**RESEARCH REPORT**

VTT-R-00161-25

# BioCarbonValue – High-value carbons from agricultural biomass Final Report

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**Summary**

The BioCarbonValue project aimed to produce high-value biocarbons from agricultural feedstocks, focusing on sustainable alternatives to fossil-based carbons. The project involved industry partners and two research institutions, emphasizing the use of agricultural sidestreams for energy storage, water purification, and biocomposites.

Key objectives included evaluating quality of agricultural residues, developing biocarbon products, and conducting techno-economic assessment and biocarbon market review. The project employed a multi-faceted approach, selecting promising feedstocks such as wheat straw, reed canary grass, oat husks, wheat straw lignin, and willow, and using slow pyrolysis and activation methods to produce variety of bio- and activated carbons. Digital solutions for efficient biomass supply chain management were also explored.

Key findings revealed that higher pyrolysis temperatures generally resulted in lower yields but improved the carbon content and thermal stability of the biocarbons produced. The importance of feedstock quality was highlighted, as variations in ash content significantly impacted the properties of the resulting biocarbons. The non-condensable pyrolysis gases were analyzed at different carbonization temperatures, providing valuable information for their possible utilization. Up-scaling experiments demonstrated the feasibility of agricultural sidestreams for high-volume biocarbon production.

The project investigated high-value applications for agro-based biocarbons, focusing on energy storage, water purification, and biocomposites. Chemically activated carbons from wheat straw lignin performed well in supercapacitors and wastewater treatment using steam-activated biocarbons provided promising results. High-temperature biocarbons were found a viable option as a replacement for fossil based, non-renewable materials in composites.

A techno-economic assessment highlighted the potential for biochar production in Finland, emphasizing supply chain costs, production optimization, and market opportunities. The project also examined the biocarbon market, noting significant interest in expanding the Nordic biochar market and the growing activated carbon market.

The BioCarbonValue project demonstrated the potential of agricultural biomass for high-value biocarbon production, with promising applications and market opportunities. Further research is recommended to optimize production processes, ensure feedstock consistency, and develop the agro-based biocarbon market.

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# Preface

The research project titled "High-value carbons from agricultural biomass", also known as BioCarbonValue, was conducted by VTT and LAB University of Applied Sciences from January 1, 2023, to December 31, 2024. This collaborative research effort received funding from Business Finland and was part of the ExpandFibre ecosystem launched by Fortum and Metsä Group.

The project was led by Research Team Leader Aino Kainulainen at VTT, with Senior Scientist Virpi Siipola serving as the project manager. VTT acted as the project coordinator and was responsible for the biocarbon development and application testing for water purification and energy storage. Eliisa Punttila acted as the project manager at LAB University of Applied Sciences. LAB responsibilities were studying the enhanced utilization of agricultural biomass as a feedstock for diversified refining industry.

The BioCarbonValue project steering group consisted of a diverse array of representatives from companies involved in different aspects of the biocarbon value chain, such as feedstock supply, biocarbon production, and end-use applications. The companies and organizations involved in the steering group included the City of Heinola, Fortum, Chempolis, Fifth Innovation, PUHI, Carbofex, Carbo Culture, Neova Group, Sumitomo SHI FW, and Premix.

We would like to thank Business Finland for their funding and support for the BioCarbonValue project. We wish to thank the dedicated research staff and students at VTT Technical Research Centre of Finland Ltd and LAB University of Applied Sciences. Your hard work, expertise, and collaboration have been invaluable in achieving the project's objectives. We also wish to acknowledge the contributions of our industry partners, whose collaboration and insights have enriched the project. Special thanks to City of Heinola, Fortum, Chempolis, Fifth Innovation, Carbo Culture, Carbofex, PUHI, Sumitomo SHI FW, Neova, and Premix. Your involvement has been crucial in ensuring the practical applicability and impact of our research.

Espoo and Lahti 29.4.2025

Authors

# Contents

# Introduction

Replacing fossil coal and graphite with biocarbon is crucial for transitioning to a low-carbon economy. Fossil-based feedstocks like coal and oil industry sidestreams are used for activated carbons and other carbon products in various applications, including batteries, biocomposites, and purification systems. With an existing market size of $6.6 billion for activated carbon (in 2024) and $22.35 billion for carbon black (in 2023), the production of these materials is already substantial (BCC Research 2025 & Grand View Research 2023). Additionally, new markets and applications are emerging, such as battery carbons.

Natural graphite mining is costly and poses environmental risks, while the demand for graphite in batteries is expected to rise by 500% by 2050 (Ritoe et al., 2022). Currently, renewable carbons are not widely available to replace fossil-based carbons in high-value applications. Research is ongoing to find alternative sources through the carbonization of forestry and agricultural sidestreams. Promising results have been seen with biocarbon from wood-based lignins and spent grain.

The global market for high-value carbons used in non-energy applications is substantial and rapidly growing. For instance, natural graphite is considered a critical raw material regarding the production of batteries and use in steel industry[1]. However, the supply of fossil-based graphite is limited and cannot meet the future demand for these technologies. Therefore, there is an urgent need to develop sustainable and renewable sources of carbon.

The use of alternative feedstocks for producing activated carbon has been increasingly researched over the past years. In recent years, the focus has shifted towards utilizing sidestreams from forestry and agriculture. For example, activated carbon made from pine bark has proven to be just as effective in VTT's laboratory tests as the widely used fossil-based activated carbon (Siipola et al., 2020). Additionally, tests on biocarbon produced from spent grain have demonstrated promising results in electronic applications, such as electrode material in solar panels (Tiihonen et al., 2020). Despite these advancements, several knowledge gaps and uncertainties remain, preventing the large-scale deployment of biocarbons in the market.

Replacing fossil-based carbon with biobased alternatives is also essential for transitioning to a sustainable economy. Fossil carbon is still widely used for energy, especially in China and India. The carbon used in electrochemical devices, composites, and purification applications also originates from coal and graphite mines, primarily in Asia. The demand for graphite in batteries and electric vehicles is expected to rise significantly, and the manufacturing of synthetic graphite is costly and environmentally harmful. Therefore, exploring biobased sources for graphite and other carbons is crucial.

Agriculture produces large volumes of untapped biomass that could be used as high-value industrial raw materials. The 70–90% of the field production by-streams consists of grain straws (Pahkala & Lötjönen, 2015), but also increasing amounts of, so far unutilized, carbon-binding zones, nature conservation, and fallow fields biomass are available. Sustainable exploitation of already existing material, along with existing collection and logistics facilities, provides an opportunity to advance the bio-circular economy.

[1] European Commission: Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Grohol, M. and Veeh, C., *Study on the critical raw materials for the EU 2023 – Final report*, Publications Office of the European Union, 2023, **https://data.europa.eu/doi/10.2873/725585**

## Target

**The BioCarbonValue** project was carefully planned to address existing bottlenecks in the high-volume production and use of biocarbons as fossil coal replacements. Despite previous research using forest-based sidestreams and wood as biocarbon raw materials, this information could not be directly transferred to agro-based biomass use. The project aimed to fill knowledge gaps in all parts of the value chain, requiring high-quality scientific research before strategic decisions could be made to expand or modify existing infrastructure for biocarbon production and use.

**The BioCarbonValue** project aimed to produce sustainable business concepts that were carbon neutral or negative. Specific environmental and economic benefits included in the project were:

**Climate impact**: Producing sustainable carbon materials reduced environmental impact and improved human health in developing countries.

**Promoting business:** Solving bottlenecks in the straw supply chain enhanced the profitability of field biomass ecosystems and created business opportunities in international markets.

**Resource efficiency:** Gradual replacement of fossil carbons with bio-based materials in applications like batteries, biocomposites, and water purification.

**Knowhow:** Developing technical and scientific expertise in high-value bio-based carbon products and training new experts in the field.

## Objectives and expected results

**The BioCarbonValue** project aimed to find biobased alternatives for fossil carbons from underutilized agricultural sidestreams. The project addressed scientific and practical challenges related to bringing agrobiomass-based biocarbons to market. This included developing biocarbon products that could meet industry standards and covering the entire value chain from feed material producers to end-users. The project's goal was to estimate production costs, explore biocarbon markets, and provide essential data for biocarbon research and development and industry.

The specific objectives the project focused on:

- **Agricultural biomass as a feedstock**: Evaluating the potential of cereal straw and other agricultural residues for high-value applications.
- **Energy storage and biocarbons**: Developing biocarbons for supercapacitors and batteries, including chemical activation treatments.
- **Water purification and biocarbons**: Testing biobased activated carbons for contaminant removal and microplastics retention.
- **Biocomposites with biocarbons and agrocellulose**: Analyzing the potential of biocomposites based on agro-sources, including conductive biocarbons and agro-cellulose.

The project aimed to provide valuable information on the performance of biocarbons in various applications, contributing to the development of a sustainable biocarbon industry.

# Enhanced utilization of agricultural biomass as a feedstock for diversified refining industry

## Summary of the work and achievements

Availability and sustainability of raw materials for biocarbon production and especially the bottlenecks that are restricting the utilization of field biomass in processes are the first issues to evaluate in the biocarbon value chain. Especially in the northern regimes, weather conditions pose challenges for the utilization of field biomass, affecting to the collection and storage practises and causing heterogeneity to the biomass quality. The BioCarbonValue project aimed to address the characteristics, qualitative variation and processability of the most potential field biomasses, variations in the raw material quality in relation with the boundary conditions of the refining processes, advanced monitoring method, and valorization and digital solutions for the specific side-streams generated by crop production or biomass refining industry. In the beginning of the project, five promising feedstocks were selected for the research: wheat straw, reed canary grass, willow, oat husk and wheat straw lignin.

## Key results and impacts

The key results include

- Information on the availability and sustainability of studied field biomasses and food industry side stream as well as their analyzed lignin and carbohydrate content
- Straw weathering experiment with demonstration of Near Infrared (NIR) Spectroscopy in quality monitoring of field biomass, as well as discussion of the challenge of quality criteria definition
- Demonstrations from different pre-treatment technologies, for lignin and willow
- Review of available AI and automation technologies to increase efficiency and predictability of field biomass supply chain

# Availability and properties of the most potential field biomass

Contact person: Eliisa Punttila, LAB

## Introduction

In the beginning of the project, the project consortium selected five promising raw materials for the research that were regarded as the most interesting from the market point of view. Wheat straw, willow and grain husk were raised from the companies' interests. Reed canary grass (RCG) was selected to represent reed species and due to its international potential. Wheat straw lignin was selected especially for the energy storage application tests. To conduct the carbonization and application test in the project, samples of these raw materials were received from farms located in Päijät-Häme (straw, reed canary grass and willow), from food industry (oat husk) and from biorefinery (wheat straw lignin).

## Materials & Methods

The availability of the selected biomasses was evaluated by using literature, focusing on especially the annual production volumes, current utilization cases and which sustainability aspects should be considered in their production. The chemical content of the biomasses was analyzed in the laboratory with a special interest in lignin and carbohydrate content.

## Results & Discussion

Wheat straw, reed canary grass, willow and oat husk are very different in their current availability in Finland. Exact information of the annual volumes was not available, but they were estimated based on available data (Table 1). For willow, exact information of the current cultivation area in Finland was not found.

*Table 1. Estimated annual production volumes in Finland (based on Punttila 2024a; Punttila 2024b).*

| Raw material | Estimated annual volume, tons |
|---|---|
| Straw (wheat) | 150,000 - 350,000 |
| Straw (wheat, oat, rye, barley) | 650,000 - 1,500,000 |
| Reed canary grass | 9,000 |
| Oat husk | 400,000 |
| Willow | - |

Although the annual volumes especially for straw and oat husk are high, it is uncertain how much could be utilised for example in biocarbon production now or in the future. There are currently several other utilisation and competitive solutions that are currently available or under investigation. Straw is currently underutilised biomass due to the lack of supply network, which is challenging especially from the logistics and storage point of view. Sustainability issues for cereal production residues can be managed with sustainable cultivation practices.

There could be potential for increasing cultivation areas of RCG or willow, by shifting from conventional farming to paludiculture at peat lands or utilizing land areas that are not needed for food production. However, cultivation of these crops would require a long-term commitment from landowners and farmers.

The all studied raw materials were interesting regarding their lignocellulosic content and biorefinement value. Lignin, cellulose and hemicellulose contents as results from laboratory analyses are illustrated in Table 2. The lignin and carbohydrate content varied between the raw materials and batches and may be affected by the pre-treatment methods.

*Table 2. Lignin, cellulose and hemicellulose contents determined from extractive-free raw materials (part of dry matter, %) (modified from Pulkkinen & Punttila 2025).*

| Raw material | Lignin, % | Cellulose, % | Hemicellulose, % |
|---|---|---|---|
| Wheat straw | 25.9 | 14.8 | 19.3 |
| Reed canary grass | 24.8 | 27.4 | 18.1 |
| Oat husk | 23.2 | 23.3 | 42.2 |
| Willow, batch 1 | 28 | 30.1 | 9.5 |
| Willow, batch 2 | 29.9 | 8 | 11 |
| Willow, batch 2 pressed | 26.3 | 25 | 15.7 |

### Publications & theses

Punttila, E. 2024a. Energy crops for biochar production. LAB Pro. Available at https://www.labopen.fi/en/lab-pro/energy-crops-for-biochar-production/

Punttila, E. 2024b. Wheat straw and oat husk volumes and use in Finland. LAB Pro. Available at https://www.labopen.fi/lab-pro/wheat-straw-and-oat-husk-volumes-and-use-in-finland/

Pulkkinen, M. & Punttila, E. 2025. Peltobiomassojen ligniini- ja hiilihydraattimääritykset. LAB Pro. Available at https://www.labopen.fi/lab-pro/peltobiomassojen-ligniini-ja-hiilihydraattimaaritykset/

## Monitoring and classifying the field biomass quality

Contact person: Eliisa Punttila, LAB

### Introduction

The field biomass quality raises several issues to be solved: how the required or desired quality is defined or classified, how it is maintained throughout the supply chain, and how the quality is monitored and verified on the field. Currently, the quality monitoring on the field is based on sensory evaluation or manual moisture or temperature measurement. The BioCarbonValue project focused on demonstrate the possible quality decay of straw during storage and Near Infrated (NIR) Spectroscopy in quality monitoring, and to establish quality criteria for field biomass.

### Materials & Methods

The straw weathering experiment aimed to demonstrate different storage practises and to reveal possible quality decay that is not possible to observe with sensory evaluations. NIR technology was tested in monitoring these kind of non-visible quality changes, and chemical and microbiological analyses were made for verifying possible quality changes. The test setup in laboratory conditions was prepared to simulate outdoors storage under a roof or wrapped in plastics and possible freezing. The experiment lasted for 6 months.

In addition, examples of quality criteria for field biomass in different application cases were collected from literature. Quality criteria and possible classification were also discussed with company representatives.

### Results & Discussion

The six-month long straw weathering experiment including storage in cool and moist conditions, plastic wrapping and freezing, did not cause any visible impact on straw material. No clear changes in the quality were observed either when testing with NIR and chemical analyses. As a conclusion, originally dry and good quality straw preserved very well in these conditions during a half-year period. If the observation period would have longer, the quality of straw originally poorer, the possible degradations and thus molecular changes could have strengthened the signals with NIR or chemical analyses. Since the straw quality remained at good level in the straw weathering experiment, it was not possible to classify different quality with NIR.

However, setting up the quality criteria for field biomass as raw material for biocarbon production or any other circular bioeconomy purpose is very challenging. The quality demands are application and process specific, and it also depends on the business model, in which part of the supply chain the field biomass quality should be defined. To set up clear classification, for example high-quality, suitable or poor-quality raw material from a point of view certain bioeconomy purpose, it would require further research and optimisation from each application point of view.

#### Publications & theses

Punttila, E. & Rahtola, M. 2025. Quality definition for field biomass in the circular bioeconomy. LAB Pro.

Rintala, N.; Welin, M.; Punttila, E. & Pulkkinen, M. 2025. Use of NIR technologies in agro-biomass quality monitoring. LAB RDI journal.

## Pre-treatment technologies to improve valorization of biomasses

Contact person: Eliisa Punttila

### Introduction

In the case of field biomasses, the road from harvest to the biocarbon production is usually not straightforward – different pre-treatment processes are needed before the raw material is ready for pyrolysis. Properties of biomasses are varying as well as their processability. Pre-treatment processes are needed to decrease the moisture, to cut to smaller pieces, to pack into a smaller volume or to improve the utilisation possibilities with other ways. Pre-treatment processes are essential in increasing and enhancing the utilisation of field biomasses and side streams for different bioeconomy value chains.

### Materials & Methods

Pre-treatment processes were demonstrated for wheat straw lignin and field biomasses. Hammer mill and pelletizing were used for wheat straw, reed canary grass and willow. Granulating and pelletizing were tested with wheat straw lignin. For willow, also high-pressure press as mechanical drying method was demonstrated.

### Results & Discussion

All field biomasses were suitable for crushing with hammer mill and pelletizing. Especially in case of straw, pelletizing would provide remarkable benefit for logistics and storage, since the volume decreased by 96.5%. If the raw material is pelletized, it may ease also transportation of biocarbon, if the structure remains in the process.

The wheat straw lignin is regarded as challenging material to handle, since it is small particle powder. In granulation test, granulates were formed when additives were used, but not with pure lignin. The pelletizing required testing with different settings after the pellets were successfully formed.

Also, the high pressure pressing as a mechanical drying method were tested for willow. Fresh willow chips was pressed with 45-70 bar pressure and the best result was achieved with 45 bar pressure. The moisture content decreased from 59.7% to 53.1%, but the extract was collected. As a pre-treatment method it was quite energy-intensive, but it would improve the possibilities to collect and utilise extracts from field biomasses. The extracts may include bioactive compounds and other valuable substances. This pre-treatment also had impact on the structure, which had influence on the chemical composition of willow (see Pulkkinen & Punttila 2025).

#### Publications & theses

Ruokamo, K. & Punttila, E. 2024. Pajun esikäsittelymenetelmien testausta. LAB Pro. Available at https://www.labopen.fi/lab-pro/pajun-esikasittelymenetelmien-testausta/

Ruokamo, K. 2024. Ligniinin esikäsittely ennen pyrolyysiä. LAB Focus. Available at https://blogit.lab.fi/labfocus/ligniinin-esikasittely-ennen-pyrolyysia/

## Digital solutions for efficient utilization and increasing predictability

Contact person: Malahat Ghoreishi, LAB

### Introduction

Industry 4.0, also known as the Fourth Industrial Revolution, is the current trend of increased automation and data exchange in manufacturing production. Industry 4.0 includes several new technologies, such as the Internet of Things (IoT), big data, cloud computing (CC), digital twins, artificial intelligence (AI), and additive manufacturing, which are assisting various industries to improve their performance and productivity (Issa et al., 2018).

According to McKinsey & Company (2016), 'Supply Chain 4.0 [is] the application of the Internet of Things, the use of advanced robotics, and the application of advanced analytics of big data in supply chain management: place sensors in everything, create networks everywhere, automate anything, and analyse everything to significantly improve performance and customer satisfaction.' Supply chains produce vast amount of data that need to be effectively managed and analysed to meet sustainability objectives. A key feature of Industry 4.0 technologies is their ability to collect and analyse big data, which can drive supply chain innovation and optimize logistics processes (Wang et al., 2016). McKinsey & Company (2016) identified six primary value drivers for improvements in Supply Chain 4.0, as outlined in the Figure 1 below.


*Figure 1. Digital supply chain compass (Mckinsey, 2016).*

Data provides the foundation upon which all business decisions and actions are based, and the right data, when collected and analysed correctly and accurately, can help organizations make informed decisions about where to focus their efforts, how to allocate resources, and what strategies to implement (Lopes de Sousa Jabbour et al., 2018). Data must be converted into information, knowledge, and wisdom in order to be able to enhance the performance and efficiency of a supply chain at both the strategic and operational levels (Kristoffersen et al., 2020). Additionally, Industry 4.0 technologies are disruptive, and companies thus need to rethink and redesign their supply chains as well as business models for efficient transformation a sustainable and circular model.

Transparent data sharing among supply chain partners enhances supply and demand planning, production scheduling, and delivery. It also benefits end-to-end performance management and facilitates more efficient decision-making (McKinsey & Company, 2016). Effective data management within a supply chain boosts transparency and visibility, reveals hidden costs, and eliminates redundant operations. Given the complexity of supply chains, developing robust data management capabilities will enable data integration and establish a common language among different partners (Yu et al., 2018).

Furthermore, Data plays a vital role in predictive maintenance (Niyonambaza et al., 2020). It is essential to collect both maintenance history data and raw sensor data for this purpose. Deb et al. (2019, p. 512) suggest that service providers should reuse existing knowledge and information about customers and their past needs and maintain a reusable knowledge repository to quickly find solutions and take prompt actions. This relates to a theme in logistics outsourcing literature: product life extension. Disassembling and restoring failed products or equipment to operational status requires access to product-specific data, making information-sharing between manufacturers and service providers a key performance driver. However, Janicke et al. (2020) note that further advancements in data analytics are needed to detect quality issues in supply chains using second-life components/products and to ensure that repurposed devices/products maintain their integrity through different ownership stages.

The agricultural supply chain is one of the crucial systems which can confront national stability if not managed well. It requires a real time monitoring and precise data sharing on products through the entire upstream and downstream processes to ensure the quality, quantity, and condition of the products that reach consumers. This requires information from the field on raw materials, collections, storage, production processes, and transportation (Masi et al., 2021). This type of data and information is required to increase transparency and traceability of the supply chain and to enhance sustainable solutions. The aim of this task was to investigate on digitalization of biomass supply chain. It is essential to identify how to implement straw supply chain sustainably to increase the profitability of the entire biomass ecosystem. The important issue is to increase the predictability and traceability of the supply chain.

## Materials & Methods

For this study, a literature review on the existing solutions has been conducted. The aim was to explore the role of Industry 4.0 technologies in supply chain management and integrate it to a possible solution for the case of straw supply chain sustainability.

## Results & Discussion

In case of supply chain management in biochar some existing solutions from digital supply chain management of agricultural products can be integrated. The solutions consist of integrating AI with blockchain for traceability and data integration can create highly intelligent applications to address agricultural challenges. Supply chain management is advancing in agriculture, with blockchain providing transparent and distributed supply chain management capabilities. Combining IoT, AI, and blockchain enhances real-world application performance, meeting the dynamic needs of agricultural supply chain stakeholders (Singh and Singh 2020; Dwivedi et al. 2021). Decentralized AI applications and algorithms, built on blockchain, offer a trusted, shared data platform for storing knowledge, recording, and decision-making. This platform ensures reliable records of AI algorithms throughout the learning and decision-making process (RegPac 2022).

Although the value of digital twin and analytics become increasingly clear, many companies are struggling for a successful implementation these technologies and capturing their full potential. This is due to technical challenges of implementing digital twin which include developing the core engine of the solution, designing a user interface to aid decision-making, and integrating the solution into the IT infrastructure through two-way interfaces with existing systems, like the enterprise resource planning systems of plants (Mckinsey & Company, 2020). For this, Mckinsey & Company (2020) introduces a threefold approach for capturing value shown in the below Figure 2 and describing that success requires two other aspects beside the strong technical capabilities:

- Adequate industry and supply-chain expertise is essential to define the digital twin's objective function. The solution needs a comprehensive perspective and the appropriate level of physical and timing detail to support well-informed decisions about precision, implementation speed, and execution.
- Change-management efforts should target all stakeholders, from farmers to agricultural players. Farmers need to be prepared for changes in crop-collection planning and logistics, and informed about the potential benefits, such as increased compensation for their crops. For instance, when an agricultural player recently optimized its supply chain with a digital twin, up to two-thirds of farmers experienced changes in their crop collection periods, and crop compensation rose by 3 to 5 percent. Agricultural supply-chain teams also need to shift their mindset, using digital twins for planning and exception management instead of relying on frequent rescheduling and crisis management.

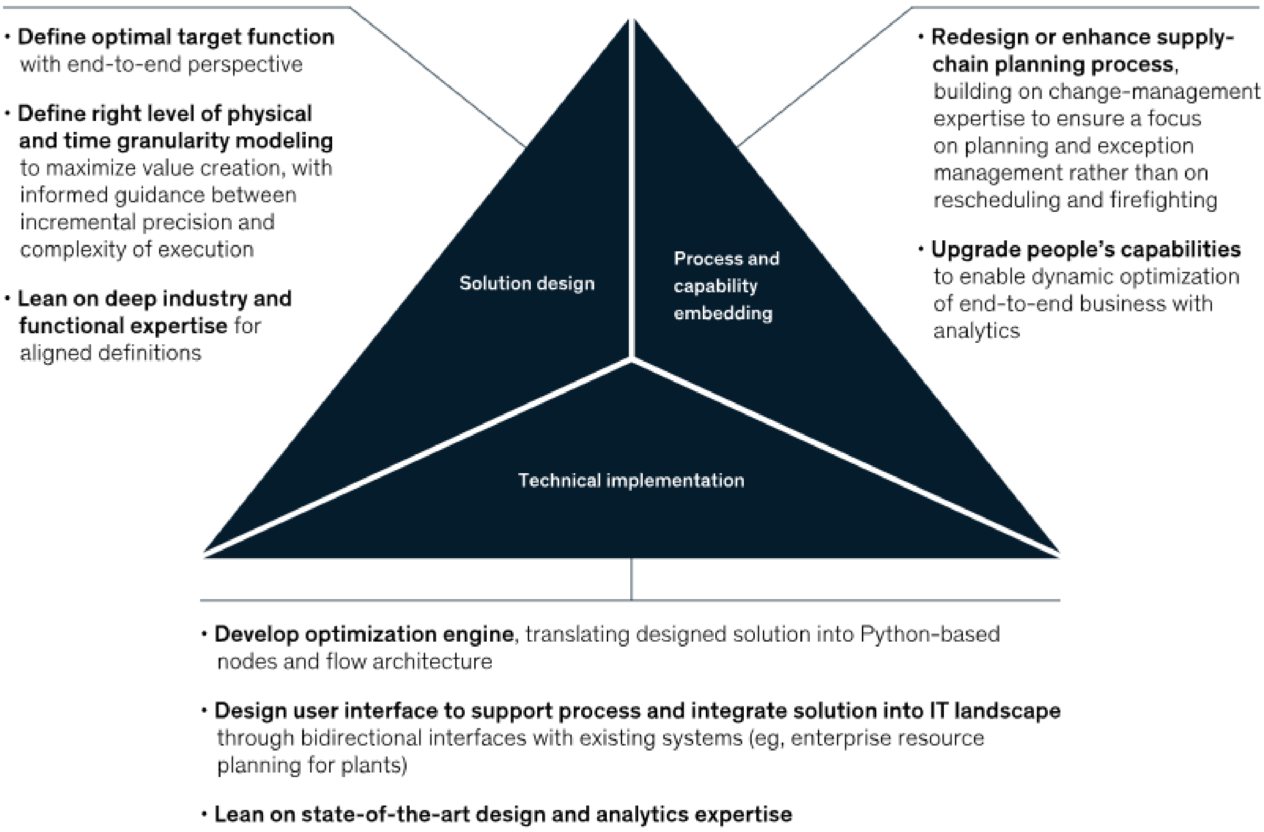


*Figure 2. Digital twin and analytics value capture approach in agricultural supply chain management.*

**Publications & theses**

Ghoreishi, M. et al. Enhancing sustainable supply chain of agricultural biomass through Digital technologies: Case of Finland.

# Agricultural sidestreams into biocarbons and activated carbons

## Summary of the work and achievements

The research on biocarbon development in the BioCarbonValue project focused on producing biocarbons from selected feedstocks, including wheat straw, wheat straw lignin, oat husks, reed canary grass, and willow, through slow pyrolysis. The work involved carbonizing the field biomasses at three different temperatures (500°C, 700°C, and 900°C) to study changes in mass and biocarbon quality. The project also included steam activation experiments to investigate porosity development and surface area of the biochar. Chemical activations were used with the wheat straw lignin as it was pre-selected feedstock for energy storage applications. The biocarbons were tested for specific applications, which targeted high-volume needs (water purification), growing demands (energy storage), and emerging needs (biocomposites). The project aimed to compare field biomass-derived biocarbons with forest-based and commercial fossil carbons and determine biocarbon requirements for the chosen applications. Results of the lignin activations and application tests are reviewed under section "High-value applications for agro-based biocarbons".

## Key results and impacts

The key results from the research include:

- **Pyrolysis temperature impact:** Higher pyrolysis temperatures generally led to lower biocarbon yields but produced biocarbons with higher carbon content and greater thermal stability.
- **Feedstock differences:** Chemical analysis revealed differences between woody biomass (willow) and field biomasses, with field biomasses having higher ash contents, which affected the carbon content and fixed carbon levels of the biocarbons.
- **Steam activation**: The BET surface areas of the prepared activated carbons ranged from 450 to 800 $m^2/g$, with the maximum value observed in activated carbon from wheat straw biocarbon prepared at 700°C. Increasing the activation temperature to 900°C enhanced the surface area of selected biocarbons by approximately 200-300 $m^2/g$.
- **Challenges:** High ash content in biocarbons posed challenges for specific applications, such as water purification, due to pore blocking. It can also be limiting factor in applications with stringent requirements on impurities. Suitable pre- or post-treatments for the biomasses, biocarbon, or activated carbons could mitigate these issues.

The results demonstrated the potential for utilizing field-based materials in the production of high-value biocarbon, although the chemical quality of the feedstocks, particularly the ash content, posed challenges.

# Biocarbon development through slow pyrolysis and activation for field-based feedstocks

Contact person: Virpi Siipola, VTT

## Introduction

Slow pyrolysis can be used to produce biocarbon from a wide variety of organic raw materials, which can be used in many applications, such as soil amendment, filter media or a precursor for higher value products like catalysts or activated carbons. Slow pyrolysis is characterized by low heating rates and long residence times and changing the process parameters one can significantly influence the yield and properties of the resulting biocarbon, condensed gases, and non-condensable gases.

Temperature plays a crucial role in determining the yield and quality of biocarbon. Higher pyrolysis temperatures generally lead to lower biocarbon yields but produce biocarbons with higher carbon content and greater thermal stability (Pahnila et al., 2023; Tripathi et al., 2022). For instance, biocarbon yield can decrease from around 71% at 325°C to about 22% at 800-1000°C (Tripathi et al., 2022). Higher temperatures also enhance the development of larger pores and increase the aromatic carbon content in the biocarbon(Liu et al., 2018). Heating rate is another important factor. Lower heating rates tend to increase biocarbon yield, especially at temperatures above 500°C (Li et al., 2016; Pahnila et al., 2023). This is because slower heating allows for more complete thermal decomposition of the biomass, resulting in higher fixed carbon content and better structural properties (Li et al., 2016). Retention time or residence time also affects biocarbon yield. Longer retention times generally lead to higher biocarbon yields as they allow for more thorough carbonization of the biomass (Pahnila et al., 2023). However, excessively long retention times can lead to diminishing returns in yield improvement and may increase energy consumption. In the current work, slow pyrolysis heating rate and carbonization time were selected based on pretesting and previous experiments and kept constant for all the experiments. The selected operating variable was the temperature.

Activation is a significant step in improving the properties of biocarbons produced through slow pyrolysis. This process involves treating biocarbon to increase its surface area and porosity, making it more effective for applications such as adsorption and catalysis. There are two main methods of activation: physical and chemical. Physical activation generally involves exposing biocarbon to high temperatures in the presence of gases like steam or carbon dioxide. This method helps develop a porous structure, enhancing biocarbon's adsorption capacity. Chemical activation involves treating biocarbon with activating agents such as potassium hydroxide (KOH) or phosphoric acid ($H_3PO_4$). This approach can produce highly microporous activated carbons with specific surface chemistries tailored for particular applications (Ohra-aho et al., 2020; Siipola et al., 2018, 2020; Tiihonen et al., 2020). The choice of activation method and conditions can significantly influence the properties of the resulting activated carbon, making it essential to tailor the process based on the intended application.

This section will review the results of the BioCarbonValue project, focusing on the slow pyrolysis and activation experiments performed on selected agro-based sidestream materials. The selection criteria for the raw materials are presented under the section “Enhanced utilization of agricultural biomass as a feedstock for diversified refining industry” of this report. Wheat straw lignin treatments and results are presented under section “High-value applications for agro-based biocarbons.” The carbonization experiments were performed at the VTT piloting center in Espoo, Finland.

## Materials & Methods

**Slow pyrolysis** experiments were conducted for 4 raw materials: wheat straw (WS), oat husks (OH), reed canary grass (RCG) and willow (WL), to investigate the effects of slow pyrolysis conditions on biocarbon yield and quality (Figure 3). The raw materials were ground but not dried as their moisture contents were at maximum of 10%. Additional slow pyrolysis experiments were performed for the mechanically pressed willow, which process is described in the “Enhanced utilization of agricultural biomass as a feedstock for diversified refining industry” section of this report. These raw materials: the mechanically pressed and original willow used in that test, were dried prior to carbonization.

The experiments were performed using a batch reactor, employing three different temperatures: 500°C, 700°C, and 900°C. The carbonization time was 2 h for all experiments. At each temperature, the biocarbon was recovered, and the condensed gases were collected. The non-condensable gases (NCG) were analyzed using a µ-GC analyzer. This comprehensive analysis allowed for the calculation of mass balances for the various feedstocks. The biocarbons were further analyzed for their elemental composition (C, H, N, S, and O), ash content, volatile matter. Fixed carbon amounts were calculated as dry based from the results. Additionally, thermal and electrical conductivities of the biocarbons were tested.

**Steam activation** experiments were conducted to investigate the porosity development and surface area of the biocarbon regarding their production temperature. Activations were performed using steam as an activator at 800°C. Selected biocarbons were also activated using higher temperature of 900°C. Activations were performed using the same batch retort as the carbonizations. Water flow used for the steam generation was 4,5 ml/min and the retention time was 3 h at the target temperature. Activated carbons were analyzed for the elemental composition (C, H, N, S, and O), ash content, volatile matter, and fixed carbon content. Additionally BET surface area and pore size distribution analysis were performed.

*Figure 3. Used raw materials in the project from left to right: wheat straw, willow, oat husks and reed canary grass.*

## Results & Discussion

### Slow pyrolysis of the field biomasses

The mass balances from the slow pyrolysis experiments demonstrated differences between the feedstocks (Figure 4). Wheat straw exhibited the highest proportion of NCG in comparison to other feed materials. Oat husks generated the highest yields of liquids (bio-oil/tar) and the lowest yields of NCG. The biocarbon yields were relatively consistent across all feedstocks, with oat husks showing a marginally higher yield, and willow exhibiting the lowest yield. When comparing dry ash-free yields, willow produced higher biocarbon yields compared to WS and RCG, but lower that OH. Wheat straw, tested from two distinct batches collected from different farms and varying storage periods, showed differences in ash content that influenced biocarbon yield, with batch 1 exhibiting higher ash content than batch 2 (Table 4). This different between batches was also seen in the upscaling experiments, where wheat straw pellets were used as feedstock.

The mechanically pressed willow underwent carbonization otherwise under the same conditions as the other feedstocks, but using only one temperature of 500°C. The willow used in the pressing test originated from a different batch, which influenced the comparability of results with those from the initial batch of willow experiments. Slow pyrolysis was also conducted on non-pressed willows from this new batch. The findings revealed no significant differences in the dry biocarbon yields between mechanically pressed and non-pressed willow, both achieving a yield of 29%. In contrast, the first batch of willow yielded 31%.

However, the most notable differences were observed in the liquid and NCG yields. The willow batch used in the mechanical pressing test produced a significantly higher amount of NCG (41%) and a lower amount of liquids (30%), likely due to the quality of the biomass. This willow was more recently harvested, moist, and one year older than the willow used in other experiments. Variations in hemicellulose and cellulose contents between the willow batches (Table 2) were also observed, likely contributing to differences in product yield distributions.

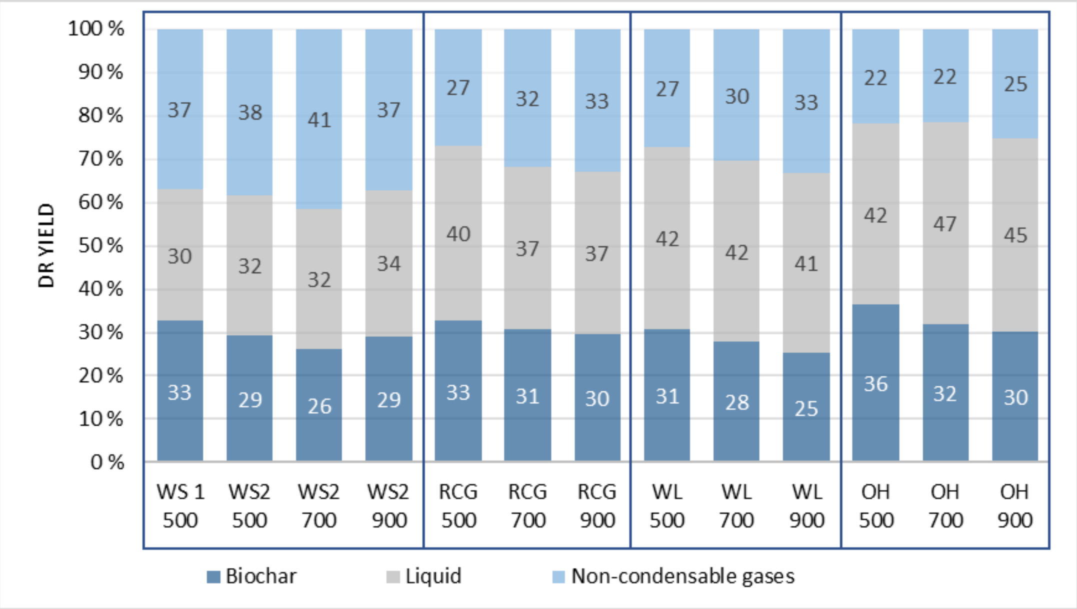


*Figure 4. Mass balances of the slow pyrolysis experiments.*

The chemical analysis results of the biocarbons in Table 3 and Table 4 show the differences between the woody biomass, willow, and the field biomasses. Ash contents of the field biomasses are very high, reaching 27 wt-% with reed canary grass biocarbon produced at 900°C. This is reflected in the dry based carbon contents of the biocarbons, which are higher with willow at all temperatures. Generally, the carbon contents increase linearly with the production temperature as they should. RCG and WS had some deviations for this linearity, but dry ash free results show the same trend as with the other feed materials. The carbon content deviations are probably related to the heterogeneous nature of these materials, as was seen with the differences in the biocarbon yields with 2 wheat straw batches. Both RCG and WS had some leaves and grains left in the straws, which increases the risk of quality variation.

*Table 3. Ultimate analysis results of the produced biocarbons.*

| Sample | Temp | Time | C | | H | N | S | $O_{calc}$ |
|---|---|---|---|---|---|---|---|---|
| | °C | min | dry, wt-% | daf, wt-% | dry, wt-% | dry, wt-% | dry, wt-% | dry, wt-% |
| WS, 1st batch | 500 | 120 | 65 | 82 | 2.3 | 0.8 | 0.1 | 11 |
| WS, 2nd batch | 500 | 120 | 82 | 91 | 2.3 | 1.6 | 0 | 4.1 |
| | 700 | 120 | 80 | 89 | 0.1 | 1.3 | 0 | 8.5 |
| | 900 | 120 | 82 | 95 | 0.2 | 1.5 | 0.1 | 2.6 |
| OH | 500 | 120 | 76 | 91 | 2.4 | 0.8 | 0.6 | 4.1 |
| | 700 | 120 | 78 | 95 | 0.8 | 0.8 | 0.2 | 2.4 |
| | 900 | 120 | 79 | 96 | 0.2 | 1.3 | 0 | 1.4 |
| RCG | 500 | 120 | 71 | 84 | 2.3 | 1.2 | 0 | 10 |
| | 700 | 120 | 76 | 94 | 0.6 | 1.1 | 0 | 3.0 |
| | 900 | 120 | 72 | 98 | 0.1 | 0.9 | 0.1 | 0.1 |
| WL | 500 | 120 | 86 | 89 | 2.7 | 1.3 | 0 | 6.9 |
| | 700 | 120 | 92 | 95 | 1.1 | 1.2 | 0 | 2.2 |
| | 900 | 120 | 93 | 96 | 0.3 | 1.3 | 0 | 2.0 |

*analyzed, not calculated; daf = dry ash free; $O_{calc}$ = 100%- (C(dry) + H + N + S + ash) wt-%

Oat husks and reed canary grass did not achieve carbon contents exceeding 80 wt%. These materials, in addition to the initial batch of wheat straw (WS), exhibited elevated ash contents, thereby resulting in diminished fixed carbon levels. Cereals, straws, and grasses generally encompass substantial quantities of inorganic compounds assimilated from the soil, such as silicon present as minute phytolith particles. Phytoliths bolster plant structural integrity and mitigate water stress (Meunier et al., 2017). Prior to conducting slow pyrolysis experiments, feed materials underwent thermogravimetric analysis (TGA), where ash residue post-air incineration at 1000°C was assessed via energy-dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD). Analytical outcomes revealed that RCG ash possessed a considerable silicon content (37 wt%), succeeded by OH (13 wt%). Willow ash similarly demonstrated a significant silicon concentration (23 wt%), while WS ash presented minimal silicon content (0.4 wt%). Predominantly, calcium constituted the primary element in WS ash following oxygen (22 wt%), surpassing levels observed in other feed materials (0.5-1.4 wt%). Wheat straw ash encompassed larger proportions of sodium, potassium, and magnesium relative to other samples. Nonetheless, the analysis lacked completeness, given the mass balance of OH stood at 89%, suggesting certain elements remained undetected.

*Table 4. Proximate analysis results of the produced biocarbons.*

| Sample | Temp °C | ash, wt-% 550°C | ash, wt-% 815°C | Volatiles wt-% | Fixed carbon wt-% |
|---|---|---|---|---|---|
| WS, batch 1 | 500 | 21 | nd | 11 | 68 |
| WS, batch 2 | 500 | 10 | 10 | 9.8 | 80 |
| | 700 | 11 | 10 | 3.5 | 86 |
| | 900 | 14 | 14 | 2.0 | 84 |
| OH | 500 | 16 | 16 | 8.1 | 76 |
| | 700 | 18 | 17 | 2.2 | 80 |
| | 900 | 19 | 18 | 1.8 | 80 |
| RCG | 500 | 16 | 16 | 11 | 72 |
| | 700 | 20 | 20 | 2.5 | 78 |
| | 900 | 27 | 27 | 0.7 | 72 |
| WL | 500 | 4.9 | 3.2 | 12 | 84 |
| | 700 | 4.6 | 3.6 | 2.9 | 93 |
| | 900 | 4.9 | 3.8 | 2.4 | 93 |

High ash content in biocarbons can present challenges for specific applications such as batteries or metallurgy due to the stringent limitations on impurities. Ash can also obstruct pore structures, thereby inhibiting the attainment of high surface areas in activated carbons. Although washing processes can mitigate ash content, they incur additional costs. In agronomy, biocarbons with elevated ash levels may function as fertilizers, though the bioavailability of nutrients like phosphorus is contingent upon the feedstock material (Glaser & Lehr, 2019). Nevertheless, certain applications, such as biocarbon-enhanced concrete, exhibit tolerance for higher ash concentrations. In addition, development of new and enhancing existing pre-treatment methods can promote the use of high-ash feed materials in wider application field.

### Thermal conductivity and electrical resistivity

The thermal and electrical conductivities were measured for the prepared biocarbons and the results are presented in Figure 5. Thermal conductivity was measured using hot disc TPS method from powdered biocarbons. Electrical resistivity was measured as a function of compressive force up to 50 MPa. The electrical resistivity of the biocarbons was decreased as a function of biocarbon preparation temperature. Thermal conductivity was slightly increased as a function of preparation temperature, but remained very low compared to the reference material, which was a graphite material KS-44. Based on the results the wheat straw biocarbon prepared at 900°C was selected for the biocomposite testing, which results can be found under section "High-value applications for agro-based biocarbons".

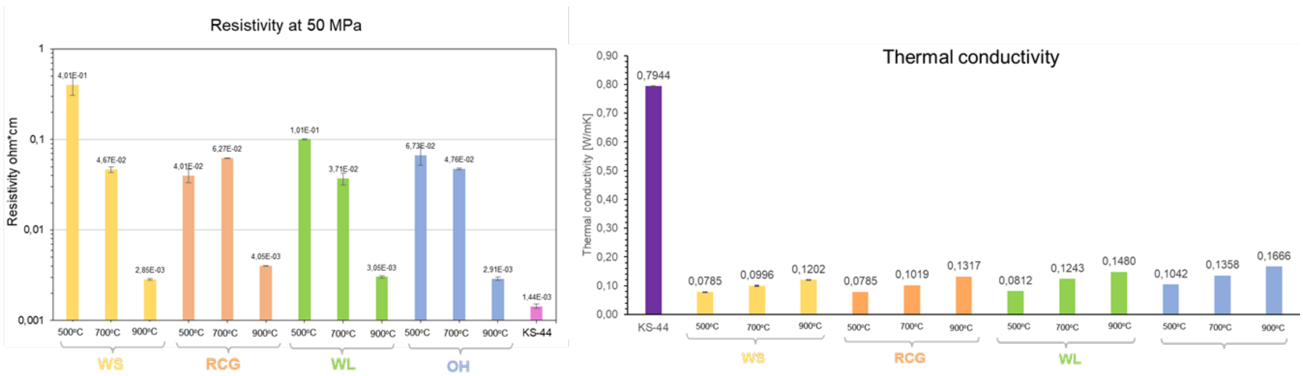


*Figure 5. Electrical resistivity and thermal conductivity results of the prepared biocarbons.*

### Non-condensable gases composition

During the slow pyrolysis tests, the generated pyrolysis gases passed through a condensing system where the condensable gas compounds were removed and collected. The remaining non-condensing gas (NCG) compounds were analyzed using a gas chromatograph (GC) with sampling intervals of 4-5 minutes. The primary compounds produced during slow pyrolysis included $H_2$, CO, $CO_2$, and $CH_4$. Additionally, some heavier hydrocarbons were present in the gas but in much smaller quantities.

The composition of the NCG varied with the production temperature. At 500°C, during the carbonization period, all major NCG compounds were present in the gas with proportions of 27-43 vol-% of $H_2$, 24-29 vol-% of $CH_4$, 12-19 vol-% of CO, and 16-21 vol-% of $CO_2$. Differences between feed materials were generally not significant. The most notable difference was observed in $H_2$, where WS produced 9 to 16% more compared to other feed materials, with WL having the lowest proportion (27 vol-%). The proportion of CO was lowest with WS (~12 vol-%) and highest with RCG (~19 vol-%). Willow produced the highest $CO_2$ proportion (~21 vol-%), while WS had the smallest (16 vol-%).

As the temperature was increased to 700°C, the proportion of hydrogen ($H_2$) in the non-condensable gases (NCG) significantly increased compared to other NCG compounds. The $H_2$ proportions rose to 55-68 vol-%. Among the feed materials, reed canary grass (RCG) had the lowest $H_2$ proportion, while the other feed materials did not show significant differences from each other and ranged from 65-68 vol-%. The proportions of methane ($CH_4$) and carbon dioxide ($CO_2$) decreased to 10-17 vol-% and 3-7 vol-%, respectively, while carbon monoxide (CO) remained at a similar level as at 500°C.

Increasing the temperature further to 900°C altered the NCG composition to consist predominantly of $H_2$ and CO, with only traces of $CH_4$ or $CO_2$ present. At this temperature, the $H_2$ proportions were 62-72 vol-% and CO proportions were 27-38 vol-%. Wheat straw (WS) and willow (WL) had the highest $H_2$ proportions (73 and 73 vol-%, respectively), whereas RCG had the highest CO proportion (38 vol-%), with WS and WL having the lowest CO proportions (27 vol-% both materials).

The results show how the gas composition changes by changing the carbonization temperature. This information can be useful when considering the utilization of the pyrolysis gases. Minor differences between the feed materials was found, which information can be used to refine the process if the NCGs are of interest.

### Steam activations of the biocarbons

The biocarbons produced from field biomasses at 3 different temperatures were subjected to steam activation treatment to explore the dependence of their porosity and surface area development regarding production temperature. The yields of the activated carbons increased as a function of the biocarbon production temperature (Figure 6). The probable reason for this is the ash content of the biocarbons which was increased with the production temperature (Table 4). Ash accumulation in the activated carbon pores can prevent the activation agent, steam, from entering the pore structure. The steam can also react with some of the ash components, tars and volatiles in the biocarbon.

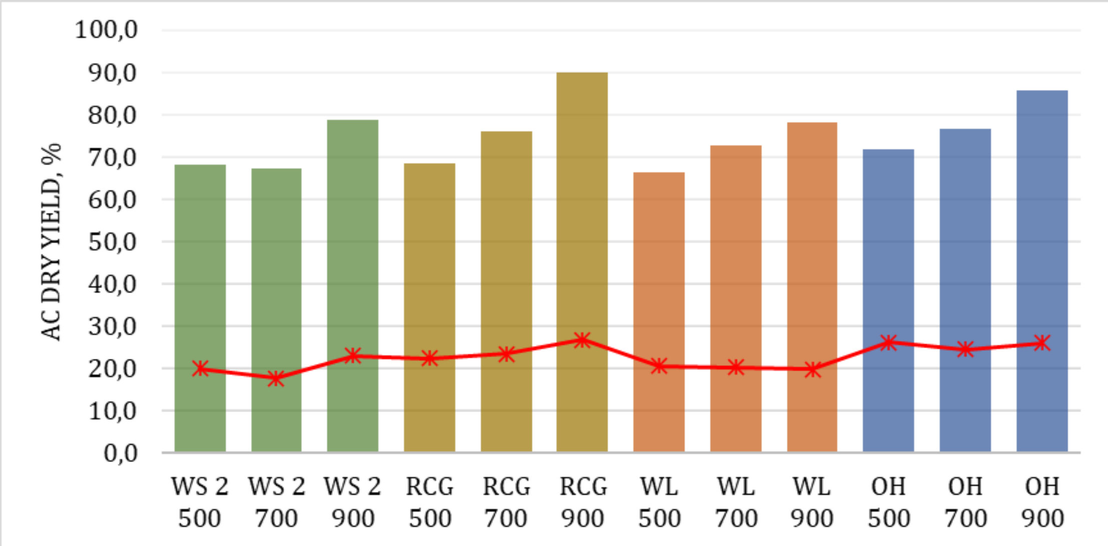


*Figure 6. Activated carbon yields. The total yield is marked with the red line. The precursor biocarbon is marked at x-axis.*

The ash content in biocarbon samples exhibits a decreasing trend with increasing pyrolysis temperature, reaching a minimum of 5.5 wt-% in WL900 (Table 5). Volatile matter content remains consistently low across all samples, with WS2 500 presenting the highest value at 2.0 wt-%. Fixed carbon (FC) content demonstrates a positive correlation with temperature, attaining a peak of 94 wt-% in WL900. These observations suggest that elevated pyrolysis temperatures facilitate the reduction of ash and volatile matter content while augmenting the fixed carbon content, which is essential for applications necessitating high carbon purity. The reduction in ash content can be attributed to the enhanced decomposition of organic matter and volatilization of inorganic compounds at higher temperatures. The biocarbons produced at 500°C had more volatiles and tars trapped inside the pores for the steam to react with causing high burn-off whereas the biocarbons produced at 900°C were more thoroughly carbonized and less reactive. The total yields in Figure 6 marked by a line does not show significant differences between the activated carbons, or between biocarbon production temperatures.

*Table 5. Proximate analysis results of the produced activated carbons.*

| Feed biocarbon | ash 550 wt-% | Volatiles wt-% | FC, db wt-% |
|---|---|---|---|
| WS1 500 | 36 | 1.2 | 64 |
| WS2 500 | 15 | 2.0 | 84 |
| WS2 700 | 17 | 1.3 | 82 |
| WS2 900 | 15 | 1.3 | 84 |
| OH 500 | 23 | 1.3 | 77 |
| OH 700 | 23 | 1.0 | 76 |
| OH 900 | 21 | 0.8 | 80 |
| RCG 500 | 25 | 1.0 | 75 |
| RCG 700 | 24 | 0.6 | 76 |
| RCG 900 | 22 | 0.5 | 78 |
| WL 500 | 6.5 | 1.4 | 93 |
| WL 700 | 5.8 | 1.8 | 93 |
| WL 900 | 5.5 | 1.7 | 94 |

The activated carbons exhibit a progressive increase in carbon content with rising slow pyrolysis temperatures, culminating in a maximum of 93 wt-% in WL900 activated carbon (Table 6). Hydrogen content remains relatively low across all samples, with WS2 500 demonstrating the highest concentration at 0.8 wt-%. Nitrogen content shows slight variability, peaking at 1.1 wt-% in WS2 500. Sulfur content is consistently minimal (<0.1 wt-%) across all feed materials. Oxygen content decreases with increasing biocarbon production temperature with WS and RCG, with WS1 500 and WS2 500 exhibiting the highest values at 10 wt-%. Oat hush and willow activated carbons do not show similar trend. These findings underscore the temperature-dependent compositional changes in biocarbon, influenced by the feed material used.

*Table 6. Ultimate analysis results of the produced activated carbons.*

| Feed biocarbon | C, wt-% | H, wt-% | N, wt-% | S, wt-% | $O_{calc}$, wt-% |
|---|---|---|---|---|---|
| WS1 500 | 64 | 0.2 | 0.5 | <0.1 | 10 |
| WS2 500 | 79 | 0.8 | 1.1 | 0.1 | 10 |
| WS2 700 | 82 | 0.2 | 0.8 | 0.1 | 6 |
| WS2 900 | 85 | 0.1 | 0.9 | 0.1 | 5.1 |
| OH500 | 75 | 0.3 | 0.6 | <0.1 | 4.6 |
| OH700 | 75 | 0.3 | 0.5 | <0.1 | 5.6 |
| OH900 | 77 | 0.2 | 0.7 | <0.1 | 4.6 |
| RCG500 | 74 | 0.2 | 0.5 | <0,1 | 8.1 |
| RCG700 | 76 | 0.2 | 0.6 | <0,1 | 8.0 |
| RCG900 | 78 | 0.2 | 0.8 | <0,1 | 6.8 |
| WL500 | 92 | 0.3 | 1.0 | <0,1 | 2.3 |
| WL700 | 92 | 0.3 | 1.0 | <0,1 | 2.5 |
| WL900 | 93 | 0.2 | 1.1 | <0,1 | 2.3 |

The BET surface areas of the prepared activated carbons ranged from 450 to 800 $m^2/g$, with the maximum value observed in activated carbon from WS biocarbon prepared at 700°C (Figure 7). The activated carbons were microporous, consisting of 68-87 % of micropores. Willow and RCG had slightly higher proportions of mesopores compared to OH and WS, maximum mesopore proportion (31 %) detected for RCG500. A declining trend in surface areas was also noted with increasing biocarbon preparation temperatures, particularly pronounced in RCG biocarbons. This trend is likely attributable to the relationship between yields and ash content. At higher preparation temperatures (700°C and 900°C), the steam reaction with the carbon structure becomes less effective due to the elevated ash content. The ash most likely obstructs reaction sites within the biocarbon, inhibiting pore-forming reactions between carbon and steam. Consequently, the surface area decreases as the biocarbon preparation temperature increases. The RCG biocarbons exhibited the highest ash contents, reaching 27 wt-% at 900°C, which corresponded to the lowest surface areas observed in these experiments. Increasing the activation temperature to 900°C enhanced the surface area of selected biocarbons by approximately 200-300 $m^2/g$, with a maximum value of 1093 $m^2/g$

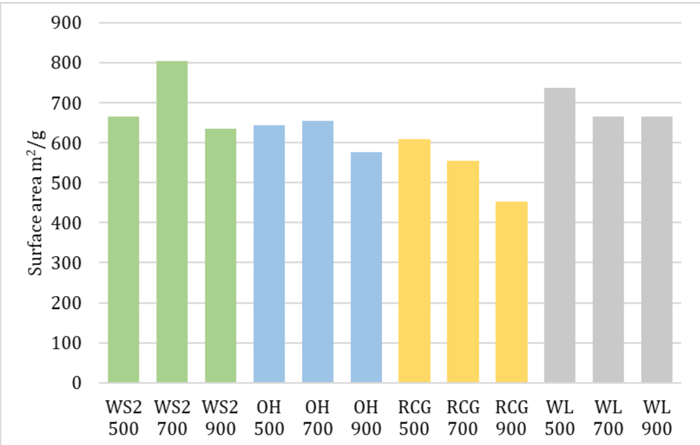


*Figure 7. BET surface areas of the activated carbons prepared from biocarbons prepared at different pyrolysis temperatures.*

obtained for activated carbon derived from WL500. The increase in temperature facilitates the reaction between steam and the carbon structure, likely promoting the volatilization of some of the ash compounds. This process reduces the ash content and unblocks reaction sites within the biocarbon, thereby enhancing pore formation and increasing the surface area.

### Conclusions

The results of the slow pyrolysis and steam activation experiments demonstrate the potential for utilizing field-based materials in the production of high-value biocarbon. However, the chemical quality of the feedstocks, particularly the ash content, poses a significant challenge. This issue can be mitigated by implementing suitable pre- or post-treatments for the biomasses, biocarbon, or activated carbons to reduce ash content. Alternatively, applications can be identified where ash content is not a limiting factor. Additionally, variations observed in willow and wheat straw batches highlight another challenge in using these biomasses, as quality or product distribution can vary depending on the collection location or harvesting time. The biocarbon quality challenge could also be addressed through the use of pre- or post-treatments. Variation caused by different harvesting times or age of the biomass on the pyrolysis product distribution (biocarbon vs liquids and NCG), which was seen with willow, can be taken into account in the harvesting schedule, but some variation can still be found in the yields which needs to be taken into account when using these biomasses.

## Upscaling biocarbon production

Contact person: Virpi Siipola, VTT

### Introduction

Biocarbon scale-up experiments were carried out to examine the industrial production potential of agro-based raw materials. Wheat straw pellets were selected as the test material. These pellets underwent carbonization at six different locations using three types of reactors: fluidized bed, rotary kiln, and screw kiln. Altogether 7 reactors were tested (3 rotary, 3 screw and 1 fluidized bed reactor) The reactors varied in terms of manufacturers, feeding capacities, and other potential operating conditions and capabilities (e.g., temperature range, ability to monitor forming gases, and collect bio-oil). Therefore, multiple tests using different reactor types were conducted to better understand these variations. The operators were not given specific parameters for the tests other than the pyrolysis temperature. The reactors were operated at 500°C and 700°C. The operators selected other test conditions based on their own previous experience on high quality biocarbon production using their equipment. This resulted in feeding rates from 4 to 100 kg/h with retention times mostly from 35 to 40 minutes. One screw experiment had a shorter 12.5-minute retention time. This public report summarizes the key findings and insights of the experiments. Some detailed information are not included due to confidentiality considerations.

### Results & Discussion

Biocarbon total yields, which include the start-up and shut-down phase biocarbons, ranged from 21% to 45% on a dry basis for the rotary and screw kilns with no significant differences observed between the kiln types (Table 7). Small differences can be associated with the small differences in feeding rates and retention times. The higher temperature of 700°C decreased the yields by 5 to 9 wt-%. The chemical quality of biocarbons depends on the raw material batch, influencing carbon content and ash amount. These qualities remained consistent across reactor types or feeding rates if sourced from the same batch. Fluidized bed reactor yielded less than rotary and screw kilns due to the smaller particle size needed, which increased gasification and carbon dust formation during carbonization. Maximum combined yield of biocarbon and carbon dust from fluidized bed reactor was 25% (db) using 40 Hz feeding rate and 15 min retention time. The actual retention time was strongly affected by the feeding step, which was almost 2 h for the lowest feeding rate 20Hz. The retention time was calculated to start when all material was fed into the reactor. The biggest differences in the upscaling experiments were attributed to different pellet batches: the experiments conducted with the same batch gave similar yields and qualities regardless of the operating parameters. Biggest difference in the wheat straw batches was with the ash content which ranged from approximately 5 wt-% to 10 wt-%.

*Table 7. Operating data and yield results from the rotary and screw kiln upscaling experiments.*

| | Rotary kiln | | | | | Screw kiln | | | |
|---|---|---|---|---|---|---|---|---|---|
| Test no | #1 | | #2 | | #3 | #4 | | #5 | #6 |
| Pellet batch | 1 | | 2 | | 3 | 2 | | 3 | 2 |
| Test | 500 °C | 700 °C | 500 °C | 700 °C | 500 °C | 500 °C | 700 °C | 500 °C | 500 °C |
| Feeding rate, kg/h* | 12.5 | 12.5 | 3.9 | 3.9 | 60 | 8.6 | 8.6 | 5.0 | 100 |
| Retention time, min | 25 | 25 | 40 | 40 | 40 | 35 | 35 | 40 | 12.5 |
| Biocarbon total yields, db, % | 27 | 21 | 34 | 25 | 36 | 30 | 25 | 35 | 26-45 |

With the exception of the fluidized bed reactor, all reactors successfully processed the pellets without the need for drying or grinding. The primary challenge identified in the experiments was the variability in raw material quality between batches, which impacts the consistency of the produced biocarbons. Generally, the ash content of wheat straw pellets is high, influencing both the carbon content and the fixed carbon levels of the biocarbons. In addition to ash, the disintegration of the pellets during the process and pellet dust formation can pose a challenge using these reactors. Based on the results wheat straw pellets are viable for biocarbon production across all tested reactors.

# High-value applications for agro-based biocarbons

## Summary of the work and achievements

The BiocarbonValue project explored high-value applications for agro-based biocarbons, focusing on three main areas: energy storage, water purification and biocomposites. One of the aims of the project was to develop biocarbons from agricultural biomass that could replace fossil-based carbons in these applications. The work involved testing the performance of the produced biocarbons and activated carbons the selected applications and comparing them with commercial carbons.

## Key results and impacts

- **Energy storage:** The activated carbons produced from wheat straw lignin demonstrated promising performance as electrode materials in supercapacitors, with specific capacitance values comparable to commercial activated carbons. The results indicated that agro-based biocarbons could be a viable alternative for energy storage solutions.
- **Water purification:** Agro-based activated carbons show substantial potential for micropollutant removal, particularly when optimized for mesoporous structures and chemical characteristics. Future research focusing on production process optimization, feedstock consistency, and economic viability will further establish their competitive positioning relative to commercial fossil-based alternatives.
- **Biocomposites:** Results demonstrated that electrical conductivity to biocomposites is possible to achieve but relatively high biocarbon loadings may be required. The mechanical properties

were also found to strongly correlate with biocarbon and fiber loadings. The findings indicate that optimizing various biocomposite properties is feasible, and thereby encouraging the use of innovative, sustainable and renewable materials to replace fossil-based, non-renewable materials in composites.

These findings highlight the capability of agro-based biocarbons to substitute fossil-based carbons in high-value applications, thereby promoting the development of sustainable and eco-friendly materials.

## Energy Storage

Contact person: Taina Rauhala, VTT

### Introduction

Energy storage devices can be categorized into high power density devices, such as supercapacitors, and high energy density devices, such as batteries. The carbons utilized in these applications have distinct requirements for optimal performance. Supercapacitors necessitate a high surface area with a microporous pore structure, whereas battery carbons benefit from a high degree of graphitization and a hard carbon structure. Hard carbons, described as 'non-graphitizable' carbons, feature highly disordered graphite layer stacks with larger spacing between them, allowing larger molecules like Na to enter the structure (Figure 8 (Crabtree et al., 2015)). These materials cannot be converted to ordered graphite structures even at high temperatures (up to 3000°C). To achieve these specific characteristics, advanced preparation methods are required, including chemical treatments for precursor materials combined with high-temperature treatment under an inert atmosphere. In the BioCarbonValue project, our goal was to produce and test biocarbon for both energy applications.

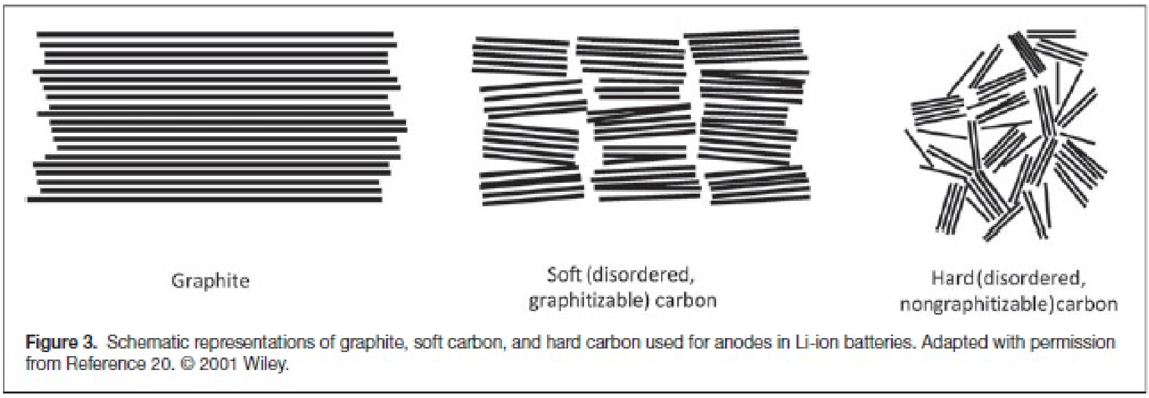


*Figure 8. Various graphite structures in carbons, Crabtree et al., 2015.*

One of the experiments in the project involved using wheat straw lignin as a raw material for energy storage applications. Carbonized lignin has shown potential in electrochemical applications as a replacement for fossil coal, particularly due to its ability to form the hard carbon structure required for Na-ion batteries. However, research has predominantly focused on forest-based lignins, such as kraft lignin. There are few studies on the potential of other lignin types, and current knowledge indicates that lignin quality depends on both the raw material and the separation method. Consequently, various types of lignin produce different types of biocarbons, making it difficult to generalize results from one lignin type to all lignins. This variability has been observed in recent research by VTT, where kraft and hydrolysis lignins were tested for supercapacitor applications (Guizani et al., 2024).

### Materials & Methods

Chemical activation experiments for the wheat straw lignin were performed using $K_2CO_3$ as an activation chemical. The experimental plan included variation of temperatures between 841 and 1000°C with retention times ranging from 30-90 minutes. The produced activated carbons were analyzed similarly as the steam activated carbons.

The applicability of the activated carbons produced from wheat straw lignin for supercapacitor use was assessed through measuring the specific capacitance of the materials (charge storage capability in F/g) in a three-electrode cell with aqueous 0.5 M $Na_2SO_4$ as electrolyte. For the sodium-ion battery application testing, three-electrode cells with a sodium metal counter electrode and a non-aqueous $NaPF_6$ electrolyte in a mixture of ethylene carbonate and ethyl methyl carbonate was used. Before testing, the hard carbons were ground either through ball milling or hand grinding and sieved (106 µm sieve). For the sodium-ion battery materials, the specific capacity (mAh/g) was measured as a function of current density.

### Results & Discussion

Most of the tested activated carbons gave specific capacitance values in the range of 30-60 F/g, which are lower than the value measured for a commercial state-of-the-art activated carbon produced from coconut shell raw material (100 F/g). However, a few of the activated carbons produced from wheat straw lignin showed values above 110 F/g, thereby surpassing the value of the commercial reference material. A modeling approach was also used to understand the effects of the various synthesis parameters (temperature, impregnation ratio, time) on the final performance of the activated carbons. In addition to the specific capacitance, the final performance in a supercapacitor device is affected by the electrical conductivity of the materials as well as the stability of the materials in long term cycling. Hence further testing of the materials in larger supercapacitor cells is recommended for the high capacitance materials.

In the sodium-ion battery testing, the hard carbons produced from wheat straw lignin gave specific capacity values in the range of 130–170 mAh/g, depending on the carbonization temperature. The values were 30-50% lower than the value given by a commercial state-of-the-art fossil-based hard carbon (250 mAh/g). Within the studied temperature range, the lower temperatures produced biocarbons with higher capacity but lower coulombic efficiency, indicating a higher occurrence of unwanted side reactions in the battery and a lower stability. However, further improvement of biocarbon performance can be achieved through optimization of feedstock, carbonization parameters and post-processing, as some lignin-based carbons in in-house testing have shown capacities above 200 mAh/g. Moreover, the coulombic efficiency and stability of the materials could be improved in the future, for example through applying a coating on the particle surface, which is a common practice in commercial battery materials.

## Water purification

Contact persons: Virpi Siipola, VTT

### Introduction

Stricter micropollutant treatment requirements are on the horizon for wastewater treatment plants (WWTPs) within the European Union (EU), as outlined in the revised Urban Waste Water Treatment Directive (UWWTD). Over the coming two decades, WWTPs will gradually be obliged to introduce advanced treatment steps to remove micropollutants. Micropollutants are substances present at trace concentrations of micrograms or nanograms per liter, which potentially pose serious risks to ecosystems and public health. Conventional wastewater processes do not effectively remove all of these contaminants, and recognized mature technologies for achieving the mandated 80% load reduction include ozonation or activated carbon systems.

The adoption of a large-scale AC system could substantially increase WWTPs environmental impacts. For instance, Finland's largest municipal WWTP, Viikinmäki, was projected to require up to 1.4 million kilograms of fresh PAC annually to meet micropollutant removal goals with a combined system of ozonation and AC. Such a massive annual demand can translate to substantial life-cycle emissions if fossil-based materials are used in AC production as a feedstock and/or as an energy source for the production. A promising strategy to reduce these life-cycle impacts is to switch from fossil-based resources to renewable resources.

The main objective of this work was to benchmark the efficiency of agricultural-feedstock-derived activated carbon against commercial carbons in removing representative micropollutants carbamazepine, diclofenac, sulfamethoxazole, and benzotriazole from treated municipal wastewater. These micropollutants were selected due to their poor removal in conventional processes, regulatory importance, and diverse physicochemical properties. The secondary objectives are (1) to associate the retention mechanisms among carbon and contaminant characteristics, and (2) to determine which production conditions (e.g., carbonization temperature) yield the desired AC properties.

This research has both practical and scientific significance. From a practical perspective, understanding how effectively agro-based carbons can perform under typical WWTP conditions is critical for utilities facing upcoming micropollutant regulations. If agricultural feedstocks can achieve comparable performance at an acceptable cost, they may mitigate the theoretical carbon emission burden otherwise imposed by fossil-based AC, while also contributing to local livelihoods. From a scientific perspective, the study deepens knowledge on how biomass composition, pyrolysis parameters, and pore development interplay to influence specific adsorption mechanisms for various pollutants.

## Materials & Methods

Wastewater treatment experiments evaluated the effectiveness of produced ACs in adsorbing selected micropollutants (carbamazepine (CBZ), diclofenac (DCF), benzotriazole (BTA), and sulfamethoxazole (SMX)) from treated municipal wastewater. These pollutants were selected based on regulatory importance in the EU and varying physicochemical properties (hydrophobicity, charge, molecular size). Three commercially produced activated carbons, coal-based Aquasorb MP25 (AC-C), peat/wood-based Norit SAE2 (AC-PW), and peat-based Novactor PAC-700 (AC-P), served as benchmarks for comparison.

Micropollutant batch adsorption experiments were conducted using effluent samples from Viikinmäki municipal wastewater treatment plant during three sampling campaings. The water samples were collected in the outflow tunnel, put into 5-liter containers and stored at +5 °C until experimentation. AC suspensions (2 g/l) were prepared by mixing 0.4 g of AC in 200 g MilliQ water, hydrated for 30 minutes before use. In each adsorption run, 2 ml of AC suspension was mixed with 400 g wastewater to achieve a final concentration of 10 mg/l AC. Samples were agitated at 170 RPM and +15 °C for 30 minutes, filtered through 0.45 μm membranes, and stored at +5 °C prior to micropollutant analysis. Concentrations of micropollutants were measured using a Waters Xevo TQS-XS triple quadrupole mass spectrometer coupled to a Waters Acquity I Class+ UPLC system.

Heavy metal batch adsorption experiments were conducted similarly as described for the micropollutant batch adsortpion experiments, with the exception that two sampling campaings were applied. One sampling event was during normal operation and the other during snowmelt conditions.

Micropollutant and heavy metal removal was quantified using Equation 1:

$$R(\%) = ((Ci - Ca)/Ci) \times 100 \qquad \text{(eq. 1)}$$

where Ci is initial concentration and Ca is concentration after treatment.

Average removal was calculated using Equation 2:

$$\bar{R} = (1/n)\ \Sigma\ Ri \qquad \text{(eq. 2)}$$

where Ri is the removal of each pollutant, and n is the number of pollutants.

Results are reported as mean ± standard deviation to reflect variability. Differences in removal efficiencies between AC samples and commercial carbons were evaluated using the two-sided Mann-Whitney U-test at $p<0.05$. Pearson correlation coefficients were computed to relate removal efficiencies to AC characteristics, with p-values indicating significance where applicable.

For microplastics removal, the hypothesis tested was that pristine polyethylene (PE) microplastics exhibit greater adsorption onto activated biochar compared to non-activated biochar, due to the more hydrophobic surface associated with activated biochar. Batch adsorption experiments were performed by mixing pristine hydrophopic spherical PE beads having particle size of 38-45 µm with activated biochar and untreated biochar in aqueous suspensions. The experimental conditions involved suspending carbons at a concentration of 40 g/L and microplastics at 2 g/L in a 20 ml of MilliQ water in a 500 ml borosilicate jar. These mixtures were agitated on a shaker table at a speed of 190 RPM for a contact duration of 24 hours. Following the agitation period, microplastic beads were decanted, and biochar samples were subsequently examined using optical microscopy to assess adsorption.

## Results & Discussion

### Micropollutant Removal

Activated carbons derived from agro-feedstocks demonstrated variation in porosity, chemical composition, and micropollutant removal performance. WS-700 exhibited the highest BET surface area of 805 $m^2/g$ among agro-based carbons, surpassing even certain commercial carbons such as peat/wood-based (AC-PW, 800 $m^2/g$) and peat-based carbons (AC-P, 755 $m^2/g$). However, despite higher surface areas, the pore volumes of agro-based ACs remained lower compared to commercial counterparts, notably due to their predominant microporous structures. Figure 9 presents the pore size distributions of the activated carbons selected for the micropollutant removal batch experiments. WS-700 had microporosity of 76%, whereas commercial carbons like AC-P contained significantly higher mesoporosity (52%). This disparity in pore size distribution influenced their micropollutant removal efficiencies, especially for compounds with larger molecular structures.

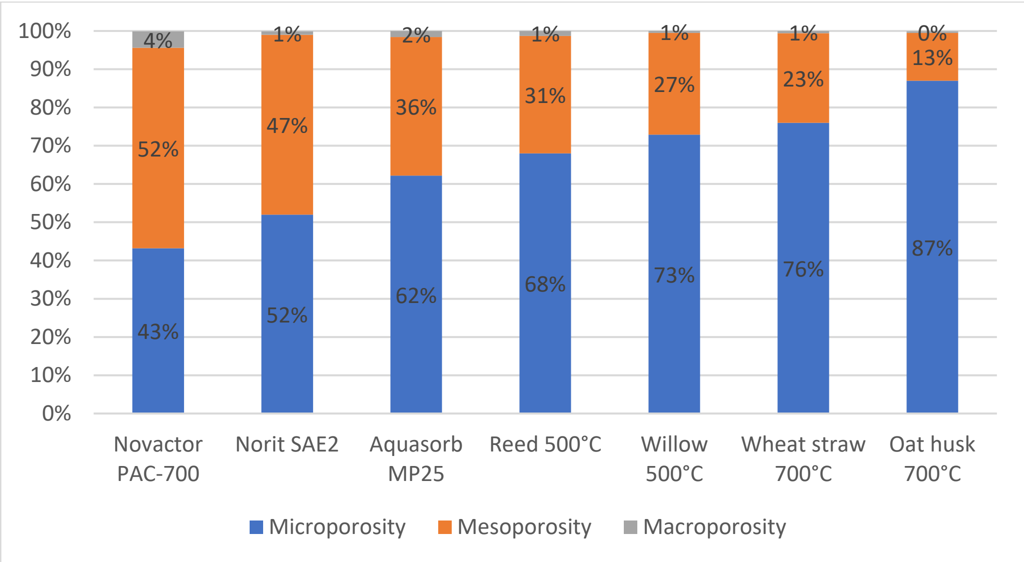


*Figure 9. Pore size distributions of the activated carbons selected for the micropollutant removal batch experiments.*

Carbonization temperature significantly affected the carbon characteristics, generally resulting in decreased surface areas and pore volumes with increasing temperature, although WS-500 diverged from this pattern due to differences in initial feedstock composition. Such variations highlight the importance of feedstock consistency in AC production.

As presented in Table 8, WS-700 and R-500 achieved the highest micropollutant removal efficiencies among agro-based ACs, with average removal efficiencies of 18% and 17%, respectively. The average removal efficiencies were higher with commercial carbons (26-27%). Notably, as presented in Table 9, R-500 displayed no statistically significant difference with diclofenac removal to commercial alternatives, attributable primarily to its mesoporous structure despite its lower BET surface area (610 $m^2/g$), and possibly the presence of silicon ash. Conversely, O-700 showed markedly lower efficiency, likely due to the very high microporosity and lower pore volume.

During the sampling events, the wastewater treatment process operated under normal conditions, and the water composition among the samples did not exhibit any significant differences. The concentrations of micropollutants were as follows: carbamazepine in the range of 0.17–0.21 µg/l, benzotriazole in the range of 1.46–1.95 µg/l, sulfamethoxazole in the range of 0.10–0.13 µg/l, and diclofenac in the range of 1.17–1.65 µg/l.

*Table 8. Means (± standard deviation) of the pollutant removal with the selected Acs.*

| | Carbamazepine | Benzotriazole | Sulfamethoxazole | Diclofenac | Total |
|---|---|---|---|---|---|
| AC-P | 18 ± 6 | 50 ± 6 | 16 ± 4 | 20 ± 3 | 26 ± 15 |
| AC-PW | 26 ± 6 | 44 ± 8 | 18 ± 4 | 19 ± 7 | 27 ± 12 |
| AC-C | 22 ± 9 | 45 ± 4 | 18 ± 4 | 20 ± 2 | 26 ± 12 |
| WS-700 | 14 ± 4 | 38 ± 10 | 9 ± 4 | 11 ± 4 | 18 ± 13 |
| R-500 | 15 ± 8 | 34 ± 20 | 9 ± 5 | 11 ± 4 | 17 ± 12 |
| WW-500 | 3 ± 6 | 28 ± 11 | 4 ± 4 | 10 ± 3 | 11 ± 15 |
| O-700 | 1 ± 9 | 12 ± 14 | 2 ± 2 | 4 ± 4 | 5 ± 9 |

Note: N=6

*Table 9. p-values of the Mann-Whitney test for pollutant removal efficiencies (N = 6). (No significant differences at 0.05 level highlighted with dark grey).*

| Compound | CBZ | BTA | SMX | DCF |
|---|---|---|---|---|
| O-700 vs Commercial | <0.001 | <0.001 | <0.001 | 0.012 |
| WS-700 vs Commercial | 0.055 | 0.486 | <0.001 | <0.001 |
| WW-500 vs Commercial | 0.006 | 0.151 | 0.002 | 0.024 |
| R-500 vs Commercial | 0.033 | 0.004 | 0.001 | 0.21 |

Chemical composition analyses revealed WW-500 as having the highest carbon content (91.5%) and lowest ash content (6.5%), comparable to commercial peat-based carbon AC-P (90.8% carbon and 8.0% ash). In contrast, R-500 and O-700 recorded the lowest carbon (approximately 74.4-74.9%) and highest ash contents (22.8-24.7%). The ash composition, specifically the silica content, proved influential in pollutant removal performance, notably in diclofenac adsorption through potential silanol complexation mechanisms. The ash in reed and oat husk prominently featured silica, contrasting with alkali and alkaline earth metal predominance in wheat straw.

As presented in Table 10, micropollutant removal performance correlated significantly with AC characteristics, particularly total pore volume and mesopore volume, confirming previous literature assertions emphasizing pore structure importance over mere surface area. Micropollutants exhibited decreasing sorption efficiencies following the order BTA > DCF > CBZ > SMX, consistent across most ACs except O-700. Additionally, the H/C ratio negatively correlated with sorption efficiency, indicating aromaticity's crucial role in enhancing π-π interactions with aromatic pollutants.

*Table 10. Pearson correlation coefficient and p-value (bilateral) between pollutant sorption efficiencies and activated carbon characteristics. Significant correlations are shown only. (Dark grey: correlation coefficient 0.6 or higher.).*

| Characteristic | Statistic | CBZ | BTA | SMX | DCF |
|---|---|---|---|---|---|
| BET ($m^2/g$) | Pearsons correlation | 0.396 | 0.389 | 0.535 | 0.513 |
| | p-value | 0.009 | 0.011 | <0.001 | <0.001 |
| Total pore volume ($cm^3/g$) | Pearsons correlation | 0.608 | 0.626 | 0.796 | 0.777 |
| | p-value | <0.001 | <0.001 | <0.001 | <0.001 |
| Micropore volume ($cm^3/g$) | Pearsons correlation | 0.375 | 0.347 | 0.498 | 0.466 |
| | p-value | 0.014 | 0.024 | <0.001 | 0.002 |
| Mesopore volume ($cm^3/g$) | Pearsons correlation | 0.602 | 0.627 | 0.777 | 0.765 |
| | p-value | <0.001 | <0.001 | <0.001 | <0.001 |
| Macropore volume ($cm^3/g$) | Pearsons correlation | 0.313 | 0.479 | 0.509 | 0.548 |
| | p-value | 0.044 | 0.001 | <0.001 | <0.001 |
| Microporosity (%) | Pearsons correlation | -0.598 | -0.635 | -0.732 | -0.741 |
| | p-value | <0.001 | <0.001 | <0.001 | <0.001 |
| Mesoporosity (%) | Pearsons correlation | 0.614 | 0.638 | 0.741 | 0.741 |
| | p-value | <0.001 | <0.001 | <0.001 | <0.001 |
| Macroporosity (%) | Pearsons correlation | | 0.462 | 0.468 | 0.511 |
| | p-value | | 0.002 | 0.002 | <0.001 |
| C (%) | Pearsons correlation | | 0.409 | 0.391 | 0.478 |
| | p-value | | 0.007 | 0.011 | 0.001 |
| H (%) | Pearsons correlation | -0.565 | -0.621 | -0.624 | -0.632 |
| | p-value | <0.001 | <0.001 | <0.001 | <0.001 |
| H/C | Pearsons correlation | -0.576 | -0.678 | -0.682 | -0.699 |
| | p-value | <0.001 | <0.001 | <0.001 | <0.001 |
| Ash (%) | Pearsons correlation | | -0.391 | -0.399 | -0.48 |
| | p-value | | 0.01 | 0.009 | 0.001 |

Despite the promising performance of agro-based ACs, the results indicate necessary optimization for these materials to compete effectively with commercial products. Specifically, increasing mesoporosity and pore volume while maintaining high surface areas is crucial. Achieving this balance might involve lower carbonization temperatures to facilitate mesopore formation and preserve functional groups beneficial for pollutant interactions. Feedstock consistency also emerged as a critical factor, emphasizing the need for standardized processing and characterization methods to ensure reproducible performance. Moreover, further investigations into adsorption behaviour at higher adsorbent dosages, as used in practical powdered activated carbon applications, are necessary. Higher dosages and longer retention times, as seen in commercial systems like Actiflo® Carb, may foster equilibrium conditions more favourable to micropollutant adsorption and thus could significantly enhance performance.

Agro-based activated carbons might also offer environmental advantages through potentially lower greenhouse gas emissions compared to fossil-based carbons, even if the required dosages were double compared to fossil-based alternatives. Such life-cycle assessments would be essential for a holistic comparison with fossil-based alternatives.

Conclusively, agro-based activated carbons demonstrate substantial potential for micropollutant removal, particularly when optimized for mesoporous structures and chemical characteristics. Future research focusing on production process optimization, feedstock optimization, and economic viability will further establish their competitive positioning relative to commercial fossil-based alternatives.

**Heavy Metal Removal**

Sampling for the second Heavy metal removal experimental series occurred during snowmelt conditions, leading to increased wastewater treatment plant inflow. These elevated flows slightly increased concentrations of lead, nickel, and zinc. Consequently, meltwater influx emerges as an essential factor when assessing heavy metal removal efficiencies, due to considerably elevated mass flows compared to typical operating conditions. Regulatory obligations for wastewater treatment efficiency are evaluated based on quarterly and annual averages, where transient high mass flow events can notably influence these evaluations.

While the dataset does not allow robust statistical analyses, the observed results offer valuable indicative insights. It must be noted, however, that the samples represent singular, snapshot observations from the treatment plant, with inherent variability in water composition and constituent concentrations.

The findings suggest that agro-based activated carbons demonstrate comparable heavy metal removal performance to commercial activated carbons. During normal plant operation, cadmium and lead removal efficiencies exceeded 80% with all studied carbons, as shown in Figure 10. Conversely, nickel and zinc removal were negligible. During storm water conditions, the removal of nickel and zinc were notably higher, as shown in Figure 11. The higher removal efficiency during stormwater conditions is likely due to higher initial heavy metal concentrations while presumably having diluted concentrations of other constituents. These findings highlight the persistent challenge nickel and zinc present in water treatment processes, with agro-based activated carbons showing comparable limitations to commercial carbons in their removal.

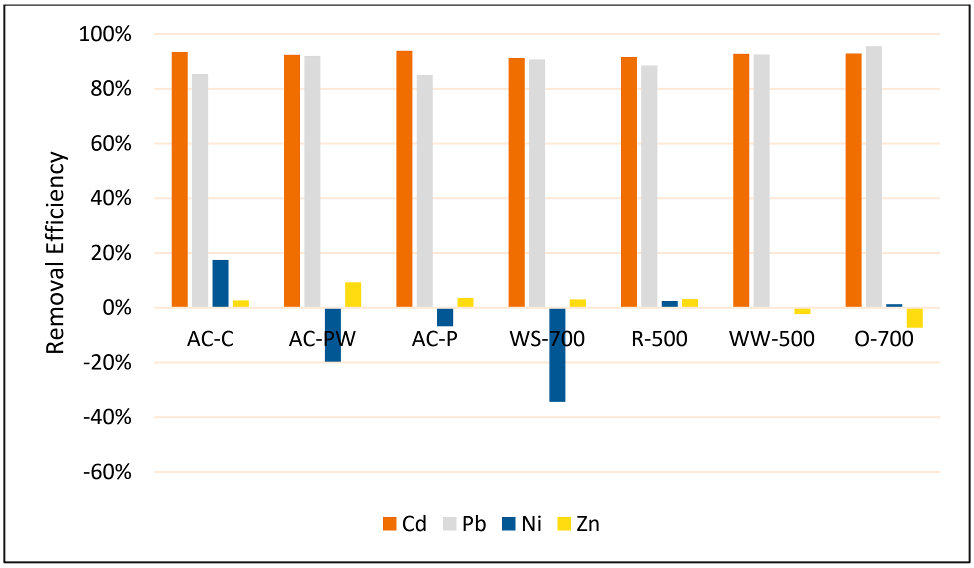


*Figure 10. Heavy metal removal efficiencies during normal conditions.*

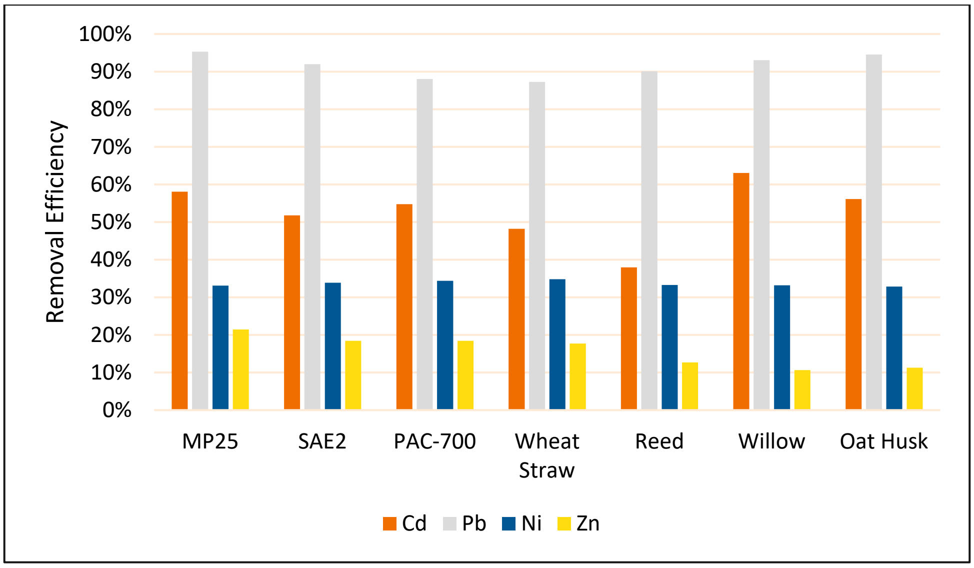


*Figure 11. Heavy metal removal efficiencies during stormwater conditions.*

**Microplastics Removal**

Due to the lower density of PE compared to water, microplastics floated at the water surface, as seen in Figure 12, while biochars settled at the bottom. High shaker speed coupled with a relatively small volume of water facilitated contact between the floating microplastics and submerged biochar particles. However, it is important to acknowledge that this laboratory-scale experiment represents a simplified theoretical scenario and does not replicate the complex dynamics and environmental conditions encountered in real-life scenarios. Environmental microplastics typically exhibit irregular shapes and surface functionalities resulting from degradation processes, whereas pristine microplastics possess regular morphology with aromatic surfaces.

Microscopic analysis revealed no observable adsorption of microplastics onto either activated or non-activated biochar surfaces. This outcome indicates that buoyant forces and surface tension phenomena dominated over the anticipated hydrophobic interactions between microplastics and carbon surfaces. Consequently, hydrophobic adsorption forces appeared insufficient to overcome these physical interactions under the experimental conditions tested.

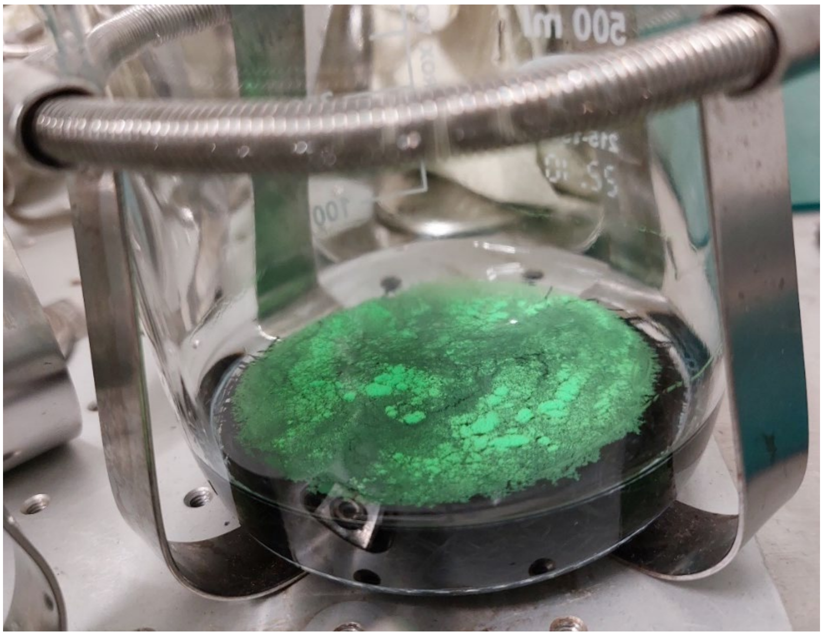


*Figure 12. Green fluorescent PE-beads floating on the top while biochar is immersed on the bottom.*

### Publications & theses

Rintala, V., Agro-based Activated Carbon for Wastewater Treatment of Micropollutants, Master's thesis, Aalto University, 2025.

## Biocomposites

Contact person: Ossi Martikka, LAB

### Introduction

In order to replace more fossil-based materials, novel applications for renewable materials must be found and proven. Biocomposites provide an interesting opportunity for reducing carbon footprint of traditional plastic products while introducing novel properties while doing so. Biocomposite as technical term means a mixture of two or more materials, of which at least one is biobased. In this study, the matrix part of composite was kept fossil-based while the other components had varying origin. The biobased components investigated were biofiber and biochar, both made of wheat straw. The findings indicate that the amount of fossil-based matrix can be reduced while introducing novel properties to biocomposite by using biochar and/or straw based biofiber. For most of the mechanical properties of the composites, good, linear correlation between the different components and mechanical performance was found, enabling further modeling and optimizations.

### Materials & Methods

LAB UAS investigated the properties and performance of biocomposites containing agrocellulosic fibers, Biochar and commercial carbon black as reference material. In all cases, polypropylene (PP) was used as matrix. The composite material mixture was produced firstly by manually mixing the components in predetermined weight-% ratios, then compounding them using an extruder and granulating them mechanically prior injection molding the materials into actual dumbbell shaped test specimen. In order to determine the impact of different materials and their relative ratios, tensile strength and moduli, flexural strength and moduli, Charpy impact strength, and surface electrical conductivity were determined.

The reference material used was PP Borealis RF365p and the same material was also used as matrix in all composites. The fiber (Fiber) was pelletized wheat straw, Biochar (Biochar) was also wheat straw based, processed and pyrolyzed by VTT, and the reference carbon, commercial carbon black (CB), was Cabot XE72 Carbon black. The tested compositions are shown in Table 11. Composite materials were compounded using Brabender PlastoGraph single screw extruder, and the test specimen were produced using KraussMaffei injection molding machine. The processing parameters were kept constant with all materials.

*Table 11.* Compositions of the studied materials [w-%].

| PP | Fiber | Biochar | CB |
|---|---|---|---|
| 100 % | | | |
| 90 % | | | 10 % |
| 80 % | | | 20 % |
| 70 % | | | 30 % |
| 90 % | | 10 % | |
| 80 % | | 20 % | |
| 70 % | | 30 % | |
| 90 % | 10 % | | |
| 80 % | 20 % | | |
| 70 % | 30 % | | |
| 90 % | 5 % | | 5 % |
| 80 % | 10 % | | 10 % |
| 70 % | 15 % | | 15 % |
| 90 % | 5 % | 5 % | |
| 80 % | 10 % | 10 % | |
| 70 % | 15 % | 15 % | |

The results indicate that it is possible to achieve electrical conductivity to biocomposites by 30 w-% addition of Biochar. In all cases with Biochar and/or fibers as components of the biocomposite, the mechanical performance showed linear, declining trend. However, the performance was well predictable, suggesting the possibility of predetermining the biocomposite performance thus enabling optimization of e.g., the cost of biocomposite material and carbon footprint.

## Results & Discussion

Electrical performance of the materials was determined by measuring the resistance over 100x10mm$^2$ distance of injection molded specimen at 100V voltage. Results indicate that some conductivity was achieved with 20 w-% of CB and 30 w-% of Biochar added to pure PP matrix. In case of actual biocomposite, conductivity was observed only with CB at 15 w-% of loading of both CB and fiber. The finding strongly suggests that CB provides electrical properties with loading levels above 10 w-% - for determining the exact threshold further investigation is required. This also suggests the possibility of creating electrically conductive biocomposite with load levels of Biochar at proximity of 30 w-%. The measurement results are shown in Table 12.

*Table 12. Electrical properties of the materials studied.*

| Composition | | | | Electric resistance on specimen surface | |
|---|---|---|---|---|---|
| PP | Fiber | Biohar | CB | Ω/m @ 100V | Std.Dev. |
| 100 % | | | | inf | |
| 90 % | | | 10 % | inf | |
| 80 % | | | 20 % | 600000 | 2345,2 |
| 70 % | | | 30 % | 100000 | n/a |
| 90 % | | 10 % | | inf | |
| 80 % | | 20 % | | inf | |
| 70 % | | 30 % | | 200000 | n/a |
| 90 % | 10 % | | | inf | |
| 80 % | 20 % | | | inf | |
| 70 % | 30 % | | | inf | |
| 90 % | 5 % | | 5 % | inf | |
| 80 % | 10 % | | 10 % | inf | |
| 70 % | 15 % | | 15 % | 4325000 | 15801,5 |
| 90 % | 5 % | 5 % | | inf | |
| 80 % | 10 % | 10 % | | inf | |
| 70 % | 15 % | 15 % | | inf | |

## Mechanical performance

The naming convention for materials is as follows: All the materials have composition of PP + Fiber + Biochar + CB = 100% (in weight ratio) and PP is the constant matrix used in all materials. Therefore, the component(s) added/blended with the matrix are indicated with their abbreviation followed by an underscore and their respective ratio in the biocomposite.

In case of tensile performance, the addition of the tested materials into PP matrix had a decreasing impact. For tensile performance, the effect of CB related to the loading level did not show correlation. In the case of all the other materials, the correlation between the loading level and performance was found to be negative. The findings are illustrated in Figure 13.

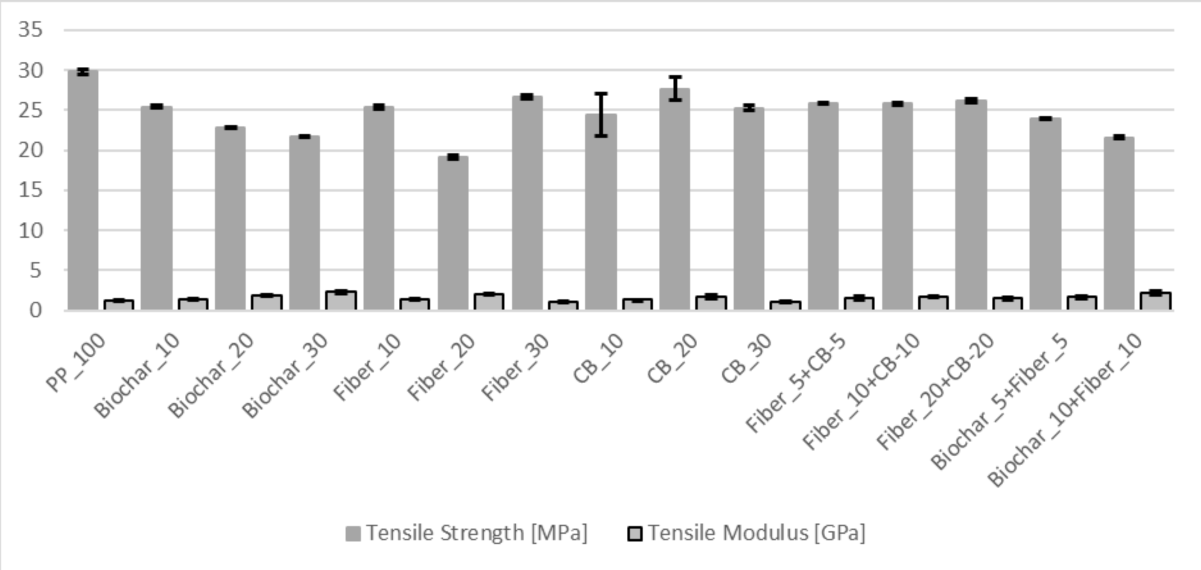


*Figure 13. Tensile performance with standard deviations.*

The impact to flexural performance was significantly different compared to tensile performance – both flexural strength and modulus increased with added components except with plain straw fiber. With it, the tensile strength did not significantly alter with the loading level while in case of moduli the performance improvement with higher loading level of fiber. The findings are illustrated in Figure 14.

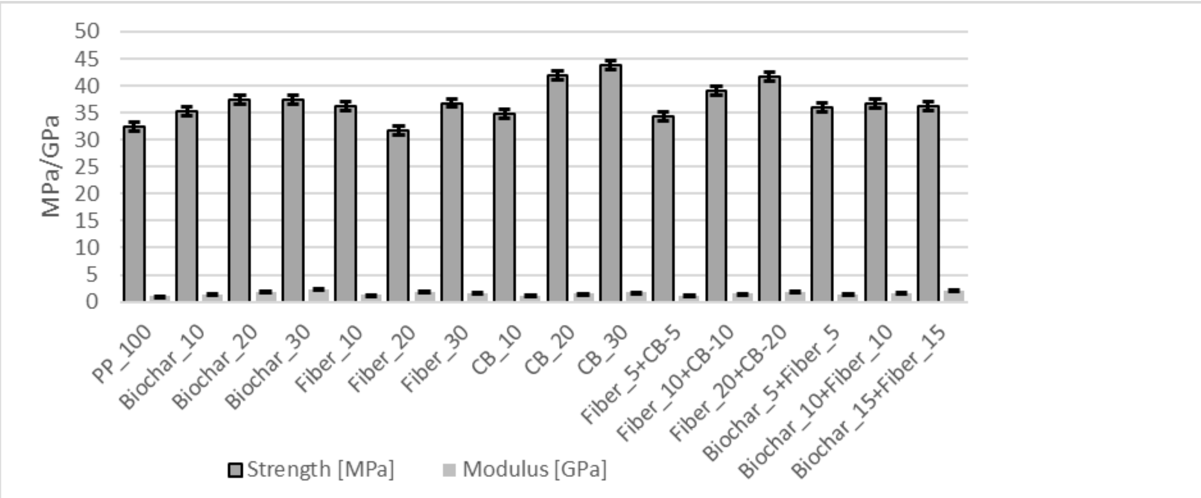


*Figure 14. Flexural performance with standard deviations.*

The impact strength of the composites was lower than that of the reference PP. In general, the findings followed the trend set with tensile performance; the higher addition level of components into the PP matrix decreased the performance. Somewhat contradictory results were obtained with materials containing fiber – the trend of change in performance was not statistically obvious. The findings are illustrated in Figure 15.

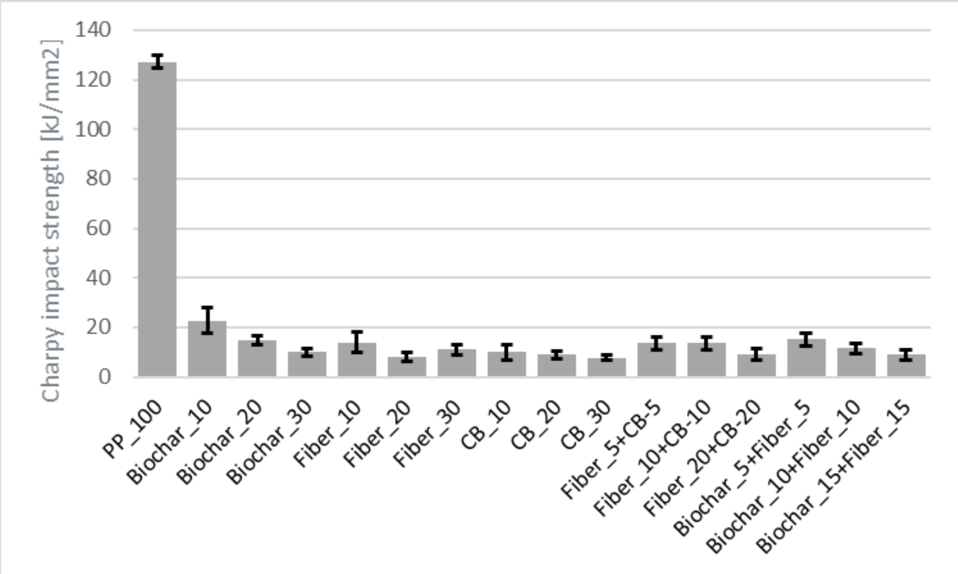


*Figure 15. Charpy impact strength with standard deviations.*

## Regression models

To estimate the effect of separate components and their loading level on the performance of composites, regression models were created. The regression models obtained are as follows:

Tensile strength [MPa] = 27,6267 - 0,254883*Fiber - 0,0230068*Carbon black - 0,193839*Biochar, where $R^2$= 59,5628 %.

Tensile modulus [MPa] = 999,721 + 38,0967*Fiber + 18,4516*Carbon black + 41,8614*Biochar, where $R^2$= 81,1246 %.

Flexural strength [MPa] = 33,3521 + 0,379432*Carbon black + 0,195514*Biochar + 0,0589859*Fiber, where $R^2$= 78,5294 %.

Flexural modulus = 939,329 + 25,6423*Carbon black + 41,0693*Biochar + 35,0828*Fiber, where $R^2$= 92,0439 %.

Charpy impact strength [kJ/mm2] = 17,5719 - 0,296555*Fiber - 0,354149*Carbon black - 0,18949*Biochar, where $R^2$= 33,7069 %.

In case of impact strength, the model did not have good predictability, but for the other models $R^2$ varied from 60 to 92% suggesting moderate/good predictability of the models on the performance of the composites. Also, these models indicate the strength of the effect of different materials on a specific parameter. These regression models can be further used for multioptimization, with contradicting and internally conflicting goals. With the optimization process, the best solution and composition can be predetermined while retaining sufficient performance of the biocomposite for a particular end-use scenario.

## Conclusions

In most cases, the impact of different materials and their loading levels on the performance of the composite created was mostly linear and can be used to predict the performance of biocomposites. For example, the mechanical performance of a biocomposite material can be predetermined using the formulae and equations created in order to optimize the composition. With the findings, a sufficient mechanical performance level can be achieved while e.g., achieving electrical properties while minimizing the use of fossil plastic.

The BioCarbonValue project enabled the in-depth research and creation of novel data and understanding on how various factors impact the performance of biocomposites containing Biochar. The findings also show that optimization of various biocomposite properties is possible thus promoting the use of novel, sustainable and renewable materials for replacing fossil based, non-renewable materials in composites.

## Techno-economic assessment, biocarbon market and foresight

### Summary of the work and achievements

The BioCarbonValue project conducted a techno-economic assessment to evaluate the feasibility of biochar production from agricultural biomass, specifically straw, in Finland. The assessment included a detailed analysis of the straw supply chain, biorefinery plant technical specifications, and economic parameters. The project aimed to address the challenges and opportunities associated with biochar production, including the costs, profitability, and market potential. Additionally, the project explored the broader biocarbon market and foresight, examining the current state, trends, and future outlook of the biochar and activated carbon markets.

### Key results and impacts

The key findings from the techno-economic assessment and biocarbon market foresight include:

- **Supply chain costs**: The total supply chain costs for 100,000 tons of straw were estimated to range between €10.6 million and €15.8 million.
- **Capital investment and operational costs**: For a production plant with a capacity of 12.5 tons of straw biomass per hour, converting 30-35% into 3.75-4.375 tons of biochar per hour through continuous pyrolysis, the capital expenditures for the model biorefinery plant were estimated to range from €30 million to €40 million. The estimated annual operational expenditure for the biorefinery ranged from €5.8 million to €6.4 million.
- **Revenue Projection**: The required annual revenue to cover all supply chain and operational costs was projected to range from approximately €19 million to €33 million.
- **Market Sales Price**: To be profitable, the market sale price for one ton of biochar should range between €584 and €1,104.
- **Biochar Market Potential**: The global annual biochar production in 2023 was estimated at 352,304 tons, with 75,000 tons in Europe and 21,000 tons in the Nordics. The Nordic biochar market is still in its early stages, with strong interest in expansion and various promising application areas.
- **Activated Carbon Market**: The activated carbon market size in 2024 was estimated to be $6.6 billion, with a projection to reach $10.2 billion by 2029. The total annual market volume of activated carbon in Europe is around 650,000 tonnes, with the majority imported from Asia.

## Techno-economic assessment of biocarbon

Contact person: Malahat Ghoreishi, LAB

### Introduction

In Finland, approximately 1 million dry tons of straw can be harvested annually. Out of which, 0.4 million dry tons are designated for animal bedding and other agricultural uses, leaving 0.6 million dry tons available for potential harvesting and utilization in biorefineries, energy production, or other applications. However, various challenges, farming techniques, and residue management practices prevent the harvesting of all the straw (Laitila et al., 2016). Residue management methods for straw include incorporating it into the soil, leaving it on fields for degradation and nutrient recovery, using it for mulching, composting, bioenergy production, or baling for animal feed and bedding. While some methods positively impact soil quality and create value, others can harm soil properties, nutrient content, and produce harmful emissions. Sustainable crop and residue management is crucial to ensure safe cultivation and residue handling, leading to value-added products or improved soil health which increases positive impacts on environment and communities (Sen et al., 2024, 167-201).

Biochar production via pyrolysis is one possibility of value-added use for straw residues, due to its high carbon content and composition of cellulose, hemicellulose, and lignin as well as high availability as an agricultural residue. However, biochar production from agricultural biomass is relatively new, as straw commonly can be utilized for non-agricultural use such as pulp and paper production, biofuel generation, and building insulation. Therefore, biochar presents unique business opportunities and advantages with potential applications across various sectors (Huang et al., 2024).

In Europe, biochar production is primarily driven by its potential for permanent carbon removal, making it a significant carbon dioxide removal technology. The market growth is further supported by carbon credits and sustainable agricultural practices, necessitating increased biochar production capacities (European Biochar Industry, 2024; Fortune Business Insights, 2024). In 2023, biochar production capacity was concentrated in several countries, such as Germany, Sweden, Denmark, Finland, Austria, and Switzerland, with the Nordic countries accounting for 28% of Europe's total biochar production. Agricultural residues are becoming increasingly important as feedstock for biochar production, along with woody biomasses, manure, and wastewater sludge (European Biochar Industry, 2024; Salo et al., 2024; Fortune Business Insights, 2024).

The biochar market in Finland is still in its early stages, with biochar often produced as a side product, resulting in low annual production. Positive environmental and climate impacts, particularly soil improvement and carbon sequestration, present significant market opportunities. Furthermore, utilizing by-products such as bio-oil and gases generated during biochar production introduces new applications and market prospects. However, uncertainties related to costs, profitability, and feedstock availability are the primary risks to the expansion and development of the biochar market in Finland (Salo et al., 2024; Salo, 2018; European Biochar Industry, 2024; Mishra et al., 2023.). Therefore, the main objective of this task was to evaluate the feasibility of biochar production from using straw in Finland.

### Materials & Methods

A techno-economic assessment method was utilised to fulfil this task. For this, first a literature review was conducted on the biochar market in Europe and Finland, and different biochar production possibilities. According to the literature, various pyrolysis technologies, raw materials, process capacities, and process parameters were considered. Based on the findings, relevant data on technical and economic parameters has been collected. This work has been conducted using publicly available data, partly upscaling the data according to the needs of the used model plant.

**Straw supply chain description and economic specifications:**

The economic details of the supply chain are shown in Table 13 below. Considering the value of straw, baling, plasticizing, transport, storage, and management expenses, the total supply chain costs for 100,000 tons of straw are estimated to range between €10.6 million and €15.8 million.

*Table 13. Economic specifications of straw supply chain (Wehrenbrecht, 2024).*

| Parameter | Cost in €/ton | Total cost for 100.000 tons in € | Adapted from source |
|---|---|---|---|
| Straw value (dry mass) | 20 – 28 | 2,000,000–2,800,000 | Punttila et al. 2021 |
| Baling | 54 – 66 | 5,400,000–6,600,000 | Punttila et al. 2021 |
| Plasticising (20 – 50% of bales) | 2,7 – 10,8 | 27,000–540,000, | Punttila et al. 2021 |
| Transport | 16 – 32 | 1,600,000–540,000 | Punttila et al. 2021 |
| Storage costs (for 90.000 tons) | 10 – 13 | 900,000–1,300,000 | Huhnke 2017 |
| Management costs | 6 – 8 | 600,000–800,000 | Laitila et al. 2016 |

**Biorefinery plant technical description and specifications**

The production plant has a capacity of 12.5 tons of straw biomass per hour, converting 30-35% into 3.75-4.375 tons of biochar per hour through continuous pyrolysis. This process reduces residence time to 10-40 minutes at a heating rate of 5°C per minute. Non-condensable pyrolysis gases are combusted for heat, which is used in the reactor and for heating the plant or the district heating network. The plant consumes approximately 301.7 kWh/ton of biochar for electricity, 3.41 $m^3$/ton of water, and 1819 kWh/ton for heating and cooling. Fuel consumption is 11.4 liters/ton of biochar, using diesel. Heating costs are excluded due to the complexity of estimates and the use of pyrolysis gas combustion (Koutonen, 2023). The technical parameters relevant to evaluating the biochar production plant are shown in Table 14.

*Table 14. Technical parameters of the biochar production plant (Wehrenbrecht, 2024).*

| Parameter | Value | Unit | Based on |
|---|---|---|---|
| Material inflow | 12.5 | t/h straw | Model based |
| Material outflow | 3.75 – 4.375 | t/h biochar | Model based |
| Electricity use | 301.7 | kWh/ton of biochar | Koutonen 2023 |
| Water consumption | 3.41 | $m^3$/ton of biochar | Koutonen 2023 |
| Heating and cooling | 1819 | kWh/ton of biochar | Koutonen 2023 |
| Fuel (diesel) | 11.4 | l/ton of biochar | Koutonen 2023 |
| Biochar yield | 30-35 | % | Mishra et al. 2023 |
| Bio-oil yield | 30-35 | % | Mishra et al. 2023 |
| Pyrolysis gas yield | 35-40 | % | Mishra et al. 2023 |
| Pyrolysis temperature | 500 | °C | Mishra et al. 2023 |
| Heating rate pyrolysis | 5 | °C/min | Mishra et al. 2023 |
| Residence time (continuous pyrolysis) | 10-40 | min | Previous task of this project |
| Operational hours | 8000 | h/year | Model based |

**Economic specifications of the biorefinery plant**

Table 15 presents three different CAPEX estimations for a biochar production plant with a capacity of 12.5 tons per hour. Three scaling factors (0.6 to 0.8) were used to account for various possibilities, excluding dryer costs due to the lack of need for straw raw material. The cost-to-capacity method, which accounts for non-linear cost relationships with equipment capacity changes, was applied. Due to limited public data on pyrolysis plant capital costs, these estimations may be inaccurate. However, Haeldermans et al. (2020) provide more reliable cost estimates based on manufacturer information for a 3-ton per hour biorefinery plant. Using three different scaling factors helps mitigate cost uncertainty (evaValuation, 2015; Haeldermans et al., 2020).

Formula 1 was used for the calculation method for capital expenditures, considering the base costs (denoted as "base") from Haeldermans et al. (2020) and using R as the scaling factor.

$$\cos t_x = \cos t_{base} * \left(\frac{size_x}{size_{base}}\right)^R$$

Using the above Formula and various scaling factors, the capital expenditures for the model biorefinery plant are calculated and shown in Table 15. Including costs for the pyrolysis plant, on-site storage and handling, office and laboratory equipment, and additional machinery, but excluding dryer costs, the total estimated capital expenditures range from €30 million to €40 million.

*Table 15. CAPEX estimation for biorefinery plant (Wehrenbrecht, 2024 adapted from Haeldermans et al., 2020).*

| Equipment | Costs in € with scaling factor 0.6 | Costs in € with scaling factor 0.7 | Costs in € with scaling factor 0.8 |
|---|---|---|---|
| Pyrolysis plant | 21,189,259 | 24,439,631 | 28,188,601 |
| On-site storage and handling | 7,063,086 | 8,146,544 | 9,396,200 |
| Office and laboratory equipment | 941,745 | 1,086,206 | 1,252,827 |
| Additional machinery | 588,591 | 678,879 | 783,017 |
| Excluding costs of dryer | -216,601 | -249,827 | -288,150 |
| Total | 29,999,282 | 34,101,431 | 39,908,794 |

In addition to significant capital investment costs, the biorefinery incurs annual operational expenses. These include costs for water, electricity, fuel, rent or building expenses, maintenance, insurance, and staff. The table below details operational costs, estimated using consumption values and unit costs from relevant sources. While prices may vary by location and market conditions, the estimated annual operational expenditure for the biorefinery ranges from €5.8 million to €6.4 million.

*Table 16. Operational costs at the model biochar production plant (Wehrenbrecht, 2024).*

| **Parameter** | **Value** | **Unit** | **Source based on** |
|---|---|---|---|
| Electricity | 1,357,650–1,583,925 | € per year | Blackgreen |
| Water consumption | 204,600–477,400 | € per year | Statista 2024 |
| Fuel (diesel) | 598,500–698,250 | € per year | Global Petrol Prices 2024 |
| Rent or building cost | 750,000 | € per year | Blackgreen |
| Maintenance | 450,000 | € per year | Blackgreen |
| Staff | 2,282,800 | € per year | Haeldermans et al. 2020 |
| Insurance | 180,000 | € per year | Koutonen 2023 |
| Total Costs | 5,823,550–6,422,375 | € per year | |

In addition to raw material, capital, and operational costs, there are transportation and logistics expenses post-biochar manufacturing. Biochar is assumed to be transported to a nearby local warehouse via truck, stored for about a week, and then further transported. Based on an average bulk density of 300 kg/m$^3$ and a height of 2.1 m, the estimated local warehouse space requirement is 1000 m$^2$. Biochar is transported from the local storage facility to a harbor by truck or railway, where it is stored before being shipped to customers in Finland or exported. Due to the complexity and unknown customer locations, the transport route from the harbor is not included in the calculation. The estimated annual logistic costs range from €847,200 to €976,200, as detailed in the Table 17 below.

Table 17. Logistic costs of biochar (Wehrenbrecht, 2024 adapted from Blackgreen).

| **Parameter** | **Value** | **Unit** |
|---|---|---|
| Transport from factory to nearby warehouse (truck) | 3.7 | €/ton |
| Handling of storing | 0.3 | €/ton |
| Local storage freight and freight handling costs | 120,000–140,000 | €/year |
| Local warehouse space rent | 1.6 | €/m$^2$/month |
| Space requirements | 1,000 | m$^2$ |
| Local storage costs | 19,200 | €/year |
| Transfer loading costs | 1.8 | €/ton |
| Transport costs to harbour | 20 | €/ton |
| Total transport costs | 654,000–763,000 | €/year |
| Indoor storage cost (port) | 3 | €/m$^2$/month |
| Space requirement | 1,500 | m$^2$ |
| Port storage costs | 54,000 | €/year |
| Total logistic costs | 847,200–976,200 | € |

## Results & Discussion

### Revenue projection and feasibility assessment

Based on the results of the techno-economic evaluation, the revenue of the biochar production plant model in Finland can be determined. Table 18 outlines the primary expenses associated with the biorefinery plant, covering the entire value chain from straw procurement, capital investment, operational costs, to logistics.

*Table 18. Summary of total costs for the biorefinery plant (Wehrenbrecht, 2024).*

| Parameter | Minimum costs in € | Maximum costs in € |
|---|---|---|
| Straw supply chain costs | 10,600,000 | 15,780,000 |
| Capital investment costs | 29,999,282 | 39,908,794 |
| Operational costs and logistics | 6,670,750 | 7,398,575 |
| Total | 47,270,032 | 63,087,369 |

Three scenarios have been created to explore different business possibilities and revenue projections, based on profit margins of 10%, 20%, and 30%. Each scenario considers either the minimum required costs (€17,270,750) or the maximum required costs (€23,178,575) for straw acquisition and operational expenses. The necessary revenue to cover all supply chain and operational costs was calculated using the Formula below, considering the three profit margin scenarios. The total costs include straw supply chain, operational, and logistic expenses. The revenue projections are presented in Table 19.

$$required\ revenue = \frac{total\ costs}{1 - desired\ profit\ margin}$$

*Table 19. Required revenue projection with different profit margins (Wehrenbrecht, 2024).*

| Required revenue projection | profit margin 10% | profit margin 20% | profit margin 30% |
|---|---|---|---|
| with minimum required costs | 19,189,722 € | 21,588,438 € | 24,672,500 € |
| with maximum required costs | 25,753,972 € | 28,973,219 € | 33,112,250 € |

Revenue projection result indicates that the required annual revenue ranges from approximately €19 million to €33 million, depending on cost factors and profit margins. These results help determine the market sales price of biochar. The calculation uses three profit margin scenarios and two sale volumes based on the estimated annual biochar production. The outcomes, calculated using below Formula, are shown in Table 20.

$$market\ price\ per\ unit = \frac{required\ revenue}{sales\ volume}$$

*Table 20. Required market sales price per ton of biochar (Wehrenbrecht, 2024).*

| **Required market price per ton of biochar** | **sales volume 30.000 tons** | **sales volume 35.000 tons** |
|---|---|---|
| 10% profit and minimum required costs | 640 € | 548 € |
| 20% profit and minimum required costs | 720 € | 617 € |
| 30% profit and minimum required costs | 822 € | 705 € |
| 10% profit and maximum required costs | 858 € | 736 € |
| 20% profit and maximum required costs | 966 € | 828 € |
| 30% profit and maximum required costs | 1,104 € | 946 € |

To be profitable, the market sale price for one ton of biochar should range between €584 and €1,104. The current market price in Europe varies from €400 to €1,950. The projected price for the model plant in Finland falls within this range, making it a feasible and profitable option. However, the wide market price range is influenced by factors such as location, feedstock price, biochar quality, and application. In overall, the techno-economic assessment indicates that biochar production in Finland using straw as biomass is viable.

Although the results indicate that using straw for biochar production in Finland is profitable, there are opportunities to enhance feasibility and lower costs. Several key possibilities are outlined in the Figure 16 below.

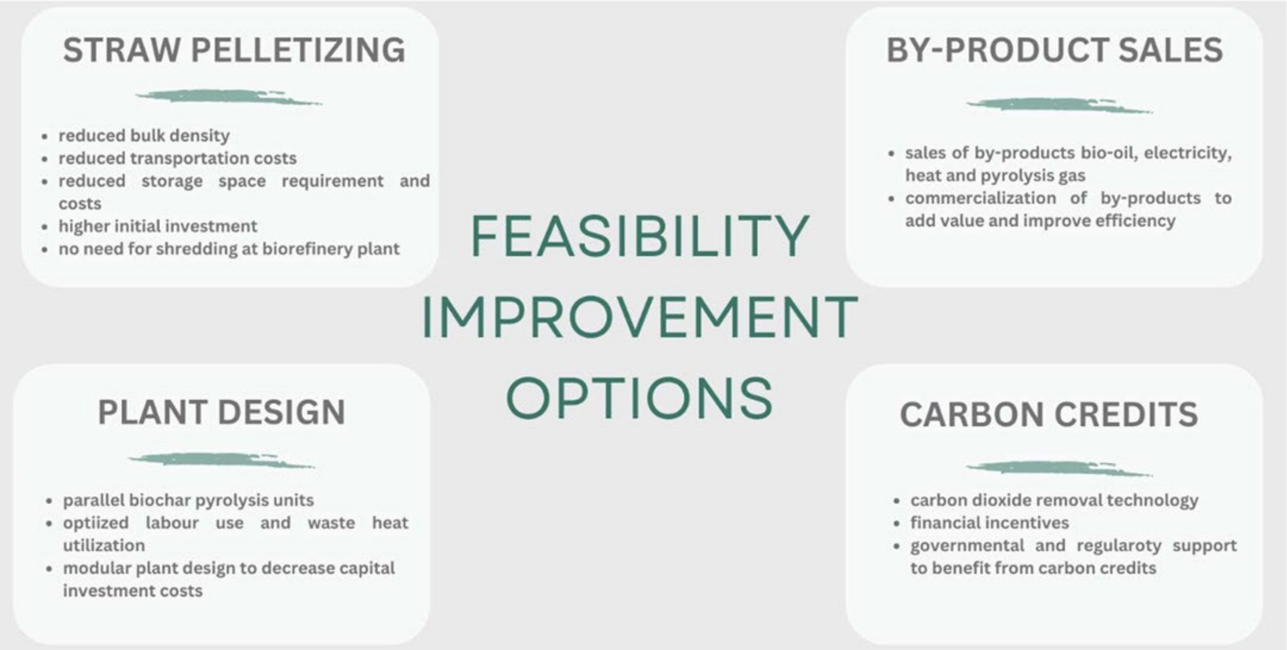


*Figure 16. Summary of possibilities to improve biochar production feasibility (Wehrenbrecht, 2024).*

**Publications & theses**

Wehrenbrecht, N. Techno-economic assessment of biochar production in Finland using straw. Bachelor's thesis, LAB University of Applied Sciences, 2024.

# Biochar market and foresight

Contact person: Esko Salo, VTT

## Introduction

Recent progress in biochar and biocarbon research has significantly enhanced the understanding of biochar's multifunctional properties that enable various applications across various industries. These applications span from soil improvement and environmental remediation (Guo et al., 2020; Nguyen et al., 2023) to use in metallurgy (Suopajärvi et al., 2017) and incorporation into construction materials, such as cement additives (Roychand et al., 2023; Gupta et al., 2021, 2022). Beyond biochar itself, surplus heat and by-products like bio-oil and distillates are gaining attention as valuable resources with emerging applications and market potential (Hagner et al., 2020; Qambrani et al., 2017).

In addition, the potential of biochar extends beyond its primary form; through physical or chemical activation, it can be further refined into products such as activated carbon (Tiihonen et al., 2021), carbon black (Kane et al., 2022), or biobased graphite (Guizani et al., 2023; Sagues et al., 2020). These carbon products have already well-established and growing markets in several applications, such as air, gas, and water purification, energy storage, and automotive industry.

Market demand for carbon materials is influenced by several key drivers, which vary depending on the specific carbon type and its application. These drivers include increasingly strict environmental regulations, industrial transformation, the shift toward electrification, population growth, and efforts to improve quality of life, particularly in developing countries. However, at present, many carbon materials still originate from fossil-based feedstocks such as coal, natural graphite, and by-products of the oil industry (Andrews, 2021; Bosch et al., 2022). While coconut shells can be used as feedstock for activated carbon, they are often produced unsustainably, and the feedstock is limited by region-specific availability. In this context, biomass-derived biochar represents a sustainable and renewable alternative to fossil-based carbons that can be produced from a wide range of locally available biomass (Arena et al., 2016; Vilén et al., 2022; Yahya et al., 2015).

Biochar is currently produced primarily in small and pilot-scale facilities, utilizing a range of feedstocks, processes, and business models. Due to the diverse character of the biochar industry and the limited market data, the business environment in which the biochar market is developing, as well as the barriers and drivers of biochar development, are currently not well understood. The lack of reliable and accessible biochar market research that would consider regional approaches, market status, trends, and future outlook has been recognized as one of the key barriers that limit the widespread adoption of the industry by previous research (Thengane et al., 2021).

This project aimed to address these knowledge gaps by employing a combination of approaches to explore the current state of the biochar and activated carbon markets, assess the business potential of agro-biomass-derived biochar, and examine the broader business environment, emerging trends, key challenges, and prerequisites for successfully scaling the biochar industry.

This public report summarizes the key findings and insights. Some detailed analyses and results are not included due to confidentiality considerations.

## Materials & Methods

The study employed a combination of literature review and empirical data collection to investigate the biocarbon and biochar market landscape.

The literature review focused on the current state of the biocarbon and biochar markets in selected regions, including global, European, and Nordic contexts. Additionally, the review encompassed the activated carbon and carbon black markets at both the international and European levels. Moreover, the market status of selected end-use applications and the production potential of biocarbon derived from agricultural feedstocks within Europe was also considered.

Empirical data was collected through two main methods. First, an online survey was conducted targeting key stakeholders in the Nordic biochar ecosystem. This included business actors, academic researchers, and other relevant groups. A total of 72 responses were received, representing 64 distinct organizations. Second, ten in-depth online interviews were carried out with market-leading Nordic biochar producers to gain deeper insights into business models, market dynamics, and future development prospects.

## Results & Discussion

### Biochar markets

Global annual biochar production in 2023 was estimated at 352,304 tons (IBI & USBI, 2023), with 75,000 tons in Europe and 21,000 tons in the Nordics (Biochar Europe, 2024). According to Biochar Europe (2024), biochar production in Europe is estimated to reach 115,000 tonnes by 2024. The global economic value of the biochar industry (including all biochar-related market activities) was $610 million in 2023, with the potential to reach $2,950 million by 2025 (IBI & USBI, 2023).

The Nordic biochar market is still in its early stages of development. Most biochar producers operate as small enterprises and often treat biochar production as a side business rather than their core activity. Despite its nascent state, Nordic businesses report high intrest towards establishing new biochar production facilities (Salo et al. 2024). Biochar in the Nordics is being applied across a range of areas. The study by Salo et al. (2024) identified five particularly important current and future application areas: carbon removal, water filtration and management, soil remediation, landscaping, and composting. While these areas are considered foundational for market development, other applications such as metallurgy, electrochemical industries (for instance, battery and activated carbon applications), construction materials, and wastewater treatment are among the promising application areas for growth by 2040. These sectors, particularly high-volume ones like metallurgy, could play a significant role in scaling up biochar production.

Regarding co-products of pyrolysis such as heat, bio-oil, and gases were considered to have in the overall feasibility of biochar production. Carbon credits and biochar were considered the main products of interest, while heat was recognized as the most important co-product. Although bio-oil and distillates were seen as having potential, they also face commercialization challenges, especially related to regulatory compliance, such as the EU's REACH regulations.

The study identified several barriers limiting the development of the biochar market. These include regulatory and legal constraints, particularly concerning the use of waste-based feedstocks, variability in biochar pricing and quality, and technological uncertainties that create investment insecurities. Moreover, limited public awareness, lack of practical experience, and insufficient government support were also considered as significant challenges. In addition, the so-called "chicken-and-egg" dilemma was identified, in which low market demand hinders investment in supply infrastructure, while limited supply, in turn, limits the growth of demand.

Nevertheless, some stakeholders viewed the environmental and climate benefits of biochar as the main drivers of development. These benefits were often considered more important than immediate economic returns, indicating that many actors are willing to prioritize broader environmental and sustainability goals over short-term profitability.

The study emphasized the need for additional, practice-oriented research that investigates application-specific co-benefits, production technologies, and novel uses of biochar and its co-products to support market development. On the policy side, recommendations include integrating biochar into national and EU-level climate strategies, establishing clear standards for biochar quality and application, and introducing financial instruments and incentives to stimulate early market growth. From an industry perspective, development could be advanced through collaborative business models, industrial symbiosis, and more defined commercialization pathways.

Finally, biochar networks and associations were identified as key enablers – essential for raising awareness, shaping policy, promoting collaboration, and helping to harmonize practices across the region. In conclusion, the Nordic biochar market shows substantial growth potential, particularly if supported by appropriate policy frameworks, targeted research, and collaborative industry efforts. The environmental and climate benefits of biochar, coupled with its wide application potential, position it as a promising tool in advancing regional sustainability and circular economy goals.

**Activated carbon markets**

According to BCC Research (2025), the activated carbon (AC) market size in 2024 was estimated to be $6.6 billion, projected to reach $10.2 billion by 2029 with a CAGR of 9.3%. The key AC applications include water treatment (34% of the market) and air purification (21.7% of the market). The market size of activated carbon in Europe was estimated at around $1.5 billion in 2024, which is 22.5% of the global market.

The total annual market volume of AC in Europe is around 650,000 tonnes (BBC Research 2025). According to the World Integrated Trade Solution (WITS), Europe imported 194,185 tonnes of activated carbon in 2023, with a total trade value of $443 million—equating to an average value of approximately $2,281 per tonne. It is important to note that activated carbon can be regenerated and reused, and therefore, the demand for new activated carbon is lower than the actual market volume. The leading importing countries for Europe include China (87,856 tonnes), India (31,493 tonnes), the United States (14,542 tonnes), the Philippines (14,192 tonnes), and Australia (13,750 tonnes).

**Publications & theses**

Salo, E., Weber, K., Hagner, M., & Näyhä, A. (2024). Nordic perspectives on the emerging biochar business. Journal of Cleaner Production, 143660. https://doi.org/10.1016/j.jclepro.2024.143660

# Summary and recommendations

This report presents findings from the **BioCarbonValue** project, which focused on producing high-value biocarbons from various agricultural feedstocks biomass. The project aimed to address the challenges of replacing fossil-based carbons with sustainable alternatives, emphasizing the importance of agricultural sidestreams to create biocarbon products for applications in energy storage, water purification, and biocomposites.

The project involved a collaborative effort among various stakeholders, including industry partners and research institutions. The project aimed to enhance the utilization of agricultural biomass as a feedstock for diversified refining industries, addressing existing bottlenecks in biocarbon production and application. Key objectives included evaluating the potential of agricultural residues, developing biocarbon products, and conducting techno-economic assessments of biocarbon markets.

The project employed a multi-faceted approach, including the selection of promising feedstocks such as wheat straw, reed canary grass, oat husks, wheat straw lignin and willow. Various pre-treatment technologies were tested to improve the valorization of these biomasses, and slow pyrolysis methods were used to produce biocarbons at different temperatures. Additionally, the project explored digital solutions for efficient biomass supply chain management, aiming to increase predictability and sustainability.

**Key Findings**

**Biocarbon Production**

The production of biocarbons through slow pyrolysis demonstrated that higher pyrolysis temperatures generally resulted in lower yields but improved the carbon content and thermal stability of the biocarbons produced. The project highlighted the importance of feedstock quality, as variations in ash content significantly impacted the properties of the resulting biocarbons. The composition of the slow pyrolysis non-condensable gases in each studied temperature was analyzed, providing important information for pyrolysis gas utilization. Up-scaling experiments using fluidized bed reactor, rotary and screw kilns with wheat straw pellets demonstrated feasibility of agricultural sidestreams for high-volume biocarbon production.

**Applications**

The project investigated high-value applications for agro-based biocarbons, focusing on energy storage, water purification, and biocomposites. Activated carbons derived from wheat straw lignin showed promising performance as electrode materials in supercapacitors, indicating their viability as alternatives to fossil-based materials. Additionally, agro-based activated carbons demonstrated substantial potential for micropollutant removal in wastewater treatment, aligning with upcoming regulatory requirements in the EU. High temperature biocarbons were found feasible option as a replacement for fossil based, non-renewable materials in composites.

**Techno-Economic Assessment, Biocarbon Market, and Foresight**

The project conducted a comprehensive techno-economic assessment to evaluate the feasibility of biochar production from agricultural biomass in Finland. The assessment included a detailed analysis of the straw supply chain, biorefinery plant technical specifications, and economic parameters. The findings highlighted the potential for biochar production from agricultural biomass, emphasizing the importance of addressing supply chain costs, optimizing production processes, and exploring market opportunities to ensure profitability and sustainability.

The project also explored the broader biocarbon market, examining the current state, trends, and future outlook of the biochar and activated carbon markets. The global annual biochar production in 2023 was

estimated at 352,304 tons, with 75,000 tons in Europe and 21,000 tons in the Nordics. The Nordic biochar market is still in its early stages, with strong interest in expansion and various promising application areas. The activated carbon market size in 2024 was estimated to be $6.6 billion, with a projection to reach $10.2 billion by 2029. The total annual market volume of activated carbon in Europe is around 650,000 tonnes, with the majority imported from Asia.

**Conclusion and recommendations**

The BioCarbonValue project successfully demonstrated the potential of producing high-value biocarbons from agricultural biomass. The key findings include promising performance in energy storage, water purification, and biocomposites, as well as the feasibility and profitability of biochar production in Finland. The project identified the need for further research and optimization to address challenges such as feedstock consistency, porosity requirements, and economic viability. Recommendations for further work include optimizing production processes, ensuring feedstock consistency, developing the market for agro-based biocarbons, conducting life-cycle assessments, and fostering collaboration between research institutions, industry partners, and policymakers.

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## Certificate Of Completion

| | | |
|---|---|---|
| Envelope Id: F5D1ABDA-8220-4581-867F-320D71CECC9E | | Status: Completed |
| Subject: Complete with Docusign: VTT-R-00161-25 | | |
| Source Envelope: | | |
| Document Pages: 54 | Signatures: 1 | Envelope Originator: |
| Certificate Pages: 1 | Initials: 0 | Christina Vähävaara |
| AutoNav: Enabled | | Tekniikantie 21, Espoo |
| EnvelopeId Stamping: Enabled | | ., . P.O Box1000, FI-0204 |
| Time Zone: (UTC+02:00) Helsinki, Kyiv, Riga, Sofia, Tallinn, Vilnius | | Christina.Vahavaara@vtt.fi |
| | | IP Address: 10.111.40.7 |

## Record Tracking

| | | |
|---|---|---|
| Status: Original<br>29 April 2025 \| 10:09 | Holder: Christina Vähävaara<br>Christina.Vahavaara@vtt.fi | Location: DocuSign |

| Signer Events | Signature | Timestamp |
|---|---|---|
| Tom Granström<br>Tom.Granstrom@vtt.fi<br>Research Manager<br>Teknologian tutkimuskeskus VTT Oy<br>Security Level: Email, Account Authentication (None), Authentication | <br>Signature Adoption: Pre-selected Style<br>Using IP Address: 130.188.17.16 | Sent: 29 April 2025 \| 10:19<br>Viewed: 29 April 2025 \| 15:51<br>Signed: 29 April 2025 \| 15:53 |



**Authentication Details**
SMS Auth:
Transaction: f2728c4f-2dba-440b-9786-5e737f6e7eb1
Result: passed
Vendor ID: TeleSign
Type: SMSAuth
Performed: 29 April 2025 | 15:51
Phone: +358 50 5124232

**Electronic Record and Signature Disclosure:**
Not Offered via Docusign

| In Person Signer Events | Signature | Timestamp |
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| Editor Delivery Events | Status | Timestamp |
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| Agent Delivery Events | Status | Timestamp |
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| Intermediary Delivery Events | Status | Timestamp |
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| Certified Delivery Events | Status | Timestamp |
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| Carbon Copy Events | Status | Timestamp |
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| Witness Events | Signature | Timestamp |
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| Notary Events | Signature | Timestamp |
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| Envelope Summary Events | Status | Timestamps |
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| Envelope Sent | Hashed/Encrypted | 29 April 2025 \| 10:19 |
| Certified Delivered | Security Checked | 29 April 2025 \| 15:51 |
| Signing Complete | Security Checked | 29 April 2025 \| 15:53 |
| Completed | Security Checked | 29 April 2025 \| 15:53 |

| Payment Events | Status | Timestamps |
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