegas, Nevada, USA, forthcoming.
11) Several announcements on LinkedIn on Bio4SAF activities:

i. https://www.linkedin.com/posts/swerim_ferrochrome-fecr-biocarbon-activity-7183115538997338112-6T8E?utm_source=share&utm_medium=member_desktop&rcm=ACoAAAhn1LUBoxQp43dF7ul2WUZ1CbtVixGiXDk
ii. https://www.linkedin.com/posts/utku-yakar_esg-biochar-decarbonization-activity-7249461209622544385-V3za?utm_source=share&utm_medium=member_desktop&rcm=ACoAAAhn1LUBoxQp43dF7ul2WUZ1CbtVixGiXDk
iii. https://www.linkedin.com/posts/swerim_research-ferrochrome-fossilco2emission-activity-7202290929611759616-BJuo?utm_source=share&utm_medium=member_desktop&rcm=ACoAAAhn1LUBoxQp43dF7ul2WUZ1CbtVixGiXDk
iv. https://www.linkedin.com/posts/swerim_infacon-bio4saf-research-activity-7243894356280041472-MpSZ?utm_source=share&utm_medium=member_desktop&rcm=ACoAAAhn1LUBoxQp43dF7ul2WUZ1CbtVixGiXDk
v. https://www.linkedin.com/posts/swerim_the-annual-swerim-day-hosted-by-our-ceo-activity-7255593529618452480-I6Yt?utm_source=share&utm_medium=member_desktop&rcm=ACoAAAhn1LUBoxQp43dF7ul2WUZ1CbtVixGiXDk

11. Sustainability Award

The **Bio4SAF project** received the **Global Sustainability Award 2024** in Hong Kong. This prestigious accolade was presented by the ICDA FeCr Association to our esteemed project partner, **Vargön Alloys AB**.

12. References

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[4] Jernkontoret, "HYBRIT - fossilfri stålproduktion," https://www.jernkontoret.se/sv/vision-2050/koldioxidfri-stalproduktion/.
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[7] K. Umaki, M. Öhman, M. Lundgren, L.S Ökvist, H. Ahmed, and E.A Mousa, "Bio4Metals: Bioreduktion för metalliska processer," Biokol hett i norr, slutkonferens Kultureshus, Luleå, 2019.
[8] A. T. M. T. G.R. Surup, "Charcoal as an alternative reductant in ferroalloy production- A review", Processes 2020, 8, 1432.
[9] S.I. Angadi, D.S Rao, A. R Prasad, and R. B. Rao, "Recovery of ferrochrome values from flue dust generated in ferroalloy," *Mineral Processing and Extractive Metallurgy IMM Transactions section C*, 2011.

13. List of Appendices

Appendix 1: Biocarbon development on a technical scale
Appendix 2: Industrial campaign report
Appendix 3: Dust measurement at Vargön SAF
Appendix 4: HSC Chemistry evaluation of SAF campaign
Appendix 5: Life Cycle Analysis
Appendix 6: Paper presented at INFACON Conference, 2024

Acknowledgment

The Bio4SAF project partners would like to express their sincere gratitude to Energimyndigheten for funding the project and invaluable support towards the successful realization of the project. We are confident that our collective efforts will yield positive impacts on both the energy sector and the environment, and we look forward to continuing our collaboration towards achieving a fully sustainable and environmentally friendly ferroalloy and metals industry.

Photos of Bio4SAF Team during the campaign at Vargön, February 2024