Zurich University
of Applied Sciences

Life Sciences and
Facility Management

Institute of
Natural Resource Sciences

# Biochar Beyond Soil

## Investigating potential NET applications for promising biochar feedstocks in material applications

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Commissioned by the Federal Office for the Environment (FOEN)

# Imprint

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# Abbreviations

| Abbreviation | Term |
|---|---|
| ATR | Attenuated total reflectance |
| BC | Biochar |
| CBC | Coffee silverskin biochar |
| CCS | Carbon capture and storage |
| $CO_2$-eq | $CO_2$ equivalents |
| DM | Dry matter |
| EBC | European biochar certificate |
| FTIR | Fourier-transform infrared spectroscopy |
| GWP100 | Global warming potential in 100 years |
| KVA | Kehrichtverbrennungsanlage (engl. municipal waste incineration plant) |
| Mt | Metric tons |
| NET | Negative emission technology |
| NIR | Near infrared |
| PAH | Polycyclic aromatic hydrocarbons |
| PLA | Polylactic acid |
| PBAT | Polybutylene adipate co-terephthalate |
| PE | Polyethylene |
| PP | Polypropylene |
| PS | Polystyrene |
| PET | Polyethylene terephthalate |
| TEA | Techno-economic Analysis |
| TGA | Thermogravimetric analysis |
| t/a | Tons per year |
| WBC | Biochar produced from woody wastes |
| WHB | Wheat bran biochar |
| Yr. | Year |

# Executive Summary

- This study focussed on three potential material applications of biochar to reduce or compensate $CO_2$-emissions in an industrial context “beyond soil” application.
- Application of biochar to concrete, asphalt and plastics was investigated due to the substantial mass flows involved, life-cycle emissions intensity of the products and known pioneer products containing biochar for each industry being on the market.
- The pyrolysis of wheat bran and coffee silverskins, based on shortlisting from Gutzwiller et al., (2022), leads to emissions of -4.08 and -3.44 kg $CO_2$-eq/kg biochar respectively when pyrolyzed with a PyroFarm P40 (thermal output 125 kW) batch reactor.
- Based on conservative biochar addition amounts the annual potential for biochar in asphalt, concrete and plastics of 434’850 t exceeds the theoretical availability of the selected biomasses by a factor of 8.
- Concrete and asphalt applications are most promising due to the substantial mass flows, high recycling rates (< 80%) and landfilling as the prevalent disposal method. Whilst a high storage permanence is in mineral matrices is assumed investigations on carbon leakage through mechanical, chemical, and biological processes are lacking.
- The sequestration of biochar in conventional plastics is challenging due to the short life cycle of products and 92% being incinerated. End-of-life technologies such as re-pyrolysis of plastics containing biochar, composting of bioplastics containing biochar and carbon capture and storage (CCS) at incineration plants should be investigated to determine if sequestration over climatically relevant timescales is possible.
- The purchasing cost of wheat bran feedstock increases the cost of the produced biochar to CHF 1’755.80 resulting in a cost of CHF 525.90 per t $CO_2$ prior to application, exceeding the cost of commercially available biochar from woody wastes. The cost of silverskin biochar is substantially lower at CHF 392.50 per ton and CHF 115.60 per t of $CO_2$.
- Characterisation of the biochar shows that higher concentrations of S and O in coffee silverskin is a result of a greater number of surface functional groups, which may also be responsible for its poorer thermal stability.
- A high carbon content, high specific surface area and low particle size are generally favourable for most material applications due to lower reactivity of biochar, higher sequestration potential, ease of dispersion and high number of interaction sites with surrounding material matrix.
- A case study with biocomposites containing polylactic acid (PLA) and biochar was used to evaluate alternative solutions to ensure carbon from biochar is sequestered in plastic applications.

- Biocomposites containing 5 wt. % biochar from wood and wheat brain had the most stable biocomposite production conditions and similar thermal degradation curve to pure PLA, with particle size and distribution likely a contributing factor.
- The case study found that in a lab-setting biochar can be thermally recovered from the PLA composite for wood and wheat bran biochar, provided that an oxygen limited environment is maintained, and the temperature does not exceed original pyrolysis temperature.
- Lastly, biodegradation of the biocomposite is not inhibited by biochar addition and may provide an opportunity to cascade carbon into agricultural applications, if contaminant concentrations are not exceeded, or even recycle the carbon into a second use cycle.

# 1 Introduction

## 1.1 Background

In 2019, the Federal Council decided that Switzerland should not emit more greenhouse gases by 2050 than natural and engineered sinks can absorb (net zero target). On January 27, 2021, the Federal Council approved the "Long-Term Climate Strategy for Switzerland." The long-term climate strategy shows that Switzerland can greatly reduce its greenhouse gas emissions in the areas of transport, buildings, and industry by 2050 by moving away from fossil fuels. In 2050, however, greenhouse gas emissions from industry (especially cement production), waste management and agriculture that are difficult to avoid will remain at a level of around 12 million metric tons of $CO_2$ equivalents per year. According to the long-term climate strategy, these are to be offset with $CO_2$ capture and storage technologies (CCS; approx. 5 million tons of $CO_2$ of fossil or geogenic origin) and negative emission technologies (NET; approx. 7 million tons of $CO_2$ of atmospheric origin). Various plant-based and technical approaches are known to achieve negative emissions, but these are currently only implemented on a very small scale.

The pyrolysis of biomass to produce biochar offers a technology to contribute to negative emissions in Switzerland. According to the Federal Council's report of September 2, 2020, (in fulfilment of postulate 18.4211 by National Councillor Thorens Goumaz, Dec. 12, 2018), theoretical negative $CO_2$ emissions of up to 2.2 million tons of $CO_2$ annually could be generated if almost all the biomass that can be used sustainably in Switzerland is pyrolyzed. Recent estimates of potential demand from applications in agriculture and urban green areas range between 1.35 - 1.61 million tons of $CO_2$-eq annually (2023 Federal Council's report in fulfilment of postulate 19.3639 by National Councillor Bourgeois Jacques, Jun. 18, 2019), which is in line with calculations of 1.5 million tons of $CO_2$-eq used by (Brunner & Knutti, 2022; Schmidt et al., 2021). However these estimates require that biochar produced from sources other than untreated woody wastes are utilised, the application of which in agriculture is currently prohibited (Bundesamt für Umwelt, 2023). Biomass, particularly of woody origin, has many uses and plays a central role in the decarbonization of multiple sectors of the economy, creating competition for the feedstock.

Novel biochar uses in the built environment open the possibility for the utilisation of non-woody biomass. This newer branch of biochar research spans a wide variety of industrial products ranging from catalysts (Cha et al., 2016), filter media (Ahmad et al., 2014), composites (Infurna et al., 2023), concrete, asphalt, and plaster production (Legan et al., 2022; Rondón-Quintana et al., 2022; Y. Zhang et al., 2022). Often the use of biochar is associated with either sequestration of carbon in durable building materials (Y. Zhang et al., 2022) or the substitution of fossil fuel derived products such as carbon black or activated carbon in composite, filter, and catalyst applications (Liu et al., 2015). The porosity, high surface area and chemical properties of biochar can also lead to several co-benefits in asphalt, concrete and composite applications ranging from improved thermal resistivity, decreased thermal conductivity, altered water absorption and increased strength depending on addition amounts (Infurna et al., 2023; Legan et al., 2022; Rondón-Quintana et al., 2022). In studies on carbonation in concrete the addition of biochar also lead to increased uptake of $CO_2$ (Chen et al., 2022; Legan et al., 2022; Praneeth et al., 2020). However, the successful implementation of biochar in the built environment requires an understanding of which materials have a high and climatically relevant sequestration potential, what properties (physical and chemical, including potential contaminants) and addition amounts of the biochar are critical to ensure the final product is not compromised.

## 1.2 Study aim

The aim of this study is to evaluate novel applications for biochar in the built environment that have a high potential to store carbon within biochar over long time scales. Building upon work from the PYROCHAR project (Gutzwiller et al., 2022) on suitable non-woody pyrolysis feedstocks a) coffee silverskin and b) wheat bran were chosen to be examined as they were identified as two biomasses with bioenergy potential that were considered suitable for biochar production. As both feedstocks are not “untreated wood”, their application to agricultural soil is "not recommended” in Switzerland (BAFU, 2023) making them ideal candidates for novel material applications “beyond soil”. To evaluate novel applications for these biochars in the built environment three work packages were developed.

### 1.2.1 WP1: Techno-Economic Analysis

A techno-economic analysis (TEA) was used to estimate the potential for carbon sequestration in material applications with the following objectives:

a. **Identification of application fields**: What are promising novel applications for biochar and what are their mass flows?
b. **Determine emission reduction potential**: What is the $CO_2$ sequestration potential at production for biochar produced from coffee silverskin and wheat bran.
c. **Determine biochar addition amounts:** What quantities of biochar can be integrated into these applications?

d. **Evaluate sequestration potential in application:** how does the life cycle of the material application (recycling, end-of-life) influence the sequestration of carbon?
e. **Calculate cost effectiveness:** What are the costs associated with biochar production of wheat bran and coffee silverskin?

### 1.2.2 WP2: Biochar characterisation

In addition to the existing EBC characterisation of biochar from coffee silverskin (CBC) and wheat bran (WHB) (performed by Gutzwiller et al., 2022), particle size, thermal stability and functional groups were analysed and compared to a commercially available wood biochar (WBC). Properties that had significant implications for the material applications identified in WP1 were discussed.

### 1.2.3 WP3: Biocomposite Case Study

A wide body of literature on biochar addition to various biopolymers is available, with 20 publications between 2015-2022 on the topic (Krähenbühl, 2022). These examined biochar feedstock, pyrolysis conditions, addition amounts and evaluated the biocomposites thermal and mechanical performance. However only 3 studies examined end-of-life options such as a degradation, none of which compared the influence of biochar and fate of carbon from the biochar. Consequently, the aim of this work package was to perform a lab-scale study on the thermal and biological degradation of biocomposites containing polylactic acid (PLA), due to its prevalence, and biochar to determine whether the carbon from biochar can be re-used or sequestered in a downstream application.

# 2 Methodology

## 2.1 WP1: Techno-Economic Analysis (TEA)

### 2.1.1 Identifying application fields

A literature review was performed to identify promising material applications for biochar to increase carbon sequestration in Switzerland. Data from the recent study *"MatCH - Material and energy resources and associated environmental impacts in Switzerland"* project (Matasci et al., 2019) were used to determine mass flows and emissions within Switzerland for several materials. For each potential application field, data on imports, inland production, recycling, and disposal were collected. A selection of applications was chosen based on a) the size of the mass flow significant for carbon sequestration, and b) its recyclability or end-of-life behaviour, respectively.

### 2.1.2 Emission reduction potential of selected biochars

Life cycle assessment results produced by the PYROCHAR study for both feedstocks (wheat bran and coffee silverskin) for a batch PyroFarm P40 (thermal output of 125 kW) pyrolysis reactor were used (Gutzwiller et al. 2022). In that study the global warming potential over 100 years (GWP100) in kg $CO_2$-eq emissions per kg of feedstock biomass were calculated by determining the emissions linked to the provision of biomass, transport, and pyrolysis and raw materials associated with the pyrolysis unit along with credits received from replacing heating energy from conventional natural gas furnaces. In this study these values were used with biochar yield data to calculate the emission reduction potential per kg of produced biochar. The stoichiometrically determined carbon sink potential of biochar was also calculated. Emissions associated with transport and processing for final application in materials were not included due to time and data limitations.

### 2.1.3 Potential biochar addition amounts in the selected applications

To determine the amount of biochar that can be added to the selected application commercially available products containing biochar were investigated, pilot projects were collated and pioneers in the field were interviewed. Data on established carbon additives, such as carbon black, was also used to evaluate technically established addition amounts in industry.

### 2.1.4 Carbon sink permanence

A crucial component of a high-quality NET is the permanence of the carbon sink, with the IPCC defining carbon that is not mineralized in soil over 100 years as a permanent sink fraction of the biochar in soil applications (IPCC, 2019). Other classifications beyond soil differentiate between temporary (<1,000 yr.) or permanent (>100,000 yr.) timescales (Scott et al., 2015). For this report material applications will be evaluated as to whether they are able to store carbon from biochar in a stable matrix for a duration that exceeds 100 years by examining a single life cycle, recycling rate and method along with whether the common disposal methods can result in loss of carbon to the atmosphere.

### 2.1.5 Economical parameters

Economical parameters include the cost associated with the provision of biomass, storage, and pyrolysis. Biochar production costs using coffee silverskin and wheat bran as feedstocks were calculated using methodology developed in the PYROCHAR project (Gutzwiller et al., 2022). The $CO_2$ captured per ton of biochar was determined stoichiometrically using the carbon content data from biochar produced by the PyroFarm unit and combined with economical parameters to determine the cost of carbon sequestration in CHF per ton of $CO_2$. Additional costs and emissions from biochar preparation (e.g., milling and drying) after purchase were not included.

## 2.2 WP2: Biochar characterisation

Characteristics of the two selected biochars, coffee silverskin (CBC) and wheat bran (WHB) were taken from the PYROCHAR study (Gutzwiller et al. 2022) (see Appendix 1). Biochar produced from woody wastes (WBC) produced during the INkoh project (Project UTF 607.19.19) by Inkoh AG (Maienfeld, Switzerland) was used to provide a comparison to commercially available wood biochar. Additional characterisation of the functional groups was performed using attenuated total reflectance (ATR) Fourier transform infrared spectroscopy (FTIR) using a Nicolet iS20 FTIR Spectrometer (Thermo Scientific, USA). Particle size was measured using a Mastersizer 3000 (Malvern, USA). Biochars thermal stability was investigated via a 4-step-thermogravimetric analysis (TGA) using a TGA 1 (Mettler Toledo, USA) with parameters described in Table 1.

## 2.3 WP3: Biocomposite Case Study (Biochar + PLA)

### 2.3.1 Biocomposite production

The PLA granulate “PLA Ingeo 4043D” (Natureworks ®, USA), was used for biocomposite production. It is a commercial, multipurpose extrusion grade matrix with good characteristics for 3D printing in a broad number of applications. Biochar was ball-milled using a MM 400 (Retsch, Germany) at a frequency of 25 Hz for 1 minute. Both biochar and PLA granulate was dried at 80 °C for 4 hours prior to extrusion with a lab-scale Composer 450 (3Devo, Netherlands) extruder (Figure 1). The extruder consists of 4 heating zones set to 180, 190, 220, 180 °C and a hardened steel screw operating at 4.5 rpm. To maintain a consistent filament thickness of 2.85 mm the extrusion speed was modulated automatically by the device. Inconsistencies in the production conditions were monitored by the device and used to evaluate the influence of biochar on biocomposite production. To compare the influence of biochar on the biocomposite and its degradation 5, 10 and 20 wt. % was added for each biochar type. Additionally, only the PLA matrix was extruded to provide a control variant.

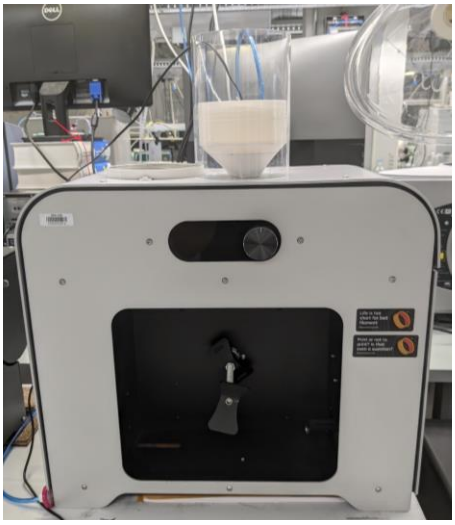


**Figure 1** - Composer 450 (3Devo, Netherlands) used for the extrusion of biocomposites.

### 2.3.2 Biodegradation

Biodegradation experiments were performed analogously to industrial composting conditions at 58 °C for a period of 1.5 months based on SN EN ISO 14855. Biocomposites were shredded to < 2mm with the SM 300 (Retsch, Germany) and mixed with 25 g characterized compost from the local Biomasse-Hof (Wädenswil, Switzerland). Negative pressure from the consumption of $CO_2$ by a solution of 1 M NaOH was measured using OxiTop®-IDS B 6 (Xylem Analytics, USA) and used to calculate oxygen demand and therefore degradation of carbon.

**Figure 2** - Biodegradation experiments performed in an incubator at 58 °C.

### 2.3.3 Thermal degradation

The thermal degradation of the biochars and biocomposites was investigated using a 4-step-thermogravimetric analysis (TGA) using a TGA 1 (Mettler Toledo, USA) (Figure 3). Weight changes were measured using the heating parameters in Table 1. Biocomposites were cryo-milled using MM 400 (Retsch, Germany) at a frequency of 30 Hz for 2 minutes and 30 seconds prior to TGA.

| Step | Start temperature (°C) | End temperature (°C) | Duration (min) | Rate (°C/min) | Gas |
|---|---|---|---|---|---|
| 1 | 25 | 110 | 8.5 | 10 | Nitrogen |
| 2 | 110 | 110 | 5 | 0 | Nitrogen |
| 3 | 110 | 800 | 69 | 10 | Nitrogen |
| 4 | 800 | 800 | 10 | 0 | Air |

**Table 1**: Heating parameters during the thermogravimetric analysis


**Figure 3** - Thermogravimetric Analysis Device used for measurements.

# 3 Results and Discussion

## 3.1 WP1: Techno-Economic Analysis

### 3.1.1 Identifying application fields

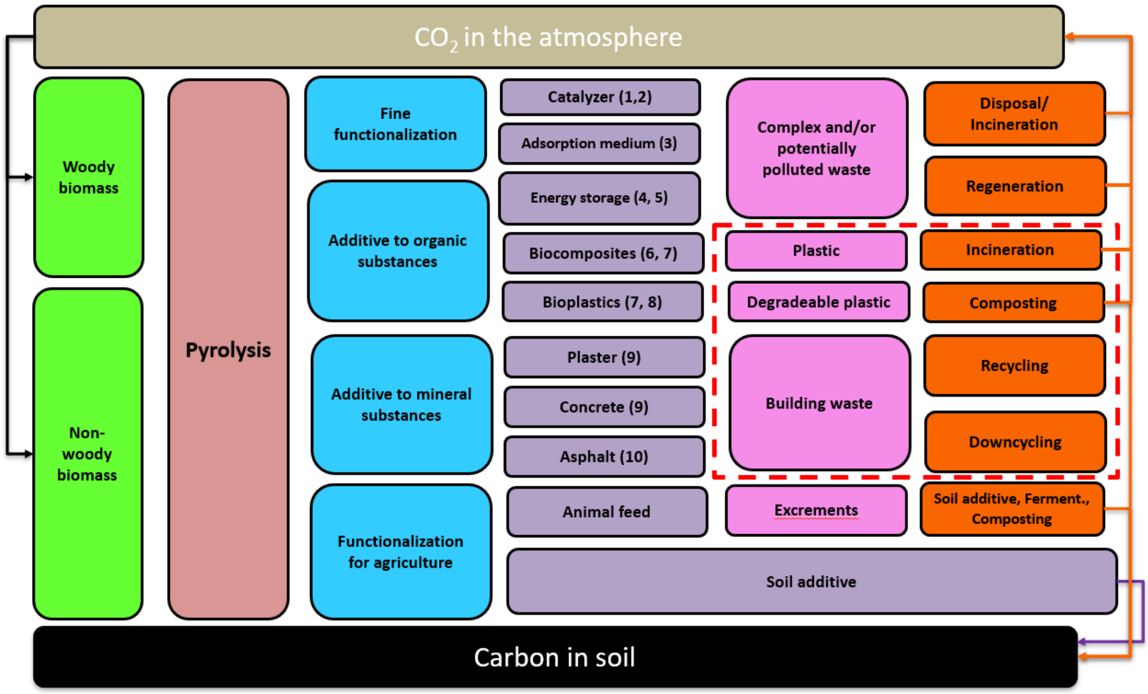



**Figure 4** – Scope of use cases, from suitable biomass for biochar production to end-of-life (EOL): Suitable biomass (green), pyrolysis (red), use category (blue), product category (violet, literature references in brackets), waste category (pink) and end-of-life (orange). The dashed red line indicates the selection included in this study.

Research on the application of biochar in materials ranges include high tech applications such as catalysts (Cha et al., 2016; Liu et al., 2015), filter media (Ahmad et al., 2014) and battery systems (Norouzi et al., 2019; Senthil & Lee, 2021). However, these incur large research, development and production costs whilst utilising minimal amounts of biochar from either a product design perspective or simply due to the relatively low volumes of the final product. Lastly at the end-of-life these products consist of complex combinations of potentially polluting materials, making the reuse of carbon challenging. Whilst replacing fossil carbon with sustainable carbon from biochar is important across all industries, these high-tech applications were therefore excluded from consideration.

This leaves the integration of biochar into lower cost, bulk materials such as concrete, masonry (e.g., plaster), asphalt and plastics (Gupta & Kua, 2017; Kane et al., 2022; Y. Zhang et al., 2022). Table 2 shows the Swiss mass flows involved in the import, inland production and consumption of these materials (Matasci et al., 2019). Concrete represents by far the most substantial mass flow with the highest annual inventory increase of 38.8 Mt per year. Whilst both plastics and asphalt are considered imports, they are imported as raw goods that are processed prior to application and therefore undergo additional processing steps in Switzerland. Interestingly the contribution of asphalt from recycling in Switzerland exceeds the imported amounts by almost a factor of 2. Regarding outflow and disposal, asphalt, concrete and masonry have a high recycling rate of 83, 85 and 80% respectively. Material plastic recycling on the other hand is very low (7%), with 92% of plastics being incinerated.

| Category | Unit | Asphalt | Concrete | Masonry | Plastics |
|---|---|---|---|---|---|
| Import | t/a | 1'313'207 | 8'207'510 | 0 | 2'117'332 |
| Domestic production | t/a | 0 | 31'592'527 | 2'899'754 | 0 |
| Secondary inflow from recycling | t/a | 2'485'514 | 5'597'138 | 1'521'200 | 66'185 |
| **Total Inflow** | **t/a** | **3'798'721** | **45'397'174** | **4'420'953** | **2'183'517** |
| | | | | | |
| Incineration | t/a | 0 | 0 | 0 | 885'700 |
| Landfill | t/a | 509'081 | 991'983 | 380'300 | 12'018 |
| Recycling | t/a | 2'485'514 | 5'597'138 | 1'521'200 | 66'185 |
| Export | t/a | 0 | 2'379 | 0 | 985'830 |
| **Total Outflow** | **t/a** | **2'994'595** | **6'591'500** | **1'901'499** | **1'949'733** |
| | | | | | |
| Direct material consumption | t/a | 1'313'207 | 39'797'658 | 2'899'754 | 1'170'962 |
| Inventory increase | t/a | 798'559 | 38'798'934 | 2'518'254 | 233'565 |
| Recycling rate* | % | 83% | 85% | 80% | 7% |

**Table 2** - Mass flows for selected industries with potential for biochar integration (own calculation, based on Matasci et al., 2019).
* Recycling rate = share of recycled material divided by "Total Outflow" without "Export"

| Category | Asphalt | Concrete | Masonry | Plastics |
|---|---|---|---|---|
| Import | 0.29 | 0.08 | NA | 2.70 |
| Domestic production | NA | 0.08 | 0.31 | NA |
| Secondary inflow | 0.01 | 0.01 | 0.01 | 0.59 |
| **Total Inflow** | **0.11** | **0.07** | **0.20** | **2.63** |
| | | | | |
| Incineration | 0.00 | 0.00 | 0.00 | 46.06 |
| Landfill | 0.00 | 0.00 | 0.00 | 0.00 |
| Recycling | 0.00 | 0.01 | 0.00 | 0.16 |
| Export | NA | 0.08 | NA | 2.46 |
| **Total Outflow** | **0.00** | **0.01** | **0.00** | **1.53** |
| | | | | |
| Direct material consumption | 0.48 | 0.08 | 0.35 | 14.06 |

**Table 3** - Tons of $CO_2$-eq per ton of produced material annually. Total values represent the cumulative emission intensity (own calculation, based on Matasci et al., 2019). NA = not available.

Emissions data from the study (Matasci et al., 2019) were used to calculate the emissions intensity (tons of $CO_2$-eq per ton of produced material annually) in Table 3. Whilst plastic mass flows in Table 3 are comparatively low, compared to asphalt, concrete and masonry the emission intensity of plastic products throughout production and disposal are considerable and a matter of concern. Based on these findings three material categories for biochar were developed for further analysis and estimations for carbon sequestration (Figure 5). Asphalt and concrete are construction materials, with high recycling rates > 80%, that are widely used. These materials can permanently incorporate biochar as $CO_2$-sink, even if the construction should be dismantled in the future (see Figure 5A and B). Masonry was excluded from this point onwards due to the differentiation of products within that market increasing the complexity of performing appropriate estimations. The third material category (plastics, see Figure 5C), is widely used in a great variety of applications in Switzerland and currently has a very low recycling rate with incineration as the primary disposal pathway. A fourth use-case (see Figure 5D) was selected in this study following the visionary idea that biochar in the future might act as filler in biodegradable plastic materials, e.g., polylactic acid (PLA), which might be recovered and reused after end-of-use.

**Use case A)**: Biochar (BC) as C-source is added to concrete during production. At the end of

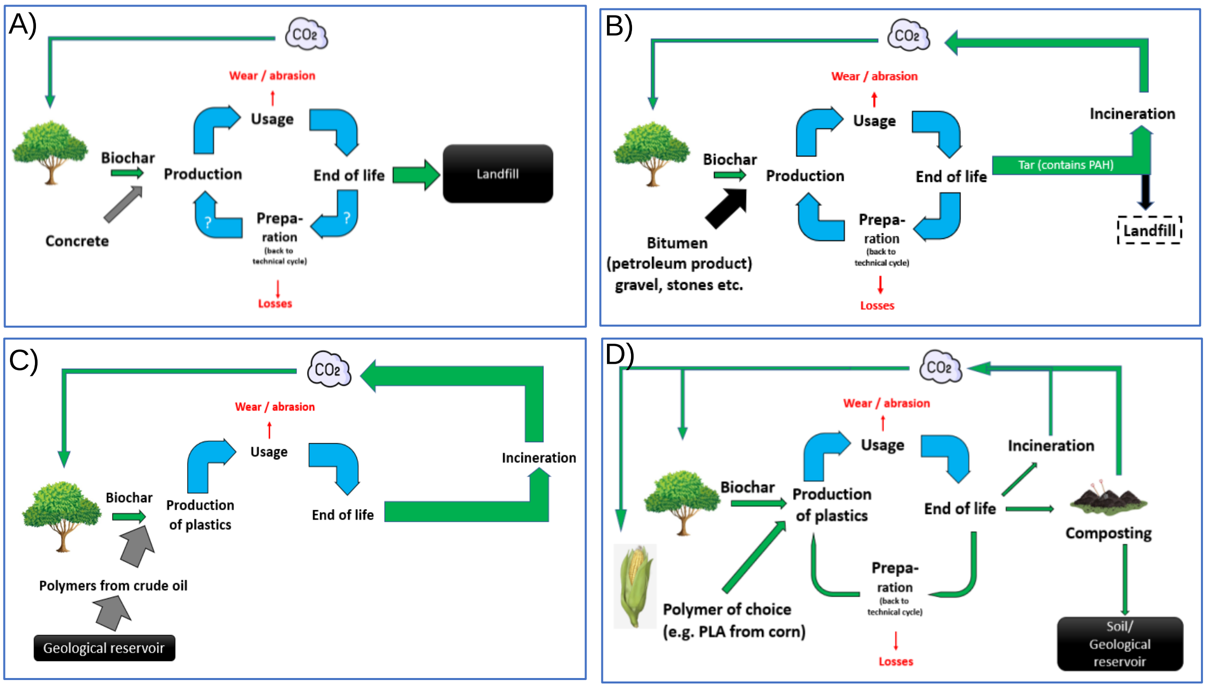



**Figure 5** - Four use cases for C-sequestration using biochar in a circular context. A) Addition of biochar to concrete; B) Addition of biochar to asphalt; C) Addition of biochar to plastic polymers from fossil sources, without recycling; D) Addition of biochar to plastics polymer from renewable sources, with biochar recycling

one lifespan, the BC-concrete may be recycled and reused as aggregates in a second lifespan. At the end of the lifetime, BC-concrete can be disposed in a landfill for geological timespans.

**Use case B)**: BC is added to bitumen, gravel, and stones, to produce asphalt during production, in an amount that reduces the $CO_2$ footprint during production. Used asphalt is already recycled to a large extent, and the BC in the asphalt has the potential to stay within the technical cycle. However, bitumen is made from petroleum. “Legacy” asphalt may contain polycyclic aromatic hydrocarbons (PAH) > 250 ppm which cannot be recycled (Rubli, 2020).

**Use case C)**: BC is used as additive to conventional plastic. This reduces the $CO_2$ footprint over the lifespan to a certain extent by directly replacing plastic or carbon black normally used for pigmentation. Since most of the plastic waste is incinerated in Switzerland, a NET potential only exists if “Carbon Capture and Storage” (CCS) is implemented during incineration.

**Use case D)**: BC is used as additive to a renewable plastics source (e.g., polylactic acid, PLA). In this case, the incineration would be $CO_2$-neutral. Composting of certain biodegradable polymers such as PLA is possible in a controlled industrial setting. There is a limited number of potential products using PLA and BC. Conventional mechanical recycling for biodegradable polymers is not yet established.

### 3.1.2 Emission reduction potential of selected biochars

Life cycle assessment data for both feedstocks (wheat bran and coffee silverskin) for a batch pyrolysis reactor (PyroFarm 125 kW) from the PYROCHAR study was used from Gutzwiller et al. (2022). According to the GWP100 methodology used in the study the pyrolysis of 1 kg of wheat bran contributes to a reduction potential of -0.98 kg $CO_2$-eq and the pyrolysis of 1 kg of coffee silverskin leads to a comparable value of -0.93 $CO_2$-eq per kg. With yields of 24 and 27% respectively each kg biochar produced has negative emissions potential of -4.08 for wheat bran and -3.44 kg $CO_2$-eq for coffee silverskins (Table 4). Both values exceed the stoichiometrically available carbon due to credits from replacing heat produced with natural gas through heat from pyrolysis. As both biomasses are residual products from other processes, according to the EBC C-Sink Certification, they are exempt from emissions associated with their provision.

| Parameter | Unit | Wheat bran | Coffee silverskin | Source |
|---|---|---|---|---|
| *BIOCHAR PRODUCTION VALUES* | | | | |
| Biomass availability | t DM/a | 158’950 | 59’500 | Gutzwiller et al., 2022 |
| Biochar yield | Wt. % | 24 | 27 | Gutzwiller et al., 2022 |
| Theoretical production ceiling | t biochar/a | 38’148 | 16’065 | Gutzwiller et al., 2022 |
| Sustainable production ceiling | t biochar/a | 18’279 | 13’685 | Gutzwiller et al., 2022 |
| *STOICHIOMETRICALLY DETERMINED CARBON SINK POTENTIAL* | | | | |
| Organic Carbon Content | Wt. % | 68.8 | 70.2 | Gutzwiller et al., 2022 |
| Stoichiometric carbon sink | kg $CO_2$/kg biochar | 2.52 | 2.57 | Calculated |
| Theoretical carbon sink | t $CO_2$-eq/a | 96’235 | 41’351 | Calculated |
| Sustainable carbon sink | t $CO_2$-eq/a | 46’112 | 35’225 | Calculated |

| | | | | |
|---|---|---|---|---|
| *EMISSIONS REDUCTION POTENTIAL* | | | | |
| Emission reduction potential[a] | kg $CO_2$-eq/kg biomass | -0.98 | -0.93 | Gutzwiller et al., 2022 |
| Biomass to produce biochar[b] | kg biomass/kg biochar | 4.17 | 3.70 | Calculated from yield |
| Emission reduction potential | kg $CO_2$-eq/kg biochar | -4.08 | -3.44 | Calculated (*a* × *b*) |
| Theoretical reduction potential | t $CO_2$-eq/a | -155'771 | -55'335 | Calculated |
| Sustainable reduction potential | t $CO_2$-eq/a | -74'639 | -47'137 | Calculated |

**Table 4** – $CO_2$ data of biochar produced from wheat bran and coffee silverskin calculated stoichiometrically and with LCA data from Gutzwiller et al., 2022.

### 3.1.3 Potential biochar addition amounts in the selected applications

Based on interviews with companies performing pilot projects (Axel Preuß, CarStorCon, personal communication 03.08.2023, von Burg & Hulliger, 2023, Marcel Huber, 2021) a conservative biochar addition amount of 2 wt. % to asphalt was chosen for calculations. Similarly, a value of 1 wt. % biochar in concrete mixtures was considered realistic without drastically altering the qualities of the final product (Axel Preuß, CarStorCon, personal communication 03.08.2023, Christian Wengi, Logbau AG, personal communication 07.08.2023). Determining appropriate addition estimates for plastics proved more challenging due to the highly diversified product types and limited statistics on the current and future proportion of black plastics on the market. A high-resolution inventory of plastic flows in Switzerland performed by Klotz & Haupt (2022) found that 44% was used for packaging, 26% for building materials and 24% for household durables with electrical equipment, agricultural and automotive plastics making up the remaining 6%.

| Parameter | Unit | Asphalt | Concrete | Plastics |
|---|---|---|---|---|
| Domestic production and import | t/a | 1'313'207 | 39'800'037 | 2'117'332 |
| Conservative addition amount | Wt. % | 2% | 1% | 0.5% |
| Recycling | | Thermal and mechanical process | Mechanical process | Thermal and mechanical process |
| Disposal | | Landfilling | Landfilling | Incineration |
| Biochar demand | t/a | 26'264 | 398'000 | 10'587 |
| NET Potential* | $CO_2$-eq/t/a | 96'389 | 1'460'661 | 38'853 |
| Annual Emissions from production and import | $CO_2$-eq/a | 380'569 | 3'149'518 | 5'710'622 |
| Compensation potential** | % | 25% | 46% | 0.68% |

**Table 5** – Addition potential for biochar in asphalt, concrete and plastics. (own calculation, based on Matasci et al., 2019). *NET Potential was calculated using an average of -3.76 kg $CO_2$-eq/kg biochar from the LCA data in Table 4 for WBC and WHB and includes credits from replacing thermal energy from gas.
**Compensation of import related emissions through the addition of biochar.

Historically black plastics are produced using carbon black produced from incomplete combustion of hydrocarbons. They are found in all the main plastic categories and the addition of carbon black is used for pigmentation, ultraviolet (UV) protection, modifying electrical conductivity, increasing strength and thermal stability (Brewer, 2003; Pfaff, 2017). Food packaging in the EU limited to a carbon black loading of 2.5 wt. % (Commission Regulation (EU) No 10/2011 of 14 January 2011 on Plastic Materials and Articles Intended to Come into Contact with Food, 2011). Similar loadings between 1-2 wt. % are also used for pigmentation and UV protection in piping, wiring, engineered plastics, with some agricultural films containing up to 12.5 wt. % carbon black (Donnet et al., 1993). Higher loadings of 40 wt. % were found in conductive polymers (Pfaff, 2017) and products containing biochar such as HP Tech BioC 50/70/0.3 ET (carbonauten®, Germany) containing 50% biochar indicate a realistically achievable addition amount in a commercial product. Whilst the exact share of black plastics within these categories is unknown, black plastic in packaging was found to make up 10–15 % of domestic plastic waste in developed countries such as Denmark and the UK (Turner, 2018). Consequently, a rough estimate of 0.5 wt. % was used under the assumption that 20% of the plastics market would adopt black plastics with a loading of 2.5 wt. %.

The total potential for biochar addition of 434'850 t/a (Table 5) substantially exceeds the theoretical potential of 54'213 t/a for biochar production from coffee silverskin and wheat bran (Table 4) by a factor of 8. It also exceeds the maximum sustainable biochar production potential of 160'443 t/a across all 6 substrates shortlisted in the PYROCHAR study (Gutzwiller et al., 2022) by a factor of 2.7. Based on the conservative addition estimates none of the emissions from production and import are completely compensated, however successful trials with 5 wt. % biochar in asphalt (Axel Preuß, CarStorCon, personal communication 03.08.2023) and existing concrete products with ~2 wt. % biochar (Christian Wengi, Logbau AG, personal communication 07.08.2023) would lead to a compensation of 63% and 93% respectively. Considering that the biochars examined have carbon contents between 68 and 71% (Gutzwiller et al., 2022) utilising biochar with a higher carbon content would further improve sequestration performance. Lastly the LCA calculations in Gutzwiller et al., (2022) and used in the calculations in Chapter 3.1.2 to determine emission reduction values were performed for a 125-kW batch pyrolysis reactor, which is not representative of the market for pyrolysis reactors currently in use.

Compared to asphalt and concrete, plastic has a much higher inflow footprint of 2.63 t $CO_2$-eq per t compared to 0.11 t $CO_2$-eq and 0.07 t $CO_2$-eq per year (Table 3, calculated using values from Matasci et al., 2019). As the addition of biochar directly replaces fossil polymers or fossil carbon black used for pigmentation in addition to the 0.7% of production emissions that are compensated through negative emissions associated with carbon in biochar an additional 0.6% of the emissions are reduced by substituting resources derived from fossil fuels. For both concrete and asphalt the mass of biochar added was only considered to replace materials such as sand and gravel. The most carbon intensive components, namely bitumen for asphalt and cement in concrete, were not considered for replacement as these are often tied to norms (SN 640 420 for asphalt) and standards used by the industry. Addition of biochar to cement is being intensively researched as it can encourage carbonation and hydration processes in cement, indicating further sequestration co-benefits may be possible.(Kazemian & Shafei, 2023; Kua et al., 2017; Li & Shi, 2023; Praneeth et al., 2021) However a review by Maljaee et al., (2021) found that substitution of cement with biochar often lead to a decrease in compressive and flexural strength, with pyrolysis temperature and silicon content having a influence. Consequently substitution of cementitious components should include prior investigations of biochar characteristics and applications in context where the mechanical stresses are appropriate.

### 3.1.4 Carbon sink permanence

One of the key challenges for storing carbon from biochar over climatically relevant timescales for plastic is ensuring long product lifetime, effective recycling, and appropriate disposal. Both concrete and asphalt are considered durable materials with lifetimes measured in decades, high recycling rates and landfilling as the preferred end-of-life solution. Consequently, the EBC C-Sink Guidelines consider concrete applications to be permanent, with asphalt applications requiring monitoring (EBC, 2021) to determine whether they are incinerated (which will be the case of asphalt with PAH concentration of > 250mg/kg). The assumption is that carbon loss to the atmosphere through combustion, chemical oxidation or biological degradation is unlikely in these mineral matrices, however when compared to biochar in soil no publications exist examining long-term biochar dynamics in these materials. Physical leakage during mechanical recycling must also be investigated and limited, as light biochar particles may be part of the dust fraction during handling. Lastly the oxidation of biochar in asphalt during mixing, application and recycling temperatures (up to 300 °C) is unlikely when utilising biochar pyrolyzed at conventional production temperatures (400-850°C), however it should also be investigated to empirically determine whether losses may occur.

Lifetimes of plastic vary substantially depending on their application field. Considering that 44% of plastic is used for packaging (Klotz & Haupt, 2022) a substantial amount is likely to be "single use". Even the most durable plastics used in building applications do not exceed the lifetime of concrete used for the substructure. Extending the duration of use and therefore sequestration time requires a higher recycling rate, which is currently very low (7% in Switzerland, see Table 2). This is further hampered by the fact that black plastics absorb light emitted, thus interfering with the current process of plastic identification by near infrared technology (NIR), which leads to non-identification and thus disposal (Faraca & Astrup, 2019). Biochar with its high carbon content is likely to lead to similar identification challenges and poses a problem for ensuring that the carbon is retained in the cycle. Whilst CCS technologies are being piloted at incineration plants, such as the KVA[1] Linth, this critical step will be necessary to guarantee emission reduction for biochar in today's conventional landscape of plastics and incineration technology.

This highlights the need for research and implementation of novel technologies that may allow the carbon to be successfully re-used in a circular economy setting, including:

- **Closed loop recycling,** whereby biochar containing products are tracked and can be returned from recycling with minimal contamination.
- **Pyrolysis,** an established method for valorising waste plastics and often used to recover carbon black from tires may provide an opportunity to thermally utilise the plastic whilst potentially retaining the added biochar filler.
- **The use of biodegradable polymers**, whereby the biochar embedded in the polymer can then be cascaded through fermentation or composting steps, eventually being applied to the soil.

### 3.1.5 Economical parameters

The production cost for biochar from wheat bran (WHB) and coffee silverskin (CBC) was calculated using methodology (calculations in Appendix 2) from the PYROCHAR study for a commercial pyrolysis unit (Biomacon C400-I) and compared to biochar from tree bark examined in that study andd summarised in Table 6. The average cost of WHB prior to milling for 2021 was CHF 37 per 100 kg, with prices at the mill for the first quarter of 2023 averaging 38.7 CHF per 100 kg (Bundesamt für Landwirtschaft, 2023). As the disposal of CBC incurs costs for roasteries only the cost of pelleting was included in the calculations. The high purchasing price of wheat bran has a substantial impact on the cost of sequestering $CO_2$. Due to the lower energy density of both the coffee silverskins and wheat bran a greater amount of biomass is required to achieve comparable energy production, leading to a much higher biochar production. Of the feedstocks listed in Table 6, coffee silverskin, at CHF 123.2 per ton of $CO_2$-eq, is the most cost-effective feedstock for biochar production. EBC-AgroBio Inkoh biochar produced from woody wastes costs CHF 1'518 per ton of biochar if purchased as a big bag of 1.2 $m^3$ (bulk density data from 08.2022 and prices as of 08.2023). Consequently, the price of wheat bran is unlikely to be competitive.

[1] KVA = Kehrichtverbrennungsanlage (engl.: waste incineration plant)

| Parameters | Unit | Tree bark | Coffee silverskin (CBC) | Wheat bran (WHB) |
|---|---|---|---|---|
| Annual costs | CHF | 355'109 | 340'998 | 735'344 |
| Annual sales to district heating | CHF | 220'800 | 220'800 | 220'800 |
| Annual biochar production | t | 237'664 | 306'225 | 293'057 |
| $CO_2$ content | t | 748’365 | 1’039’712 | 978’465 |
| Cost per ton of biochar | CHF/t | 565.10 | 392.50 | 1755.80 |
| Cost per ton of $CO_2$ | CHF/t $CO_2$ | 179.50 | 115.60 | 525.90 |

**Table 6** – Annual costs associated with production of biochar with a Biomacon C400-I (400kW). Data and calculations from Gutzwiller et al. (2022) and performed for novel substrates in Appendix 2. Calculations for $CO_2$ were based on the carbon content of the biochar and not the LCA data from chapter 3.1.2 due to differing pyrolysis units. Tree bark was calculated by Gutzwiller et al. (2022) and included as it was considered an optimal novel feedstock for biochar production.

Currently biochar addition to concrete leads to a substantial markup on price ranging from 20-30% (Axel Preuß, CarStorCon, personal communication 03.08.2023) to 100% (Christian Wengi, Logbau AG, personal communication 07.08.2023). Whilst this is somewhat dependent on the differing biochar addition amounts used the reality is that the reduction of biochar costs through scaling, cheaper biomass sources (currently primarily woody wastes) and financial incentives is likely to be critical to increase adoption.

## 3.2 WP2: Biochar Characterisation

### 3.2.1 Physical and chemical properties

Biochars exhibited differing inner surface areas and particle size distribution, with WBC generally exhibiting the greatest inner surface area of 427 $m^2$/g, followed by 293 $m^2$/g for WHB and 43 $m^2$/g for CBC (Table 7). Particle size distribution data of the milled samples shows that 90% of measured particles (D90) for WBC are smaller than 33.6 µm, whereas WHB and CBC exhibit much larger sizes of 65.2 and 167 µm (Table 7). When examining the particle size distribution in Figure 6, the WHB peak is less well defined, with CBC exhibiting a slightly bimodal distribution due to a collection of particles at ~100 µm.

| Parameter | Unit | Woody waste (WBC) | Wheat bran (WHB) | Coffee silver skin (CBC) |
|---|---|---|---|---|
| Surface Area | $m^2$/g | 427 | 293 | 43 |
| Particle size (D90) | µm | 33.6 | 65.2 | 167.0 |
| $H/C_{org}$ Ratio | mol/mol | 0.47 | 0.17 | 0.28 |
| O/C Ratio | mol/mol | 0.001 | 0.021 | 0.068 |
| pH in $CaCl_2$ | | 12.5 | 9.5 | 10.4 |

**Table 7** – Physical and chemical characteristics of the biochars (dried). Apart from particle size, all data were taken from Gutzwiller et al. 2022 and the INKoh Project.

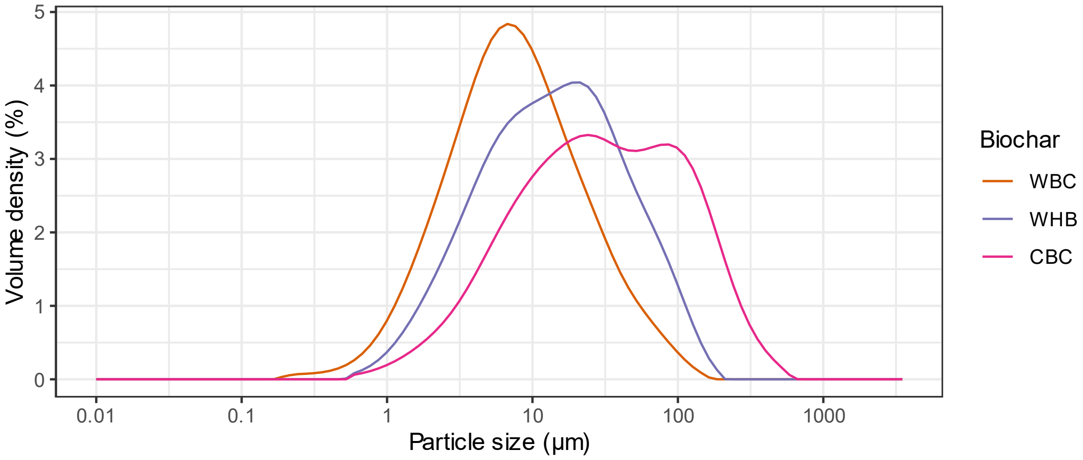



**Figure 6** - Particle size distribution for biochars. Values based on an average from 6 replicate measurements.

The proximate analysis of the biochars in Figure 7 shows that WBC has a substantially higher organic carbon content of 85.3 % and relatively low ash content of 10 % when compared to 25.5 and 28.7 % for WHB and CBC respectively. WHB and CBC also exhibit a 4 times higher nitrogen concentration than WBC, with CBC having a 10 times higher sulphur concentration. Both WHB and CBC contain 3.1 and 5.1 % oxygen, leading to a substantially higher O/C ratio when compared to WBC (Figure 7), indicating more remaining polar functional groups containing oxygen. WBC however has a much higher $H/C_{org}$ ratio of 0.47, which is associated with increased aromaticity and stability.

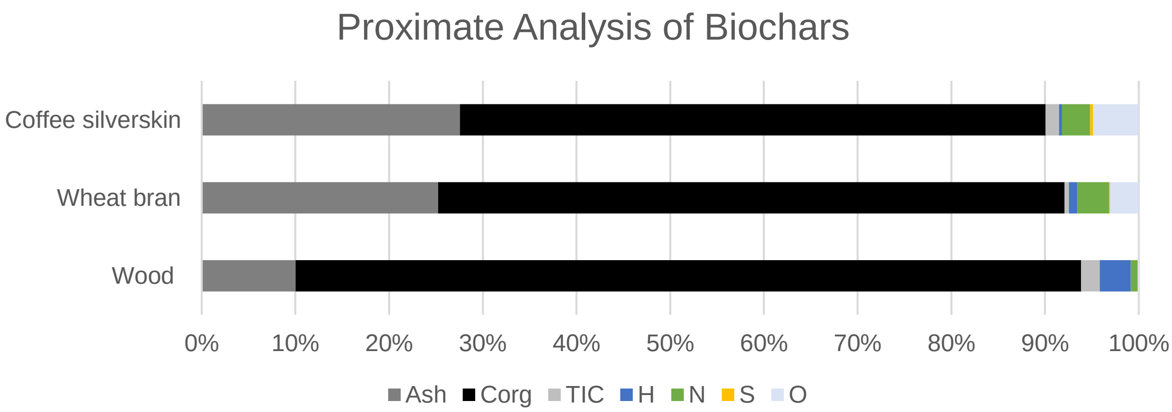



**Figure 7** - Proximate analysis of biochar produced from coffee silverskin, wheat bran and wood. Data from Gutzwiller et al., (2022)

### 3.2.2 Functional groups

Results from FTIR qualitatively confirm the higher O/C ratios and sulphur concentrations in the proximate analysis, with CBC exhibiting more clearly identifiable peaks which are likely a result of O-H and S=O groups found at 1350 $cm^{-1}$ (Figure 8). WHB also exhibits a broad peak between 1000 – 1300 $cm^{-1}$ which is likely due to a combination of S=O and C-O groups. WBC exhibits a relatively featureless spectrum throughout, with no distinct peaks to reflecting the results from the proximate analysis. Both CBC and WHB exhibit a slight peak between 800-900 cm$^{-1}$ typically associated with out of plane C-H bending in aromatic compounds such as PAHs. However, none of the biochars show no peaks in the higher wavelengths (circa 3000 cm$^{-1}$) typically associated with aromatic groups, indicating that PAHs are unlikely to be prevalent.

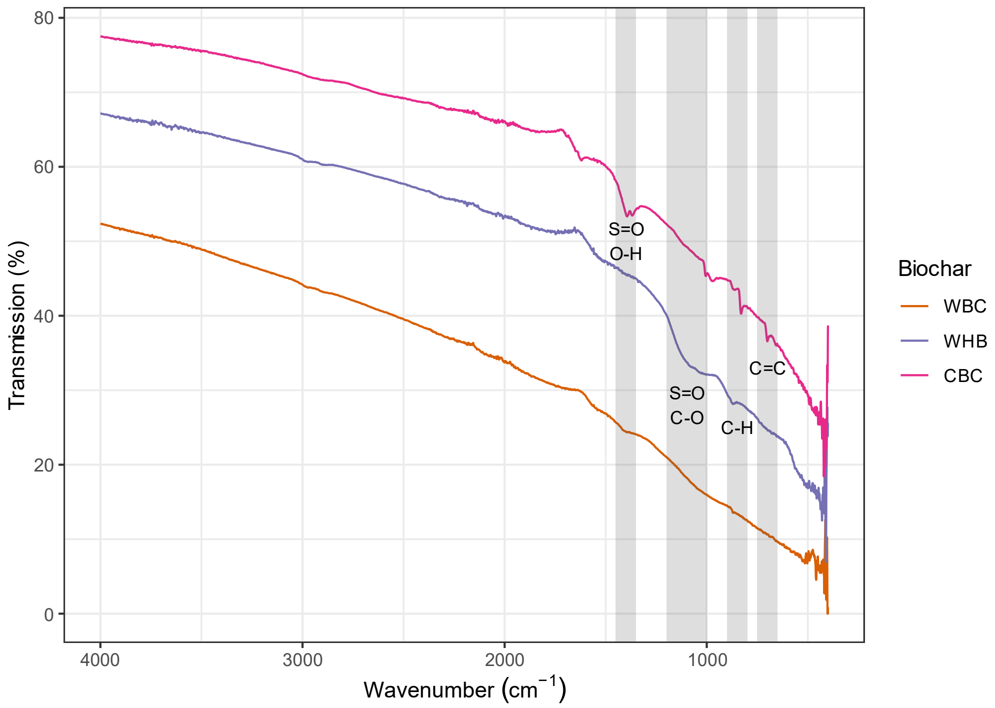



**Figure 8** - FTIR spectra for three biochars. Peaks are labelled.

### 3.2.3 Thermal stability

All 3 biochars exhibited a loss in weight between 25 and 120 °C, likely due to a loss of moisture. Between 200 and 800 °C under inert conditions CBC showed the greatest weight loss of 24.8 %, compared to only 6.4 % for WHB and 5.7 % for WBC. This indicates that despite similar pyrolysis conditions for CBC and WHB, the presence of more functional groups in CBC leads to reduced stability at higher temperatures. Isothermal conditions at 800 °C in the presence of air led to the combustion of all biochars with similar rates of decrease in weight, with longer durations expected to show a weight reduction down to the ash content of each biochar. These results indicate that re-pyrolysis under conditions which do not exceed the initial production temperatures of biochar with higher O/C ratios are unlikely to lead to a substantial loss of carbon, provided no oxygen can enter the pyrolysis process. Further testing in lab and pilot scale reactors is required to determine if this stability can be retained when larger amounts are pyrolyzed under more variable conditions.

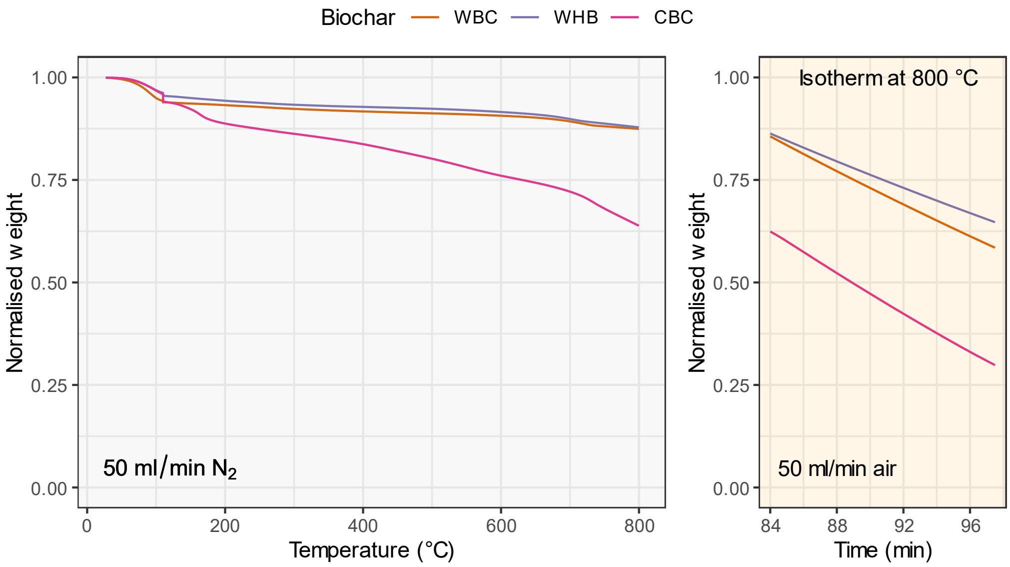



**Figure 9** - Thermal degradation of biochars under inert conditions between 25 - 800 °C (left) with an additional isotherm performed under atmospheric conditions at 800 °C for 15 minutes.

### 3.2.4 Toxic elements and organic contaminants

| Parameter | Units | Wheat bran (WHB) | Coffee silverskin (CBC) | EBC-Consumer Materials limits |
|---|---|---|---|---|
| Heavy metals | | | | |
| Arsenic (As) | mg/kg | < 0.8 | < 0.8 | 13 |
| Lead (Pb) | mg/kg | < 2 | < 2 | 120 |
| Cadmium (Cd) | mg/kg | < 0.2 | < 0.2 | 1.5 |
| Copper (Cu) | mg/kg | 55 | 188 | 100 |
| Nickel (Ni) | mg/kg | 6 | 6 | 50 |
| Mercury (Hg) | mg/kg | < 0.07 | < 0.07 | 1 |
| Zinc (Zn) | mg/kg | 308 | 60 | 400 |
| Chromium (Cr) | mg/kg | 12 | 7 | 90 |
| Organic pollutants | | | | |
| 16 EPA PAH | mg/kg | 4.5 | 0.9 | Declaration |
| 8 EFSA PAH | mg/kg | < LOD | < LOD | 1 |
| Benzo[a]pyrene | mg/kg | < LOD | < LOD | < 1 |
| Benzo[j]fluoranthene | mg/kg | < LOD | < LOD | < 1 |
| PCBs | µg/kg | n.d. | n.d. | 200 |
| PCDD/F | ng/kg | n.d. | n.d. | 20 |

Complies with limits for EBC-Feed (Class I)
Complies with limits for EBC-AgroBio (Class II)
Complies with limits for EBC-Agro (Class III)
Exceeds the limits for EBC-ConsumerMaterials (Class IV)
n.d. Not determined
LOD Limit of detection

**Table 8** - Heavy metal and organic pollutant concentrations in biochars produced from wheat bran and coffee silverskin (Data from Gutzwiller et al. 2022)

Currently the EBC Certificate covers many important parameters that determine the suitability of biochar for various applications. The requirements for EBC-Consumer Materials are only met by WHB, whereas CBC is only suitable for EBC-Basic Materials due to the high copper content (Table 9). Consequently, CBC would not be permitted for use in plastics and would therefore be limited to applications in concrete and asphalt.

### 3.2.5 Implications for material applications

Physical and chemical properties of biochar are crucial for identifying appropriate material applications and ensuring a successful final product. Physical attributes, such as particle size distribution, determine the dispersion of biochar in matrices such as concrete, asphalt or polymers, with particle sizes below 75 μm being ideal for plastic and asphalt (Nagarajan et al., 2016; R. Zhang et al., 2018, 2022) and even smaller for admixtures in cementitious materials (Gupta et al., 2022). Whilst processing steps, such as ball-milling can be used to further decrease particle size, achieving lower and uniform particle sizes rapidly, as is case for WBC and WHB, requires less energy and time. A higher surface area also provides more interaction or adhesion sites within a matrix, generally improving the strength, whilst also increasing thermal insulation (Y. Zhang et al., 2022).

Physical properties can be influenced by pyrolysis conditions, but they are also linked to the carbon content and carbon type found in the feedstock (Tomczyk et al., 2020). The pyrolysis of biomass with lower amounts of lignocellulosic carbon also leads to biochars with higher ash content such as CBC and WHB. From a sequestration perspective, a high carbon content is desirable (Logbau, personal communication 2023) and often associated with a more pure/inert substance, with beneficial qualities such as low density, high porosity and thermal stability (Y. Zhang et al., 2022). Elevated or specific ash compositions have been found to be beneficial for some polymer applications (Das et al., 2018) and the customisation of biochar with certain minerals is an area of research interest (Peng et al., 2021). However, differences in ash composition and differences in the chemistry of building materials require a case-by-case analysis supported by experimental trials. Considering that using carbon black with less than $< 1$ % ash (Brewer, 2003) is established across many industries a higher carbon content is likely to be favoured commercially.

Functional groups of the biochar also influence its surface reactivity and is well studied for contaminant removal where negatively charged surfaces of the biochar play an important role in exchanging cations (Yang et al., 2022). Functionalisation of biochars to achieve specific qualities is commonplace but largely dependent on the desired characteristics and interactions with other components of the building material and also requires a case-by-case evaluation. Results from this study indicate that biochars containing a greater number of functional groups (such as CBC) may also be thermally less stable, with the groups in question being more easily oxidizable. This is particularly important if recycling of materials contains a thermal process, as is the case for asphalt and plastics.

Contaminants, such as heavy metals and organic contaminants, not only determine what application the biochar is certified for by the EBC. They are also important when considering the end use within that material category. Existing standards, for example in the case of food packaging limit Benzo[a]pyrene to 0.25 mg/kg in carbon black (Commission Regulation (EU) No 10/2011 of 14 January 2011 on Plastic Materials and Articles Intended to Come into Contact with Food, 2011). Similarly asphalt with PAH concentrations above 250 mg/kg are not permitted for re-use as construction materials (Rubli, 2020) and should be considered when deciding on which biochar to add, as only a declaration of the 16 EPA PAHs is required according to the EBC (Table 8).

## 3.3 WP3: Biocomposite Case Study (Biochar + PLA)

A wide body of literature on biochar addition to various biopolymers is available, with 20 publications between 2015-2022 on the topic (Krähenbühl, 2022). These examined biochar feedstock, pyrolysis conditions, addition amounts and evaluated the biocomposites strength and elasticity. However only 3 studies examined end-of-life options such as a degradation. Consequently, the aim of this work package was to investigate the thermal and biological degradation of biocomposites containing PLA, as an example of a common biodegradable polymer, and biochar as these are crucial for determining whether the carbon from biochar can be re-used or sequestered in a downstream application.

### 3.3.1 Biocomposite production

The production of the biocomposite based on PLA was possible without clogging for all biochars across all addition amounts. The produced filament thickness, which should be tightly controlled at 2.85 mm to ensure successful printing, was negatively influenced by biochar addition amount and varied depending on the biochar type. Figure 10 shows that pure PLA exhibited the highest density of values at the desired 2.85 mm, with coffee silverskin biochar (CBC) performing worst.

The higher biochar content of 10 and 20 wt. % lead to a greater deviation of values for biocomposites containing both wood (WBC) and wheat bran biochar (WHB) as the formation of biochar aggregates reduces dispersion within the PLA matrix. Biocomposites containing biochar from coffee silverskin did not vary in filament thickness distribution, with all addition amounts performing poorly. This is likely to be a result of the bi-modal distribution and overall larger particle sizes of CBC biochar leading to a poor distribution (Figure 6). Additionally, the higher copper content of CBC, compared to WHB (Table 8) is likely to reduce thermal stability of the process as copper has a high thermal conductivity.

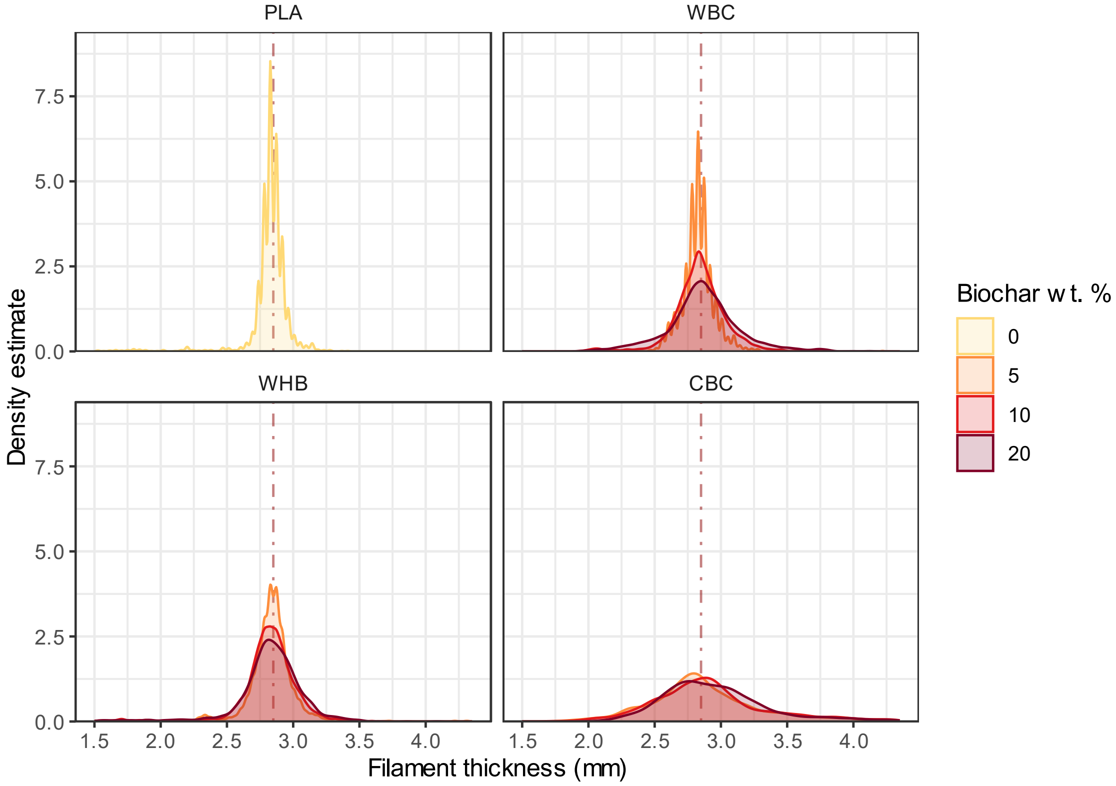
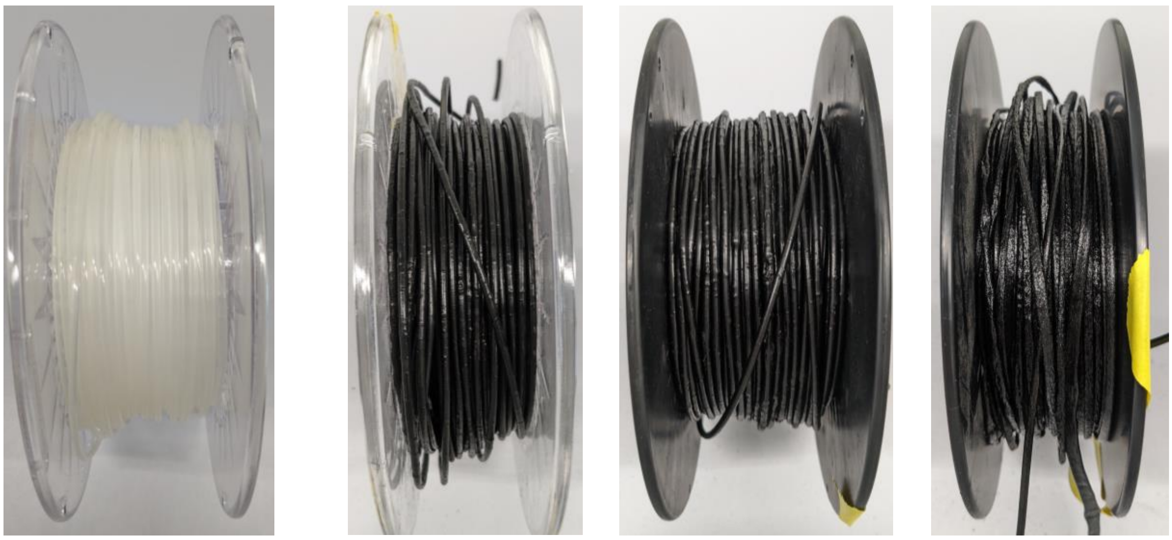



**Figure 10** - Smoothed density estimates of filament thickness throughout the extrusion. The target value of 2.85 mm is indicated by the dashed red line. WBC: PLA + wood biochar; WHB: PLA + Wheat bran biochar; CBC: PLA + Coffee silverskin biochar. PLA: Polylactic acid without biochar



a) PLA
b) Wood biochar (WBC)
c) Wheat bran biochar (WHB)
d) Coffee silverskin biochar (CBC)

**Figure 11** - Biocomposite spools produced using pure PLA and 5 wt. % biochar additions

A qualitative examination of filaments made from pure PLA and biocomposites containing 5 wt. % biochar in Figure 11 indicates that the addition of biochar leads to a substantially darker and completely opaque filament. Whilst surface inconsistencies are visible across all biocomposites containing biochar, the texture and oval shape of CBC shows the greatest deviation and confirms the largely unstable extrusion conditions. Biochar addition amounts beyond 5 wt. % also lead to a filament that produced dust upon contact with objects or skin, indicating that the biochar was not completely integrated into the PLA matrix.

### 3.3.2 Biocomposite characterisation

FTIR spectra in Figure 12 show, that the addition of biochar decreases the overall transmittance for all biochar types when compared to pure PLA, particularly at wave numbers below 1000 $cm^{-1}$. Despite this overall decrease most of the peaks associated with functional groups are clearly identifiable and match those of pure PLA.

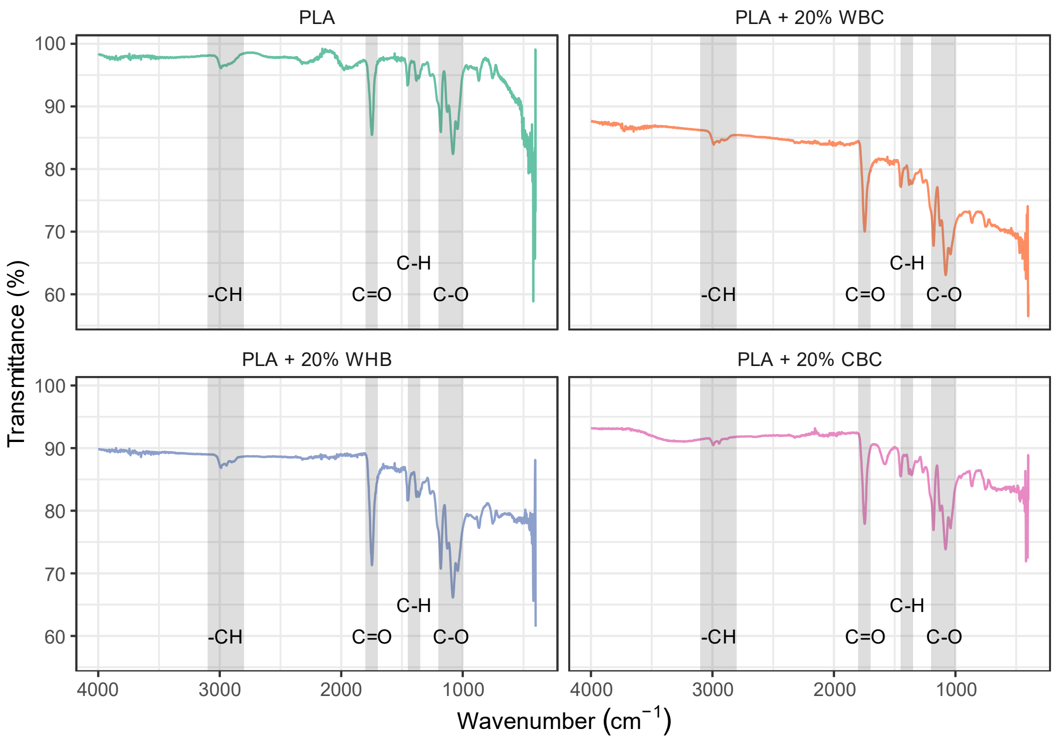



**Figure 12 -** FTIR spectra for pure PLA and biocomposites containing PLA and 20 wt. % biochar.

### 3.3.3 Biodegradation

Preliminary results from the first 40 days of biodegradation in Figure 13 show that the negative pressure produced by respiration does not change for all but the positive control (PC) as most of the respiration is dominated by compost. Biocomposites containing biochar generally begin exhibiting a negative pressure earlier than PLA at circa day 22, with biocomposites containing

5 & 10 wt. % CBC biochar showing a marked decrease from day 12 onwards. Biocomposites containing WBC degrade similarly to PLA, with biocomposites containing WHB and CBC degrading earlier and more substantially throughout the experiment. Differences in degradation between 5, 10 and 20 wt. % biochar are negligible and well within the standard deviation, indicating that the addition amount in this range has no influence. Generally, the experiments run with 20 wt. % biochar showed poor stability throughout measurement.

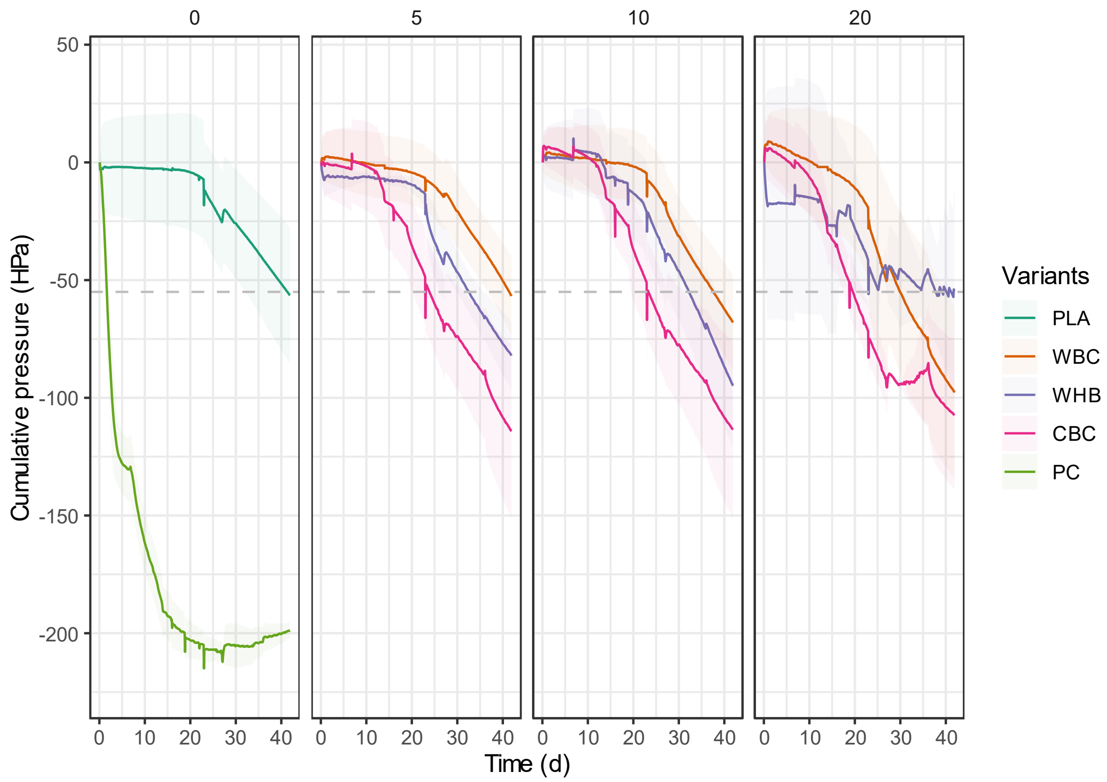



**Figure 13** – Preliminary mean (n = 2 for 20 wt. % variants and n = 3 for others) biodegradation results within the first 40 days of degradation. The plot on the left contains variants without biochar such as PLA and a rapidly degradable positive control (PC). The plot in the middle and on the right show the consumption of oxygen during the degradation of biocomposites containing 5,10 and 20 wt. % biochar. The shaded area represents the standard deviation.

These preliminary results indicate that the addition of biochar does not negatively affect biodegradation. It may even increase the onset and rate of biodegradation under industrial composting conditions, with biocomposites, whose production tolerances deviated from the ideal (WHB and CBC, see Figure 11), showing more rapid degradation. Whilst it is not possible at this stage to determine if this is a result of the degradation of biochar itself or increased degradation of the biocomposite both Musioł et al., (2022) and Pudełko et al., (2021) found that the poor distribution of biochar in the matrix, allows water to penetrate into larger aggregates on the surface of the biocomposite, which is likely to increase degradation.

A continuation of the experiment is required to determine if complete degradation of the biocomposites is achieved and whether microbial degradation of biochar occurs once the easily bio-available PLA is consumed. Here the higher $H/C_{org}$ ratio of WBC may lead to increased stability and prove beneficial (Cross & Sohi, 2013). If biodegradation is successful, biocomposites containing biochar may provide an opportunity to cascade the carbon into an agricultural application and ensure sequestration through application to soil. This poses a certification challenge currently not covered by the EBC, as biochar certified to less stringent contaminant limits for "EBC Consumer Materials" could end up in agricultural applications. The concentration of contaminants in the final compost must be investigated to develop appropriate guidance. An additional challenge is that biodegradation certificates (ASTM, CEN, ISO) generally outline either a near complete degradation of biomass or carbon, which may be impossible, if recalcitrant biochar is available in high concentrations.

### 3.3.4 Thermal degradation

The addition of biochar to PLA reduced the thermal stability of the product, leading to earlier onset degradation with increasing biochar amounts. Biocomposites generally degraded completely under inert conditions between 200 and 300 °C, which are typically achieved during pyrolysis. As such the thermal recycling of PLA-biochar biocomposites through pyrolysis may be a viable option, with the pyrolysis of conventional plastics such as PE, PP and PET commonplace for extracting oil and syngas (Anandaram et al., 2022; Anuar Sharuddin et al., 2016). Further testing in a larger reactor with more variable conditions along with analysis of the produced gases and bio-oils is required to determine the suitability of this process.

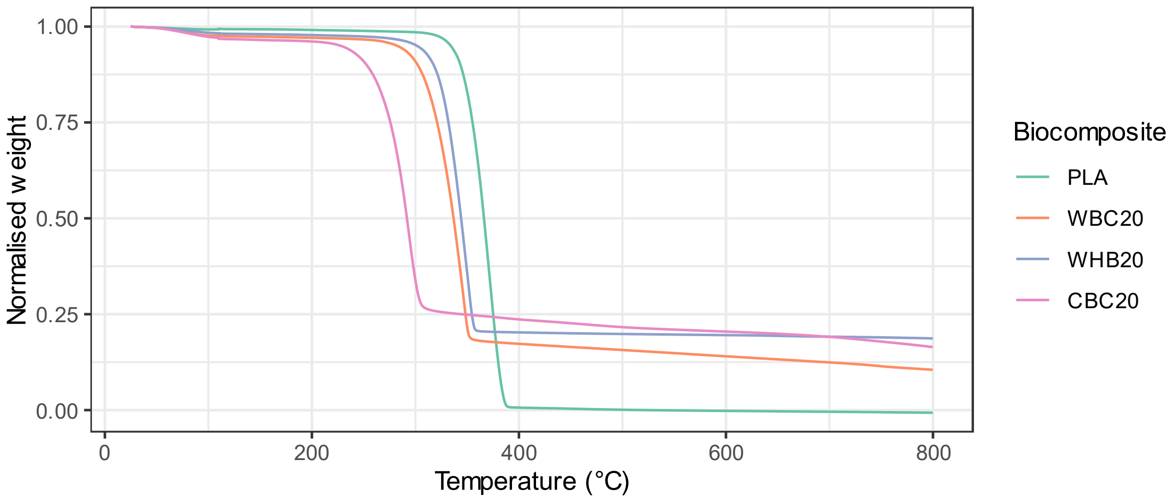



**Figure 14 -** Thermal degradation of pure PLA and biocomposites consisting of PLA and 20 wt. % biochar under oxygen free conditions.

Similar to the production data, coffee silverskin biochar (CBC) substantially altered the degradation properties of the biocomposite, with early onset degradation occurring at 215 °C. This is likely a result of the high copper content of 188 mg/kg, which increases the thermal conductivity of the material. Biocomposites containing wood and wheat bran biochar behave very comparably to the PLA control, with only slightly earlier degradation. Whilst the PLA control reaches a negligible weight beyond 400 °C, wood and wheat bran achieve a second stable weight, indicating that the biochar is not degraded as temperatures increase to 800 °C over a period of 40 minutes. Increased biochar loading (Figure 15) also leads to earlier degradation across all biochar types.

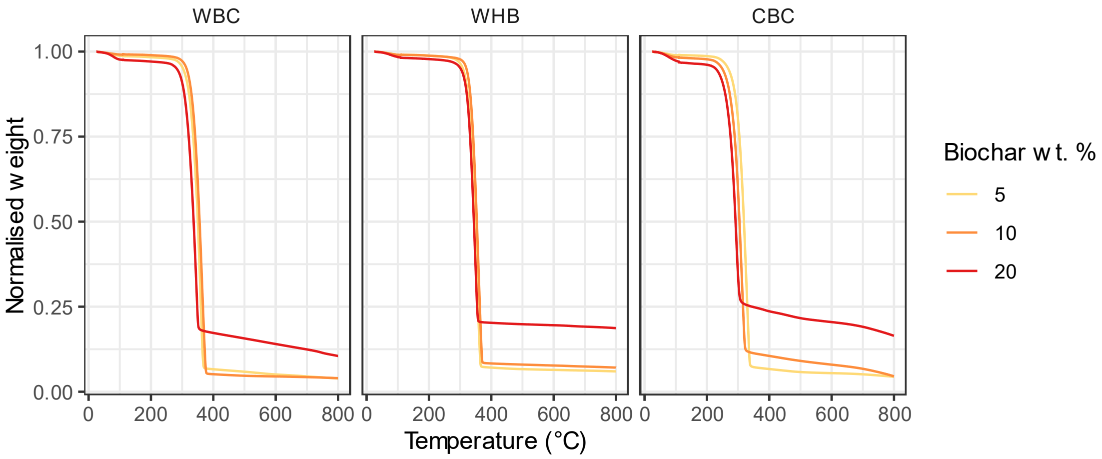



**Figure 15** – Thermal degradation of biocomposites arranged by added biochar weight.

### 3.3.5 Biocomposite testing

Further testing of biocomposites, including tensile strength, impact strength, differential scanning calorimetry and print adhesion are required to completely evaluate the biocomposites suitability for specific applications. Based on the consistency of filament thickness and qualitative handling of the filament in Chapter 3.3.1 addition amounts beyond 5 wt. % lead to a very brittle filament that is likely to be limited to completely static applications, where elasticity is not required. With additions of 20 wt. % handling of the biocomposite resulted in the shedding of fine biochar particles due to a poor distribution during extrusion. Whilst this can be improved by using a twin-screw extruder it is unlikely that biocomposites with such a high biochar content will be used beyond applications as a master batch for colorant purposes. Consequently, mechanical evaluation of biocomposites containing 0.5 – 5 wt. % biochar is recommended to determine the suitability of these biocomposites in various applications. The addition of more elastic biopolymers such as polybutylene adipate co-terephthalate (PBAT) is also commonplace in combination with PLA and may reduce the brittleness of the final product without compromising biodegradability (George et al., 2023).

# 4 Conclusion

This study aimed to evaluate novel applications for biochar “beyond soil” in the built environment, based on alternative pyrolysis feedstocks. To achieve this goal, four use cases were defined.

The application of biochar in **concrete** (**use case A**) and/or **asphalt** (**use case B**) is considered most promising in the short term, due to the large mass flows, the longevity of the products, and their high recycling rates. Reducing the cost of biochar, increasing the permitted addition amounts, replacing carbon intensive components (e.g., bitumen or cement) and ensuring a high carbon content in the biochar utilised, can lead to a complete compensation of emissions from import and production. However, carbon leakage during recycling and disposal, particularly for asphalt due to the thermal component, still needs to be quantitatively investigated to confirm the theoretical storage permanence.

Application to **conventional plastics (use case C)** is attractive due to substantially higher carbon intensity per mass of plastic produced. However, the potential for carbon sequestration through biochar addition to conventional plastics is currently limited. Black plastics represent a small market segment. Plastic products have short life-cycle durations, low recycling rates and are incinerated as the preferred method of disposal.

Overall, the estimated annual biochar application potential of 434’850 t for the three use cases A to C exceeds the theoretical production for the investigated biochars and the sustainable potential for novel Swiss feedstocks shortlisted as viable for biochar production (Gutzwiller et al., 2022).

On the commercial side, of the investigated feedstocks only biochar from CBC was found to be commercially viable, with an estimated cost of CHF 392.5 per ton, despite a lower emission reduction potential of 3.70 kg $CO_2$-eq/kg biochar compared to 4.17 kg $CO_2$-eq/kg biochar for WHB. Characterisation, however, showed that CBC exhibited unfavourable properties such as substantially lower specific surface area, larger particle sizes and greater thermal degradation due to a greater number of easily oxidizable functional groups. This, in addition to the high copper content of 188 mg/kg limits it to applications in materials such as asphalt and concrete. Generally, a preference for biochar with high carbon content is likely to be most appealing material applications due to its improved dispersion, chemical stability, and higher $CO_2$ storage potential.

Finally, a biocomposite consisting of **biochar mixed with polylactic acid (PLA, use case D)** was used as a model for exploring the potential recovery of biochar through re-pyrolysis and the degradation of the biodegradable plastic through composting, to examine solutions to the current limitations of carbon sequestration in conventional plastics. WBC and WHB mixed with PLA generally performed acceptably for addition amounts up to 5 wt. %. The result was an opaque black biocomposite that was still identifiable as PLA using the FTIR technology. Thermal recycling of carbon from biochar may be possible for WHB and WBC under inert conditions (e.g., pyrolysis) below the original production temperatures, as PLA is completely degraded at 400 °C.

Cascading carbon from biochar into agricultural applications via composting seems technically feasible, as the degradation of PLA is not inhibited by the addition of biochar. Whether biochar is microbially degraded under composting conditions was not investigated in this study. Recycling of carbon from biochar into direct reuse was not investigated in this study but might become interesting in a future circular economy.

# 5 Outlook

Biochar applications beyond soil provides an opportunity to valorise underutilised biomasses in materials that have a high sequestration permanence. Based on the findings from this report suggestions for future research areas are collated in

| Research area | Description |
|---|---|
| Determining carbon leakage during use, disposal, and recycling | Losses through thermal treatment of asphalt and plastics must be determined by investigating the stability of biochar in these mixtures at various temperatures. Leakage from mechanical, chemical and biological processes in mineral matrices throughout the life cycle must be determined. |
| Reducing the premium for products containing biochar | Currently biochar addition increases the cost of the final product substantially. Possibilities for reducing the cost through scaling, financial incentives (e.g., carbon credits) along with potentially cheaper biomasses need to be evaluated further. |
| Improving acceptance and adoption of novel materials containing biochar | Another barrier to adoption is acceptance of novel products in structural applications. Continued testing of material properties, longevity combined with integration into existing norms is required to build trust in the final product. |
| Identifying and quantifying co-benefits | Products containing biochar come at a cost and due to limited biomass availability are likely to initially be utilised in a premium segment of materials. Therefore, valuable co-benefits such as $CO_2$ capture through mineralisation in concrete, increased insulation and other improved material properties (Cuthbertson et al., 2019; Kua et al., 2017; Li & Shi, 2023) should be investigated and marketed. Similarly negative effects such as decreased albedo (Qin et al., 2021) should be considered. |
| Investigating the potential for biochar in masonry | Masonry was excluded due to the differentiation within masonry exceeding the scope of the study. However, with a domestic production of 2'899'754 t/a it is comparable to asphalt in terms of mass flows and may prove an interesting field for biochar integration. |
| Investigating the potential reuse of biochar from renewable plastic biocomposites | Reuse of biochar from biodegradable plastic may be interesting for the circular economy. Current direct material consumption of plastic in Switzerland (in t/year) reaches almost the same annual consumption as masonry, but with a lower recycling rate of 7%. An increased use of biopolymers combined with biochar recycling might lead to a reduced demand for fossil petroleum. An increased reuse of biochar would mitigate the demand for the available resources of wood. |

**Table 9** - Suggestions for future research areas related to biochar integration in materials.

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# 8 Appendix

**Appendix 1** - Biochar characterisation and methodology used.

| Package | Parameter | Method |
|---|---|---|
| *EBC-Basic Package* | Water content | 51718 |
| | Ash content 550°C | Analogous to DIN 51719 |
| | Carbon, Hydrogen, Nitrogen | DIN 51732 |
| | Sulphur | DIN 51724-3 |
| | Oxygen (Difference) | DIN 51733 |
| | Carbonate-$CO_2$ | DIN 51726 |
| | $C_{org}$ (Difference between $C_{tot}$ and C-Carbonate) | Calculation |
| | H/C und O/C | Calculation |
| | Trace elements arsenic, lead, cadmium, copper, nickel, mercury, zinc, chromium, boron, manganese, silver in microwave pressure digestion | DIN EN ISO 17294-2 / DIN 22022-4 |
| | Main elements phosphorus, magnesium, calcium, potassium, sodium, iron, silicon, sulphur, in fusion digestion | DIN EN ISO 11885 |
| | PAH 18 (EFSA + EPA) | DIN EN 16181 |
| | pH-Value | DIN ISO 10390 |
| | Salt content | DIN ISO 11265/BGK, Chapter III. C2 |
| | Water holding capacity (WHC) | DIN EN ISO 14238, Appendix A |
| | Electrical conductivity of the solid biochar | SAA-H-Lf-Biochar.040 |
| *Additional Parameters* | Dioxins/Furane (17) + PCB (12+7) | High-resolution HRMS |

**Appendix 2** - Calculations used to determine biochar production costs and cost per stoichiometric ton $CO_2$ sequestered.

# Wirtschaftlichkeit

BIOMACON-Simplex-Converter 400 kWth
Vergleich Wärmegestehungskosten, Kaskad-E GmbH
Anpassungen ZHAW für Baumateralien, Silberhäutchen und Weizenkleine 30.09.2023

| P R O Z E S | Rinde | Silberhäutchen | Weizenkleie | Einheiten |
|---|---|---|---|---|
| Brennstoff-Bedarf brutto | 207.8 | 213.3 | 213.3 | kg pro Stunde |
| Aschegehalt (pro TS) | 3.8 | 2.6 | 0.4 | % |
| Feuchtegehalt | 15.0 | 15.0 | 15.0 | % |
| Brennstoff-Bedarf netto (exkl. Asche) | 169.9 | 176.6 | 180.6 | kg TS pro Stunde |
| Aschedurchsatz | 6.7 | 4.7 | 0.7 | kg Asche pro Stunde |
| Verkohlungsgrad | 26.9% | 33.9% | 29.8% | kg Kohle pro kg Input TS |
| Kohle-Output, TS | 40.8 | 56.7 | 53.4 | kg TS pro Stunde |
| Kohle-Output, TS inkl. Totalasche (Kohleproduktion) | 47.5 | 61.4 | 54.1 | kg TS inkl. Asche pro Stunde |
| Heizwert Kohle (trocken W = 0%) | 9.1 | 6.6 | 7.0 | kWh/kg TS |
| Heizwert Holz (trocken W = 0%) | 47.7% | 44.4% | 41.6% | kWh/kg TS |
| Brennwert Ho (Brennwert) | 4.77 | 4.68 | 4.68 | kWh/kg |
| Heizwert Hu | 4.36 | 4.25 | 4.25 | kWh/kg Feuchtmasse |
| Brennstoff-Leistung | 906.0 | 906.0 | 906.0 | kW |
| Vollbetriebsstunden | 5’000 | 5’000 | 5’000 | h pro Jahr |
| Wärmelieferung an Verbund: | 5’000 | 5’000 | 5’000 | h pro Jahr |
| Bruttowärme / Kohleproduktion: | 5’000 | 5’000 | 5’000 | h pro Jahr |
| Energieleistung Kohle | 371.5 | 371.5 | 371.5 | kW |
| Eigenstrombedarf (Dauerleistung) | 20.0 | 20.0 | 20.0 | kW |
| Verluste Kohle, bezogen auf Brennstoffinput | 41.0% | 41.0% | 41.0% | |
| Wirkungsgrad Brenner inkl. Verluste Kamin, bezogen auf Pyrolysegas | 85.0% | 85.0% | 85.0% | |
| Verluste Wärmetauschung & Abstrahlung | 6.0% | 6.0% | 6.0% | |
| Wirkungsgrad thermisch total, bezogen auf Brennstoffinput | 44.2% | 44.2% | 44.2% | |
| thermische Nennleistung (Nutzleistung) | 400 | 400 | 400 | kW |
| Brutto-Wärmeproduktion Pyrolyse (inkl Rückkühlung, inkl. Netzverluste) | 2’000’000 | 2’000’000 | 2’000’000 | kWh pro Jahr |
| Brutto-Wärmeproduktion Spitzenkessel | 0 | 0 | 0 | kWh pro Jahr |
| davon Rückkühlung | 0 | 0 | 0 | |
| Netto-Wärmeproduktion total | 2’000’000 | 2’000’000 | 2’000’000 | kWh pro Jahr |
| davon Netzverluste | 160’000 | 160’000 | 160’000 | kWh pro Jahr |
| Nutzärmeproduktion Pyrolyse (Verkauf) | 1’840’000 | 1’840’000 | 1’840’000 | **kWh pro Jahr** |
| Nutzwärmeproduktion Pyrolyse an Mühle (Eigenproduktion) | 0 | 0 | 0 | |
| Nutzwärmeproduktion Spitzenkessel für Wärmeverbund (KVA WV) | 0 | 0 | 0 | |
| Nutzwärmeproduktion Spitzenkessel an Mühle (Erdgaskessel) | 0 | 0 | 0 | kWh pro Jahr |
| Brennstoffverbrauch brutto | 1’039’150 | 1’066’690 | 1’066’690 | kg pro Jahr |
| Endenergiebedarf | 4’530’011 | 4’530’011 | 4’530’011 | kWh pro Jahr |
| Wärmeausbeute | 1.92 | 1.87 | 1.87 | kWh th./kg Brennstoff |
| CO2-Emissionen | | | | kg/kWh Endenergie |
| Pflanzenkohleproduktion | 237’664 | 307’132 | 270’481 | kg pro Jahr |
| Kohleproduktion netto (exkl. Asche) | 204’099 | 283’558 | 266’854 | kg pro Jahr |
| C-Anteil langfristig in Materialien gespeichert (gemäss EBC-Sink) | 100.0% | 100.0% | 100.0% | |
| Kohleproduktion Sequestrierung | 204’099 | 283’558 | 266’854 | kg pro Jahr |
| CO2-Sequestrierung | 748’365 | 1’039’713 | 978’465 | kg pro Jahr |
| | | | | |
| I N V E S T I T I O N E N | 755’000 | 755’000 | 755’000 | |
| | 371’000 | 371’000 | 371’000 | EURO |
| * Kernanlage (Offerte Unternehmen), Eurokurs: 1.00 | 371’000 | 371’000 | 371’000 | CHF |
| Positionen, die bauseits vom Kunden bereitzustellen sind: | | | | |
| * Stromversorgung 3x400V, 32A 50Hz | 5’000 | 5’000 | 5’000 | CHF |
| * Notkühlung (Tischkühler Nennleistung) | 25’000 | 25’000 | 25’000 | CHF |
| * Pufferspeicher, 30l/kW, plus Expansionsgefäss") | 40’000 | 40’000 | 40’000 | CHF |

| | | | | |
|---|---|---|---|---|
| * Frischwasserbereitstellung 3bar (auch bei Stromausfall, DN32), Abwasserverohrung | 3'000 | 3'000 | 3'000 | CHF |
| * Internetanschluss für Fernwartung | 1'000 | 1'000 | 1'000 | CHF |
| * Überdachung zum Schutz der Elektronik | 0 | 0 | 0 | CHF |
| * Silo Inputsubstrat, Schubbodentrockner mit 35m3 Volumen und 5-15m3 Trocknungskapazität/Tag (auch 54 kW Notkühler), Spanner Re² GmbH | 0 | 0 | 0 | CHF |
| * Silo Inputsubstrat, 0.5m3 pro kW (10 Tage Autonomie bei Vollbetrieb) | 91'000 | 91'000 | 91'000 | CHF |
| * Eintragsschnecke Inputsubstrat | 0 | 0 | 0 | CHF |
| * Pflanzenkohleaustrag und Lagerung | 18'000 | 18'000 | 18'000 | CHF |
| * Kaminanlage | 15'000 | 15'000 | 15'000 | CHF |
| * Heizungsarbeiten und hydraulische Anbindung | 30'000 | 30'000 | 30'000 | CHF |
| * Automatisierung (Schubbodentrockner, Eintrag, Austrag, Fernwärmenetz) | 20'000 | 20'000 | 20'000 | CHF |
| * Heizungsraum: 50 kCHF plus 250 CHF pro Kubikmeter Raumvolumen | 100'000 | 100'000 | 100'000 | CHF |
| (Raumvolumen-Bedarf) | 200 | 200 | 200 | m3 |
| * Reserve | 36'000 | 36'000 | 36'000 | CHF |
| Investitionsförderung: Kt. Thurgau, 200 CHF/MWh*a Erzeuger | | | | CHF |
| Investitionsförderung: Klimastiftung / KliKK * 10a | 0 | 0 | 0 | CHF |
| Investitionsförderung: Kt. Thurgau, 50 CHF/MWh*a Netz | 0 | 0 | 0 | CHF |
| Totale Investition Anlage | 655'000 | 655'000 | 655'000 | **CHF** |
| Totale Investition Gebäude | 100'000 | 100'000 | 100'000 | **CHF** |
| Totale Investition Nahwärmenetz | 0 | 0 | 0 | **CHF** |
| | | | | |
| E C O - G R U N D L A G E N | | | | |
| Kapitalverzinsung | 3.5% | 3.5% | 3.5% | |
| Unterhalt | 2.3% | 2.3% | 2.3% | |
| Amortisation Anlagen | 15 | 15 | 15 | a |
| Amortisation Tiefbau / Gebäude | 40 | 40 | 40 | a |
| Amortisation Nahwärmenetz | 60 | 60 | 60 | a |
| Brennstoffkosten spezifisch, Preis HKW (4.0 Rp./kWh) | 0.200 | 0.180 | 0.550 | CHF pro kg Feuchtgewicht |
| Stromkosten Pyrolyse | 15 | 15 | 15 | Rp./kWh |
| Stromverbrauch Pyrolyse | 100'000 | 100'000 | 100'000 | kWh/a |
| Brennstoffkosten spezifisch, Preis HKW (4.0 Rp./kWh) | 0.174 | 0.170 | 0.170 | CHF pro kg Feuchtgewicht |
| Brennstoffkosten Spitzenkessel, Flaschengas: 0.8 CHF/kg | 0.8 | 0.8 | 0.8 | CHF/kg |
| CO2-Abgabe ab 2018: 120 CHF/Tonne CO2 (Spitzenkessel) | 120 | 120 | 120 | CHF/Tonne CO2 |
| Verkauf Pyrolyse-Wärme | 12 | 12 | 12 | Rp./kWh |
| Verkaufspreis Pflanzenkohle | 700 | 700 | 700 | CHF pro Tonne PK |
| Pflanzenkohleproduktion | 238 | 307 | 270 | Tonne/a |
| CO2-Vergütung (freiwilliger Markt: 70 CHF/t, CO2-Gesetz Obergrenze: 320 CHF/t) | 100 | 100 | 100 | CHF/Tonne CO2 |
| C-Anteil langfristig in Materialien gespeichert (gemäss EBC-Sink) | 748 | 1'040 | 978 | Tonnen CO2/a |
| | | | | |
| J A H R E S K O S T E N | | | | |
| Jahreskosten Investition Anlagen (Annuität) | 56'870 | 56'870 | 56'870 | CHF pro Jahr |
| Jahreskosten Investition Gebäude (Annuität) | 4'683 | 4'683 | 4'683 | CHF pro Jahr |
| Jahreskosten Investition Nahwärmenetz (Annuität) | 0 | 0 | 0 | CHF pro Jahr |
| Unterhaltskosten | 14'785 | 14'785 | 14'785 | CHF pro Jahr |
| Betriebskosten | 50'000 | 50'000 | 50'000 | CHF pro Jahr pro Anlage |
| Big-Bag-Kosten | 5'942 | 7'678 | 6'762 | CHF pro Jahr |
| Brennstoffkosten Pyrolyseanlage | 207'830 | 192'004 | 586'679 | CHF pro Jahr |
| Stromkosten Pyrolyseanlage | 15'000 | 15'000 | 15'000 | CHF pro Jahr |
| Brennstoffkosten Flaschengas | 0 | 0 | 0 | CHF pro Jahr |
| CO2-Abgabe (Spitzenkessel) | | | | CHF pro Jahr |
| Jahreskosten brutto | 355'109 | 341'020 | 734'779 | **CHF pro Jahr** |
| - Vergütungen: | | | | |
| - Verkauf Nutzwärme Pyrolyse an Wärmeverbund | 220'800 | 220'800 | 220'800 | CHF pro Jahr |
| - Verkauf Pflanzenkohle | 166'365 | 214'992 | 189'337 | CHF pro Jahr |
| - CO2-Vergütung (freiwilliger Markt, KliK) | 74'836 | 103'971 | 97'847 | CHF pro Jahr |
| **Jahresgewinn vor Steuern (EBT)** | **106'892** | **198'743** | **-226'796** | **CHF pro Jahr** |