Fuel 217 (2018) 240–261

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Review article

# Properties of biochar

Kathrin Weber[a,*], Peter Quicker[b]

[a] Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[b] Unit of Technology of Fuels, RWTH Aachen University, Aachen, Germany

ARTICLE INFO

*Keywords:*
Biomass
Biochar
Biocarbon
Biocoal
Charcoal
Pyrolysis
Torrefaction

ABSTRACT

Biochar can be used in a large number of applications, ranging from heat and power production to soil amendment. The properties of carbonized biomass depend on the feedstock and the process conditions. Selection of suitable conditions to produce a char with the desired properties therefore requires knowledge of dependencies and influencing factors, both quantitatively and qualitatively. This paper reviews and summarizes the results from a large number of experiments on biochar production in order to give a general overview of the properties that can be achieved by feedstock selection and process design. Production processes include both torrefaction as well as slow pyrolysis at high temperatures. The data evaluation has shown that among all process conditions, the treatment temperature has by far the most dominant influence on all properties. Especially the rather narrow temperature range between 200 and 400 °C causes the most significant changes and is therefore very sensible to influences and possibly difficult to control.

## 1. Introduction

Biochar, the solid product of biomass pyrolysis, has been produced and utilized for several thousand years and is best known as charcoal (when produced from woody biomass). The applications of biochar are very diverse, ranging from heat and power production, flue gas cleaning, metallurgical applications, use in agriculture and animal husbandry, building material, to medical use. In an attempt to reduce greenhouse gas emissions, it has gained increasing popularity in the last years as a replacement for fossil carbon carriers in several of these applications.

Carbonization decomposes parts of the biomass, but retains a large part of its carbon content. The properties are altered; the product becomes more carbonaceous and hence easier to use as a substitute in technical processes. Feedstock and carbonization conditions are chosen depending on the desired properties of the char. Torrefaction, a pyrolysis in the temperature range of up to 300 °C, significantly improves a number of problematic characteristics of raw biomass. Among them are mechanical properties such as grindability. These are often a limiting factor in co-firing and co-gasification applications, in which equipment designed for coal is to be used to process biomass. Other qualities such as a very high carbon content, can only be achieved by treatment temperatures. In addition to technical applications in heat and power generation, gas and water purification and metallurgy, biochar has been used as a soil amendment to improve soil fertility and sequestrate carbon. It is clear that the various fields of applications have different demands and requirements.

This paper gives a broad overview on the properties of biochar and how they can be achieved by selecting feedstock and process conditions. It includes an evaluation of the UC Davis biochar database, containing 210 separate publications at the time of evaluation [1], an extensive literature research as well as results from self-performed experiments. The literature named in the reference list refers to all publications, which have been reviewed in detail, in addition to the data collected in the database. The data collection was originally performed for publication in a book on the production, properties and utilization of carbonized biomass [2], but has been reviewed and significantly extended for the present work. A vast number of publications can be found in different fields, ranging from fuel technology to agricultural science and even archeology[1]. This review can therefore not claim to be a complete and exhausting overview of the entire work performed on biochar. However, the data considered was sufficiently large to allow for some general conclusions.

A short summary of the most important aspects of the production process is given in Section 2. Part 3 shows how mass, energy and carbon yield are influenced by process conditions. The chemical properties of biochar range from elemental composition to reactivity and pH-value and are described in Section 4. Part 5 focuses on the physical properties

* Corresponding author.
*E-mail address:* kathrin.weber@ntnu.no (K. Weber).

[1] A search in Web of Science (Thomson Reuters) for the keyword “biochar” showed that the annual publications increased from 122 in 2010 to almost 1400 in December 2017. Obviously, only a fraction of these contains experimental data on the production and properties of biochar, but the number reflects the rapidly increasing interest in the topic.

https://doi.org/10.1016/j.fuel.2017.12.054
Received 19 September 2017; Received in revised form 8 December 2017; Accepted 13 December 2017
Available online 02 January 2018
0016-2361/ 

of carbonized biomass. A short summary of the review is given in the last section.

While fast pyrolysis and gasification also result in a solid with increased carbon content (so strictly speaking biochar), this is merely a by-product from the process and the quality often not sufficient for many applications. For example, chars from flash pyrolysis may often have comparably low carbon contents; the solid product from gasification may contain harmful substances such as polycyclic aromatic hydrocarbons [2]. This review focuses on slow pyrolysis (including torrefaction) only, where the process conditions are specifically used to alter the properties of the char. Carbonized biomass produced via hydrothermal carbonization (in this case often referred to as hydrochar) are also not subject of this review. This restriction stems from the fact that currently only biochars from pyrolytic processes have technical and commercial relevance.

Most of the properties are evaluated graphically based on a large number of data, oftentimes several hundred individual measurements. In addition, values from single publications are used as examples to gain further insight or show individual trends. The selection and classification of the properties presented in this work was not always straightforward, as some effects resulting from physical and chemical properties may overlap and/or influence each other. Some properties are a direct result of others. All properties included in this review were found to be relevant for at least one practical application of biochar.

## 2. Production of biochar

Biochar is the solid product of biomass pyrolysis. Charcoal is produced from woody feedstocks and has been manufactured and utilized for several thousand years [2]. Even though charcoal is the most common and best-known type of biochar, all biogenic materials can principally be converted into biochar. Pyrolysis is the thermochemical decomposition of a fuel at elevated temperatures and without the addition of external oxygen. The process starts with the drying of biomass. The particle is further heated and volatile matter released from the solid. The volatile compounds can form permanent gases (such as $CO_2$, $CO$, $CH_4$ and $H_2$) or condensable organic compounds (e.g. methanol and acetic acid). Subsequent reactions in the gas phase include cracking and polymerization and can therefore alter the entire product spectrum. Three products can be distinguished: Permanent gases, one or more liquid phase(s) (water and tar) and a solid residue. The reaction pathways to these different products are partly competing and the product distribution can be influenced by the process conditions, mainly process temperature and residence time. Depending on the desired product of the process, some general guidelines can be established in order to maximize the yield of a certain product group.

The goal of fast (or flash) pyrolysis is the production of a liquid oil. The condensable volatiles, which are released from the solid feedstock, should therefore quickly be cooled in order to avoid cracking into light gases or polymerization into char. The biomass is rapidly heated to the reaction temperature, typically within a few seconds. Gases are quenched to avoid secondary reactions. The liquid yield may be up to 75% of the dry matter of the feedstock [2].

In biochar production however, the main interest is the carbonaceous solid product. The evaporation of water and the release of volatile components cause an increase in the relative fixed carbon content of the solid. It is believed that polymerization of organic compounds in vapors and gases may lead to secondary char formation and increases the solid yield. The heating rate is low and the residence time long. In a traditional charcoal production process (charcoal pit), it may take several weeks until the carbonization is completed. Typical temperatures for slow pyrolysis are around 500 °C, but ultimately depend on the desired product properties. A very high carbon content of more than 95% may require treatment temperatures close to 1000 °C, which can be achieved for woody feedstocks, but pose problems for agricultural residues and other materials with low ash melting temperatures. These are therefore normally not treated beyond 700 °C. Pyrolysis in the temperature range between 200 and 300 °C is referred to as torrefaction. The main goal is to retain and concentrate most of the energy content in the solid, and significantly improve mechanical properties of the biomass (such as grindability), which may otherwise be limiting for some applications.

Apart from the process conditions, the characteristics of the feedstock impact the conversion process and product properties. Biomass is mostly composed of the three organic compounds cellulose, hemicellulose and lignin. These behave differently during heat treatment and hence the composition of the biomass directly influences product yield and properties. Hemicellulose describes a group of polysaccharides with a branched chain-structure. It is the most reactive of the three main components and decomposes at temperatures of about 220–315 °C [3]. The destruction of the hemicellulose in the biomass is the main process in torrefaction. The most significant changes to almost all properties happen in the small temperature range of hemicellulose decomposition, making torrefaction a very sensitive process that can be difficult to control. Cellulose is also a polysaccharide, but unlike hemicellulose, its structure is unbranched. It is thermally more stable, decomposing at temperatures between 280 and 400 °C [2,3]. Being the most abundant organic compound on earth, cellulose has been studied for decades. Nevertheless, the thermal decomposition is still not fully understood. Lignin is a complex three-dimensional macromolecule with a variety of different chemical bonds. Hence the decomposition does not happen in a limited temperature range such as for hemicellulose and cellulose. Instead, lignin decomposes over a broad temperature range due to the large number of functional groups with different thermal stabilities. Thermal degradation starts at 200 °C and may require temperatures as high as 900 °C to be completed (depending on the residence time) [3]. Due to their different thermal stabilities, the composition in terms of cellulose, hemicellulose and lignin influences the required treatment temperature as well as the mass yield for any given set of conditions. Waste biomasses such as animal manure and sewage sludge contain no noteworthy amounts of these components due to their different origin and therefore need to be characterized differently.

## 3. Product yields

The amount of product that can be obtained from the pyrolysis of a given biomass depends on the process conditions, among them temperature and residence time. The attainable mass, energy and fixed carbon yields with their according process conditions are important for the design of an economic biochar production as they indicate the success of the conversion process. This section describes how the different yields are calculated and shows how and to what extent they can be influenced by variation of the process conditions.

### 3.1. Mass yield

The mass yield $y_m$ is the ratio of carbonized product mass $m_{carb}$ to raw biomass mass $m_{biom}$ and thereby describes how much of the original mass remains in the solid residue of pyrolysis.

$$y_m = \frac{m_{carb}}{m_{biom}} \cdot 100 \quad [\%] \tag{1}$$

It is clear that biomass with a high water content will inevitably lead to a low mass yield and is therefore not the preferable feedstock for pyrolytic biochar production. If the mass yield is not directly determined using gravimetric measurements, it can be calculated based on the ash content of both raw biomass $w_{ash,biom}$ and carbonized product $w_{ash,carb}$.

$$y_m = \frac{w_{ash,biom}}{w_{ash,carb}} \cdot 100 \quad [\%] \tag{2}$$

It should be noted that both the gravimetric approach in Eq. 1 as