ORIGINAL ARTICLE

Biochar—just a black matter is not enough

Andreas Hornung [1,2,3] · Fabian Stenzel [1] · Jan Grunwald [1]

Abstract

What differs biochar from charcoal? The simple answer is that biochar is a carbon-rich product obtained from the thermal decomposition of organic material, at the presence of no or only a bit of oxygen. In principle, the production of biochar is comparable to the production of charcoal, one of the oldest and most established processes developed by mankind. While charcoal is made traditionally from wood, biochar can be based on a wide range of biomass and biomass residues. However, a variety of technologies for the production of biochar has been developed in recent years. The technologies are based on pyrolysis, gasification, or hydrothermal carbonization and are ranging from simple units, like heated steel drums to full automated and controlled processes. Therefore, the obtained products have tremendous differences in its properties and resulting qualities. The quality defines the field of application. To obtain the required quality for each application, the right process must be applied. Consequently, it is not enough only to enrich the carbon content by thermal decomposition of organic material. The production of tailor-made biochar for specific high added–value application is much more complex. In addition, side products like liquid biofuels make business cases stronger. If it is done in the right way, biochar production combined with advanced biofuels can be an economic solution to overcome the problems of climate change. "So for the future of mankind, this black matter might give the light at the end of the tunnel."

Keywords Biochar · Thermochemical conversion · Certification · Legal regulation · EN-biofuels · Carbon sequestration

1 Introduction

Biomass stores carbon in a huge quantity of about 650 billion tonnes worldwide [1]. This is the same amount of worldwide anthropogenic CO_2 emissions of about 65 years [2]. The biggest proportion of about 82% is stored in wood. However, CO_2 is also released by natural processes, for example, by aerobe degradation of harvested or dead biomass. A long-term storage of carbon or respectively CO_2, which was naturally captured by wood during its growth phase, is possible by the conversion of wood into biochar. To make the biochar production more sustainable, the range of feedstock should be extended to biogenic residues like agricultural residues, sewage sludge, digestate from biogas production, residues from food industry (e.g., brewer spent grain), or residues from modern processes like ethanol production from straw and macroalgae. These materials are almost by-products and need to be used in a valuable way. However, the production of biochar as the only product of a process is almost too expensive. To close the bill, side products or additional valuable products are required. Those products can be liquids, in best case fuels and green hydrogen.

The biochar topic became famous within the last 10 to 15 years. Especially the investigations of the Terra Preta de Indio in the Amazonian region increased the interest in biochar [3, 4]. But the question is: What is biochar exactly? The simple answer is that biochar is a carbon-rich product obtained from the thermal decomposition of organic material, at the presence of no or just a bit of oxygen [3]. As we can see in principle, the production of biochar is comparable to the production of charcoal, one of the oldest and most established processes used by mankind. But what is the difference between both? It is the feedstock! Charcoal is derived from wood only, whereas biochar is derived from any kind of

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biomass. However, a clear definition of biochar does not exist up to now. A part of the scientific community applies the term biochar only for carbonized material which is used in soil. Another part applies this term only for carbonized material which is produced by pyrolysis. In addition, two new terms were introduced, since the research activities in the field of hydrothermal carbonization (HTC) increased. These terms are pyrochar from pyrolysis and hydrochar from HTC [5]. Therefore, it becomes obvious that biochar is not a single substance; it is rather a group of substances with a broad range of properties [6]. Consequently, biochar can be used for a variety of applications, exemplarily named soil improver, additive in animal fodder, activated carbon, or additive in construction material [7]. In addition, biochar derived from biomass by pyrolysis can be also used as catalyst or respectively catalyst carrier [8]. But for each application, certain properties of the biochar are required. If biochar is used in a product and not energetically, the carbon is sequestered over the lifetime of the product. This reduces CO_2 from the atmosphere, which was taken up by the biomass during its growth phase. Therefore, it is a potential measure to reduce global warming [9].

Biochar is not always the same, even if it is almost always black matter. However, the properties depend on a variety of parameters like feedstock, processes, and process conditions. Legal and technical requirements have to be fulfilled for each biochar application. This study gives an overview of production, characterization, as well as possible applications of biochar and their market potentials. Standards and certificates are presented to guarantee the proper quality, because "just a black matter is not enough."

2 Feedstock for biochar production

For biochar production, almost any kind of biomass feedstock can be used. Especially, the use of organic waste or residues brings a huge benefit, because this material does not need to be cultivated separately for biochar production, as it is a by-product. However, the properties of the biochar are influenced by the kind of feedstock. One aspect is the organic
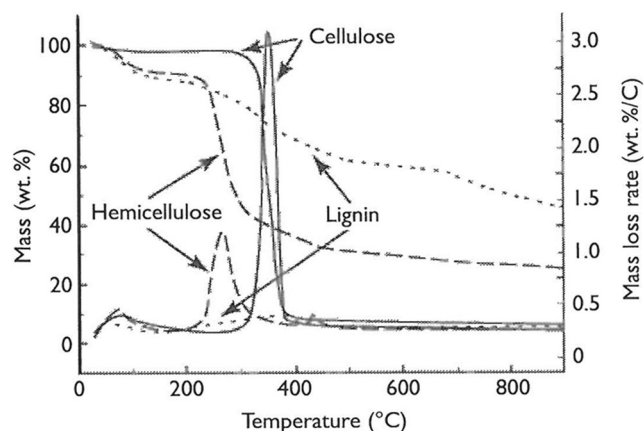
Fig. 1 TGA analysis of the pyrolysis of cellulose, hemicellulose, and lignin [10]

composition. The shares of cellulose, hemicellulose, and lignin influence the yield of biochar. Figure 1 shows the decomposition of these three components. At the beginning, hemicellulose starts to decompose by increasing temperature up to 315 °C. Cellulose starts its decomposition at about 300 °C and is almost completed at 400 °C. While the decomposition of lignin starts at around 160 °C leading to a weight reduction of around 40 wt% of the original mass. Therefore, the yield of biochar is mainly influenced by the share of hemicellulose and lignin [10].

The ash content of the feedstock influences the biochar yield indirectly, too, as almost all inorganic compounds remains in the char [11]. On the other hand, it reduces the share of carbon in the biochar. Also the heating value of feedstock with high ash content is usually lower. The following table shows exemplarily the properties of possible feedstocks for biochar production. It is shown that the heating value corresponds to the carbon content and the ash content. All values presented in Table 1 are referred to total dry matter content. However, some of the feedstocks have originally a high water content. Sewage sludge directly from a waste water treatment plant has more than 90%, as well as digestate from biogas plants and brewer's spent grain have more than 80% of water content for instance [12–14]. Depending on the downstream conversion process, the feedstocks have to be pretreated that

Table 1 Feedstocks for biochar production and its properties

Parameter	Unit	Sewage sludge	Digestate	Brewer's spent grain	Wood
Carbon	wt% (DM)	25.0	41.6	48.6	45.0
Hydrogen	wt% (DM)	4.3	5.1	6.9	6.4
Nitrogen	wt% (DM)	3.6	1.6	4.3	0.1
Sulfur	wt% (DM)	0.9	0.3	0.5	0.1
Oxygen*	wt% (DM)	19.7	31.6	36.2	47.8
Ash	wt% (DM)	46.5	8.7	3.5	0.6
Lower heating value	MJ·kg^{-1} (DM)	8.1	15.8	20.5	17.8

*Calculated by difference

means dewatering and drying to adjust the required water content and possible milling and pelletization to adjust the particle size. On the other hand, wood is a relatively dry feedstock. Fresh harvested material has a water content of about 50% [15]. Therefore, an appropriate pretreatment for fresh wood is chopping and drying.

3 Processes

As mentioned above, the production of charcoal is one of the oldest known processes of mankind. For its production, a pile of wood logs is built and covered by soil to avoid oxygen intrusion. Volatiles are emitted to the environment, and produced liquids like pyroligneous acid, for instance, are seeped into the ground. Today, modern reactors are developed to produce biochar. They fulfill environmental standards, and some of them use the side products like gases and liquids to improve the whole process efficiency. The processes can be divided into the following categories.

3.1 Hydrothermal carbonization

The HTC is best suitable for feedstock with a high moisture content, because the feedstock is mixed with water in a typical solid to water ratio of 1:6 to obtain a suspension [16]. Therefore, sewage sludge and digestate are suitable feedstocks with regard to the water content. This suspension is fed into the reactor where the conversion of the biomass takes place. The operating conditions are 180–260 °C and 15–60 bar. The residence time of the feedstock is in a range of 2–16 h. The obtained product is a suspension with carbon-enriched particles—the biochar—and the process water (see Fig. 2). The dewatering of the produced biochar is easier compared to the feedstock [17]. The disadvantage of the HTC is the huge quantity of process water with a chemical oxygen demand (COD) of about 30,000 to 50,000 mg/l [18]. If the solid content in the suspension is adjusted up to 20% DM, COD up to 100,000 mg/l is possible. The COD consists of a variety of organic compounds like aldehydes, phenols, ketones, esters, and organic acids. Among the dry matter content of the suspension, the operating temperature of the HTC process influences the concentration of the COD as well. It increases with an increase of the temperature. From a sufficient high temperature, the COD concentration begins to decrease, because of re-polymerization of the organic compounds [19]. Some approaches are focused on the recovery of the organic compounds as valuable products. However, at the current state of development, this water has to be treated before discharge [17]. For the typical ratio of dry biomass to water and a typical biochar yield of 50%, 12 tonnes of water are needed to obtain 1 ton of biochar [16]. Finally, the produced biochar has to be dewatered and dried prior to its energetic use.
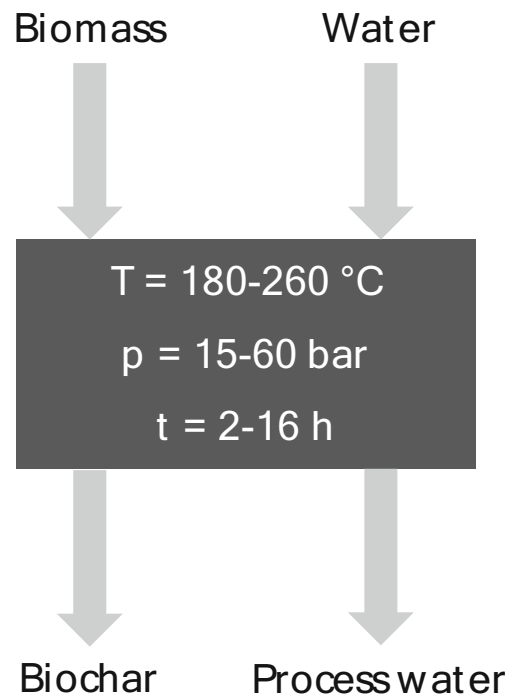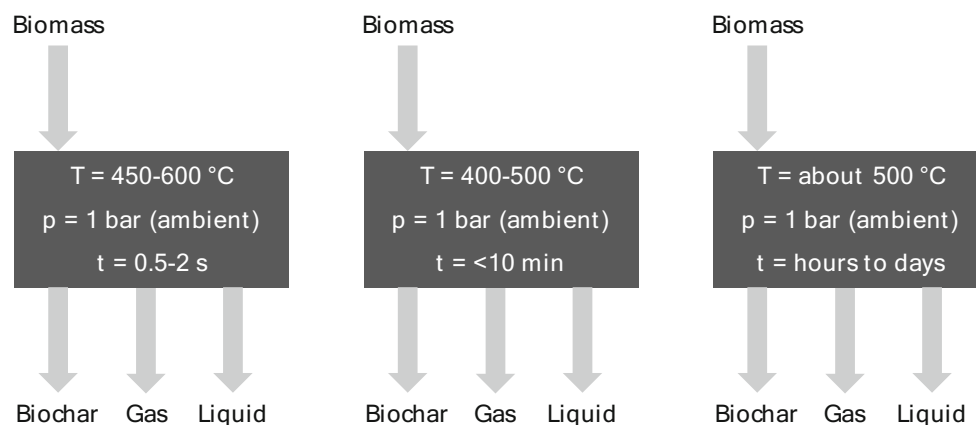
Biomass   **Water**

T = 180-260 °C

p = 15-60 bar

t = 2-16 h

Biochar   **Process water**

Fig. 2 Block diagram of hydrothermal carbonization

As mentioned above, a very famous application of HTC is the treatment of sewage sludge, because of its wet nature. One of the main benefits is the improvement of the dewatering of the sludge after HTC. However, not all pollutants in the sewage sludge are destroyed. For example, pharmaceutical residues remain partly in the hydrochar [20]. Furthermore, the process water from HTC process cannot be recirculated, because water is permanently fed into the reactor as part of the wet feedstock. These large quantities of process water have to be treated. In the case of sewage sludge treatment, the HTC plant should be installed directly on site of a waste water treatment plant. If digestate shall be treated by HTC, the process water can be used to mash the substrate for the biogas plant. However, the nitrogen content should be considered, because high nitrogen concentrations can inhibit the fermentation process. Known market player are Terra Nova Energy, SunCoal, AVALON Industries, Ingelia, and Avello Bioenergy.

3.2 Pyrolysis

Pyrolysis can be divided into three subcategories—fast, intermediate, and slow pyrolysis. However, all have one thing in common. The operation is without air or respectively oxygen [21]. In Fig. 3, all three types of pyrolysis are shown. The feedstock is dry biomass. Wood is a very common feedstock. As mentioned above, only drying and chopping are required. But also wet feedstocks, like sewage sludge, digestate, or brewer's spent grain, can be used after dewatering and drying. The products obtained are gas, liquid, and biochar. The

Fig. 3 Block diagram of fast (left), intermediate (middle), and slow (right) pyrolysis

Biomass	Biomass	Biomass
T = 450-600 °C p = 1 bar (ambient) t = 0.5-2 s	T = 400-500 °C p = 1 bar (ambient) t = <10 min	T = about 500 °C p = 1 bar (ambient) t = hours to days
Biochar Gas Liquid	Biochar Gas Liquid	Biochar Gas Liquid

distribution of the products depends on the operation parameters, like maximum operation temperature, heating rate, and the residence time.

The objective of the fast pyrolysis is to maximize the yield of the liquid product. Therefore, very high heating rates up to 1000 °C/s are applied. After a residence time of only a few seconds (0.5–2 s), the vapor phase is cooled down very fast to reduce further thermal decomposition. To realize the high heating rates, the feedstock has to be grounded down to a particle size of a few millimeters to a few micrometers. For the fast pyrolysis of woody biomass, up to 75% of liquid can be obtained [21]. But the liquid has a high water content of 20–30 wt% and a high oxygen content of about 39 wt%. In addition, the total acid number (TAN) is in a range of a few hundred mg$_{KOH}$/l, which is quite high [22]. One of the most famous representatives of the fast pyrolysis is the bioliq® process developed by the Karlsruher Institute of Technology (KIT), which is operated in pilot scale onsite the KIT campus. Further representatives are btg, ENSYN EMERGENT waste solutions, and Avello Bioenergy.

Slow pyrolysis is one of the oldest processes for biomass conversion. The focus is on a maximum yield of biochar. A typical "technology" for the application of this process was and sometimes still is the charcoal pile. In an industrial scale, a retort is used. The biomass is treated at a temperature of about 500 °C for hours or days. In addition to the biochar, some liquids like acetic acid or alcohols are produced as well, but usually the vapor phase is used for heat supply to the process. For the feedstock, no special pretreatment is needed. The moisture should be below 40–50 wt%, and the particle size can range from briquette to whole logs [21]. A famous market player here is proFagus. They apply the Degussa process in a large retort.

Between fast and slow pyrolysis, the intermediate pyrolysis takes place. The residence time of the feed is in a range of a few minutes, and heating rates of 200–300 °C/min are applied. The process usually runs at temperatures of 400–500 °C. To realize these process conditions, the moisture content of the feedstock is limited to about 40 wt%, and the particle size is

compared to coarse shredded, chopped, or briquetted material. Regarding the product yields, intermediate pyrolysis is between fast and slow pyrolysis as well. Compared to fast pyrolysis, the liquid yield is a little lower, but therefore, the biochar yield is higher. Compared to slow pyrolysis, it is the opposite [21]. A further development of the intermediate pyrolysis is the Thermo-Catalytic Reforming (TCR®). It is a two-step process where intermediate pyrolysis is coupled with a reforming step. This increases the product quality drastically [23]. The degree of carbonization is quite high compared to other carbonization processes, but also the liquid quality is far better compared to fast pyrolysis. The organic phase can be separated easily from the water phase to obtain an oil with heating value of more than 30 MJ/kg instead of 13–18 MJ/kg. Furthermore, the total acid number (TAN) is in a range of 5 mg$_{KOH}$/g and therefore quite lower compared to the oil from fast pyrolysis [22]. In addition, the TCR®-oil is thermal stable and therefore distillable and miscible with fossil fuels [23].

The most famous company which offers intermediate pyrolysis is PYREG. However, systems are also offered by WSE and Sea Marconi. The further developed Thermo-Catalytic Reforming is offered only by Susteen Technologies GmbH.

3.3 Gasification

In contrast to pyrolysis, the main product of the gasification is the synthesis gas and not the biochar. The char is rather a by-product, and because of the very poor carbon content, it is almost not considered as a char. Furthermore, air and/or steam is added as gasification agent to the process with an equivalence ratio between $0 < \lambda < 1$. The process temperature ranges from 700 to 1400 °C. Therefore, the main components of the product gas are carbon monoxide, hydrogen, and carbon dioxide. But also tar can be formed during the gasification process. The content can increase up to 150 g/m^3_N depending on gasification process. A second issue is the particulate matter in the gas. Concentrations up to 100 mg/m^3_N are measured. Both have to be removed or respectively reduced before the gas is converted in a combustion engine. If air is used as gasification

agent, a significant share of nitrogen is present in the gas as well, which leads to a dilution of the synthesis gas and a reduction of the heating value (Fig. 4) [24].

4 Characterization of biochar

4.1 Degree of carbonization

The objective of all the carbonization processes is to increase the carbon content in the product. This is combined with a separation of oxygen and hydrogen, while the ash remains in the solid phase. Depending on the process type and operating conditions, the carbonization happens in different intensities. The intensity of carbonization is also called the degree of carbonization. It is measurable with the molar ratio of O:C and H:C and is shown in the van Krevelen chart (see Fig. 5). The van Krevelen chart was originally developed to show the path of the natural carbonization of fossil fuels. However, results have shown that the carbonization of biomass to biochar follows the same pathways. Therefore, the van Krevelen chart is suitable to compare the degree of carbonization between biochars derived from different processes [26].

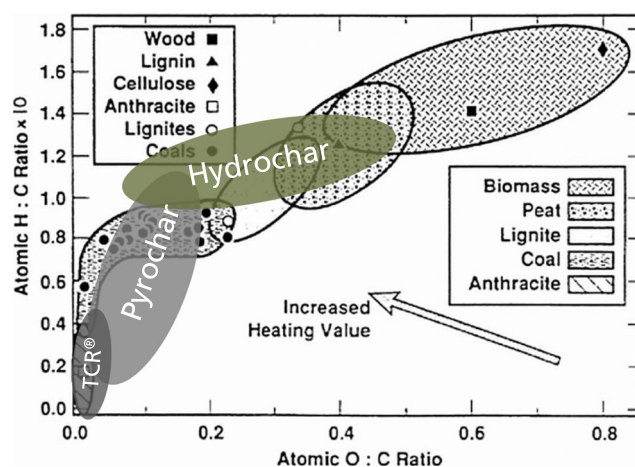Additionally opaque areas are implemented in Fig. 5 to show the variety of hydrochars, pyrochars, and chars from

Fig. 5 Areas of hydrochar, pyrochar, and TCR®-char are shown in van Krevelen diagram [25] (adapted) values from [26–28]

the TCR®-process based on data from [26–28]. It is shown that chars from HTC show the lowest degree of carbonization. That means the hydrogen and oxygen content is higher compared to pyrochars and TCR®-chars. The lowest contents of oxygen and hydrogen are observed in TCR®-chars. Therefore, the lowest ratios of O:C and H:C are obtained. The lower the O:C ratios, the higher is the stability of the char in soil. Additionally, it becomes harder for microorganisms to metabolize the char. With regard to the O:C ratio, Spokas divided biochars into three groups: < 0.2, 0.2–0.6, and > 0.6. In the same order, the following half-life times are assigned: > 1000 years, 100–1000 years, and < 100 years [6]. But further analysis methods should be applied to verify the half-life times, because hydrochars show shorter half-life-times as predicted by the O:C ratio [29]. However, biochars produced by pyrolysis or respectively by TCR® have the potential to withdraw carbon from the atmosphere for more than 1000 years, if it is used as a soil improver, for example.

Examples of TCR®-chars are also shown in Table 2. They are derived from the feedstocks mentioned in Table 1. The calculated O:C and H:C ratios fit to the TCR® area shown in Fig. 5. It was also observed that the O:C ratio increases with an increase of the carbon content and respectively with a decrease of the ash content. It is possible that oxygen is bound to carbon as functional groups on the surface of the char [30]. A further analysis of the surface with Diffuse Reflectance Infrared Fourier Transform Spectroscopy (DRIFTS), for example, can bring more detailed results on that. This method enables the analysis of strong absorbing surfaces.

The ash content influences the composition of the biochars in general, because almost all inorganics remain in the char. Therefore, the ash content increases during the carbonization process. This becomes obvious, if the ash contents of the feedstocks in Table 1 are compared to the ash contents of the biochars in Table 2.
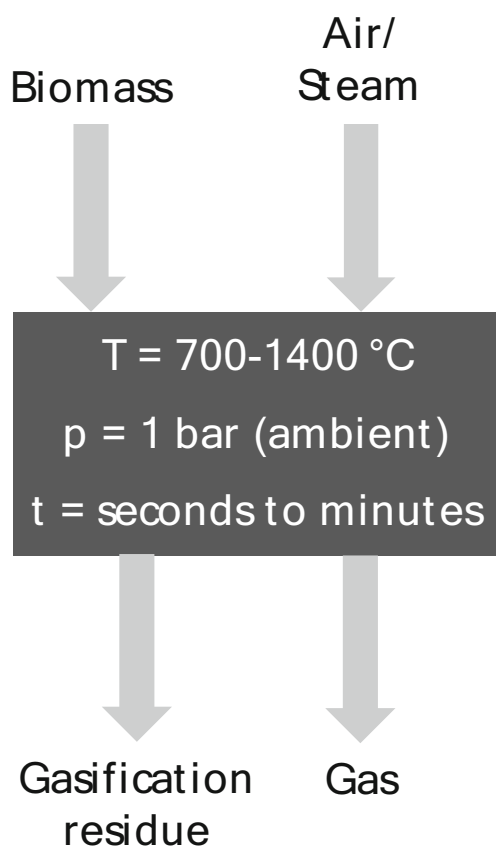

Fig. 4 Block diagram of gasification

Table 2 TCR®-chars derived from biogenic residues [28]

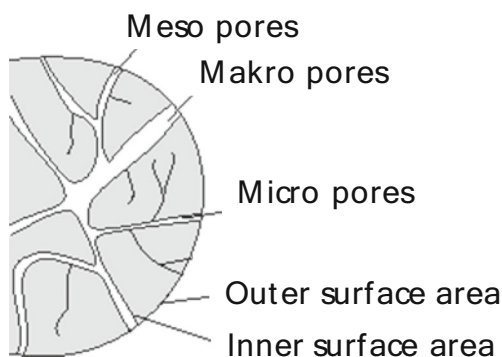| Parameter	Unit	Sewage sludge	Digestate	Brewer's spent grain	Wood
Carbon	wt% (DM)	22.2	64.0	72.6	89.8
Hydrogen	wt% (DM)	0.9	1.0	0.1	2.2
Nitrogen	wt% (DM)	2.0	1.4	4.6	0.3
Sulfur	wt% (DM)	1.0	0.5	0.4	0.1
Oxygen*	wt% (DM)	0.0	0.7	4.9	4.5
O/C	–	0.00	0.01	0.05	0.04
H/C	–	0.49	0.19	0.02	0.29
Ash	wt% (DM)	74.4	32.0	17.5	3.1
Lower heating value	MJ·kg^{-1} (DM)	8.2	23.0	26.0	34.4

*calculated by difference

4.2 Surface analysis

If biochar shall be applied as adsorbents, the surface area and structure are very important. The surface of biochar can be divided in inner and outer surface area, whereas the inner surface area is almost larger than the outer surface area. The inner surface area is defined by the pore system in the biochar. It consists out of micro, meso, and macro pores. The size of the surface area can range from a few square meters per gram to up to 2000 or 3000 m^2/g. The surface area depends on the process temperature and if the biochar is subsequently activated or not (Fig. 6) [31].

Figure 7 shows the development of the pore volume in % and the surface area in m^2/g of lignite depending on the process temperature. Both increase with increasing process temperature. It is noticeable that from 600 to about 800 °C, both the pore volume and the surface area increase very fast. Therefore, experiments with the TCR®-reactor were carried out at Fraunhofer UMSICHT to investigate the development of the pore volume depending on the temperature in the post-reforming unit. The results are shown in Fig. 8, where the pore volume is plotted versus pore size distribution.

It is obvious that the pore volume increases with an increase of the post-reforming temperature. Furthermore, the share of the fine pores increases with an increasing temperature as well. For the last trial, water was additionally injected

in the post-reforming unit. This led to an increase of the share of meso pores and the pore volume in total [33]. The latter improves the water holding capacity of the char, because the diameters in a range of 0.1–10 μm can retain the plant available water [34]. This is an additional benefit, if the biochar is used in soil. However, this effect has to be validated with other feedstock as well. The pore volume can be decreased with an increasing operating temperature, because of deformation of the porous structure, for instance [31].

4.3 Heavy metals and organic pollutants

During the thermochemical conversion of biomass in the absence of oxygen, organic pollutants can be formed. At a temperature above 500 °C, hydrocarbon radicals are generated and build polyaromatic ring structures. Typical substances are polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB). These substances can condensate on the surface of the biochar while passing through the reactor [30, 35]. Therefore, it is important to separate the vapor phase from the solid phase above the dew point of the

Fig. 6 Surface structure of adsorbent material
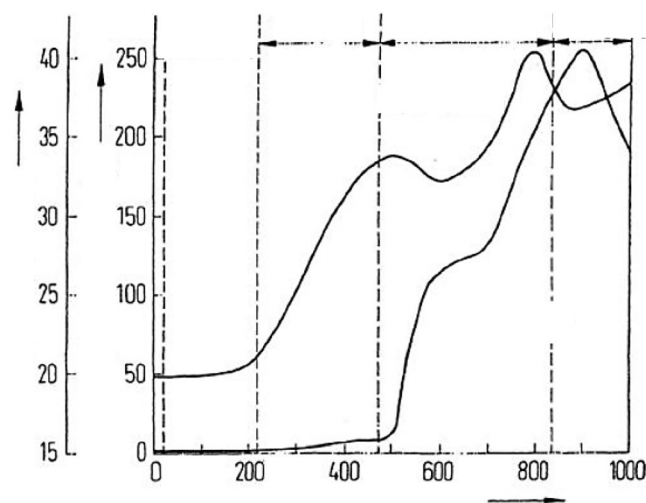
Fig. 7 Pore volume and surface area of lignite depending on process temperature [32] (adapted)

Fig. 8 Pore size distribution of TCR®-biochar derived from digestate [33]
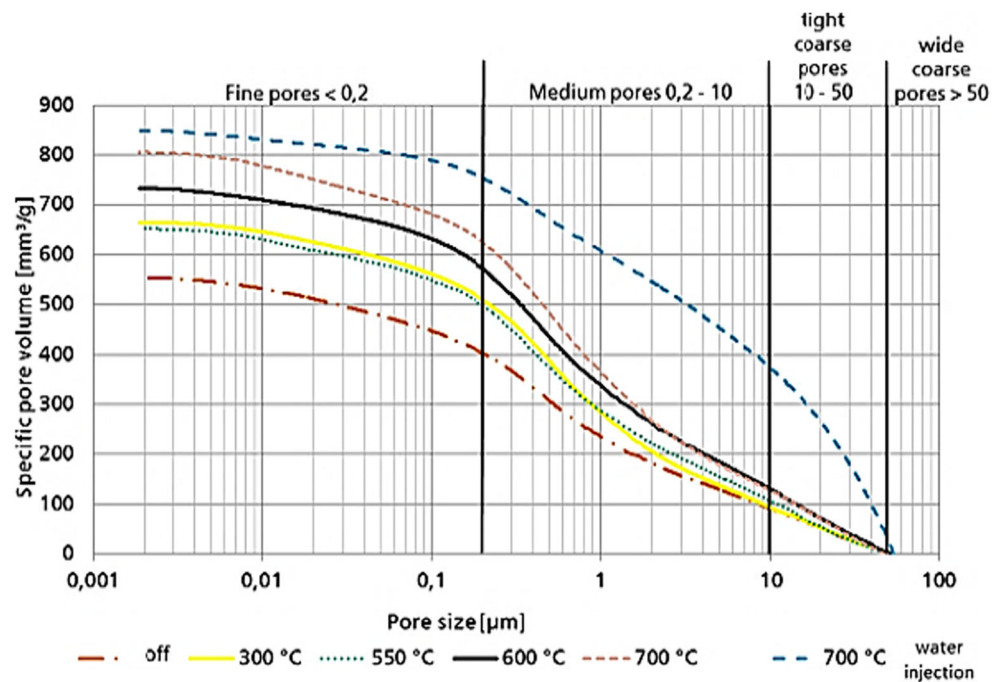
organic pollutants. Experiments have shown that with increasing operating temperature, the content of organic pollutants on chars increases for HTC and pyrolysis [36, 37], whereas for chars from TCR®, the content of organic pollutants decreases with an increase of the operating temperature in the post-reforming step. Also pharmaceutical residues are thermally destroyed during TCR®-process if these compounds are present in the feedstock, like it might be the case for sewage sludge, for instance [20].

The heavy metal content in biochar is mainly influenced by the feedstock, because almost all heavy metals which are present in the feedstock remain in the char. Only volatile components like mercury or some heavy metal chlorides of lead, cadmium, and others can be transferred to the gaseous phase during the conversion process. Experiments with sewage sludge and the char derived from it have shown that the bioavailability of heavy metals decreases during pyrolysis [38]. However, if the biochar shall be used as a soil improver, for example, the relevant legal regulations have to be proved regarding conformity. Analysis of biochars derived from digestate from biogas plants has shown that legal regulations regarding heavy metals and organic pollutants content are fulfilled [28].

5 Application of biochar

5.1 Framework conditions

For each of the following applications, different legal regulations, certificates, or standards exist to ensure the quality for

each application. That gives security to the user regarding suitability, health, and environment.

5.1.1 Soil improver

If biochar is used as a soil improver, the fertilizer regulation has to be applied. On European level, the fertilizer regulation was amended in 2019. The previous version from 2003 contained only mineral fertilizer. Therefore, one objective of the amendment was the extension to organic fertilizers. However, recycling products like biochar, ashes, and struvite from phosphorous recovery were not implemented. In 2020, three further component material categories (CMC) should be added, but this is not yet happening. One, CMC 14, would be for "pyrolysis and gasification materials." The CMCs are the allowed input materials for fertilizer production on European level.

Long time before the legislators considered biochar as a soil improver, biochar certificates were developed to define quality standards. The first one was established by the International Biochar Initiative (IBI) in the USA and Canada. They developed the "IBI Standardized Product Definition and Product Testing Guidelines for Biochar That is Used in Soil" which contains quality criteria for biochar production. The last revision was in 2015 [39]. In Europe, the European Biochar Certificate (EBC) is established. It was developed by the Ithaka Institute in Switzerland in 2010. They developed a guideline for biochar production analogous to IBI. The so-called Guidelines of the European Biochar Certificate were revised last time in 2019. In Switzerland the

application of the EBC is mandatory [40]. The newest certificate that is the so-called Australian New Zealand Biochar Initiative (ANZBI) was established in 2017. It is based on the certificates of IBI and EBC and is applied in Australia and New Zealand. The following table shows quality requirements of IBI and EBC, whereas for EBC, two product categories exist—basic and premium (Table 3).

5.1.2 Feed additive

The EBC implemented also the certification of biochar as a feed additive in their guidelines in 2019. The bases are the quality standards of the premium category. Additional to that, stricter thresholds for organic pollutants and heavy metals were developed (see Table 4).

In addition to EBC, a certification in accordance to GMP+ (Good Manufacturing Practice) is possible. For GMP+ certification, the whole process chain is audited from feedstock to conversion, storage, and transport. There is basically no limitation regarding applied feedstock, but all commercial GMP+ certified feed additives based on biochar are derived from untreated wood. An extract of thresholds for pollutants in accordance to GMP+ is listed in Table 4 as well.

5.1.3 Activated carbon

Requirements for the application of biochar as activated carbon are listed in European standards like EN 12903 for powdered activated carbon and EN 12915 for granular activated carbon. Both standards are for activated carbon, which is used for treatment of potable water. The requirements listed in the standards are the ash content limited to 15 wt%, the maximum water content of 5 wt%, and the share of water extractable components with a maximum of 3 wt%, for instance. In addition, thresholds for heavy metals and PAH are listed as well (see Table 5). As educt for the production of activated carbon, basically any carbon containing raw materials can be used. This includes materials like coconut shells, wood, peat, or coal.

5.2 Market survey for biochar

The broad range of possible applications for biochar shows the manifoldness of that black porous material. However, the three types of applications mentioned above are very promising. The markets are growing, and obtainable prices are high.

The price for biochar as a soil improver ranges from 200 to 2000 €/t. The high variety of the price is influenced by the quality of the biochar and the current market situation [44]. In Europe the biochar market will increase from about 0.31

Table 3 Quality criteria of IBI and EBC (extract) [41, 42]

Parameter	Unit	EBC basic	EBC premium	IBI
Carbon	wt%	>50	>50	Class 1: >60
				Class 2: >30
				Class 3: >10
H/C	Mol/mol	<0.7	<0.7	<0.7
O/C	Mol/mol	<0.4	<0.4	n.a.
Thresholds for pollutants				
Arsenic	Mg/kg	13	13	13–100
Lead	Mg/kg	150	120	121–300
Cadmium	Mg/kg	1.5	1	1,4–39
Chromium	Mg/kg	90	80	93–1200
Cobalt	Mg/kg	–	–	34–100
Copper	Mg/kg	100	100	143–6000
Molybdenum	Mg/kg	–	–	5–75
Nickel	Mg/kg	50	30	47–420
Mercury	Mg/kg	1	1	1–17
Selenium	Mg/kg	–	–	2–200
Zinc	Mg/kg	400	400	416–7400
PAH (Sum 16 EPA)	Mg/kg	12	4	6–300
PCB	Mg/kg	0.2	0.2	0,2–1
Dioxins (I-TEQ OMS)	Ng/kg	20	20	17
Furans (I-TEQ OMS)	Ng/kg	20	20	17

Table 4 Thresholds for pollutants in accordance to EBC and GMP+ [41, 43]

Parameter	Unit	EBC fodder*	GMP+ (extract)
Arsenic	Mg/kg	2	2
Lead	Mg/kg	10	10
Cadmium	Mg/kg	1	1
Mercury	Mg/kg	0.1	0.1
Benzo-a-pyrene	µg/kg	25	–
Hexachlorobenzene (HCB)	Mg/kg	–	0.01
Sum of non-dioxin-like PCB	µg/kg	–	10
Fuorine	Mg/kg	150	150
Sum of dioxin and dioxin-like components	Ng/kg	1.25	1.25
PCDD/PCDF	Ng/kg	0.75	–
Dioxin-like PCB	Ng/kg	0.35	–
DIN-PCB	µg/kg	10	–

*Values referred to 88% dry matter

billion US$ in 2018 to 0.59 billion US$ in 2023 [45]. This is an average growth rate of about 18% per year. The global market shows a more significant development. From 2018 to 2025, an increase of about 2.33 billion US$ is expected [46]. This corresponds to a growth rate of about 22.5% per year.

Biochar used as feed additive is offered in big bags by many online shops in a range of about 1200 to 1750 €/t. However, for smaller containers, up to 5500 €/t are charged. Because of the increasing number of suppliers, the demand to feed additives based on biochar seems to increase as well.

Activated carbon is offered in a range of about 700 to 1800 €/t. It depends on the quality and the market situation as well. The total market value is estimated on 2.35 billion US$ in 2017. It is a rapidly increasing market. From 2017 to 2018, the growth rate was about 20%, and the market volume reached 2.81 billion US$ in 2018 [47].

6 Sustainable transportation fuels as a side product from TCR®

Even if the markets for various biochar applications are growing and prices obtained are very promising, side products, like advanced biofuels, are needed to develop robust business cases. With the abovementioned Thermo-Catalytic Reforming process, two valuable side products, a hydrogen-rich gas and a thermal-stable oil, can be produced. The mass balance of the TCR®-process at a reforming temperature of 500 °C with digestate as feedstock shows that 11% of the mass is converted into TCR®-oil, while 27% by mass is converted into hydrogen-rich gas with a hydrogen content of up to 45 Vol-% [48]. The hydrogen-rich gas can be used for the supply of heat and power for the TCR®-process. As mentioned above, the TCR®-gas has a lower heating value of 13–18 MJ/m^3 depending on the feedstock. Therefore, it can be

Table 5 Threshold for activated carbon in accordance to EN12903 and EN 12915

Parameter	Powdered activated carbon EN12903	Granular activated carbon EN12915
Unit	Mg/kg DM	µg/l in extraction water
Antimony	5	3
Arsenic	10	10
Lead	10	5
Cadmium	5	0.5
Chrome	50	5
Nickel	20	15
Mercury	1	0.3
Selene	10	3
Cyanide	50	5
PAH	0.2	0.02

Table 6 Comparison of TCR®-oil composition to fast pyrolysis oil and biodiesel [22]

| Parameter	Unit	TCR® sewage sludge	TCR® digestate	TCR® wood chips	Fast pyrolysis wood	Biodiesel
Carbon	wt%*	77.4	75.8	73.2	54.2	77.2
Hydrogen	wt%*	7.7	7.4	8.0	6.9	13.2
Nitrogen	wt%*	9.6	6.0	1.5	0.0	0.1
Sulfur	wt%*	0.8	1.9	0.3	0.0	<0.1
Oxygen**	wt%*	4.5	8.9	17.0	38.9	9.4
Water	wt%	1.7	3.9	9.5	12.8	<0.1
Ash	wt% (DM)	<0.05	<0.05	<0.05	0.4	<0.1
HHV	MJ/kg (DM)	35.6	35.6	35.3	20.1	39.3
TAN	Mg$_{KOH}$/g	4.6	4.9	5.4	111–200	2

*Moisture and ash free basis

**Calculated by difference

used in a combined heat and power plant (CHP) for additional economic benefit.

The various advantages of using the TCR®-oil are the lower oxygen and water content compared to other bio-oils as well as the most important characteristic, its thermal stability, which makes it distillable and applicable for other thermal processes. These properties offer various application options for the TCR®-oil. On the one hand, the oil can be converted to heat and power in a dual-fuel CHP and fed back into the TCR®-process. On the other hand, the TCR®-oil can also be used for the production of raw gasoline and EN-compliant diesel in conventional refinery. A further advantage of the TCR®-oil is the miscibility with fossil fuels. Therefore, direct application, for example, as a blend with fossil fuels, in any kind of combustion engines without any technical adaption is possible.

As described in Chapter 3.2, the TCR® is a two-step process based on intermediate pyrolysis followed by the reforming step of the created vapors during the intermediate pyrolysis. The level of development of the TCR®-process is the demonstration scale with a throughput of 500 kg/h. As previously described, the products obtained from a broad range of biomass feedstock by TCR® process have unique properties compared to other thermochemical processes like fast pyrolysis [11, 22, 48, 49]. Table 6 shows the composition of TCR®-oil derived from various feedstocks compared to fast pyrolysis oil derived from wood and biodiesel.

It is shown that the elemental composition of TCR®-oil is close to biodiesel. Only nitrogen and sulfur need to be removed by hydrogenation. Also the heating value and the TAN are in the same range. In contrast, fast pyrolysis oil shows very different properties. Especially oxygen and water

Fig. 9 C-H-O ternary phase diagram [50]
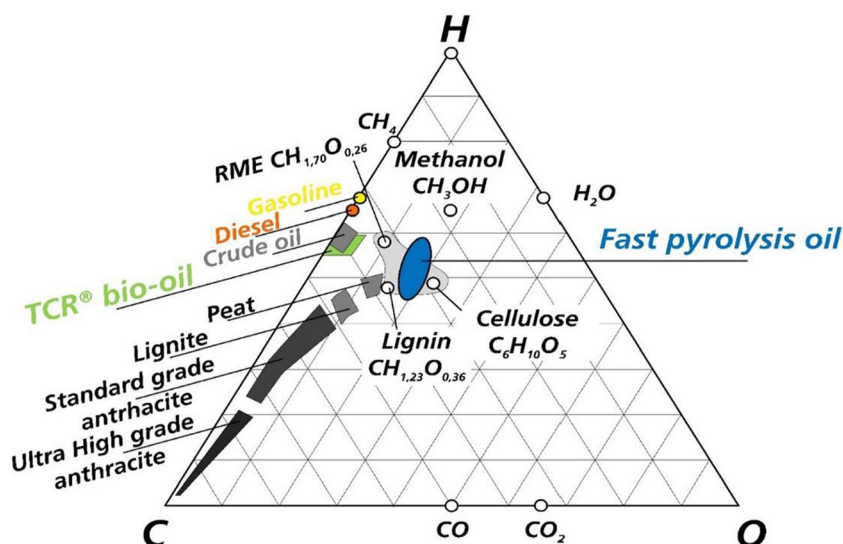
content as well as TAN are very high. Therefore, the energy content of the fast pyrolysis oil is quite low.

Regarding the C, H, and O contents, TCR®-oil is also comparable to fossil crude oil (see Fig. 9). Both, for TCR®-oil and crude oil, the areas in the ternary diagram are almost completely overlapping, while fast pyrolysis oil is more in the area of the biomass components lignin and cellulose. Due to the similar properties of the TCR®-oil and fossil crude oil and the possibility to replace the fossil crude oil with TCR®-oil, similar values can be assumed for the economic considerations. The production of 1 t of biochar results in 305 kg of TCR®-oil. The TCR®-oil produced increases the economics of biochar by €0.45 to €0.50 per kilogram.

7 Conclusion

Biochar is a carbon-enriched product from thermochemical conversion of biomass with a variety of properties and different qualities influenced by the type of feedstock and the applied production process. Therefore, it is not only one material; it is more a group of materials. Because of its diversity, it can be used for various applications. For these applications, the biochar is transformed to high-value products like soil improver, activated carbon, and feed additive. To ensure quality standards and safe application certificates, standards and legal regulations are developed. Only if the quality of the biochar for each application can be ensured, a market access is guaranteed.

The markets for biochar products have grown very fast within the recent years and achieved high market volumes. Therefore, biochar opens many opportunities for new business models. Furthermore, biochar contributes its part to mitigate the effects of climate change. Depending on its stability, the carbon, which was captured by the plants during the growth phase, is stored up to thousands of years in the char itself. This is caused by the low oxygen content in the char. In particular, biochars produced by TCR® show the lowest oxygen contents compared to the other abovementioned processes which enables these long storage times.

Even if the markets for biochar applications are growing and obtainable prices are high, business cases are more robust if side products like the liquids from pyrolysis, for example, can be turned into valuable products as well. For TCR® with its thermal stable oil, for instance, EN standard fuels like gasoline and diesel can be obtained and therefore a further income generated. In addition, the fuels become CO_2 negative, because of the carbon stored in the char.

This is different to the other processes shown. Oil obtained from fast pyrolysis with its high TAN and water content, for example, is not applicable as a substitute for fossil crude oil. From HTC no further side products are available. Some research is focusing on the recovery of valuable components from the HTC process water, but this is on an early stage.

Gasification and slow pyrolysis produce only a low calorific gas or respectively vapor phase. It can be used in a burner for heat production or after gas cleaning in a CHP for heat and power production.

If it is done right, the production of biochar combined with the use of side products like advanced biofuels can be the solution to mitigate problems of climate change. "So for the future of mankind, this black matter might give the light at the end of the tunnel."

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