Introduction to **Production and Use of Biochar** 2022

- working towards a more circular and bio-based Danish economy

By Tobias Pape Thomsen, RUC IMT

December 2022

Introduction to Production and Use of Biochar 2022

working towards a more circular and bio-based Danish economy

By Tobias Pape Thomsen

December 2022

Roskilde University
Department of People and Technology
Universitetsvej 1, 4000 Roskilde

Contact: tpapet@ruc.dk

The report is made on the initiative of Food & Bio Cluster Denmark (F&BCD)
with financial support from Roskilde University and the Danish Board of Business Development
Cover photos by the author.

About the author: Tobias Pape Thomsen is associate professor at Roskilde University in the department of People and Technology. The topics of his work circles around the production and use of biomass in the food-energy-material nexus as well as the development and analysis of new value chains for a more bio-based and circular economy.

Tobias has a background in sustainable energy engineering at DTU and has worked with pyrolysis at Risø DTU and RUC IMT for 15 years including development of pyrolysis technology, characterization of biomass and pyrolysis products, assessment of climate impact potentials, investigation of biochar end-use and much more.

Today, Tobias' work related to production and use of biochar has a main focus on quantitative sustainability assessment (i.e. material- and energy flow analysis, footprint accountings and life cycle assessments), project development, network and dissemination activities and development of experimental facilities at Roskilde University for assessment of the production and use of biochar. However, the work also expands into spheres of stakeholder and incentives analysis, sector integration and innovative resource management, design of complex systems, socio-ecological stewardship etc.

Food & Bio Cluster Denmark

RUC

Danish Board of Business Development

A note: *The main purpose of writing and publishing this report is to provide a free and broadly approachable introduction to a selection of central topics related to production and use of biochar in a Danish context. The report it thought as supplement to the recent "Knowledge Synthesis on Biochar in Danish Agriculture" published earlier this year by Lars Elsgaard et al. from AU and KU[1]. The work by Elsgaard et al. is a milestone in the development of a Danish pyrolysis sector and R&C landscape, and is particularly strong on natural science research on effects of using biochar in agricultural soil. This introduction report aspires to supplement the knowledge synthesis by providing a broader introduction to address a wider audience while covering more of the whole story about production and use of biochar. It is the hope and expectation that the resulting dissemination of relevant state-of-the-art knowledge and development perspectives into the ongoing processes related to development of a Danish pyrolysis-sector may help facilitate this process and improve the results hereof. Finally, it is the ambition that this report will provide a lot of inspiration and hopefully spark new innovation.*

The report is made on the initiative of Food & Bio Cluster Denmark (F&BCD) with financial support from Roskilde University and the Danish Board of Business Development. F&BCD contacted Roskilde University with the purpose to develop an introductory report about production and use of biochar in a Danish context. The report is written by associate professor Tobias Pape Thomsen. The final form is aimed towards "more book than paper", and the hope is that it will be relatively easy to read and navigate in.

Unlike the mentioned knowledge synthesis, this report has not undergone a thorough and structured external review process. Research assistants Andreas Kamp and Magnus Bo Karlsson from RUC IMT's METRIK research group have read a complete draft and provided many valuable comments and proposed corrections. Chapter 4 and parts of chapter 5 was sent to Associate professors Lasse Røngaard Clausen at DTU Construct and Dorette Müller-Stöver at KU PLEN for commenting. In the process of writing chapter 6, the Danish pyrolysis and gasification technology-development companies MASH Makes, AquaGreen, Dall Energy and Stiesdal SkyClean have contributed via email with input on status, development and near future plans and perspectives for their respective company. Thank you all for your time and contribution!

The main focus in this first version is on pyrolysis in a Danish context. However, there are also some central perspectives on regional and global level and also some mentioning of thermal gasification that also produces biochar. Hydrothermal processing and derived products are not in focus. This is mainly due to a lack of knowledge on my behalf. It would be very relevant to make a broader description about thermochemical biomass processing that also includes such processes.

References in this report are many, and the aim is to give inspiration for further assessment of different topics. Some of the proposed sources are free and open and some are behind payment barriers. References are placed in the background as end-notes to avoid disturbing the flow. The reference list is made predominately with active inks, and the aim is that having direct links will facilitate a faster progress in your search for additional information. All sites were visited in the end of November 2022. I apologize for the inconvenience of this approach if any of the links died in the mean time!

Finally, to all you great people from academia, industry, NGO's, public administration and elsewhere that are involved in this topic. Thank you for all your efforts! Your work is important and much appreciated
/Tobias

Figures and Tables

Report Content

1 Production and use of biochar is both new and old - and developing very fast

Production and use of biochar is drawing increasing attention from a broad spectrum of stakeholders within politics, green NGOs, metal industry, agriculture, soil physics, geo engineering, development of construction and filter materials, waste management, compensation brokers and many, many more.

Despite all the recent fuzz and buzz, the production and use of biochar has actually been known and used in various societies and civilizations for several thousand years. And there is biochar from various ages spread all around as the core production process (pyrolysis) also occurs during natural and man-made fires. So, in that regard it is fair to say that this is not new at all. However, recent development related to an accelerating climate crisis has brought about a renewed interest in the production and use of biochar. And the renewed interest has brought new development with it – technologically, scientifically, politically and economically that is accelerating as the crisis unfolds.

As a proxy for this development, Figure 1 illustrates the number of annual scientific publications over time registered in Scopus with the word "pyrolysis" or "biochar". There is a clear exponential increase in both registrations (overlapping registrations are counted in both). It can also be observed how there have been publications on pyrolysis registered in Scopus for more than 70 years while the first registrations of publications using the word "biochar" only date back around 20 years. This relates to the development of the word "biochar" in these years. There is still no full consensus on the definition or limitations of the term biochar, but in many contexts, it is used to represent "*man-made char of biomass origin that is not intended for combustion*"[2]. Articulation of non-energy uses of char from pyrolysis in the form of "biochar" indicated a shift in focus related to pyrolysis R&D. Early-stage development of biomass pyrolysis was primarily focused on the energy production potential - and therefore on the pyrolysis gas/oil products, while the char was typically regarded as a by-product that could be used for additional energy production by combustion. However, a discovery of an ancient char use praxis in Amazon as a soil improvement strategy[3] initiated a shift in focus from regarding char as a by-product that to be used for energy purposes to char being considered a main product with first one, and later many, many potential uses.

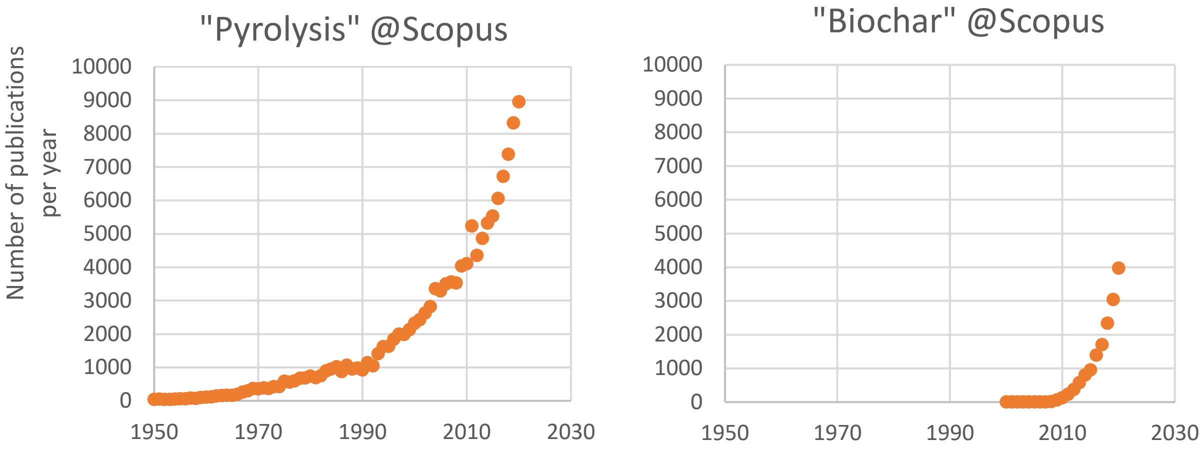

Figure 1: *Development in number of annual publications registered in Scopus4 containing the word "pyrolysis" or "biochar"*

There is also rapid development in the biochar production capacity in the world. The European Biochar Industry Consortium (EBI) estimates that in the EU alone, the installation of plants rose from an average of 3 per year in 2012-2015 to an average of more than 10 per year from 2016 to 2020 to 25 in 2021 and onwards to around 44 for 2022[5]. In the same report, EBI estimates that the biochar production capacity in the EU will almost double from 2021 to 2022 ending up at around 60,000 t biochar/year.

To support and regulate this development, certification schemes and characterization methods, guidelines, recommendations and legislation are being developed on both supra-national level, national level and municipal level involving both private and public organizations. Examples of this organizational development include:

- EU regulation EU (2019/1009) expanded on EU's fertilizer regulation with STRUBIAS (Struvite-Biochar-Ash) products in June 2022, which is now being implemented in member countries[6].
- EU regulation EU (2021/1165) allowed for biochar from plant materials to be used in EU organic food production (following the quality requirements of EU (2019/1009)) since 16/6-2022[7]
- The Danish Centre for Food and Agriculture at Aarhus University published a knowledge synthesis on biochar use in Danish agriculture under the "Framework Agreement on the Provision of research based Policy Support" with the Danish Ministry of Food, Agriculture and Fisheries (FVM)[8]
- The European Biochar Certificate has developed a whole range of methods and certification schemes for certification of biochar products for different use categories and for climate effects[9]
- IPCC included a status and effect discussion in the recent (accepted draft) report on Climate Change mitigation 2022[10], and issued a tier 1 method recommendation basis for further development to document carbon sequestration based climate effects from pyrolysis projects[11]
- There are now multiple online platforms where climate compensation from biochar projects can be bought and sold e.g. compensate.com[12], puro.earth[13] and cabonfuture.earth[14]
- Pyrolysis and biochar use is part of climate strategies in several countries e.g. Denmark[15] and Cameroun[16] as well as in long-term climate plans for several Danish municipalities[17]
- Boston Consulting Group recently entered into a long-term carbon credit purchase agreement with NetZero, a French start-up focusing at large biochar projects in tropical regions[18].

To sum it all up – development and application of this ancient thermochemical process is fast and widespread across multiple countries, sectors and stakeholders. Is this good? Perhaps. In my opinion - very likely. Because there are very interesting potentials. If we do it right. And there are risks and drawbacks that need to be acknowledged to do so. This is neither a silver bullet, a fool-proof value-generator or a one-size-fits-all solution, but the perspectives in relation to climate crisis mitigation and development of new value chains in a more circular and more bio-based economy are grand.

Biochar has been referred to as everything from a "Climate crisis kinder egg" and "new black gold" to "eco-toxicological hazard" and a "waste of carbon" and it can be difficult to establish an overview of all the effects, potentials, opinions etc. The purpose of the present report is to try to help establish this overview by providing a short introduction into this new, old technology and present some of the main potentials and limitations, perspectives and knowledge gaps that are known today. This is not simple, as many of the central aspects related to this topic are highly context dependent and the potential value creation of the production and use of biochar vary with the specific situation in which it is embedded.

In parts of the report, the scope will be broad and include perspectives on e.g., the Nordic countries, Europe and globally, while it will be narrower in other parts and primarily focus on Denmark. It will be attempted to provide recommendations for further reading continuously throughout the report.

2 What is pyrolysis and biochar?

Pyrolysis is an umbrella term for the many processes occurring during thermal decomposition of organic materials at elevated temperatures in a sufficiently inert atmosphere. The processes lead to a de-volatilization of the treated material where the material in the end is split into a volatile (typically gaseous) fraction and a recalcitrant (typically solid) fraction. The word pyrolysis is composed of the Greek words for fire (pyro) and splitting (lysis).

The pyrolysis processes occur under elevated temperatures, and it is often stated that pyrolysis processes require an oxygen-free environment. This is not entirely true. Pyrolysis also occurs in open air during wildfires, lightning strikes, campfires etc. where there is plenty of oxygen around. Under such conditions, the pyrolysis processes will often be followed by subsequent – and often parallel, ignition and rapid oxidation in a set of combustion processes, leaving just “smoke and ash”. However, if these reactions are inhibited by local oxygen limitations - and if the low levels persist until the relevant particle temperature is sufficiently low (or quenched by rain or firefighters) then the conversions processes will end, and a char residue will remain. We also experience this undeliberate “biochar”-production in daily life from both fireplaces/wood stoves, bonfires, garden waste incineration etc. where it is always possible to find some amount of charcoal the next day.

Figure 2 illustrates the processes taking place when heating biomass. Initially, the biomass will begin to dry and in processes with slow heating rates, the evaporation of water will keep the biomass temperature down until the material is dry. Biomass can dry at temperatures up to around 200 °C in both air, steam, nitrogen, exhaust gases etc. without losing more than water and very volatile components like ammonia (NH_3). After drying, the material starts to roast if further heated. The roasting process resembles that of coffee roasting and production of thermo-wood. When applied in material production, fuel pre-treatment etc. this type of process is referred to as torrefaction and takes place at temperatures typically from 220 °C to 280 °C[19].

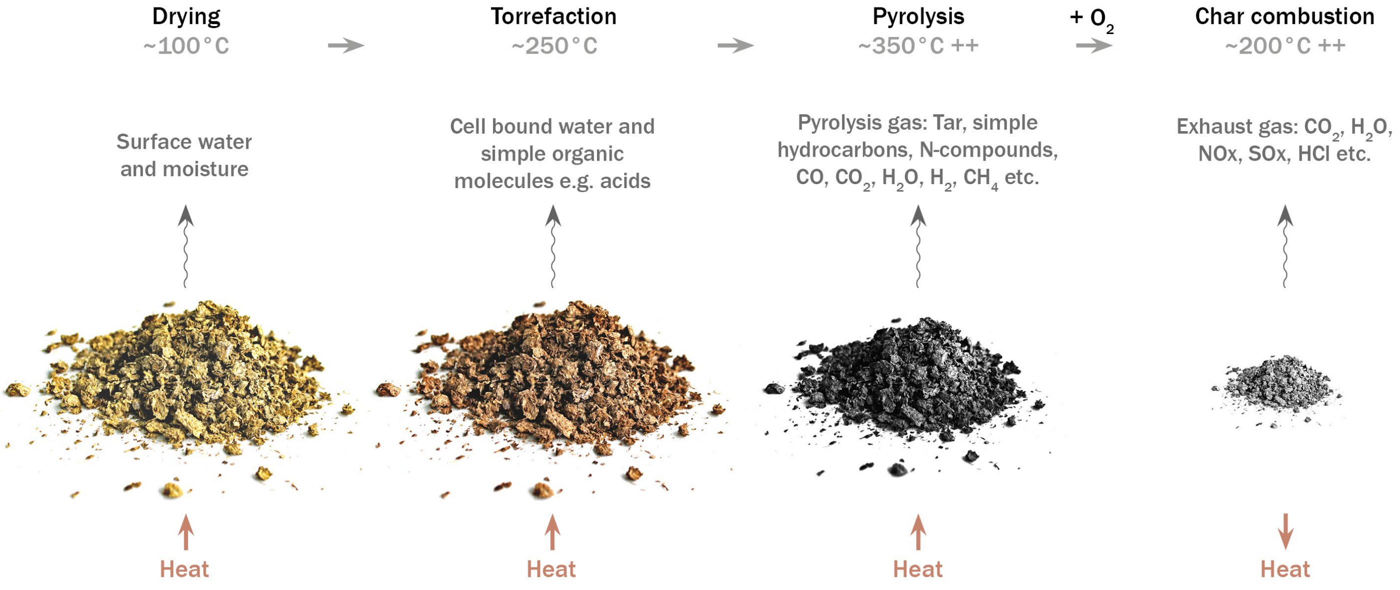

***Figure 2:** Visualization of the effects on biomass from heating in an inert atmosphere (drying, torrefaction and pyrolysis) and in an oxidizing atmosphere (incineration/combustion). Illustration by the author.*

During the torrefaction processes, cell bound water and more small organic compounds will be released. The residual material becomes harder and more brittle and less prone to e.g., microbial degradation which is why this process is also used for construction materials. The composition of the vapors from torrefaction vary substantially with the biomass and temperature profile. The vapors can be collected by condensation and contain many different compounds e.g., acids, alcohols, ketones, phenols, aldehydes, esters, etc. These liquids can be further upgraded by distillation and catalytic processes. Several relevant studies have been published on this matter in recent years in the scientific literature[20].

In the high-temperature end of the torrefaction process temperature spectrum, it is important to limit retard the reactivity of the atmosphere. This can be done by reducing oxygen content and replacing it with nitrogen, CO_2, steam etc. which are all less reactive than oxygen. While roasting at 220 °C may be unproblematic in many cases, a process with long retention time at 280 °C may require a reduced oxygen content to avoid self-ignition. However, this will vary with the biomass treated and the temperatures applied.

From 280 °C to 350 °C there is a shift towards the pyrolysis process spectrum and at 350 °C - 450 °C the pyrolysis processes will be fully initiated. At this point, there is a severe thermal splitting of the biomass taking place, and the off-gases are no longer just water and small organic molecules but a mixture of both un-condensable/permanent gases (CO, H_2, CO_2, CH_4 etc.), condensable fractions (water, tars/oils, smaller hydrocarbons) and particles. If the process is allowed to finish, the end result will be a pile of solid biochar and a combustible gas mixture with many different components.

Typically, pyrolysis takes place at higher temperatures than 350 °C, and it is more common to apply temperature profiles with peaks around 550-650 °C. At these temperatures, the retention time required for full pyrolysis of the biomass is a lot shorter than at 350 °C. There are also processes that combine relatively low temperatures with high pressures to complete the conversion processes within a reasonable retention time span. Some of these processes operate at extremely high pressures (hundreds of bars) in water and are known as hydrothermal liquefaction or hydrothermal carbonization. However, the dry pyrolysis process most often occurs at atmospheric pressure and high temperatures. To make sure that the biomass is fully pyrolyzed, it is relevant to balance 1) maximum temperature, 2) retention time and 3) particle size. Slow-pyrolysis processes typically obtain adequate levels of conversion by combining larger particles, longer retention times and medium-high temperatures (e.g. 500-650 °C) whereas flash-pyrolysis processes typically obtain adequate levels of conversion by combining small particles, short retention times and higher process temperatures (e.g. 700-800 °C).

To avoid ignition and combustion of the pyrolysis products (gases, oils and tars, biochar), an inert atmosphere or rapid cooling is required. Otherwise, both oils, permanent gases and char can burn and the result will be ashes, heat and exhaust gases containing a lot of CO_2 and water as well as varying amounts of e.g. SOx, NOx, HCl, particles, heavy metals etc. (Figure 2). The reactivity of the pyrolysis products vary, but in general both the combustible gases and freshly produced biochar is quite reactive and may burn at relatively low temperatures. Some biochar products may ignite at temperatures as low as 200 °C if exposed to sufficient amounts of air. Oxygen can typically not be completely avoided when feeding bulk amounts of biomass, and while this may influence e.g. char yield, small amounts of air is typically unproblematic as the oxygen will be quickly depleted in various reactions. To avoid char combustion the biochar produced in modern pyrolysis systems is often quenched with water or cooled in an inert atmosphere of e.g. N_2.

To get a better understanding about what occurs during biomass pyrolysis, an illustration of a pyrolysis process is provided in Figure 3 showing product mass distribution and the fate of specific key elements.

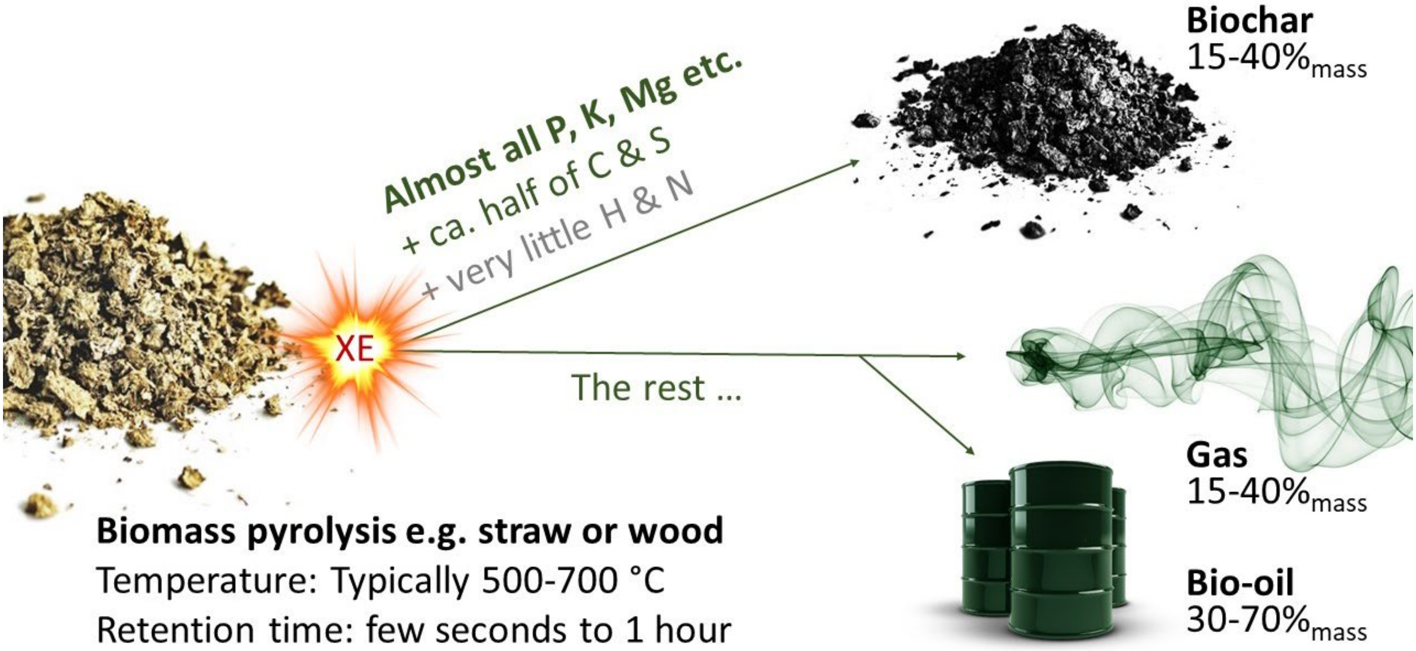

Figure 3: *Overview of pyrolysis effects on distribution of product mass and key elements. Distribution of elements based on a slow pyrolysis process while variation in mass of the specific products based on different fast and slow biomass pyrolysis processes. "XE" indicates destruction of organic xenobiotics*[A]*. Illustration by the author.*

In Figure 3, it is illustrated how slow pyrolysis (with sufficient time and temperature for full pyrolysis), can lead to a solid biochar product with i) around half of the carbon and sulfur that was in the biomass, ii) most of the non-volatile inorganics and iii) only very small amounts of nitrogen, hydrogen, and oxygen. The rest will end up in the gas product, which can be further split into a condensable fraction (bio-oil) and a non-condensable fraction (pyrolysis gas). Typically, such a split would occur by cooling the process gas after a hot filtration to remove particles from the gas.

On mass basis, it is common to see around one third of the original mass in the biochar product from a slow process, whereas lower yields are typically seen in faster processes. But this is also very much influenced by the content of volatile organics in the biomass. The pyrolysis of fats or oils yields no char while a high content of inorganics and lignin typically leads to high char yield.

Increasing temperatures will typically also reduce char yields, originating from both a small additional carbon loss and the fact that if the pyrolysis takes place at very high temperatures, there may also be significant levels of volatilized inorganics from the biochar in the gas phase. Finally, the original particle size and the heating rate, sweep gas flow rate and catalytic effects also influence the product yields.

An example with product mass yields from wood pyrolysis as a function of pyrolysis process design is provided in Table 1. The data presented is not representative for the general situation. It is data based on particular processes and biomasses. As examples, many slow pyrolysis processes are operated at temperatures above the 500 °C temperature guideline, and many gasification processes do not have as high tar/oil production levels as indicated in the table. However, the table indicates typical relationships between the different product categories as a function of the process design category.

[A] Chemical substances that are foreign to animal life

Table 1: *Simplified correlation between pyrolysis process design and product mass yield. Data from the report "Biomass Pyrolysis" under IEA task 34, prepared by Professor Tony Bridgwater from Aston University, UK*[21]

	Liquid product (bio-oil)	**Solid product** (biochar)	**Gas product** (process gas)
Fast Pyrolysis Moderate temperature (> 500 °C) and short vapor residence time (< 2 sec)	75% (25% water)	12%	13%
Intermediate Pyrolysis Low-moderate temperature (< 500 °C) and moderate vapor residence time	50% (50% water)	25%	25%
Slow Pyrolysis Low-moderate temperature (< 500 °C) and long vapor residence time	30% (70% water)	35%	35%
Gasification High temperature (> 800 °C) and long vapor residence time	5% (5% water)	10%	85%

In the following, there will be more details about the products from pyrolysis. Depending on your level and area of specific interest, you may find it useful to study additional sources of information. There is a wealth of both open-access papers and reports as well as books and pay-per-article studies describing the processes of biomass pyrolysis in more detail and some examples are proposed in the end-notes[22].

2.1 Biomass for pyrolysis

In principle, all organic material can be pyrolyzed. Figure 4 shows examples of various biomasses that have been pyrolyzed in lab-scale equipment at DTU KT (Risø) and RUC IMT/INM. However, it is far from all organic materials that can be converted without problems in any given pyrolysis process. Optimizing the pyrolysis process is an interplay between specific biomass characteristics, equipment and desired output. Some of the relevant biomass characteristics to consider include:

- Proper particle size, particle robustness and morphology to secure feeding, in-situ movement and to optimize heat transfer, bed behavior, process retention time etc.
- Proper moisture content and heating value to obtain energy sufficiency and energy product yields
- Proper density to optimize equipment dimensioning and thermal capacity
- Proper biomass ash composition to secure biochar quality and manage pyrolysis gas inorganics
- Limited content of pollutants and unwanted substances to increase char quality and reduce gas treatment processes.

Crushed straw pellets,
Denmark

Pine wood pellets,
Denmark

Shea nut pellets,
Denmark

Dry waste water sludge,
Denmark

Bagasse,
Brazil

Beet seeds,
Denmark

Empty Fruit Bunches,
Malaysia

Lignin residue pellets,
Denmark

Olive kernel residues,
Italy

Olive wood prunings,
Italy

Empty Fruit Buches,
Malaysia

Rice husks,
Mali

Road side grass,
Denmark

Vine wood prunings,
Italy

Meat and bone meal C1,
Denmark

Meat and bone meal C2,
Denmark

Water stream weeds,
Denmark

Beach cleaning waste,
Denmark

Cattle manure fibers,
Denmark

Pig manure and muck,
Denmark

Waste water sludge pellets,
Denmark

Waste water Fat fraction,
Denmark

Waste water Grate material,
Denmark

Waste water Sand fraction,
Denmark

Garden-park waste wood,
Sweden

Food waste,
Denmark

Sea weed,
Denmark

Pond sediments,
Denmark

Figure 4: *Examples of biomasses pyrolyzed in lab. Scale equipment at DTU KT (Risø) and RUC IMT/INM*[23]*. By the author.*

3 Biochar is not just biochar

Biochar can be defined as "char made deliberately out of biomass with some-other purpose than combustion". However, there are also arguments to focus the definition on the biomass-origin and include all potential uses and thus simply define biochar as "char made deliberately out of biomass". In all cases, biochar is the solid product residing after biomass pyrolysis. The biochar product is a result of many different processes and pre-conditions e.g.:

- The composition and particle size distribution and morphology of the original biomass
- The process temperature profile (heating rate, maximum temperature, retention time, cooling)
- In-process design i.e., if e.g. char is crushed in the process, if char and gas have short or long contact, if there are catalysts/bed material in the reactor, if char is extracted hot etc.
- Post-pyrolysis treatment e.g. if char cools in proximity of gas, if char is quenched, if char is oxidized/steam gasified, used as tar-cracker, impregnated, charged, aged etc.

Pictures of a range of different biochars produced at RUC IMT and DTU KT at Risø are showed in Figure 5.

The substantial differences in biomass characteristics and pyrolysis process designs and operation parameters yield biochar products with large variations in key product characteristics as well. Some examples of such characteristics are presented in Figure 6 to Figure 16 to illustrate the variation among different biochars produced from different biomasses.

Figure 5: *Pictures of biochar products from many different, Danish and Swedish biomasses*[24]*. By the author.*

3.1 Examples of variations in key biochar characteristics

The purpose of this section is to illustrate how key biochar characteristics may vary substantially, and thereby make it more tangible why biochar is not just biochar.

3.1.1 Examples of carbon- and oxygen content in biochar

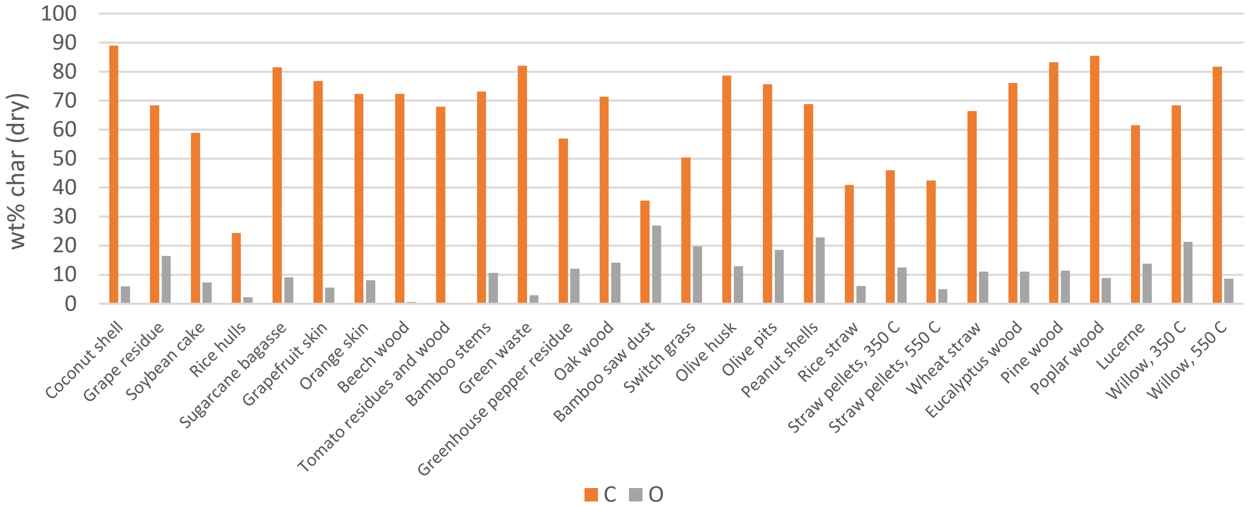

Figure 6: *Variations in content of carbon (C) and oxygen (O) in various biochar products. Data from Phyllis2-database*[25]*. Data uncertainty is significant and analytical methods vary.*

3.1.2 Examples of hydrogen and nitrogen content in biochar

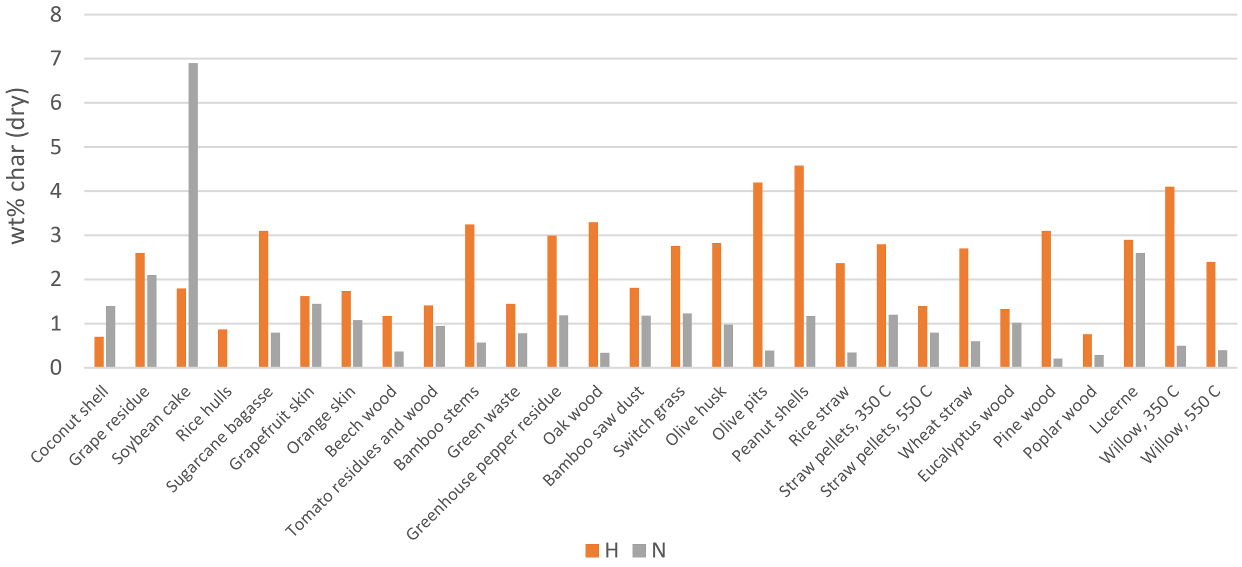

Figure 7: *Variations in content of hydrogen (H) and, nitrogen (N) in various biochar products. Data from Phyllis2-database*[26]*. Data uncertainty is significant and analytical methods vary.*

3.1.3 Examples of sodium-, magnesium-, potassium- and calcium content in biochar

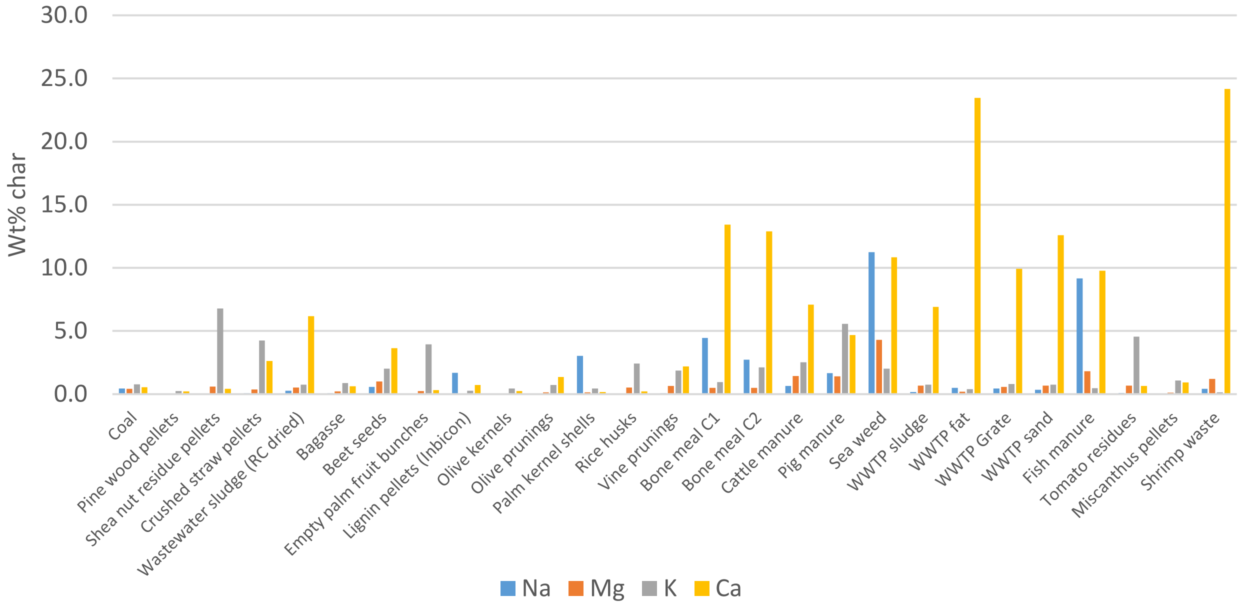

Figure 8: *Variations in content of sodium (Na), Magnesium (Mg), Potassium (K) and Calcium (Ca) in various biochar products Data uncertainty is significant and results should be used for relative comparison only. Measurements conducted with XRF with few calibration points. See ref for details on char production and biomasses*[27]

3.1.4 Examples of aluminum-, silica-, phosphorus- and iron content in biochar

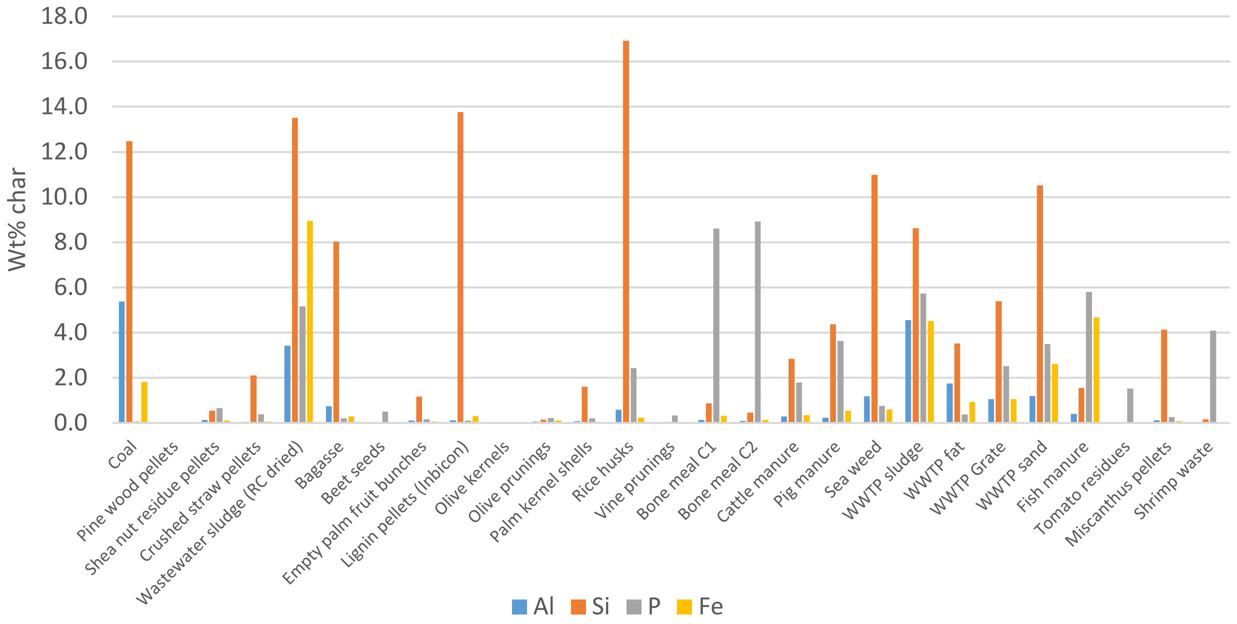

Figure 9: *Variations in content of aluminum (Al), silica (Si), phosphorus (P) and iron (Fe) in various biochar products Data uncertainty is significant and results should be used for relative comparison only. Measurements conducted with XRF with few calibration points. See ref for details on char production and biomasses*[28]

3.1.5 Examples of Sulphur- and chlorine content in biochar

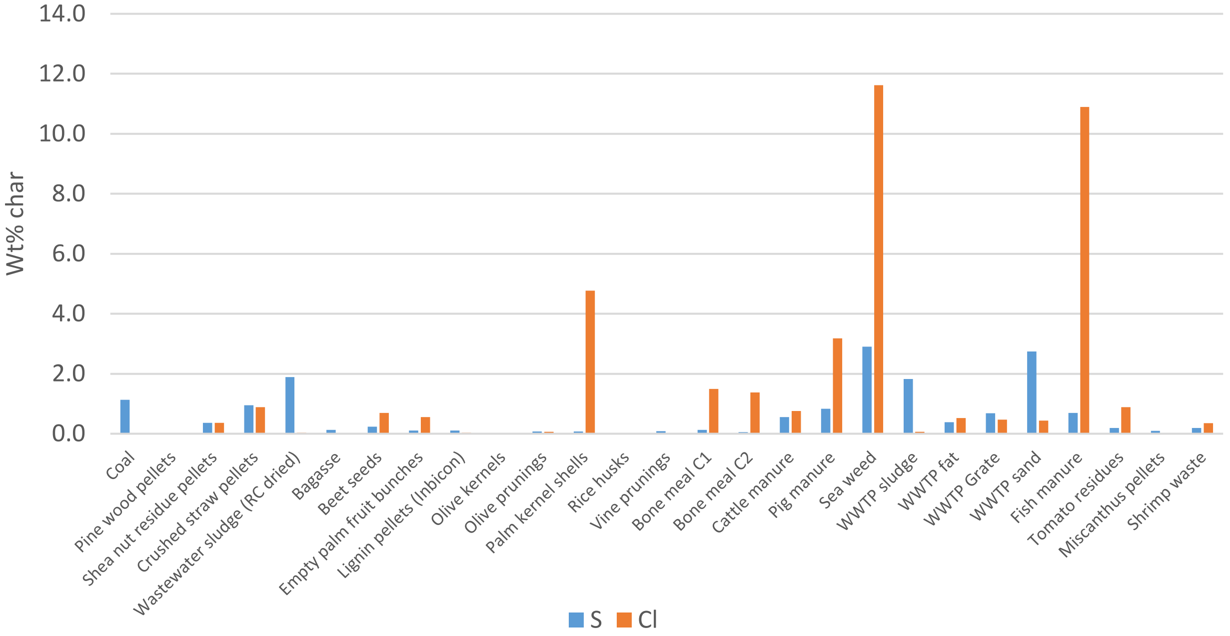

Figure 10: *Variations in content of sulfur (S) and chlorine (Cl) in various biochar products. Data uncertainty is significant and results should be used for relative comparison only. Measurements conducted with XRF with few calibration points. See ref for details on char production and biomasses*[29]

3.1.6 Examples of pH in biochar

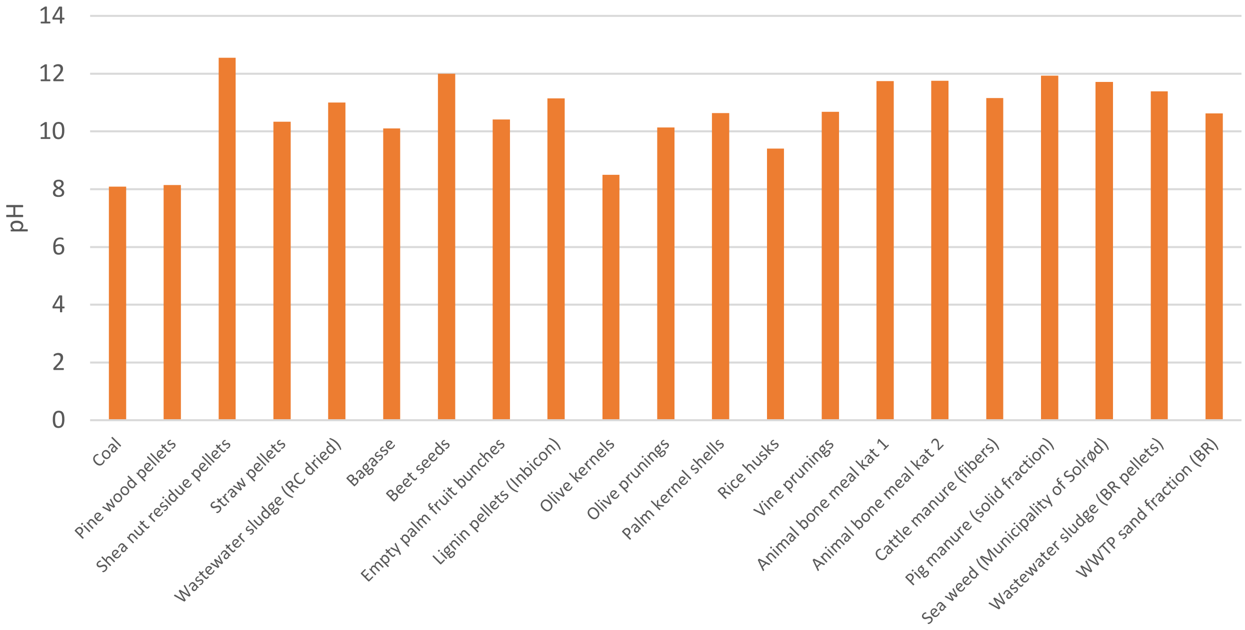

Figure 11: *Examples of pH of biochar measured in water. See ref for details on analytical method, char production and biomasses*[30]

3.1.7 Examples of bulk density of biochar and the biomass from which it was produced

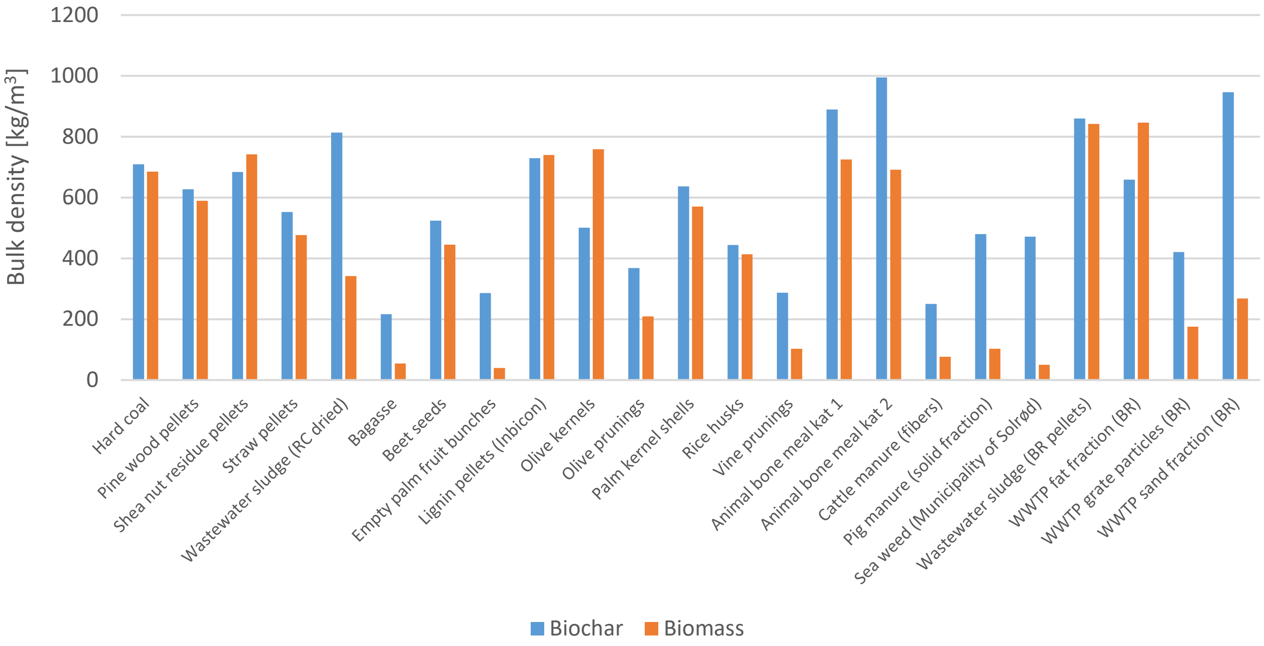

Figure 12: *Examples of bulk density measurements of dry biomasses and the biochar produced hereof. Uncertainty is significant and results should be used for relative comparisons only. See ref for details on analytical method, char production and biomasses*[31]

3.1.8 Examples of specific surface area inside biochar

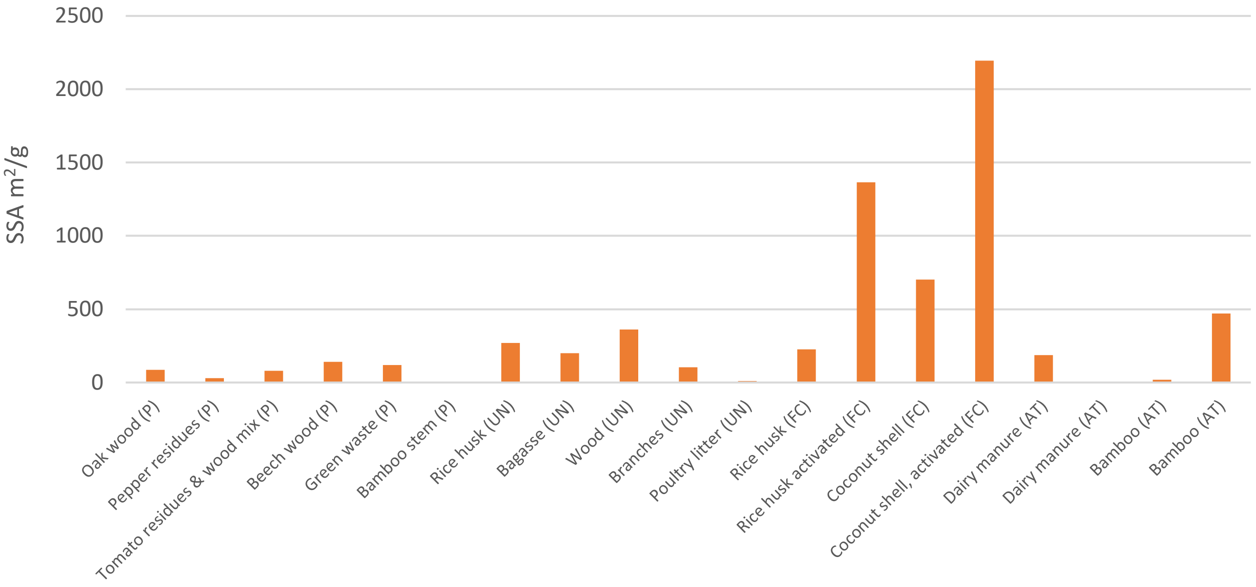

Figure 13: *Examples of Specific Surface Area (SSA) measurements on various biochar products from different biomasses and pyrolysis processes. Sources include the Phyllis2 database (P)*[32]*, data on the Drought Hero biochar product from Meiwa co. (UN)*[33] *and scientific articles by Tomczyk et al. (2020)*[34] *and Cheng & Li (2018)*[35]

The variations in the SSA results range from just a few m^2 surface per gram char to more than 2000 m^2 per gram in an activated biochar sample[36]. More examples can be found in the references. The high surface area in biochar originates from the carbon-matrix persisting after pyrolysis. An example is provided in Figure 14, showing a Scanning Electron Microscope image of pine wood biochar with visible micro-structure.

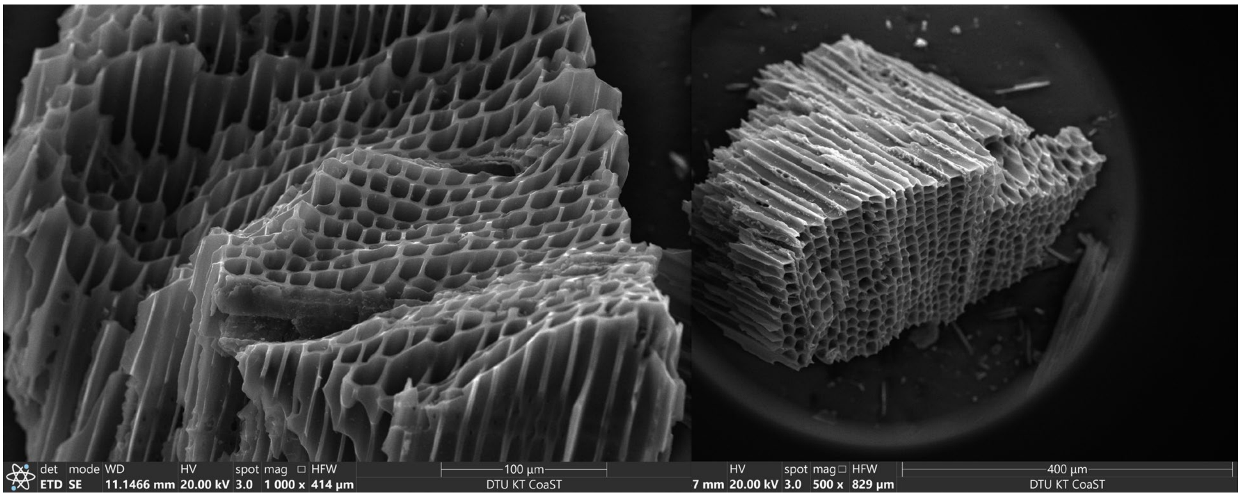

Figure 14: *Two Scanning Electron Microscope images of the same biochar made from pine wood chips in a two-stage gasifier © Giulia Ravenni, DTU KT.*

3.1.9 Examples of the content of heavy metals in biochar

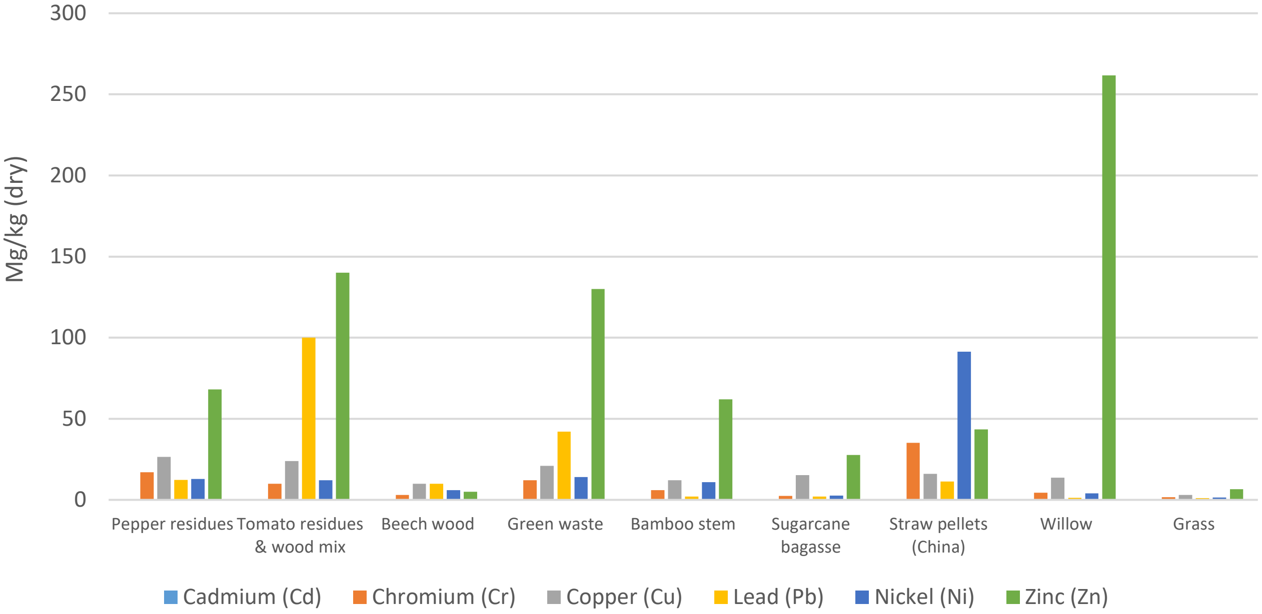

Figure 15: *Content of selected heavy metals in biochars produced in different pyrolysis processes and from different biomasses. Data from Phyllis2 database[37]. Cd-results not measured in chars from green waste, bamboo stem and sugarcane bagasse.*

The content of heavy metals largely follows that of heavy metals in the treated biomass. However, mercury is most often volatilized almost completely in pyrolysis processes while the content of certain other heavy metals e.g., cadmium, arsenic etc. can be reduced by increasing temperature[38].

3.1.10 Examples of the plant availability of phosphorus in biochar

As shown in the previous figures, biochar can contain high concentrations of nutrients like phosphorus, potassium and magnesium as well as some sulphur and residual nitrogen. To use biochar products as fertilizers, it may be valuable to know how plant available these nutrients are – both in the short and long term. The availability can vary substantially under influence of both nutrient speciation in the biochar, biochar adsorption capacity and morphology, biochar pH, biochar particle size distribution, various soil characteristics, dosing, crop type and crop rotation system, agricultural praxis, climate etc.

In addition, it can be difficult to compare the results from different nutrient availability experiments even when the same nutrient in the same biochar is investigated with different methods. There are fast and relatively cheap experiments e.g. measuring solubility of phosphorus directly in the material or after incubation with soil. Solubility can be measured in many different solvents e.g. water, citrate, NaOH etc. and different proxy methods may be applied to simulate plant uptake through roots like anion-exchange resins or diffusive-gradients-in-thin-films. More expensive experiments can include plant pot experiments with different crops, or field plot experiments at different scales.

Figure 16 shows examples from an anion-exchange resin strip phosphorus extraction of a soil biochar mixture after a 2-week incubation. The many different biochars are all produced in the same lab scale pyrolysis equipment but show very different levels of resin-strip extractability. A commercial mineral P reference is also included, yielding around 65% P-extractability after 2 weeks incubation in soil.

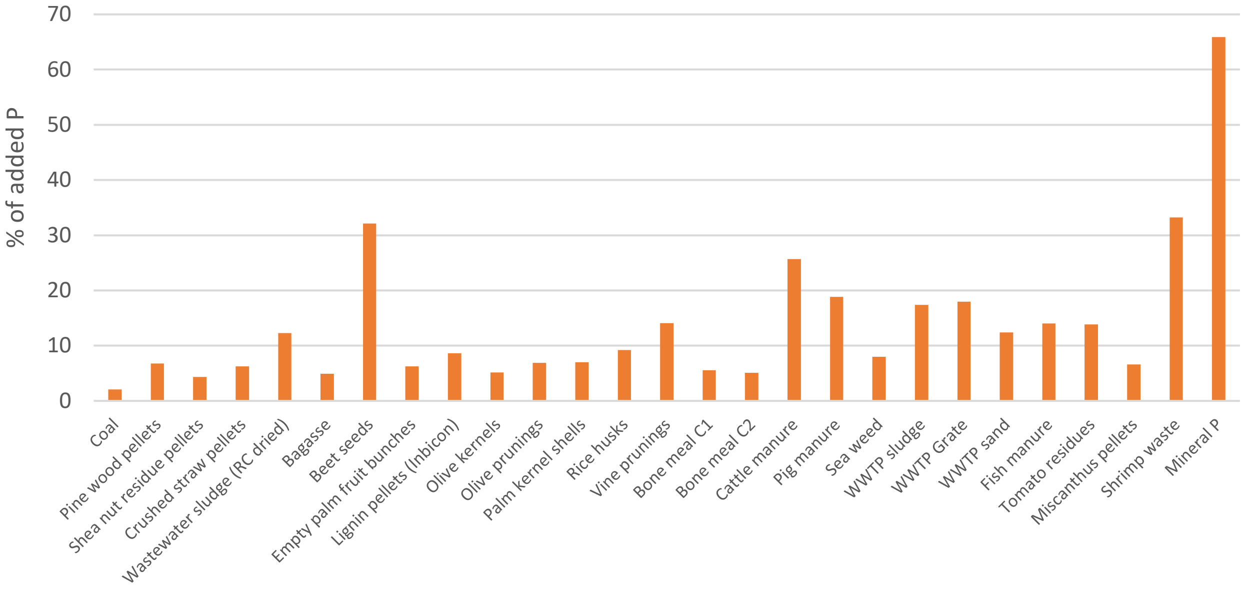

Figure 16: *Examples of P solubility in various biochars and ash products. Measured as the anion exchange resin extractability of phosphorus in incubated char and ash samples compared to a mineral fertilizer reference[39]. Results are adjusted for soil P content.*

As mentioned, there may be substantial differences between results from different experimental assessment methods and context. In Figure 16, the biochar produced from sewage sludge from Bjergmarken Renseanlæg in Denmark ("WWTP Sludge") showed an extractability of phosphorus of around 17.5% compared to 65% in the mineral reference, hence around 25% of the mineral reference extractability level. However, in a subsequent study with biochar produced in the same process from the same WWTP, it was found that resin-strip extractability of P in the char after incubation in a different soil was 40-80% of the mineral P level[40]. And, when this char was later tested against the mineral P reference in a pot growth experiment with spring barley, biomass yields from the biochar treatment was around 85% of the yields (of both roots and shoots) in the corresponding mineral P treatment[41].

It is very relevant to consider the context-specific conditions when optimizing the use phosphorus fertilizers hereunder phosphorus rich biochar. Some soil-plant systems and situations require no additional P if soil-P levels are high and plant-P requirements are not[42]. Some systems require a lot of P - and potentially a lot of immediately available P as well. Finally, there are systems that may benefit from more slow-release P sources to provide sufficient nutrients over a longer period of time while reducing the risk of leaching and soil-fixation of surplus soluble P[43].

3.1.11 Many other biochar characteristics can be relevant

There can be many other biochar characteristics than those exemplified in Figure 6 to Figure 16 that may be relevant for a specific use case. In the table below, variation in a few additional characteristics is shown, but the full catalogue is much bigger – and expanding, and the relevant set of analytical procedures will depend on the specific use-case for the given biochar.

Table 2: *Examples of biochar characteristics related to 1) water holding capacity, 2) content of polycyclic aromatic hydrocarbons (PAHs) and electrical conductivity. Data from Phyllis2 database*[44]

		Oak wood	Pepper residues	Tomato residues & wood mix	Beech wood	Green waste	Bamboo stem
Water holding capacity	wt%	76.8	n.a.	210	86.3	217	105.8
Total sum of PAH	mg/kg (dry)	22.7	9.3	1.3	0.5	1.9	65.1
Conductivity	mS/m 25 °C	16.6	1730	938	203	59.8	7.45

One of the characteristics shown here is "Total sum of Polycyclic Aromatic Hydrocarbons (PAHs)" sincein general, biochar content of PAHs is relevant to monitor closely in many use contexts. Some PAHs are highly toxic and PAHs in biochar may originate from both i) the converted biomass (sewage sludge, some digestate fibers and food waste samples etc.) and ii) be generated in the thermochemical process. Through many years of experience with thermochemical conversion of biomass it becomes clear that there will always be trace amounts of PAHs in biochar, but also that the levels (and to some extent, types) may be controlled by proper design and operation. Among the most important guidelines in this regard are:

- Make sure the biomass is fully pyrolyzed by balancing temperature, retention time, particle size distribution etc. Measure fraction of unconverted material regularly to optimize operation
- Use dry fuels for pyrolysis or prolong thermal treatment accordingly
- Always separate biochar and gas at maximum process temperatures and avoid risk of re-condensation of tars in cold-zones.

It is also important to be aware that there are thousands of PAHs, but only a fraction hereof is classified as harmful and therefore regulated. The coverage of regulation varies. One of the most specific certification schemes in this regard is the European biochar certificate that measures for both i) 16 EPA PAHs, ii) 8 EFSA PAHs and iii) benzo[e]pyrene and benzo[j]fluoranthene specifically[45]. Therefore, if a biochar product complies with EBC standards in this regard, it will comply with many regulatory frameworks as well.

3.2 Biochar certification and legal thresholds

Since biochar is a quite new product category, the certification schemes and regulatory frameworks are in many cases still under development. The European Biochar Certificate (EBC) has been on the European market the longest, and even though it is generally a voluntary industry standard in Europe, it is obligatory for all biochar sold for use in agriculture in e.g., Switzerland.

There is today not just one EBC certificate, but several different certification schemes available for different chars for different purposes. In addition, the EBC also propose a specific certification scheme for calculation of C-sink effects from biochar projects[46]. Currently, this scheme and related assessment methods are mainly relevant for pyrolysis of virgin biomasses, and it is expected that an update will be published soon. An overview of the most important parameters for certification of EBC biochars are presented in Table 3.

Commonly, for all EBC certified biochars it applies that they need to be produced in a pyrolysis process defined by temperatures ranging from 350°C to 1000 °C and a low-oxygen atmosphere. The certification also involves biochar products from thermal gasification processes, but not from e.g. torrefaction, hydrothermal carbonisation and coke production[47].

In addition to these biochar criteria for EBS certification, the EBC also has a limited *positive list of permissible biomasses for the production of biochar* as well as certain requirements related to e.g. pyrolysis process stability, end-use of pyrolysis gas products, sampling rate and sample sizes[48].

In June 2022, the European Union's fertilizer regulation was expanded with the STRUBIAS (Struvite-Biochar-Ash) products, opening the possibility to produce CE-marked biochar fertilizers and soil enhancers for the European market[49]. There are several requirements in the regulation that need to be complied with incl.:

- A limited positive list with the biomasses from which it is allowed to produce CE-marked biochars
- Specific requirements for biochar products sold under the regulation, defined in the specification for Component Material Category 14: Pyrolysis and gasification materials.
- Different sets of general requirements for different Product Function Categories under which biochar can be marketed e.g. as 1A) Organic fertilizer, 1B) Organo-mineral fertilizer and 3A) Organic Soil Improver

Table 3: *Overview of the most important analytical parameters for EBC biochar. From European-biochar.org*[50]

EBC-certification class		EBC-feed	EBC-AgroOrganic	EBC-Agro	EBC-Urban	EBC-ConsumerMaterials	EBC-BasicMaterials
Elemental analysis	Declaration of C_{tot}, C_{org}, H, N, O, S and ash-content						
	H/C_{org}	< 0.7					
Physical parameters	Water content, dry matter (@ < 3mm particle size), bulk density (TS), WHC, pH, salt content, electrical conductivity of the solid biochar						
TGA[B]	Need to be presented for the first production batch of a new pyrolysis unit						
Nutrients	Declaration of N, P, K, Mg, Ca and Fe content						
Heavy metals [all in gram per ton dry matter]	Pb	10	45	120	120	120	Need for declaration but no limit value for certification
	Cd	0.8	0.7	1.5	1.5	1.5	
	Cu	70	70	100	100	100	
	Ni	25	25	50	50	50	
	Hg	0.1	0.4	1	1	1	
	Zn	200	200	400	400	400	
	Cr	70	70	90	90	90	
	As	2	13	13	13	13	
Organic contaminants	∑16 EPA PAH	Declaration	4±2 g t^{-1} DM	6±2.2 g t^{-1} DM	Declaration	Declaration	Not required
	∑ 8 EFSA PAH	1.0 g t^{-1} DM					4.0 g t^{-1} DM
	benzo[e]pyrene benzo[j]fluoranthene	< 1.0 g t^{-1} DM for each of both substances					
	PCB, PCDD/F	See chapter 10 in EBC guidelines[51]	Once per pyrolysis unit for the first production batch. For PCB: 0.2 mg kg^{-1} DM, for PCDD/F: 20 ng kg^{-1} (I-TEQ OMS), respectively				

The requirements for the different Product Function Categories can be found in Annex I “Product Function Categories (PFCs) of EU fertilising products” part 1 while the description of requirements for “CMC 14: Pyrolysis And Gasification Materials” can be found in Annex II “Component Material Categories (CMCs)” under part 2 “Requirements Related to CMCs”[52]. Some of these requirements include the following:

- *The thermochemical conversion process shall take place under oxygen-limiting conditions in such a way that a temperature of at least 180 °C for at least two seconds is reached in the reactor.*

[B] Thermo-gravimetric Analysis

- *The pyrolysis and gasification materials shall have a molar ratio of hydrogen (H) to organic carbon (H/Corg) of less than 0.7, with testing to be performed in the dry and ash-free fraction for materials that have an organic carbon (Corg) content of less than 50 %. They shall have no more than:*
    - *6 mg/kg dry matter of PAH16,*
    - *20 ng WHO toxicity equivalents*[C] *of PCDD/F (Polychlorinated dibenzo-p-dioxins and dibenzofurans per kg dry matter,*
    - *0.8 mg/kg dry matter of ndl-PCB*[D]*,*
- *In an EU fertilising product containing or consisting of pyrolysis and gasification materials:*
    - *the chlorine (Cl-) content shall not be higher than 30 g/kg dry matter and*
    - *the thallium (Tl) content shall not be higher than 2 mg/kg dry matter, in case more than 5 % of pyrolysis or gasification additives relative to the fresh weight of total input material have been applied.*

In relation to PAH analysis, the 16 PAHs in focus are (Sum of) naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene, dibenzo[a,h]anthracene and benzo[ghi]perylene.

In the present version, the biomass positive list for CE-marked biochars does not include biomasses of animal origin including manure fibers or biogas digestate with digested manure. However, there is substantial activity on this matter and several organizations (e.g. EBI[53] and European Sustainable Phosphorus Platform[54]) are providing input and expertise to the European Commission to help expand the positive list.

Certain biochar products may also be applied as fertilizers and soil enhancers under the EU organic food certification scheme. EU regulation EU (2021/1165) allow for biochar from plant materials to be used in EU organic food production (following the quality requirements of EU (2019/1009) since 16/6-2022[55].

[C] van den Berg M., L.S. Birnbaum, M. Denison, M. De Vito, W. Farland, et al. (2006) The 2005 World Health Organization Re-evaluation of Human and Mammalian Toxic Equivalency Factors for Dioxins and Dioxin-like Compounds. Toxicological sciences: an official journal of the Society of Toxicology 93:223-241. doi:10.1093/toxsci/kfl055

[D] Sum of congeners PCB 28, 52, 101, 138, 153, 180

4 Biomass pyrolysis is - most often, much more than biochar production

The purpose of this section is to illustrate how biomass pyrolysis is often much more than production of biochar. In the first many years of modern pyrolysis development there wasn't even such a thing as "biochar", and as was shown in Figure 1, there were publications on biomass pyrolysis for several decades before the first biochar publication.

The initial focus on modern biomass pyrolysis was energy-related and concentrated on various uses of the gas and oil products for energy purposes. In Denmark, this development accelerated since the oil crisis in the 80's and especially use of biomass pyrolysis for production of bio-oil has attracted a lot of attention over the years. Also, technological processes with char gasification stages (i.e. thermal biomass gasification) to increase energy production, clean the gas product and (as a consequence of char gasification) reduce the char yield have been investigated and developed for many years.

There are several different designs of low-tech pyrolysis processes (e.g. pit reactors, charcoal piles and charcoal kilns) that yield primarily charcoal or biochar. However, these are typically not in scope for large-scale implementation in technologically advanced sectors and regions, and it is often impossible/difficult to obtain char product certification due to process variations and insufficient use of the gas/oil product from the pyrolysis process.

In the other end of the spectrum, there are highly advanced and integrated systems which produce one or several types of biochar together with e.g., condensates, distillates, wood vinegar, bio-oil and permanent gases/syn-gas.

In the following, some examples of modern pyrolysis systems are provided. These descriptions are very general, but a lot of studies have been published in recent years with more detailed information about e.g. system performances, product yields etc. for specific systems. Some examples are provided in the reference list[56].

4.1 Production of biochar and heat from dry biomass

The simplest systems for biomass pyrolysis with energy utilization are systems developed for heat production from dry biomass pyrolysis and with complete combustion of the hot pyrolysis gas directly after pyrolysis. If the pyrolysis gas temperature is kept above tar dew points, the pyrolysis splits the dry biomass in just two fractions – a solid fraction (char) and a mixed gas fraction containing both condensables (tar/oil, water etc.), non-condensable gases and particles, that can be combusted.

If the system is heated with external energy (e.g. electrical heating) then all of the heat produced from gas combustion can be supplied to external purposes e.g. industrial processes like biogas amine scrubbers, cement kilns, brick kilns, destillation, drying processes etc. or to existing heating systems or even existing Combined Heat and Power (CHP) plants to produce a combination of electricity and district heating. If the pyrolysis process is designed with heat integration, then external energy is not required, but part of the produced heat from the gas combustion is instead used to drive the process.

An illustration of two simple examples of generic pyrolysis systems for production of biochar and heat are provided in Figure 17.

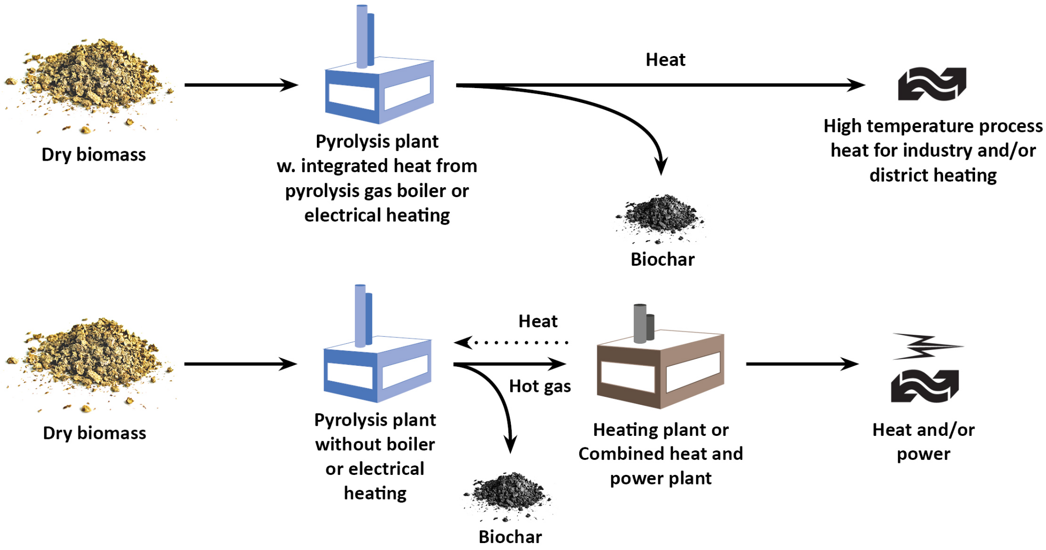

Figure 17: *Conceptualization of two systems with (dry) biomass pyrolysis for the production of biochar and heat. Illustration by the author.*

4.2 Production of biochar, heat and oil from dry biomass

For many years, there has been extensive research and development in pyrolysis systems producing bio-oil. Illustrations of two generic systems for biooil production are showed in Figure 18.

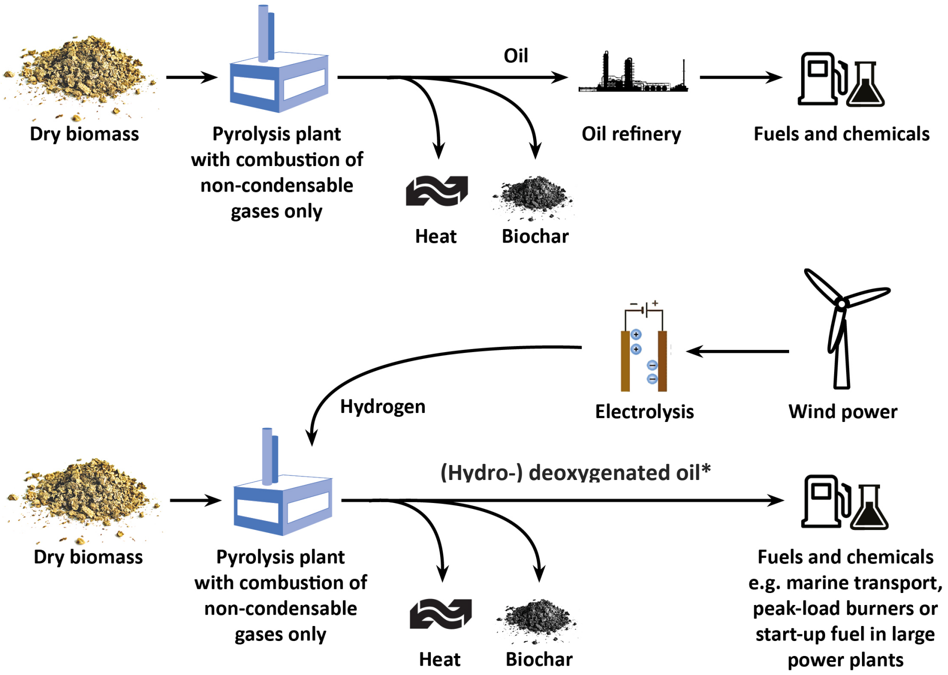

Figure 18: *Conceptualization of two systems with (dry) biomass pyrolysis for the production of biochar and bio-oil. * deoxygenation in systems without additional hydrogen and hydrodeoxygenation in systems with additional hydrogen. Illustration by the author.*

In both systems, the oil could be extracted by cooling the pyrolysis gas after removing particles in a hot gas filter. When the temperature is reduced below tar dew point, oil components begin to condensate out of the gas, where after the residual gas can be burned to produce heat for process purposes and for export.

Bio-oil has a reduced quality compared to crude oil when considering reference case oil use. The differences relate to e.g. oxygen content (higher in bio-oil), acidity (higher in bio-oil), heating value (lower in bio-oil), storage stability (lower in bio-oil). However, raw bio-oil may be used as supplement and/or raw material for advanced biofuels and chemicals. Some oils can e.g. be used as-is by dropping them into existing oil refineries alongside conventional oil in relatively low mixing ratios (< 10%) as proposed by e.g. the company BTL[57] or the oils can be gasified into e.g. DME as shown at Luleå University of Technology in 2015[58]. However, there are also many other options for upgrading the bio-oil in dedicated processes involving both physical, chemical and catalytic processes. Some of the processes include e.g.: In-situ and ex-situ deoxygenation using e.g. catalysts or thermal deoxygenation, hydrodeoxygenation and biomass pre-treatment by e.g. torrefaction. The development in bio-oil upgrading has been gaining pace for some years and a lot of studies have been published already[59]. In a Danish case, there is a massive market potential for upgraded bio-oil in the marine sector if the fundamental characteristics of the oils are improved[60]. There are also other smaller scale options related to immediate use as peak-load- or start-up fuel in heat and CHP systems. In the longer term, it is expected that there can be huge potentials in production and use of bio-oil for production of high quality fuels, chemicals[61] and new bio-based materials.

4.3 Production of biochar, heat and methanol from dry biomass

In addition to bio-oil, heat and biochar, there is also development taking place in the production of advanced fuels and chemicals from pyrolysis gas products. An example is illustrated in Figure 19 with conversion of the full pyrolysis gas stream (condesable fraction + permanent gases) to e.g. methanol under hydrogen application.

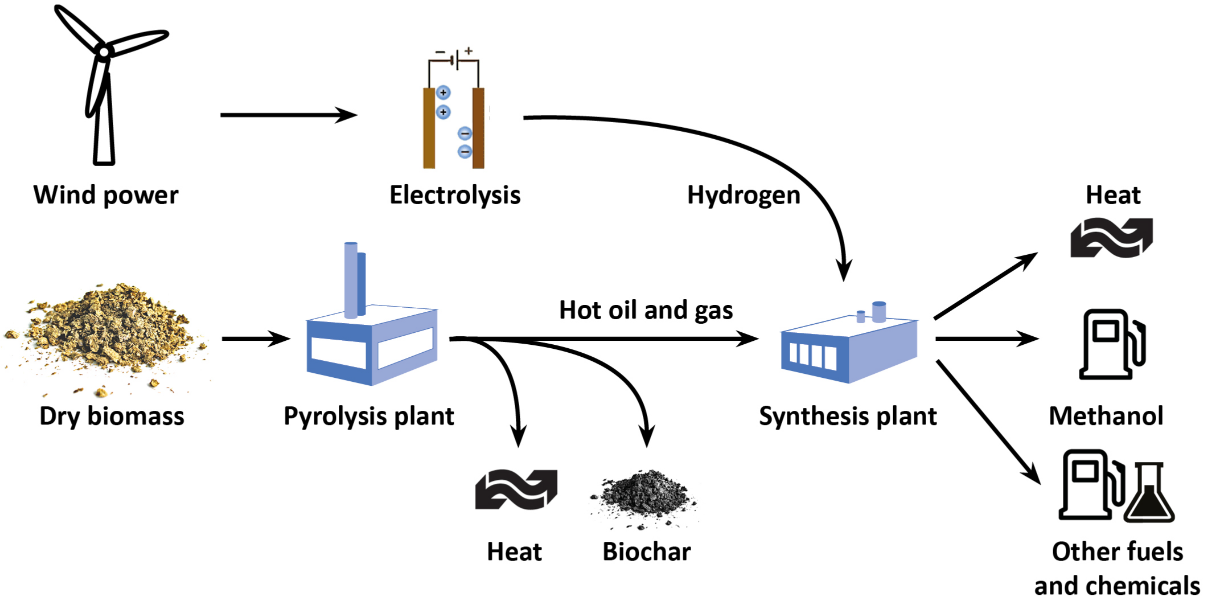

__Figure 19:__ Conceptualization of a system with (dry) biomass pyrolysis for the production of biochar, heat and advanced fuels and chemicals. Illustration by the author.

It is also an option to combine oil production and advanced gas utilization. After removing particles and extracting the oil (by cooling the gas), the residual permanent/non-condensable gas may be either burned for heat production (as illustrated in Figure 18), or it may be cleaned further and used for synthesis either alone or with addition of hydrogen from electrolysis (e.g. in a PtX setup). An example of such a system is illustrated in Figure 20 based on input from Jesper Ahrenfeldt at Stiesdal SkyClean:

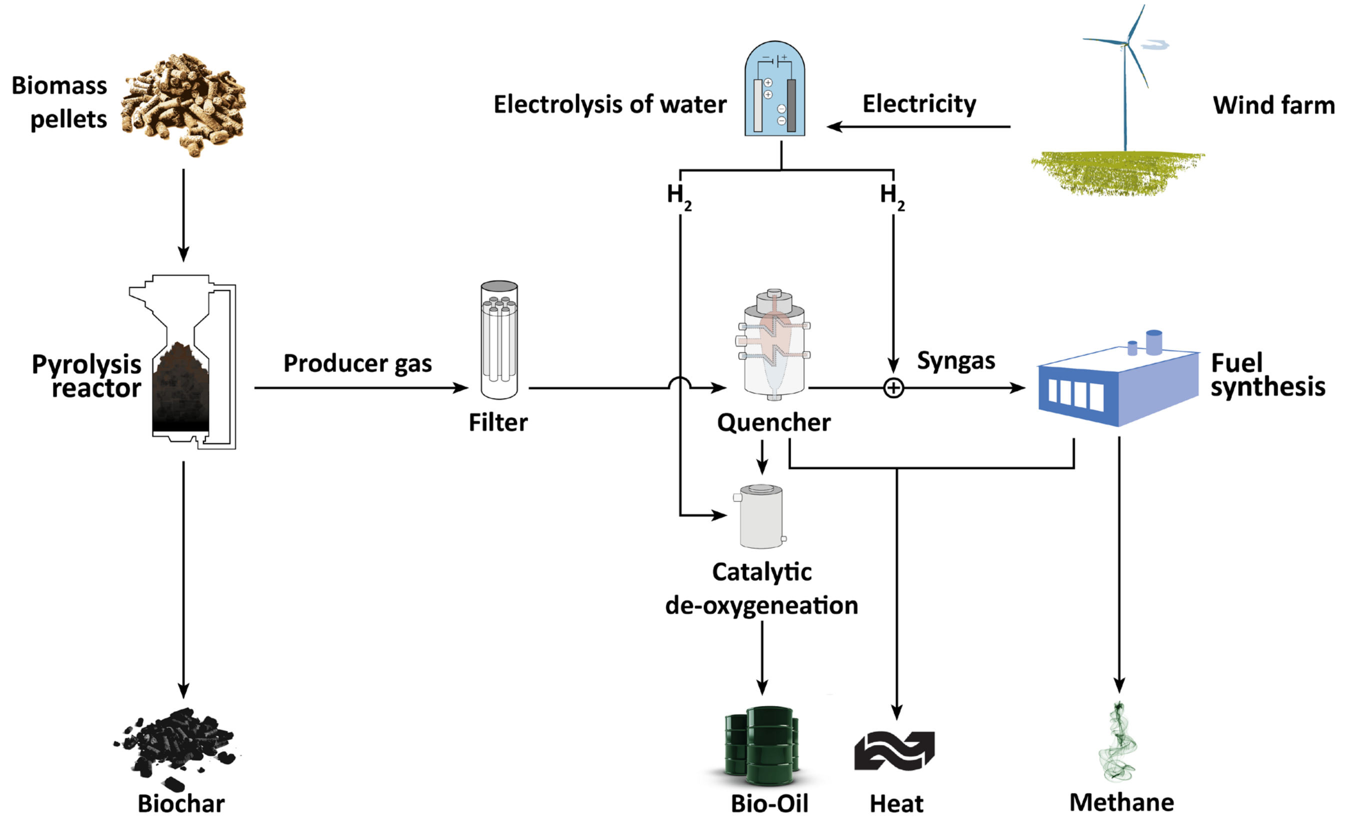

Figure 20: *Conceptualization of a system for production of biochar, bio-oil, methane and heat from biomass pyrolysis. Illustration by the author.*

In the examples above, methane and methanol are in focus, but other chemicals/fuels like DME (di-methyl-ether) have also proven to have a substantial potential in e.g. marine shipping and may be produced in processes involving both pyrolysis and thermal gasification of biomass[62].

4.4 Systems for drying and pyrolysis of wet biomasses

Biomass with high moisture content like food waste, grass, digestate etc. is also eligible for pyrolysis. However, the material typically needs to be dried first to optimize operation and economics. This can be done in either integrated systems with drying and subsequent pyrolysis in the same location, or in systems with separate locations for the drying and pyrolysis process. In general, these systems add new products in the form of condensates and gases from drying as well as a liquid phase from initial mechanical separation/filtration. There are many different configurations to consider when combining drying and pyrolysis, including e.g.:

- Integrated or de-coupled drying
- Air-drying or steam drying
- Atmospheric pressure or pressurized drying
- De-coupled low temperature or high-temperature heat-pump based drying

There are benefits and drawbacks of all systems. Conventionally, much drying has been conducted using hot air, but in recent years there has been an increased focus on drying processes that use super-heated or pressurized steam. Steam dryers are typically more compact and energy efficient than air dryers – especially in systems with a demand for district heating. In addition, the fire hazard of the drying process is severely reduced. On the other hand, the steam drying process is more technically advanced than conventional hot air drying and therefore the equipment can be costly. The Danish company AquaGreen develops systems for integrated steam-drying and pyrolysis as discussed further in the status in chapter 6. An illustration of potential implementation of an integrated system for steam drying and pyrolysis is provided in Figure 21.

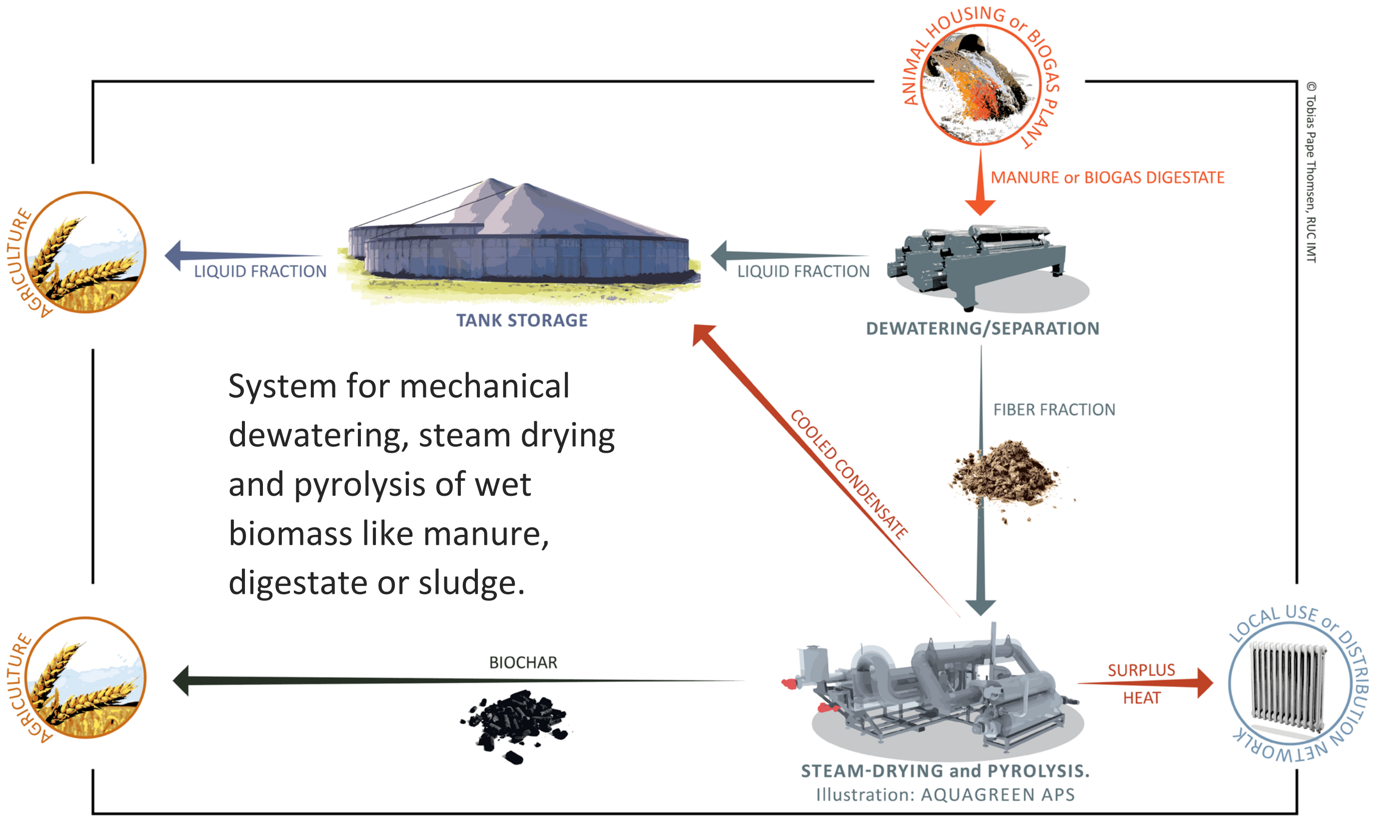

Figure 21: *Simplified diagram showing a concept for an integrated system for drying and pyrolysis of wet biomass for the production of biochar, heat and fertilizer liquids. Illustration by the author.*

As a result of ongoing electrification, more thermal conversion systems and drying systems are being developed with electrical heating. This is the case for e.g. Biogreen pyrolysis systems[63], the flash-pyrolysis systems developed by Frichs Pyrolysis[64] and the microwave assisted pyrolysis systems under development by Organic Fuel Technology[65]. Also in drying systems, there are many options for electrically driven processes. These may include various heat-pump based solutions at either high temperature[66] or low temperature[67] or separate, electrically heated stand-alone steam dryers as those developed by the Danish company AquaGreen for sludge management without subsequent pyrolysis[68].

In cases where very wet biomass should be treated in integrated systems without external energy supply, it is necessary to secure a dry matter content of around 25-30% to obtain an energy surplus in the integrated system. The dry matter content can be increased mechanically by pressing, sieving, filtering and high-speed centrifugation or by mixing with substrates with high dry matter content.

4.5 Many options to increase the product palette with various chars, gases and liquids

There are many other relevant system configurations and many other options for producing a variation of products from biomass pyrolysis than those presented in the previous sections.

In processes with initial drying there will be condensates, uncondensed vapors and exhaust gas that need to be considered for use or subsequent treatment.

It is also an option to expand the biomass pre-treatment with torrefaction to modify the physical and chemical properties of the biomass. There will be off-gases from biomass torrefaction, and these may contain both condensable and non-condensable product fractions of which some may prove to have high chemical quality and potential value.

In systems with bio-oil extraction at very low temperatures, several phases will develop in the compiled product. It is possible to separate the oil product into several different phases by storing/settling the produced oil under controlled temperatures. Often three layers may occur over time:

- On the top there will be an oily liquid
- In the middle there will be a transparent, yellow-brown liquid commonly referred to as raw wood vinegar
- In the bottom, there will be a thick bio-tar settling

The potential value and use of some of these fractions is discussed in section 5.2. The oily liquid and the heavy tar can be further treated and separated into additional product fractions e.g. by distillation. The condensable fractions may also be taken out from the hot gas in steps starting with extraction of the tarry oils at > 250 °C, and ending up with watery fractions at temperatures < 100 °C.

It is also possible to add processes for char activation (using steam and/or CO_2) or char oxidation (using air) which will generate both new char products and new gas products. Char oxidation will also generate additional heat while the steam based char activation process has a requirement for heat. The produced char can also be used in char-bed tar-cracking processes which will change both char and gas qualities[69].

5 Value propositions from production and use of biochar

It is not straightforward to describe and/or evaluate value propositions from production and use of biochar, as it constitutes a new, diverse set of possible actions and it is still under rapid development. In addition, the effects and site-specific context is trans-sectoral and may potentially involve many different stakeholders across many different types of value chains and –networks. It is a highly complex situation, and one that holds many unresolved possibilities, limitations, barriers and unexpected outcomes. The following chapter tries to outline some of these on a general level.

In 2009, Johannes Lehmann and Stephen Joseph published the first version of the book "Biochar for Environmental Management: Science and Technology"[70]. This book was updated in 2015, and provides a splendid introduction - and a lot of relevant data, related to production and use of biochar. The book also includes considerations about value propositions and value creation from production and use of biochar as illustrated in the figure below.

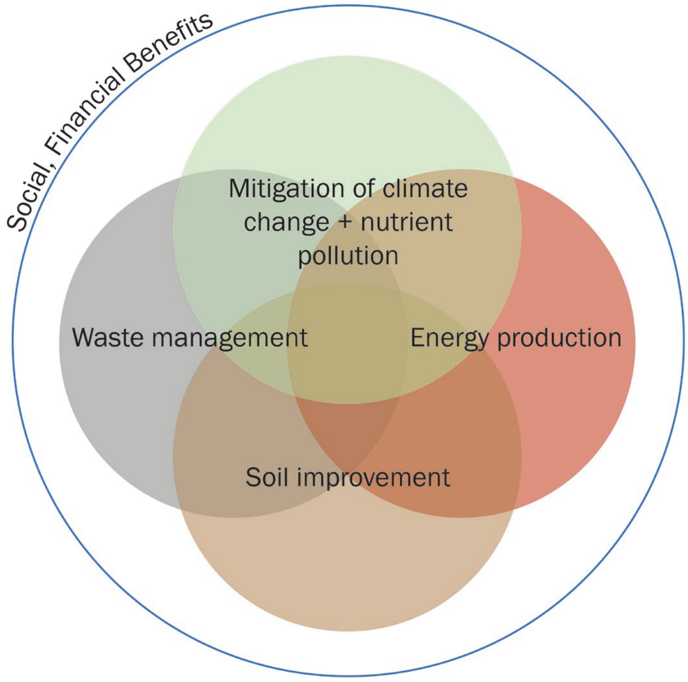

Figure 22: *Lehmann's and Joseph's value proposition framework related to production and use of biochar in a modern society. Remake from original model[71].*

In relation to the model, the authors write (from Cornell University's website) *"Biochar is not a silver bullet that will solve environmental problems without a much wider and far-reaching strategy. But it can provide an important tool to addressing a wide range of the major challenges: soil degradation and food insecurity, climate change, sustainable energy generation and waste management"*[72]. Lehmann and Joseph's central propositions are discussed in the following. The aim is to outline how production and use of biochar should be seen as a versatile multi-tool that (if applied intelligently) may help in many different ways to resolve the socio-ecological multi-crisis and help facilitate development of a more circular and more bio-based economy. Despite these potentials, biochar is not a one-size-fits-all, no-brain climate-crisis silver bullet in itself, and in chapter 7 some of the apparent risks, limitations and barriers are briefly discussed.

5.1 Value from char use

5.1.1 Char use in agriculture

In Denmark, there is an overwhelming focus on use of biochar in agriculture. Almost all larger R&D projects on production and use of biochar have an agricultural focus, and some agricultural organizations (e.g. The Danish Agriculture and Food Council) are very active in both development, dissemination and lobby activities. Denmark is a very intensely managed agricultural country, and agriculture constitutes a potentially huge market for large-scale bulk use of biochar. The agricultural focus differs from the approach in neighboring countries, and according to Harald Bier from EBI, it is perhaps also one of the most difficult char markets to develop with regard to both effect validation/documentation, praxis development, regulation etc. This may be one of the reasons why markets for biochar-use in Denmark is generally less mature than what is seen in e.g. Sweden, Finland and Germany.

With the high agricultural intensity in Denmark, it is important to investigate the potential value propositions from agricultural biochar use. Some of the effect categories to investigate include:

- Greenhouse gas emission reductions at farm level
- Soil enhancement effects
- Effect and value of biochar-based fertilizers

These effect categories are discussed briefly in the following. There are many good publications to look up for further assessment of the effects of using biochar in agricultural soils. The Danish knowledge synthesis by Elsgaard et al. from 2022 provides many valuable insights with a particularly Danish focus[73], while the extensive review by Joseph et al. from 2021 is a great resource for assessment of the general situation[74].

5.1.1.1 Greenhouse gas emission reductions at farm level

The primary effect potentials related to mitigation of the climate crisis from biochar use at farm level include 1) Pyrogenic Carbon Capture and Storage (PyCCS) effects and 2) Nitrous Oxide (N_2O) emission reduction effects. Some additional climate impact effects related to the pyrolysis process and the full system are discussed in the subsequent sections.

PyCCS: The PyCCS effect (Pyrogenic Carbon Capture and Storage) relates to the potential to establish a carbon sink when amending biochar in soil due to the significant thermal stabilization of carbon in biochar that occurs during pyrolysis. After pyrolysis, the carbon in the biochar is bound in predominantly aromatic structures that are not easily biologically degradable, and this carbon may stay in the soil for hundreds or thousands of years depending on a range of factors. A small part of the carbon in the biochar will not be fully stabilized and may be converted and released in a few months. In a meta study from 2016, Wang et al. found that on average all the assessed samples contained around 3% of this labile carbon and 97% carbon in the more recalcitrant carbon pools. In addition, the authors found that the Mean Residence Time of these two carbon pools in the soil was around 108 days for the labile carbon and 556 years for the recalcitrant carbon, respectively[75].

Obviously, it is difficult to investigate and determine carbon persistence levels e.g. 100 years after application of biochar to a soil. However, due to the large impact potential, this is an area with huge focus, and different proxy methods are being developed and validated to estimate biochar carbon stability over long time horizons. The state-of-the-art approach to this issue is using the H/C_{org} and O/C_{org} molar ratios in the biochar as proxy for the effect of the pyrolysis process and thereby the stability of the carbon in the char. This approach is relatively cheap and simple compared to incubation studies, isotope labeling etc. The proxy method has been refined several times, and in 2021 an updated proposal on the method was published encompassing soil average temperature, which is expected to play a substantial role in the carbon persistence over time[76]. However, the H/C$_{org}$ and O/C$_{org}$ do not take into consideration the variation of carbon-stability throughout a given biochar product, and there are interesting perspectives in development of new methods separating biochar carbon into persistent pools and labile pools as well.

In addition to the level of carbon persistence, the PyCCS of biochar also depend on the carbon content of the biochar. Figure 23 shows an example of variations in the estimated 100-year PyCCS effects from variation in total carbon content in the biochar. The data include an assumption of comparable carbon persistence of 75-85%. The results are from the recent Interreg ØKS project “Greater Bio”.

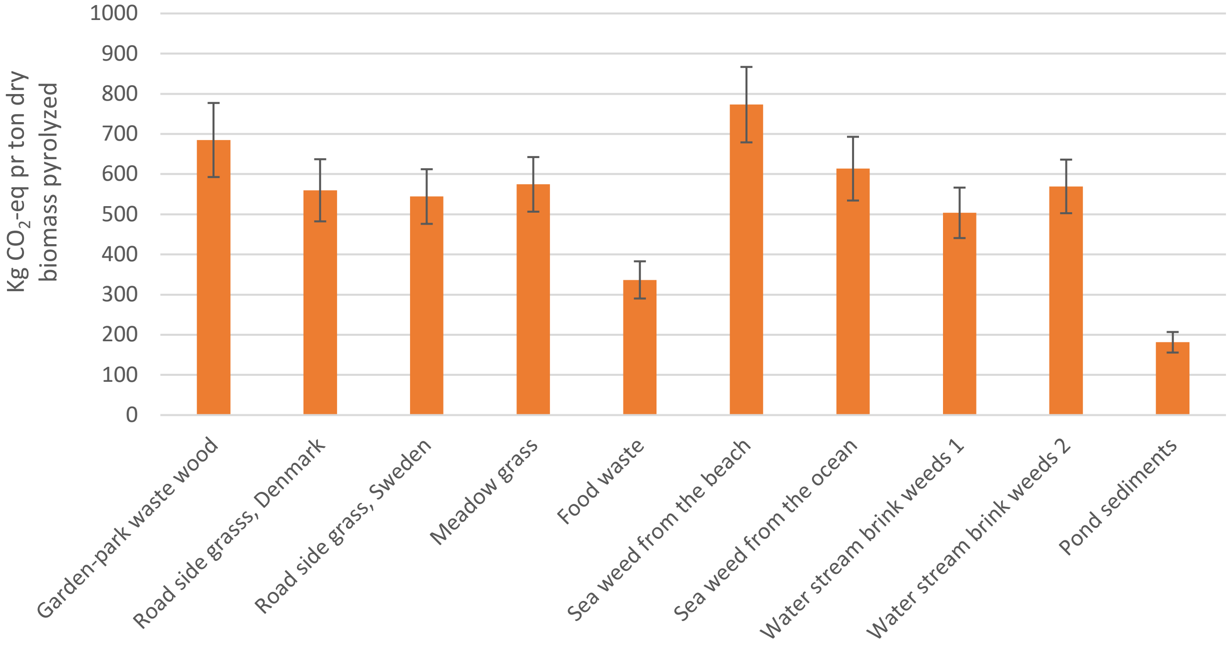

Figure 23: *Estimates of PyCCS effect of various biochar products. Biochars are all produced in the same lab-scale process. The carbon persistence is assumed to be 75-85% (error bars) in a 100-year time frame for all biochars and the PyCCS variation is based on carbon content only*[77]*.*

Due to the increase in carbon stability as a function of pyrolysis, biochar can build carbon sinks faster than amending the biomass directly to soil without prior pyrolysis treatment.

When biomass and biochar are both amended into soil, the microbes in the soil will rapidly mineralize a substantial amount of the biomass carbon while only a minor fraction of the biochar carbon will be converted. However, in the initial years after amending biomass >< biochar, this effect is diminished by the fact that a lot more carbon is amended into soil when applying straw directly, since only up to 50% of the biomass carbon is retained in the biochar during pyrolysis. Despite this difference in the amount of carbon initially sequestered, it will only take a few years before more of the carbon persists in the soil where biochar was applied. An example showing the persistence of carbon conversion from straw and straw biochar amended into soil is provided in Figure 24 based on C-tool[78] modelling of the mineralization processes. The modeling indicates that on day 1, approximately 1500 kg of CO$_2$-equivalents (CO$_2$e) is sequestered in the straw carbon while just above 600 CO$_2$e worth of carbon is sequestered in the biochar case. The large difference is due to the significant share of the straw carbon that was released as pyrolysis gas - and hence converted into exhaust gas and energy products, in the pyrolysis. Despite the large difference, the modeling indicates that it only takes a little more than one year before the balance has shifted and more carbon persist in the soil where biochar was applied.

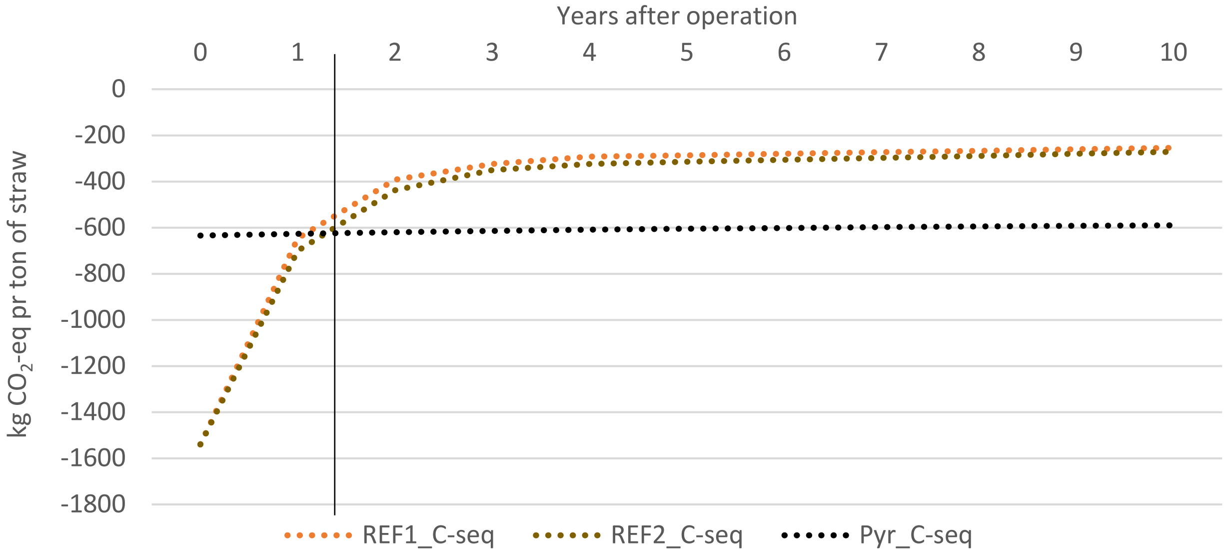

Figure 24: *Preliminary assessment of the effect of carbon sequestration on total climate impact of straw management by direct soil amendment (REF) or thermal pyrolysis and amendment of biochar (PYR). Two different research groups (AU and SDU) conducted the modelling of the straw conversion, while the conversion of biochar was modelled at DTU*[79]

The initial sequestration level and the rate of conversion in the first 5-10-20 years is relevant for near-term impact and potential mitigation of climate crisis damage here and now. For assessment of the long-term impact, it is relevant to assess the level of total carbon converted during a longer time frame. Most often, 100 years are used for assessment of long-term effects. Due to the simultaneous requirement for long-term effects and here-and-now effects (e.g. today or in 2030 or 2050) it makes sense to include results from both short- and long-term assessments. For the above example, the modeling indicated that after 20 years, the straw amendment still provide 200 CO_2e worth of carbon sequestration, while this is reduced to around 30 CO_2e after 100 years. In the pyrolysis case, the effect persisting after 20 years is found to be just below 600 CO_2e which has been reduced to around 540 CO_2e after 100 years[80].

The PyCCS effect represents a relevant addition to the energy production from biomass pyrolysis as the PyCCS constitutes a climate-crisis mitigation effect that does not decline with future reduction in the climate intensity of energy production (electricity, heat, transport fuels). Also, PyCCS opens a possibility for de-centralized and broadly distributed carbon-negative activities with various (positive) side-effects. From an economic perspective, the PyCCS effect may be of huge value as it is irreversible and therefore relatively simple to document. This is discussed further in chapter 6.

It can be argued that the PyCCS effect of amending biochar to soil will also persist if biochar is stored in other environmental or societal compartments. That will be true in many cases. It is, however, important to acknowledge the value of irreversibility when securing a sink effect. Biochar amended to soil cannot be extracted while biochar stored in a reachable location like a cavern, abandoned mine or elsewhere, may be re-extracted and used/burned in which case the sink is lost. As discussed in the next paragraphs, the biochar in the soil may also have substantial benefits that may be lost otherwise. In addition, any nutrient content in the biochar will not drive biomass production while stored outside the natural environment. This is essential to acknowledge for large-scale implementation of a pyrolysis sector in a circular, bio-based economy. On the other hand, storing biochar in bulk amounts away from soil biology – and maybe even in cold regions, may increase carbon stability levels while stored. With such an approach, any contaminants remaining in the char will also be redirected away from the natural systems. This may render non-soil storage/-use a valid option in cases where the biochar contains very high concentrations of non-volatile pollutants e.g. certain heavy metals.

N_2O emission reduction effects: There have been many studies on the potential N_2O emission reduction effect of adding biochar to agricultural soil. In a review and meta-analysis study from 2014, Cayuela et al. found substantial effects of biochar addition on soil N_2O emissions, but result variations were also found to be severe and the studies not always easy to compare[81]. Results spanned from being extremely positive to having no or even negative impact. Regardless, the researchers concluded that - overall, biochar could reduce soil N_2O emissions by up to 54% based on results from both laboratory experiments and field studies. Biomass feedstock, pyrolysis process conditions and the C/N ratio in the produced biochar were found to influence N_2O emissions severely, and a direct correlation between the biochar application rate and impact on the emission reductions was found. In an experimental study from the same year – and by some of the same researchers, it was found that in two experiments with the same experimental conditions, the addition of biochar to one type of soil decreased N_2O emissions by 76%, while the addition of the same biochar, under similar conditions, to another type of soil increased N_2O emissions by 54%[82]. Another, more recent, meta-analysis found similarly large variations in the results, and an overall average effect of 38% reduction. However, in this study it was also found that the reduction effect seems to be very short lived, and sometimes only lasts for one year[83]. Following up on this aging issue, a study from 2018 by Duan et al. showed that fresh biochar reduced N_2O emissions while 5-year old biochar increased emissions compared to the control[84]. With a huge effect potential – and a similarly large risk of negative effects, this matter is of outmost importance when the objective is to optimize value creation from agricultural application of biochar to soil. The effects of biochar on N_2O emissions are still not completely understood or determined and the effect matrix is expected to be very complex including e.g. pH regulation, aeration, electron-shuttle effects and more[85]. The effect seems highly context dependent, and the topic is a significant part of several ongoing, Danish, R&D projects including the Mitichar project lead by Sander Bruun at KU PLEN, the SkyClean Scale-up project lead by Jesper Noes from Stiesdal SkyClean, and the recent project “Optimization of biochar properties for maximum reduction of N2O emissions from agricultural soils” lead by Beatriz Gómez Muñoz from KU PLEN.

Additional GHG emission reduction effects: There are also other potential on-farm GHG emission reduction effects related to biochar use that are relevant to investigate further. These include e.g. the potential reduction of methane from composting processes and fiber stacks and the use of biochar as feed for cattle to stabilize digestion and reduce methane emissions. There are some examples of relevant literature on these topics in the references[86]. In addition to this, the nutrient recovery and soil enhancement effects of biochar may also lead to indirect emission reduction. Some of these effects are outlined in the following and others are described in a short report by Henriksen et al. about biochar in Danish agriculture 2019[87].

5.1.1.2 Soil enhancement potentials

Soil enhancement is a huge topic with many different potential effects, mechanisms and interdependencies. It is a topic that is highly prioritized in Danish biochar research together with biochar nutrient fertilizer value. In this report, only a very brief introduction is given and some recommended sources for further information are provided.

Over the years, many studies on biochar soil enhancement effects have shown significant value creation potential via increased crop yields or reduced input. Some recent examples include e.g.:

- A study by Baronti et al. from 2022 showed that 10 years after biochar was amended into soils at a vineyard, the treatment continued to increase soil water content and the water status of the plants in the plots treated with biochar[88].
- In a two-year study, published in 2022, Ahmad Khan investigated the use of biochar in wheat production in a calcareous soil[E], and found that biochar increased the effects of the nitrogen fertilizers and gave substantial increases in grain protein content, yield of grain and straw and total N concentration and uptake in all plant parts[89].
- In another field study from 2022, Thomas Kätterer et al. concluded that "*application of biochar, locally produced from available biomass residues, is a promising approach to enhance agricultural production and carbon storage on smallholder farms under a wide range of pedo-climatic*[F] *conditions in Kenya*"[90].
- Several studies show positive effects of rice straw biochar used in production of maize in Kenya[91].

In the biochar knowledge synthesis by AU, results from 6 large studies and meta-studies on biochar yield effects show average yield increases of 10-25%[92]. However, such results are mostly found in foreign studies conducted under agricultural contexts that are not comparable to the settings across Denmark. Examples of specific use of biochar in DK soils that evidently increase soil quality do exist, e.g. a series of studies on fine particulate biochar in coarse, sandy subsoils that evidently increase soil water levels and root growth[93]. However, even these beneficial effects are difficult to transfer to grain yield increases[94], and in general many of the studies conducted in Denmark on Danish soils and cropping systems have shown little or no effect, and some have even shown a negative effect on yield:

- In a large field study on Bregentved Estate in Denmark, it was found that there were indications of possible effects of straw based biochar on soil exchangeable potassium content, pH and the quantity of certain soil microbes, but with no significant effects on yield of neither winter wheat nor winter oilseed rape[95].
- The Biochar knowledge synthesis from AU (2022) describes two experiments that showed no effect in maize from application of moderate amounts of biochar and negative effects from application of excessive amounts (50 t/ha) of biochar in Kalundborg, Denmark 2011-2012[96].
- A study conducted at AU in 2016 on use of biochar in potato production, showed a reduced yield[97] while another study in the department on use of biochar in potato production (from 2022) found that the negative effects on potato yield related to reduced plant uptake of N and P, and that application of Arbuscular mycorrhizal could alleviate the negative impact[98].

The differences among such studies are often many, and it is not easy to conclude across such variations in materials and use context. However, on the very general level Sørensen and Abalos (2022) concluded that:

> *"Indeed, recent research has shown that biochar has, on average, no effect on crop yield in temperate latitudes (Jeffery et al. 2017*[99]*). Conversely, biochar promotes a 25% increase in yield in the tropics. This is because arable soils in the tropics often have low soil pH, low fertility, and low fertilizer inputs, whereas arable soils in temperate regions are more neutral in pH, have higher fertility, and generally receive higher fertilizer inputs, limiting the potential yield benefits from biochar".*
>
> Peter Sørensen and Diego Abalos[100]

[E] Soil with a high carbonate content, often clay-rich and "sticky".

[F] Microclimate in the soil, governed by temperature, water content and oxygen levels.

This does not mean that there is no optimization potential in a Danish context. It is likely that biochar application in a Danish agricultural system may still provide beneficial effects by e.g.:

- Manage soil pH
- Reduce soil density and compaction (reducing diesel use, improving various soil functions)
- Increase water holding capacity and plant available water (reducing irrigation needs and increasing growth stability in sandy soils)
- Increase nutrient retention (through both adsorption to/in char and optimized soil physics)
- Improve water infiltration (reducing flooding and water locking in compact, clay soils)
- Increase soil aggregate stability (facilitating processes for e.g. decomposition of soil organic matter as well as flows of water and air)
- Help build soil life habitats and benefit the soil biome (the "soil coral reef" hypothesis)

These – and other, potential effects of amending biochar to soil are addressed in great detail in AU's recent knowledge synthesis on biochar in Danish agriculture[101], in Lehmann and Stephen's central biochar book[102] as well as in the vast – and accelerating, number of other peer reviewed publications[103]. Continuous investigations – both mechanistic and in practical use-environments, are important due to the persisting knowledge gaps and the high context dependence of these effects. The long-term aim should be to increase yield stability, system robustness and resilience in a fluctuating climate under influence of increased global weirding as well as to reduce leaching, losses and input of fertilizers and agro-chemicals. Many potential effects related to yield are also related to nutrient efficiency increases, and while adding biochar alone may have little or no effect, adding biochar with fertilizer may provide additional benefits compared to adding fertilizer without biochar. This is addressed in a meta-study from 2019 by Ye et al.[104].

In general, soil enhancement effects are easier to obtain in poor, arid and nutrient depleted soils than in good, healthy and productive soils. To obtain effects in a Danish context, it may therefore become necessary to investigate options for e.g. post-process treatment of the char. The aim hereof will often be to improve physiochemical properties by e.g. increasing the specific surface area, increasing the number of functional groups, doping with specific metals etc. or to better position the char effects in a biological context by charging the biochar with suited nutrients or substrates or directly inoculating it with specific microbe cultures etc. There are many different approaches to post-process char enhancement and it is another huge topic that is undergoing rapid development. It overlaps in many places with the production of biochar based fertilizers as discussed in the next section. There are different general pathways to modify biochar to increase effects in relation to a specific use purpose. These pathways include e.g.

- Physical modification/ Physical activation, e.g. treatment of the char with gasification agents e.g. steam, oxygen, CO_2 or ozone, thermal modifications by heating (inert) or microwave irradiation or high-tech methods involving ultrasound waves, plasma, and electrochemical methods.
- Chemical modification/ Chemical activation e.g. acid washing, doping (of biomass before pyrolysis) or impregnation (of biochar after pyrolysis)
- Aging and surface oxidation
- Charging, mixing and co-composting
- Inoculation

More information on the different approaches to optimization of biochar soil enhancement effects can be found in the many publications available on these topics. Some examples are provided in the references[105].

Biochar addition to soil may also create value via reduced leaching and stabilization of toxins in the soil. Avoiding the movement of nutrients into aquatic compartments (i.e. lakes, streams, fjords) will reduce eutrophication in those areas, benefit the ecosystems and reduce methane emission potentials by avoided algae growth and decay. Stabilizing toxins in the soil may help preserve ground water quality in water procurement zones, and also reduce leaching of harmful substances into aquatic ecosystems. The potential benefits to ground water in a Danish setting will be preliminarily investigated in the BioStore R&D project as part of Innomission pool 1 lead by Dorette Müller-Stöver from KU PLEN. Much research on stabilization of e.g. PFAS, heavy metals etc. have been published already and a few recommendations for further reading are provided in the references[106].

5.1.1.3 Biochar-based fertilizers

Overlapping with parts of the previous section is a discussion about potential value from using biochar as a fertilizer – and/or a discussion about using biochar in the production of fertilizers. A very brief introduction to this topic is provided here, while several sources of additional information can be found in the references[107].

The potential fertilizer value from direct use of biochar relates primarily to 1) biochar content of nutrients, 2) plant availability of the nutrients and 3) biochar effects on soil influencing plant uptake of nutrients. Combined with a lot of external factors related to soil, plant and system, these characteristics will govern the rates and levels of nutrient plant availability and fertilizer value. This is illustrated in Figure 25.

There are nutrients in biochar, but as illustrated in the figures in section 3.1, there is substantial variations in the content hereof. Regarding the non-volatile nutrients, e.g. phosphorus, magnesium and potassium as well as most micro-nutrients, their concentrations in the biochar depend primarily on their respective concentrations in the treated biomass. For the more volatile nutrients sulphur and, especially, nitrogen, the concentration in the biochar depends on both biomass content of these nutrients and the design and operation of the pyrolysis process.

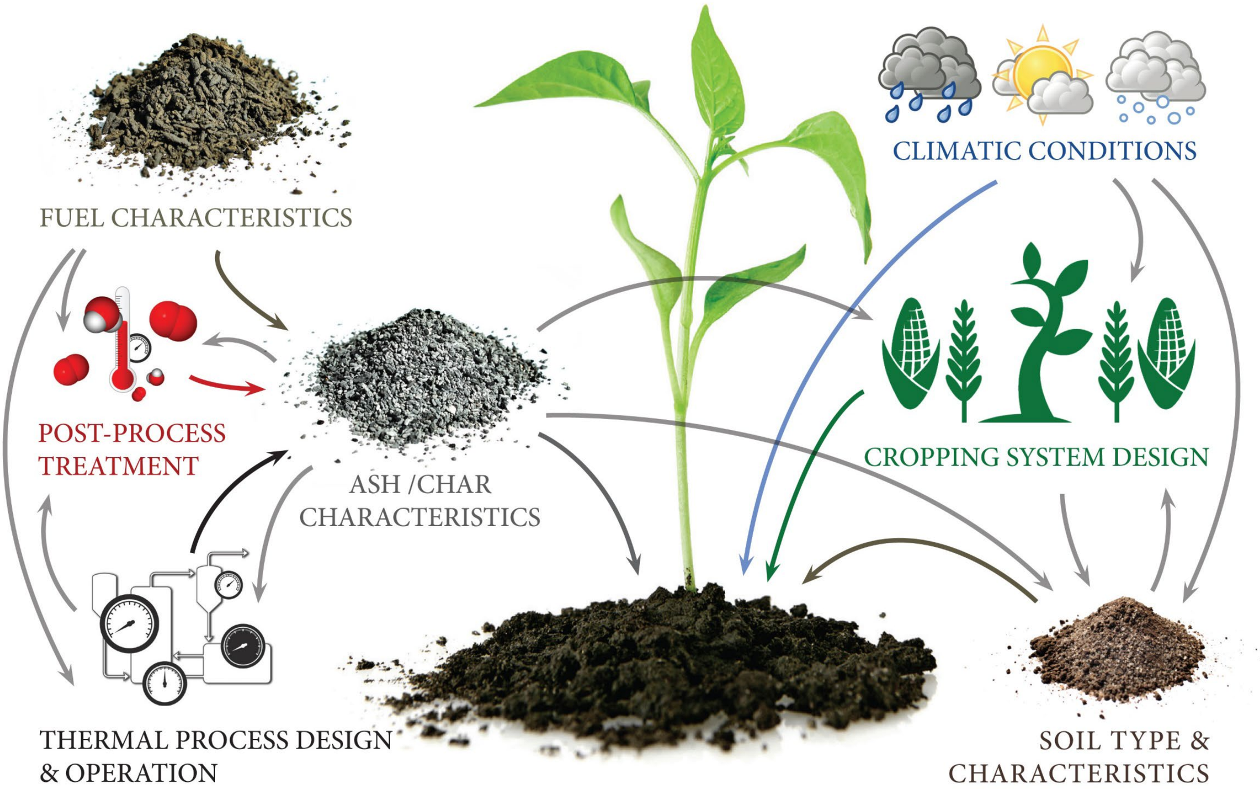

Figure 25: *Simplified visualization of some main factors governing plant fertilizer value of nutrients in biochar- or ash products. Illustration by the author.*

In addition to the nutrient content in biochar, the fertilizer value of these nutrients can also be of high importance to the crop yield. The plant availability of different nutrients in different biochars vary substantially – also with the use context. Here are some experiences from recent years:

- Nitrogen is typically present in limited amounts as most biomass-N is lost in the pyrolysis process[108]. The fertilizer quality of residual char-N is often very low[109].
- Phosphorus can be present in different concentrations from very low (e.g. wood-based) to very high (e.g. based on manure or meat and bone meal), and the plant availability depends a lot on the phosphorus species that are formed in the pyrolysis which again depend on the minerals and metals in the biomass as well as the production process settings. In addition, the soil type and plant species can play a huge role in the availability of biochar phosphorus if plant growth in the given soil is P-limited[110]
- Potassium (and magnesium) are often less active during the thermal process than phosphorus, and the plant availability of potassium in biochar has often been found to be quite high[111]
- Sulphur is more volatile than P, K and Mg but less so than N in the thermal process. The concentration in the biochar can vary substantially and so far, there are only indicative studies published on the fertilizer value of sulphur in biochar[112].

The impact of both quality and quantity of the different nutrients that a plant requires depend a lot on the soil-climate-plant context. In nutrient-depleted soils/growing media it will be highly important to provide all required nutrients in forms available to the plant to facilitate growth. In more robust soils, the requirements for both amount and quality may be less severe, and a soil rich in both organic matter and phosphorus may not show any yield impacts from application of additional phosphorus no matter how high the solubility of the nutrient[113]. Very simply put, it could be argued that biochar products with highly soluble forms of such nutrients should be prioritized for use on infertile soils whereas the biochar with slow-release of e.g. P and K could be applied to soils with less immediate requirements. In some systems, the combinations of a slow-release fertilizer and a water-soluble mineral fertilizer may also have benefits in relation to increased nutrient efficiency and reduced leaching[114].

As this was a very general – and in many cases over-simplified, presentation of selected points related to a huge topic it is recommended to look up some of the references mentioned in the end-notes.

Due to the large variation in biochar nutrient content, there will be cases where biochar can be a fertilizer and there will be cases where it cannot. However, the simple distinction between these two categories does not fully describe the options for using biochar in fertilization. In many cases, the biochar will not in itself contain/provide all the nutrients required for production of a given crop in some production context. And for this reason, it will often make sense to look at the effects of biochar on plant fertilization in a system where the biochar is supplied alongside other fertilizers and/or where the biochar is used in the production of more complete biochar-based fertilizers. In 2019, Ye et al. published a meta-study about yield effects from fertilization of biochar and other fertilizers alone or in combination. In this study, it was concluded that on the very general level i) biochar alone typically led to no significant effect on yield, ii) inorganic fertilizers typically increased yields with 15%–40% compared to the control, and iii) a combination of biochar and inorganic fertilizers gave a 30%–70% increase in yield compared to the control[115]. However, this issue is more complicated that the simple numbers indicate, and there are many different approaches to the use of biochar in plant fertilization. These pathways can include very different initiatives like[116]:

- Using the nutrient rich biochars directly in soil to provide naturally occurring nutrients to plants
- Use nutrient rich biochar as slow-release fertilizer in combination with faster fertilizers
- Mixing biochar with other substrates prior to soil amendment e.g.
    - Mineral-biochar composite fertilizers
        - Clay-biochar composite fertilizers

        - Zeolite-biochar composite fertilizers
        - Layered double hydroxide-biochar composite fertilizers
    - Mixing and charging biochar in manure- or digestate liquids
    - Co-composting biochar with organic materials e.g. garden/ park waste, food waste etc.
- Impregnation of biochar with solubilized nutrients and micro nutrients
- Co-pyrolysis of various biomasses to optimize nutrient balances and fertilizer value in biochar
- Coating and encapsulation of biochar with water soluble layers containing various nutrients
- Use biochar with low nutrient content as a soil enhancer to increase use efficiency of nutrients. To avoid the risk of negative effects on crop yield, this approach need to be optimized with regard to timing and the nutrient flows in the specific agricultural setup.

5.1.2 Char used as soil enhancer/fertilizer in urban greening, horticulture, gardens etc.

Biochar can be applied as both soil enhancer and biochar-based fertilizer in many different non-agricultural systems as well. These include e.g. urban greening systems (e.g. green roofs, rain water beds, city tree planting etc.), urban gardening systems and in horticulture (e.g. as peat substitute growing media, soil enhancer etc.) and in commercial soil production. Stockholm, Sweden is one of the first cities in Europe to test large-scale application of biochar for different urban greening projects, and a lot of experience on this use has been collected over the years[117]. In recent years, several other cities (e.g. Helsinki in Finland[118] and Minneapolis in the US[119]) have acted on the inspiration from Stockholm and are engaging in development and test of urban biochar use. There are many sources from both academic research and practical tests and applications within these topics and a few examples are provided in the references[120].

5.1.3 Value from other uses of biochar

It is argued by some researchers and stakeholders that carbonized biomass used outside agriculture, horticulture, gardening, urban farming etc. should not be referred to as biochar, but instead of charcoal, carbonized biomass etc. However, in the following, various uses of char made from biomass in non-soil application are briefly reviewed. In some cases, it may be expected that the char will ultimately end up in a soil environment anyway, while in others this is not very likely. In any case, this is a huge topic under very rapid development, and only a very general introduction is provided. Describing the value creation from these example cases is not feasible as the impact is context dependent and the development is in many places not mature or scaled. However, the potential benefit from use of biochar in various settings will often be either;

1) Product substitution (replacing fossil or mineral products with bio-based products)
2) New products and/or value chains and services hereof
3) Improved products and/or value chains

Some options for non-soil use of biochar are listed in the following. For a more elaborate list of potential uses, there are some articles recommended in the references[121].

- Environmental remediation applications
    - Inorganic pollutant removal from wastewater
        - E.g. heavy metals removal or removal of dissolved nutrients
    - Removing organic pollutants from wastewater
        - E.g. dyes, phthalates etc.
    - Removing pollutants from gases
        - E.g. sulfur compounds
- Energy storage applications via high-tech production and modification of biochar or use in e.g.

    - Electrodes in super-capacitor production
    - Anodes or inter-layers for battery production

- Biochar-based composites
    - Biochar–inorganic-based composites
        - E.g. in concrete[122], asphalt as additives, fillers and carbon storage
    - Biochar-containing reinforced plastics
    - Biochar-based, organic building materials
        - E.g. Char hemp-crete building material and various bio-composite materials for insulation, moisture control, noise reduction etc.
    - Coatings and paints
        - Filler, color, additive

- Catalytic and process-enhancing effects
    - Biochar-based catalysts
    - Biochar as anti-bacterial agents
        - E.g. silver doped
    - Process enhancer in anaerobic digestion processes
        - E.g. preventing ammonia inhibition, removing toxins and pollutants, stabilizing and enhancing methane production processes

- Feed additive and medicine
    - Animal feed to stabilize digestion and bind toxins
        - Larger animals (e.g. cows, sheep, horses) as well as poultry and pets
    - Medicine
        - E.g. Detoxification via toxin binding

5.2 Value from oil and gas use

Currently, the primary focus related to pyrolysis gas utilization is on various forms of energy utilization as also discussed in chapter 4. This could include e.g.

- Combustion of the complete, hot pyrolysis gas for production of high temperature heat
- Cooling of the gas to below tar dew-points to extract oil for use in burners or large marine engines
- Cleaning of residual gas for synthesis of fuels
- Addition of hydrogen to improve C/H ratio for fuel production

Overall, the value of the energy production relate to the costs and benefits of the pyrolysis energy product compared to the energy product it replaces. This may include e.g.:

- Environmental impact/climate intensity of reference energy source >< pyrolysis product
- Economical differences including certificates for non-fossil energy
- Energy quality differences

Except for the direct utilization for heat production, none of the above are simple, fully mature end-use pathways. Bio-oil from pyrolysis is a category of products more than a single, standardized product. It has various disadvantageous characteristics compared to fossil oil in the current infrastructure, but there are many different ways to approach and solve these issues (described in chapter 4 in general and in section 4.1.5 in particular). Use of bio-oil for energy purposes has been investigated and developed for many years, and there are numerous studies recommended in the references to expand on this topic[123].

If the oil is extracted at temperatures close to the water dewpoint, then the collected product will contain substantial amounts of water and other smaller condensable compounds. Settling the product and separating out the water fraction and the substances that follow will lead to a *wood vinegar* product. Wood vinegar is not an energy product, but a complex mixture of water (80-ish vol%), acetic acid (up to 10 vol%), phenols (up to 5 vol%) and hundreds of other ingredients i.e. various minerals, acids, alcohols and other compounds[124]. Several non-energy applications of wood vinegar have been investigated over the years, and many potential uses have been proposed including 1) fungicide/pesticide/plant protection, 2) Odor control in stables and manure, 3) biochar tablets for fodder supplement and for water cleaning, 4) Complex plant-nutrient and growth stimulator, 5) Composting agent, 6) Cleaning/bleaching/disinfectant etc.[125]

It is, however, not only the wood vinegar product that has various use potentials outside the energy- and transport sectors. Both the tar/oil fractions and the permanent gases have advanced uses under development that will valorize the chemical quality of the products to a larger extent. The most well-known use of bio-oils of this type is probably as wood preserving agent in traditional wood-based roof constructions and for boat building in e.g. Finland and Sweden[126]. In addition to traditional use as water repellant in wooden roofs, ships and other constructions, the oil/tar products from biomass pyrolysis have been investigated for use in e.g. food flavoring (liquid smoke), as insecticide, herbicide, rodent control, mollusks control, in production of bio-bitumen and bitumen-based coatings for asphalt and other bitumen-based materials, biomass-derived de-icers, bio-based adhesives etc.[127].

The oil is a highly complex product comprised of differently sized molecules and highly dependent on the biomass feedstock and the pyrolysis process conditions and extraction procedure. An example of simple oil characteristics is provided in Table 4.

Table 4: *Example of wood pyrolysis oil from fast pyrolysis compared to heavy fuel oil. From Czernik & Bridgwater 2004*[128]

Oil property	Wood bio-oil (Fast pyrolysis)	Heavy fuel oil
Moisture content, wt%	15-30	0.1
pH	2.5	-
Specific gravity	1.2	0.94
Elemental compositions, wt%		
C	54-58	85
H	5.5-7.0	11
O	35-40	1.0
N	0-0.2	0.3
Ash	0-0.2	0.1
HHV, MJ/kg	16-19	40
Viscosity (at 50C), cP	40-100	180
Distillation residue, wt%	Up to 50	1

More elaborate methods of characterizations may include composition of the organic fraction and the content of e.g. alcohols, furans, Phenols, acids/esters, guaiacols and aldehydes/ketones. The characteristics vary substantially and in recent years, a lot of progress has been made related to e.g. optimization of oxygen content and pH of bio-oils. A few examples of other studies involving characterization of bio-oils are included in the references[129].

The composition of the residual gas that remains when oils have been extracted from the pyrolysis gas, depends a lot on both biomass type, pyrolysis process conditions and the method of oil extraction. The major constituents of the pyrolysis gas (after particle removal and condensation of tar/oil, wood vinegar etc.) is typically dominated by CO_2, CO, CH_4, H_2 and smaller amounts of various C_XH_Y gases e.g. C_2H_4, C_2H_6, C_3H_8, C_3H_6 etc. In addition, there may be substantial amounts of N_2 if N_2 is used as sweep gas in the process. Some of these components may have high value if properly isolated/concentrated. For further elaboration on the gas product, see e.g. [130].

It is expected that many new potential uses of both liquid and gaseous products from biomass pyrolysis will be investigated and developed in the coming years as an effort related to the substitution of fossil-based products and the development of a more circular bio-based economy. In this process, new chemicals, composites, products, material combinations etc. across the full palette of bio-based production and bio refinery operations need to be examined – open and curiously, and a whole range of new alternative products and services across different product categories have to be developed.

5.3 Value propositions from process- and system impact

Implementing systems for production and use of biochar may provide impacts from the environmental (e.g. impact on system eutrophication, acidification, particle emissions etc.) and climate oriented (global warming potential) to resource oriented indicators (critical resources, phosphorus balances, fossil fuel depletion etc.) to social and economic indicators (distribution of wealth, equity, noise, odor, dust, labor, and job creation etc.). In this report, the focus is primarily on the indicators related to energy, environment and climate. In the following, a few examples and considerations are presented on how pyrolysis systems may generate impact measured on such indicators.

5.3.1 Examples of full system environmental impact

There is still relatively few full-system assessments on production and use of biochar. At the same time, these studies vary significantly in form and methods, even when related to the same impact indicator. Here is an example of two very different full-system biochar-oriented studies with a focus on climate impact:

- In a recent study by Werner et al. from 2022, global biosphere simulation models were used to estimate the global PyCCS effect of amending biochar into sub-tropical cropland land in a *land and calorie-neutral PyCCS approach* (yield-increases from biochar use are attributed to biochar production). Results indicate, that this type of PyCCS effects could amount to 440–2,620 Mt CO_2 per year depending primarily on the assumed yield increases achievable[131].
- In a study from 2021, it was found that pyrolysis of 1.67 Mt of Danish straw will give a PyCCS effect (100 years) of around 0.9 Mt CO_2-eq which should be compared to a C-sink effect of around 0.08 mio ton CO_2-eq if the treated straw is instead plowed directly into the soil. The full system, net climate effect – including energy production, inputs, transport, losses etc. was found to be almost twice the effect from PyCCS alone[132].

According to Elias Azzi et al. in a study from 2021, the C-sink effect of biochar use is the most commonly assessed environmental effect in life cycle assessment (LCA) studies containing biochar. Many studies also include the substitution value of the energy product and around half of the published LCA studies includes effects like “fertilizer use reduction” and “soil N_2O emission reduction”. Other potentially important effects like “avoided nutrient leaching to water” and “land-use change emissions” are only included in 10% of the studies while more marginal effects like “CH_4/N_2O/nutrient flux change in animal husbandry” or “soil albedo changes” are only very rarely assessed[133].

Despite recent developments in the assessments of full-system environmental impact of biochar production and use[134], there is a substantial need for further work and knowledge in this area. This is particularly true regarding in-soil biochar effects and effects on yield. In a review of biochar-oriented LCA studies from 2020, Jan Matustík et al. conclude that *"The benefits of carbon sequestration in biochar and the energy production usually overcompensate the greenhouse gas emissions produced during feedstock production and handling. However, the effect on other impact categories needs to be evaluated and limited and the economic sustainability of the project needs to be assured. To facilitate future progress, some methodology unification would be beneficial."*[135]. In addition, there is a growing need to investigate full-system effects of biochar production and use in a circular, bio-based economy context with advanced bio-refinery operations, under biomass resource constraints including competing uses and as part of comprehensive cascade-use systems for use of both biomass and pyrolysis products. To this day, there are no such assessments available in the scientific – or the commercial, literature, relevant for a Danish context.

5.3.2 Increased bioenergy production

In the current, geo-political situation with war in Europe and regional energy –scarcity, it may have high value to increase energy security, energy-system flexibility, energy-system integrity etc. With its versatility, the pyrolysis platform may play a role in these regards.

To evaluate potentials to increase non-fossil energy production from pyrolysis, a simple-and-stupid setup of the BP_D2020 model for procurement and use of biomass in Denmark[136] has been made. The setup is based on land use and waste production similar to the reference year 2007 and a similar import and production of food and fodder as in this reference year as well. A biomass utilization factor of <85% is applied for all produced biomasses, and any biomass not used for food, fodder, bedding, existing energy conversion (heating- and CHP plants based on combustion) or similar is collected and converted using a combination of biogas and pyrolysis. The result is a doubling of the (net) bioenergy production from domestic biomasses from 76 to 156 PJ/year (higher heating value) including losses, the energy cost for production of lost N fertilizer etc. Pyrolysis provides around 60% of this increase and biogas plants the residual 40%. In addition, this approach would lead to the production of around 2.5 Mt biochar. Based on carbon content of various biochars of 70% (Figure 6) and an assumed 100-year carbon persistence rate of 80%, this would yield a PyCCS effects just above 5 Mt CO_2e per year. This is quite a rough estimate, conducted based on an old reference system. However, the versatility and synergies of these two platforms for increased bioenergy production from existing biomasses is very promising and may contribute to development of a more distributed, bio-based energy system. It should be noted, that a lot of the biomass that is utilized for energy purposes in this simple model will be under severe competition for alternative, higher-value uses in the future. However, at the same time an increased future biomass potential may be obtained with land-use changes. A recent study by Claus Rasmussen et al. from AU (2022) proposed a series of scenarios for biomass availability in a near-future Danish context, and finds that there is a substantial potential for further increases in the biomass resource potential, especially when the amount of farm animals is reduced[137]. In addition, much of the future higher-value biomass use can be expected to produce biogenic side-streams and secondary resources (waste) eligible for processing in systems with pyrolysis and anaerobic digestion. Biomass sufficiency in a bio-based, circular economy may become as much a question of intelligent and thoroughly developed use-re-use systems and cascade value networks, as a question about virgin resource amounts. This is discussed further in section 5.3.5.

5.3.3 Stabilization of biologically active biomass

As a rule of thumb, most biomass with constant moisture content above 20-25% is prone to substantial biological degradation over relatively short time. If degradation takes place in aerated environments (well-managed compost piles, open fields etc.), most of the mineralized carbon from the biomass degradation will be released as CO_2 while only a small fraction of the carbon will be released as methane. If, however, the degradation occurs in anaerobic environments, substantially more of the carbon may be released as methane, thus causing a larger global warming effect. In addition to these two carbon-based greenhouse gases, nitrous oxide will also be released during biological conversion of biomass.

One of the potential benefits related to thermal pyrolysis of biomass is avoiding these emissions. For dry biomasses and biomasses where the reference case is an aerated degradation, the primary effects of stabilization relate to the PyCCS-potentials as described in section 5.1. However, for wet biomasses that will otherwise degrade in an anaerobic environment, thermal stabilization may reduce greenhouse gas emissions further by avoiding methane emissions. On the large scale, the most typical cases of this sort include manure or digestate stored in closed tanks, or wet fibers or sludge stored in tanks or dense piles. In a study by Julie Larsen et al. from 2018, it was estimated that 47% of the carbon lost from a pile of dewatered sludge during the first week of storage was lost as CH_4-C while more than 52% of the carbon lost from biological degradation of the sludge in the following six months was lost as CH_4-C. Similarly, it was found that, respectively, 33% and 25% of N released during the storage of the dewatered sludge during the same two periods was lost as N_2O-N. In the study, around 10% of total carbon and 3% of total nitrogen was assumed emitted as gases from sludge mineralization with methane and nitrous oxide completely dominating the climate impact of this type of sludge management[138]. These emissions could be avoided with proper stabilization of the sludge and similar biomasses. In a Danish context, it is highly relevant to investigate the potential effects of stabilizing manure fibers and fibers from biogas digestate as the amounts of these resources, are very large in Denmark. In 2020, greenhouse gas emissions from manure management in Denmark amounted to 3.1 Mt CO_2e, a number that is currently expected to decrease to around 2.2 Mt CO_2e per year in 2030 as effects of new regulation on stable management and increase biogas capacity[139]. There are currently no committed plans to further decrease these emissions, even though there are other options including sterilization, acidification etc.

Currently, there are no solid estimates of the potential benefits related to pyrolysis based stabilization of wet biomass fibers. However, this is one of the main focus points in the GUDP funded R&D project STABIL lead by Sander Bruun from KU PLEN[140]. So far, the results from the project indicate that the effectiveness of the dewatering process may be one of the most dominant parameters in these efforts as emissions from the liquid phase may compromise system benefits. Advanced systems combining different dewatering, filtering, and membrane techniques may be required to significantly reduce emissions from the residual liquid after fiber separation.

5.3.4 Re-procurement, purification and concentration of non-renewable nutrients

As discussed previously, the content of nutrients in different biomasses vary substantially. In wood and woody biomasses, the nutrient content is typically very low, while it may be very high in various material streams from agriculture, industry, and waste management. To facilitate and secure long-term sustainability of a more bio-based economy, then re-procurement and re-use of nutrients is essential. However, some nutrients are more critical in this regard than others. While nitrogen is a largely renewable nutrient that constitutes 78 vol% of dry atmospheric air, other essential nutrients like phosphorus and magnesium are less abundant with concentrated, virgin resources sometimes located in only a few areas in the World. Phosphorus is the most critical nutrient in this regard, as it is used in bulk amounts and just six countries control >90% of the global high-quality phosphate rock reserves currently identified. Most of this phosphate rock is in Morocco (74% of the known reserves), followed by China, Algeria, Syria, South Africa, United States, and Russia[141]. Both phosphorus and phosphate rock are today on EU's list of *Critical Raw Materials to the Union* alongside 28 other critical substances[142].

Despite the criticality of the P resource, there is a huge annual flow of phosphorus in and out of Denmark every year. More than 50,000 t P is imported each year in fertilizers, fodder (mainly soy), food and chemicals while almost 30,000 t P leaves the country via export of primarily meat and dairy products but also other food and fodder products[143]. The residual P is either circulated inside national anthropogenic systems, accumulated in soils, or leached into aquatic environments.

With an enormous consumption and use of non-renewable, critical, and essential nutrients, Denmark has a big responsibility to secure the quality and availability of these nutrients to the continued production of biological products and the development of a bio-based economy. However, when complex organic material streams move through the different sectors of society, there are inherent risks of polluting and diluting the nutrients they carry. This is where there may be an additional value proposition from production and use of biochar. As presented in chapter 3.1, some biochars may contain substantial amounts of non-renewable nutrients e.g. P, K, Mg, some S and micro-nutrients. In the biochar, these nutrients are more concentrated than in the original biomass. In addition, organic pollutants like plastic, phthalates, pharmaceuticals, PFAS etc. will be partly or completely destroyed in the process[144]. The pyrolysis process may also be designed to volatilize certain heavy metals like cadmium or arsenic and both stabilize and reduce the concentration of these in the final biochar products[145]. Such effects may increase nutrient circularity as illustrated in Figure 26.

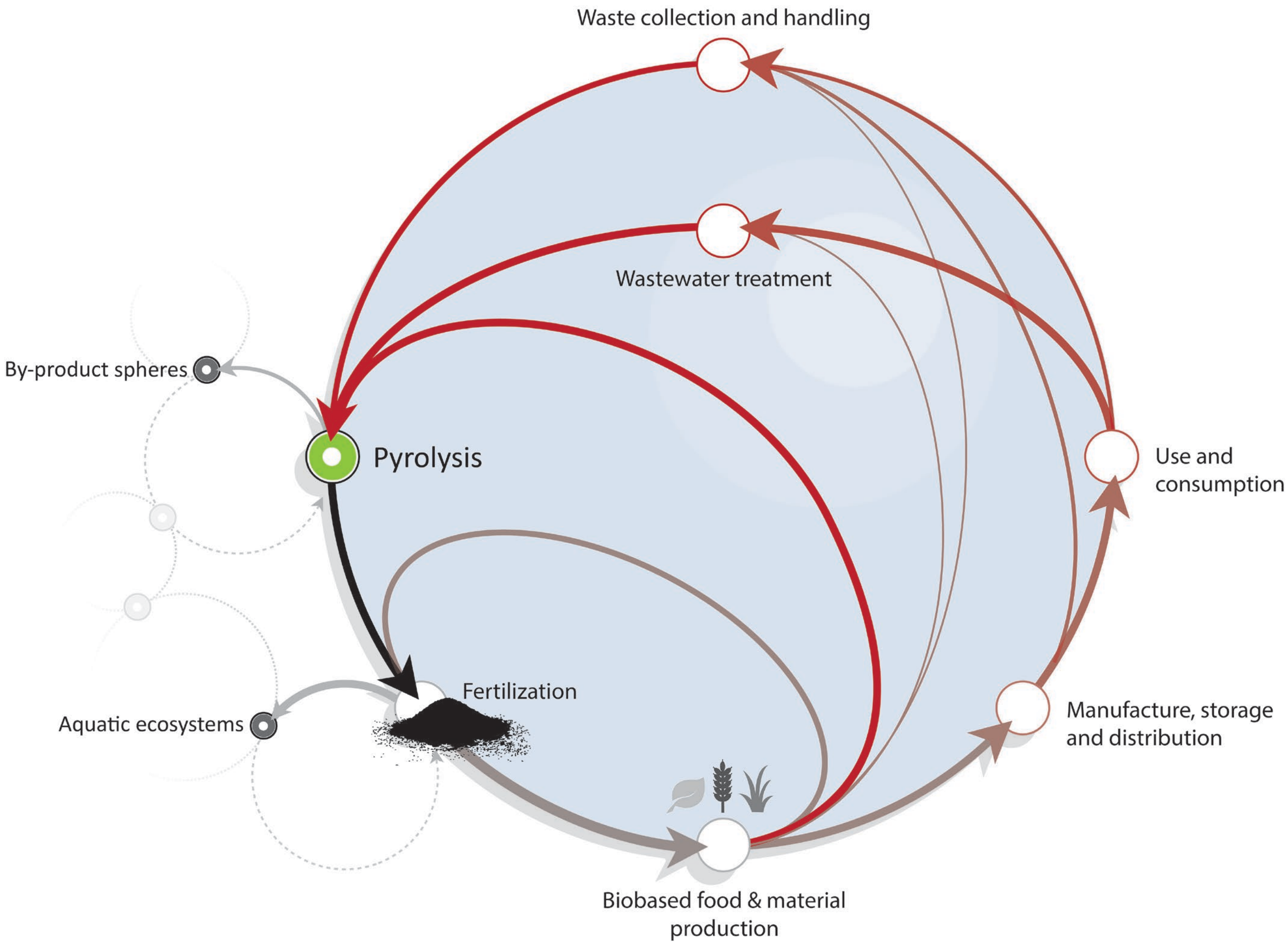

Figure 26: *The concept of a highly circular system for management of nutrients e.g. phosphorus. Red indicates increased pollution of the nutrient resource. Based on previous works on circular P systems[146]. Illustration by the author.*

Developing systems for optimized thermal nutrient management, it is important to be aware of especially four aspects: 1) As presented previously, most of the N content in the biomass is lost in the thermal process alongside a significant part of the S content, 2) There is a risk of generating toxins, e.g. PAHs and dioxins that should be avoided through design and monitoring, 3) As also described in section 5.1.1, the plant availability of the residing nutrients may vary substantially especially for chemically active nutrients like P, and 4) If processes with very elevated temperatures (e.g. 800 °C) are developed to volatilize heavy metals, then an increased thermal release of certain nutrients may also be expected[147].

It is also relevant to investigate the potential value of concentrating non-renewable nutrients like P, Mg, K etc. in biochar made from nutrient-rich biomasses. Currently, there is a serious excess of P in many parts of western Denmark while the amounts of P available from secondary resources in the eastern part is limited. If this pattern (based on soil type and quality differences, history, technological lock-in etc.) continues with predominant production of animals in the west and plants in the east, then pyrolysis of e.g. manure and biogas digestate fibers may be a way to increase the mobility of surplus phosphorus in the western part allowing for increased movement to the eastern part of the country. Improved P management on the national scale requires substantial increases in the movement of P from west to east, but a context-specific evaluation is required to determine the value[148]. For optimized nutrient management on regional or global scale, it may become valuable to export concentrated non-renewable nutrients in biochar out of Denmark and into countries with more imminent needs and bigger yield effects from it use.

5.3.5 New horizons for production and use of biochar in a circular, bio-based economy

In the previous sections, the focus is on value creation in a here-and-now context, primarily based on simple value chains for production and use of biochar as illustrated in Figure 27.

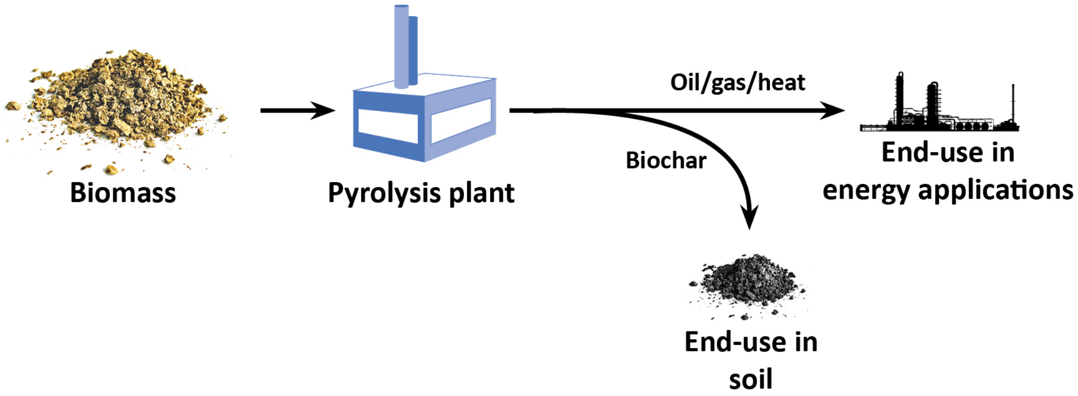

Figure 27: *Simple/short biochar production and use value chains in a here-and-now context. Illustration by the author.*

However, the most promising value propositions related to biomass pyrolysis may lie in the future context of a more circular and more bio-based economy where new options for developing value chains and cascade-use systems, integrating bio-refinery processes and increasing the carbon- and biomass use efficiency in society may become relevant. Very simply put, it is expected that new value propositions will emerge when the pyrolysis sector develops from simple systems like: 1) Biomass procurement -> 2) pyrolysis and production of biochar -> 3) End-use of biochar in soil or product and end-use of gas/oil in energy applications ... into systems where pyrolysis is used to increase carbon- and biomass use efficiency and value creation and facilitate the development of a more circular, bio-based economy in different advanced systems like: 1) Biomass procurement -> 2) Biomass use 1 -> use 2 … -> use X -> 3) Pyrolysis of biomass derivatives/spent biomass/waste and production of biochar -> 4) Pyrolysis products use 1 -> use 2 … -> use X -> 5) End-use of the majority of biochar in soil or long-lifetime product and end-use of gas/oil in various chemical applications and energy applications. An illustration showing the general concept of such a type of system is provided in Figure 28.

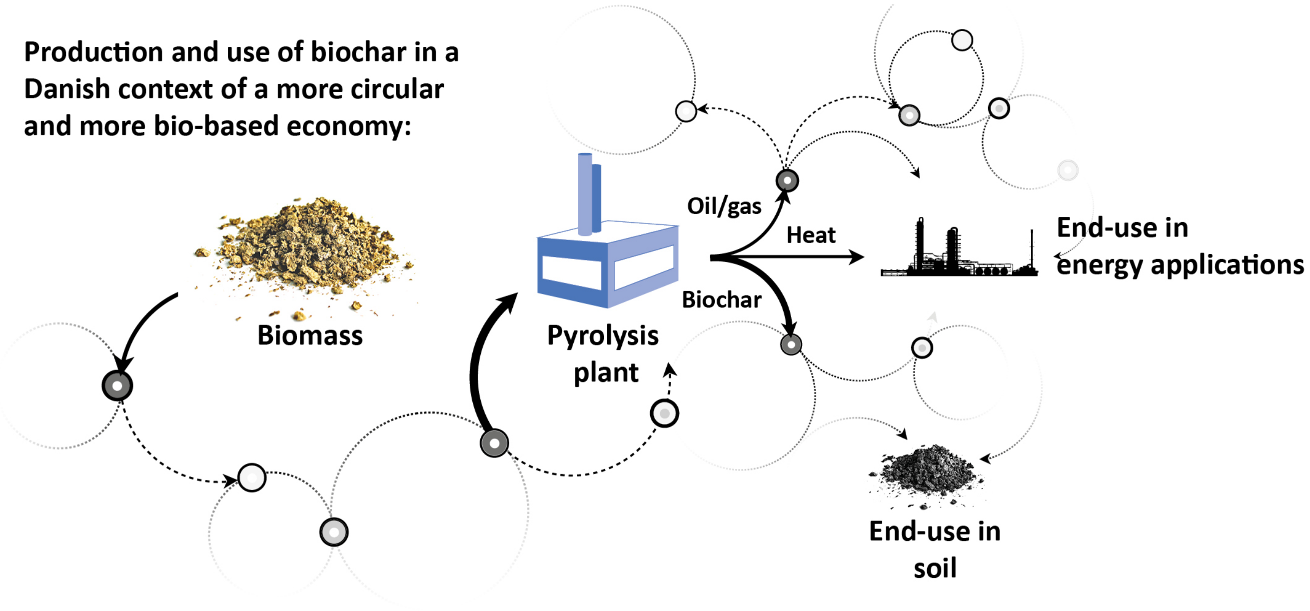

Figure 28: Conceptualization of systems with advanced and longer biochar production and use value chains in the context of a more circular and more bio-based economy. Illustration by the author.

The required cascades are being developed already, and an example of an existing value chain of this sort includes: 1) Production/procurement of biomass -> 2) Biomass use as fodder in production of meat and dairy products -> 3) Manure from production of meat and dairy products used for biogas -> 4) Biogas digestate dewatered and fibers treated in pyrolysis -> 5) Biochar amended into soil and heat used in biogas amine scrubbers. The system branches in all steps 2-4 with several other products in each step. A simple way to expand the chain between 4 and 5 could be to use the biochar as process enhancer or a filter medium at the biogas plant before end-use in soil. Filter use should preferably be to capture nutrients e.g. sulfur from gas or nitrate/phosphate from liquids to accompany the spent char into a soil application.

The integration between pyrolysis and biogas production is interesting and presents many options for synergetic development that may increase value creation from the combined set of processes. Some examples include e.g.:

- Potential increases in methane production from adding biochar to the reactor[149]?
- Cleaning biogas or process air streams in biochar filters to remove e.g. sulphur-compounds and organic odorants[150] or use biochar as carrier media in bio-filters[151]?
- Convert permanent gases and/or some tars in biogas reactor?
- Clean wastewater streams and move nutrients from liquids to chars[152]?
- Optimization of plant capacity value and yields by integration of energy and mass flows, and reduction of residence time in digesters, increasing flow and providing better fibers to pyrolysis?
- Charging biochar in digestate/liquid fraction to produce biochar-based fertilizers?

Similarly, there are ongoing activities related to e.g. integration of biogas and green biorefineries, and the large biorefinery consortium BIOCIRC[153] is already looking at options to integrate biogas, green biorefineries/grass protein extraction and thermal pyrolysis and/or hydrothermal liquefaction.

The next level of integration could include a more bio-based and circular building and construction sector, the possible integration of different bio-based processes in production and use of textiles, bio-plastics etc. The pyrolysis platform can be expected to contribute to flexibility, efficiency, and versatility of circular, bio-based value-chains as a broadly applicable technological platform. Increasing biomass use efficiency is paramount in development towards a fossil-free economy. In a situation where no fossils are used in energy- and production systems, there will be a myriad of products and services that needs biogenic input. In such a system, it cannot be expected that there will be biomass available for simple systems with single or few uses and/or systems that focus only on products and services in the lower tiers of the circular bio-economy value-pyramid[154]. The need for efficient, integrated bio-refinery processes and advanced cascade-use systems has also been emphasized in recent recommendations by the Danish National Bio-economy Panel[155]. Production and use of biochar is also included in the recommendations, as well as in the technical background analysis of biomass-production-and-use scenarios for Denmark in 2030 -> 2050. However, the perspectives on pyrolysis in this analysis are quite narrow considering only pyrolysis of biogas digestate with the aim to avoid emissions, give a small contribution to production of non-fossil energy and generate PyCCS effects[156]. This is a good example of how production and use of biochar is currently comprehended in relatively simple chains (Figure 27). It is expected that more elaborate conceptualizations of a comprehensive circular bioeconomy will be developed in the coming years, and that biomass pyrolysis will find many new roles and positions in these processes (Figure 28). A very general illustration of the framework for such conceptualizations is provided in Figure 29, communicating the postulate that the pyrolysis platform will contribute to development of many different new routes and possibilities for advanced biomass utilization and substitution of fossil-focused value chains, while securing the productivity of the biosphere.

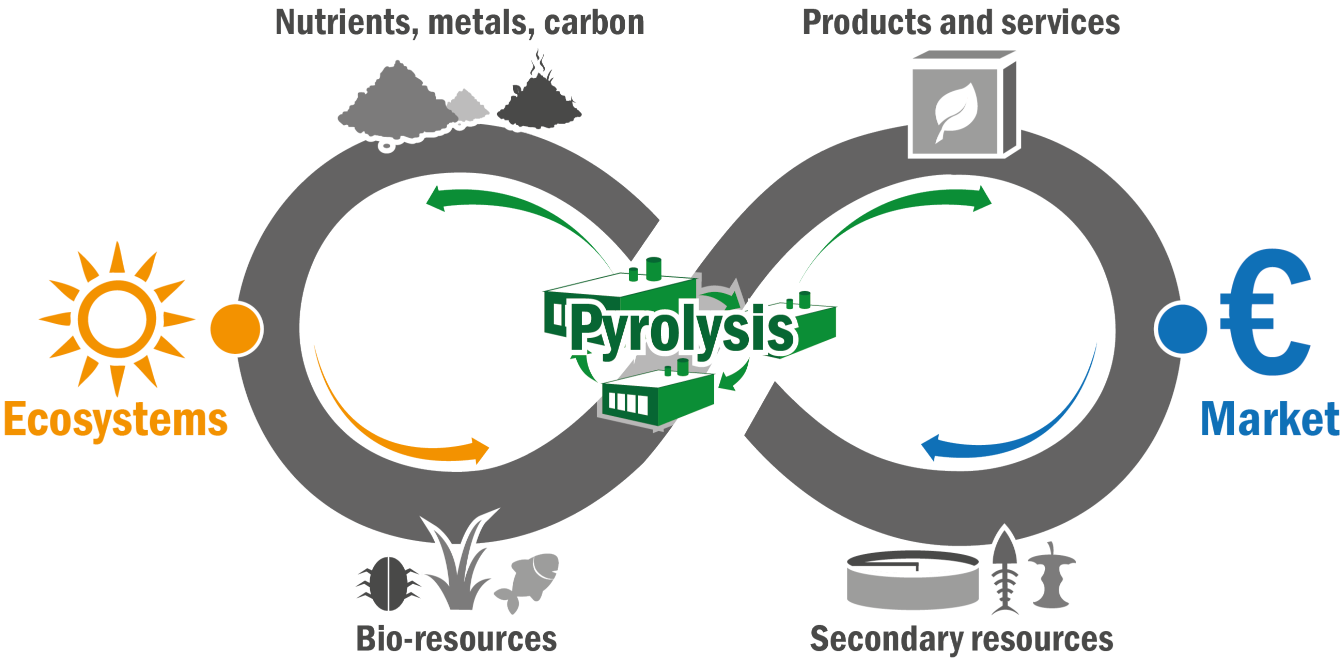

Figure 29: General conceptualization of the double role of pyrolysis in the development of a more circular and more bio-based economy. Developed from a general conceptualization of biomass- and waste processing in a report from DTU from 2019[157]. Illustration by the author.

6 Short status of biochar production and use, Denmark 2022+

This chapter provides a status on the current development and implementation of production and use of biochar in a Danish context. The focus is now (end of 2022) but plans and perspectives for near-future developments are included where relevant. But first, we want to take a quick look backwards.

6.1 A few historic milestones

A full historical description of Danish pyrolysis is out of scope of the current work, but it could be very relevant to complete such an effort to better learn from past experiences, failures, successes and mistakes. Here are a few examples of major historic (Danish) milestones that starts in the early 90's, focuses on biochar in the early 2000's and takes off in recent years:

- Since 1995, a wood gasifier has been running in Harboøre converting wood chips to heat and power, tar and ash/char. The tar is used in cold periods and burned in a boiler. The ash/char product is returned to local forests where the wood is harvested[158].
- For a few years around 2011-12, the company Blackcarbon[159] had a 300 kW screw-conveyer-based pyrolysis unit installed at Barritskov Estate operating on wood chips and broken wood crates from the neighboring company Aarstiderne[160].
- From 2010 to 2014, A 6 MW Low-Temperature Circulating Fluidized Bed (LTCFB) gasifier was built and operated at Asnæsværket by Dong Energy (now Ørsted) with the aim to convert straw, shea nut residues, dry sewage sludge and other residual biomasses into process gas for on-site CHP plants and biochar. The plant ran several successful campaigns and provided several tons of (primarily) straw-based biochar for large-scale field experiments at Bregentved Estate[161].
- From 2012 to 2014, Bregentved Estate conducted a series of large-scale field trials in collaboration with KU, Dong Energy (now Ørsted) and DTU with straw-based gasification biochar from the LT-CFB unit at Asnæsværket[162].
- Since the 1990's, Ulrik Birk Henriksen and his colleagues in the Biomass Gasification Group (at first part of DTU Mechanical Engineering and later Risø Biosystems Division and DTU Chemical and biochemical Engineering) have worked with development and characterization of technology for biomass pyrolysis, gasification, torrefaction, pelletization etc[163]. Going from an initial focus on energy production, the group developed a parallel focus on biochar production and use since 2008, after entering an ongoing collaboration with the agronomists in the ECO department and system assessment experts at NRG, all part of the Risø Biosystems Division.
- From 2008 to 2011, the first biochar-focused PhD-study is conducted in Denmark[164]. It is performed by Esben W. Bruun who is currently enrolled in a postdoc position at KU PLEN under supervision of Professor Henrik Hauggaard-Nielsen who is today employed at RUC IMT.

6.2 Organizational development in Denmark 2022 – status and main focus

Currently, the development of a Danish pyrolysis sector and the surrounding economic and political structures is driven and facilitated primarily by interests around the agricultural sector and the waste management sector. There is a technical development focus on agricultural biomasses and sewage sludge (which is also currently used primarily in agriculture), and the political focus is shaped primarily by views on the potential effects that production and use of biochar may have in agriculture. Danish agriculture dominates both land-use and climate impact. As such, it represents a large and important market for biochar amendment while being a sector where biochar's impact on the climate footprint may be substantial in both absolute terms as well as in relation to the national total. Some of the recent milestones in the organizational development in Denmark that emphasize this focus include

- Massive dissemination and lobby campaigns from the large agricultural business organization Danish Agriculture and Food Council (Landbrug & Fødevarer, L&F), promoting development within biochar have made a significant impact in the political[165]
- The Danish Ministry of Food, Agriculture and Fisheries (FVM) has commissioned a knowledge synthesis on biochar use in Danish agriculture under the "Framework Agreement on the Provision of research based Policy Support" with The Danish Centre for Food and Agriculture at Aarhus University. The synthesis report was published in September 2022[166].
- Use of biochar produced from agricultural biomass is on the political climate action plan for emission reductions in the agricultural sector with 2 Mt CO_2e per year in 2030[167].
- Denmark's recovery and resilience plan to the European Commission included several actions related to pyrolysis, and funds from the related Recovery and Resilience Facility has been channeled into a R&D call with focus on pyrolysis in agriculture (Pyrolysepuljen) and issued in a cooperation between the Danish Energy Agency and the Danish Agricultural Agency[168].

The focus in Denmark on agricultural use of biochar may seem to be a good fit-strategy for facilitation of the country's large agricultural sector and related businesses. However, it also brings some challenges when compared to the development in many other countries where the focus on use of biochar in agriculture is often less intense.

- The development in many other parts of the world has an initial focus on woody biomasses, and therefore the potential knowledge transfer to the Danish R&D efforts is limited
- The national focus on agricultural biomasses and sewage sludge may restrict the applicability in Denmark of some of the pyrolysis plant equipment developed in other countries where the primary focus is on woody biomasses
- Biochar use in agriculture is – according to EBI's Harald Bier, one of the toughest places to break through and enact market mechanisms for two primary reasons: 1) the context dependency of biochar effects in agriculture is strong and higher than in most other use contexts, and 2) the complex of rules and regulations related to use of biochar in agricultural soil is often more comprehensive and restrictive than in other use cases, while it is also undecided in many regards and therefore under continuous development[169].

Despite these potential challenges, the very keen focus in Denmark on agricultural biomasses and sludge may give the Danish technology providers a competitive edge compared to the development in other countries where development is more slowly moving in this direction also. In addition, when the incentive structures, effect validations etc. are in place for bulk use of biochar in agriculture, then this substantial market may form a basis for the sector from where development of more advanced and efficient production-and-use schemes with multiple cascades, cross-sectorial synergies etc. can take place.

Currently, there is large scale market for buying and selling agricultural biochar in Denmark. However, as described in section 6.3, there are commercial value chains for urban applications of char. In addition, there is a growing global market for compensation measures where Danish credit producers and -buyers may act. There are currently many private businesses dealing with climate compensation (buying as well as selling), and several of the market platforms for such compensation include multiple biochar projects[170]. It is currently unknown how large the accumulated market of PyCCS-based compensation from the different market platforms are. However, a single 5-year contract between the Danish-Indian pyrolysis technology company MASH Makes and the platform Carbonfuture include 50,000 ton of CO_2e[171]. On the marketplace puro.earth there are >20 different biochar projects and the prices range from 100 to 535 € per CORC (CO_2 Removal Certificate, 1 ton of CO_2e)[172].

6.2.1 Active research groups and networks

The involvement of Danish academic organizations is also increasing. Today, many different research groups are involved in R&D activities related to production and use of biochar. Some of the contributing research groups are located at the universities and departments listed below. Some of the activities these groups are involved with are briefly described in section 6.2.2. However, there may be some active researchers and projects that was missed in this status and the field is developing continuously.

- **The Technical University of Denmark (DTU):** For many years, the Department of Chemical and Biochemical Engineering (DTU KT) and the Department of Mechanical Engineering (DTU MEK) have been deeply involved in the technological development, while the Department of Management Engineering - and later on the Department of Environmental Engineering, have worked with assessment of full-system environmental impacts. DTU KT holds the country's largest collection of experimental facilities for R&D related to pyrolysis and to production and characterization of biochar. DTU MEK has a large catalogue of energy system models including thermodynamic models involving biomass pyrolysis as well as energy-related experimental setups on gas and oil use.
- **University of Copenhagen (KU):** Different research groups in the Department of Plant and Environmental Sciences (PLEN) have been involved for many years in both nutrient assessment, environmental impact assessment, soil physics etc. In addition, research groups at the Department of Economics and the Department of Geosciences and Natural Resource Management are now also involved in projects and activities related to production and use of biochar.
- **Roskilde University (RUC):** Department of People and Technology (IMT) has established lab-scale equipment for pyrolysis and for evaluation of biochar in anaerobic digestion and as gas cleaning agent while the Department of Science and Environment (INM) hosts some equipment for testing and characterization of biochar. IMT is also contributing to several different R&D projects with work packages on Climate Footprint Accounting and Life Cycle Assessment studies on production and use of biochar. Several models for such studies are under development. Finally, IMT is also establishing an additional experimental setup for bench-scale batch pyrolysis and various biochar end-use options in the university's open-access makerspace FabLab RUC[173].
- **Aarhus University (AU):** Research groups in the Department of Agroecology (AU Agro) have been involved in many projects and studies over the last decade involving biochar, plant growth experiments, biochar impact on greenhouse gas emissions etc. AU Agro led the process and work related to development of the recent knowledge synthesis on production and use of biochar in a Danish agricultural context. Smaller research groups in the Department of Biological and Chemical Engineering, Department of Environmental Science, Department of Geoscience & Department of Animal and Veterinary Sciences are today also involved in R&D activities. At AU and AAU (below), research groups have also been involved in development of technology for thermochemical processing of biomass and waste, but the focus has been on hydrothermal processes (i.e. Hydrothermal Liquefaction and Hydrothermal Carbonization)[174]. However, today there are also experimental facilities for dry pyrolysis at AU in lab-scale (Department of Geoscience and Department of Biological and Chemical Engineering) and a demonstration-scale AquaGreen steam drying and pyrolysis plant is currently located at AU Foulum.
- **Aalborg University (AAU):** The Department of Planning and the Department of Energy Technology has recently enrolled in different projects related to pyrolysis, biochar and applications of bio-oil.
- **The Geological Survey of Denmark and Greenland (GEUS):** Department of Geo-energy and Storage and Department of Geochemistry are part of activities and research projects related to assessment of PyCCS effects, stability of biochar carbon and effects of biochar use on ground water quality.

At least three networks for stakeholders interested in production and use of biochar in Denmark are already established. These include:

- **The Nordic Biochar Network**, a knowledge-oriented, free and open network for individuals interested in production and use of biochar. Activities include, workshops, conferences, online webinars, activity-map of the Nordic countries etc. The network activities are member-driven and a lot of effort is put into facilitating, initiating and supporting activities by the NBN board consisting of eight academic biochar researchers from Denmark, Sweden, Norway, and Finland. There are currently two representatives from Danish universities in the board of NBN[175].
- **The Danish Pyrolysis- and Biochar Network** (Dansk Pyrolyse- og Biokulnetværk) was loosely established in 2021 by Food & Bio Cluster Denmark, Ringkøbing-Skjern Municipality, Klimafonden Skive, Dansk Gasteknisk Center, Roskilde University and Vestjysk Landboforening. Today the network administration is conducted by Food & Bio Cluster Denmark and membership of the Danish Network requires membership of the Cluster. However, the network also arrange open events where membership is not required[176].
- **L&F's biochar Network.** The Danish Agriculture & Food Council (Landbrug & Fødevarer, L&F) has initiated a network organization with the Danish pyrolysis technology providers Stiesdal SkyClean, AquaGreen, Dall Energy and Frichs Pyrolysis to accelerate implementation and deployment efforts. The network aims towards establishing a task force where the members work together with representatives from the Danish ministries on Climate and Energy, Food and Agriculture and Environment as well as KL - Local Government Denmark (an interest organization for the 98 Danish municipalities) to identify and address barriers slowing or preventing large-scale implementation and commercialization of production and use of biochar in Denmark[177].

In addition to the Danish and the Nordic network, there are also multiple international networks. The International Biochar Initiative (IBI) and the European Biochar Industry Consortium (EBI) are two of the most active international networks with a lot of focus also on the European development.

6.2.2 Ongoing R&D 2022

More than 10 large R&D projects related to production and use of biochar in Denmark are currently started and in process. Just 5-10 years ago, there were typically 1-2 projects taking place at a time. Summing up the funding and co-financing of these active projects, there is presently around ½ billion DKK tied up herein. A list of some of the current, Danish projects is provided below:

EUDP projects:

- **SkyClean** – 2MW Process Development and Industrial Demonstration. Stiesdal SkyClean, DTU, Haldor Topsøe, Danish Gas Technology Centre (DGC), Ørsted & Energy Cluster Denmark. Funding: 23 mio. DKK. Total Budget: 36 mio. DKK[178].
- **Sustainable and flexible production of maritime fuel from biomass**. Mash Makes and DTU KT. Funding: 6.7 mio. DKK. Total budget: 8.1 mio. DKK[179].

Innomission projects (Innovation Fund Denmark):

- **LOWHIGH** - Integrate new technologies – Acidification, anaerobic digestion, separation and pyrolysis, to reduce emissions and increase energy production from manure management. SEGES, University of Copenhagen, Aarhus University, Stiesdal SkyClean, Nature Energy, JH agro, Klimafonden Skive & Samson Agro. Funding: 5 mio. DKK. Total Budget: 7.3 mio. DKK.
- **MitiChar** - Potential of straw + digestate fiber mix biochar to mitigate climate impacts and improve soil health. University of Copenhagen, Aarhus University, Stiesdal SkyClean, HedeDanmark, Agrovi[180]. Funding: 5 mio. DKK. Total budget: 6.9 mio. DKK.

- **BioStore** - Carbon stability and agro-ecosystem and groundwater quality effects of soil amendment with high doses of biochars produced by Danish companies. University of Copenhagen, DTU, AAU, RUC, GEUS, SEGES, Stiesdal SkyClean, AquaGreen & MASH Makes. Funding: 6.6 mio. DKK. Total Budget: 8.8 mio. DKK

GUDP projects:

- **STABIL** - Climate- and environmental effects from separation, steam drying and pyrolysis of pig manure and biogas digestate. University of Copenhagen, Aarhus University, Technical University of Denmark, Roskilde University, AquaGreen, Højgaards, Villads Sørensen (farmer), Nordphos[181]. Funding: 10.5 mio. DKK. Total Budget: 14.8 mio. DKK.
- **Grass Biochar** - Integration of grass biorefinery, steam drying and thermal pyrolysis to optimize value creation and climate benefits. Aarhus University, Technical University of Denmark, Roskilde University, AquaGreen, Nordphos. Funding: 6 mio. DKK. Total Budget: 8 mio. DKK[182].
- **BioAdapt** - Biochar as a tool for climate adaptation in crop production on coarse sandy soil[183]. KU PLEN, DTU KT, AU ENV, SEGES. Funding: mio .DKK. Total Budget: mio. DKK.

"Pyrolysepulje" Projects:

- **SkyClean Scale-up** – 20 MW full-scale plant for pyrolysis of biogas digestate fibers. Stiesdal SkyClean, DTU (KT & MEK), BB Bioenergi, KK Wind Solutions, Aktive Energianlæg, Topsoe A/S, Vestjyllands Andel, SEGES, KU PLEN, AU ES, AU AGRO, RUC IMT, F&BCD, Energy Cluster Denmark. Funding: 124 mio. DKK[184].
- **Dall Energy – 10 MW fluid-bed pyrolysis** of sewage sludge, straw, and other biomasses. Dall Energy and Heat supply companies in Billund Municipality. Funding: 51.4 mio. DKK[185].
- **Frichs Pyrolysis – 2 MW electrically heated flash pyrolysis** plant for treatment of chicken manure. Frichs Pyrolysis and Springkilde Eggs. Funding: 18.6 mio. DKK[186].

Independent Research Fund Denmark (DFF):

- **Optimization of biochar properties for maximum reduction of N_2O emissions from agricultural soils**. KU PLEN. Funding: 2.9 mio. DKK[187]
- **Novel rhizosphere-activated hydroxyl radical oxidation of pesticides (OHiROOT)**. AU Agro. Funding: 2.9 mio. DKK[188]

In addition, the large project "Shipping Lab – Driving Future Maritime Technology"[189] also includes activities related to the use of bio-based fuels including fuels based on pyrolysis oils. The Danish-Indian pyrolysis technology development company MASH Makes is one in a long list of partners in this project.

Finally, the non-profit organization – the CIP Foundation[190] – sponsored by CIP[G] and member companies - is currently working on a project to promote societal investments in pyrolysis and biochar as a means to create CCS-opportunities in agriculture and reduce emissions from the sector. The purpose of the foundation is to enact societal changes through specific long-term project proposals targeted towards key stakeholders and regulators. The CIP Foundation biochar project looks into e.g. the availability of relevant feed-stock, valuation of CCS in agriculture, carbon abatement costs and the potential for CO2-reductions in Denmark as well as export opportunities. The project involves analyses and open seminars, and results will be openly available.

[G] Copenhagen Infrastructure Partners

6.3 Status on production and deployment of pyrolysis plants in Denmark

This section includes an overview and status of pyrolysis technology developers and providers that are currently operating in Denmark. Invitations to contribute to this section, were sent to the companies Stiesdal SkyClean, MASH Makes, AquaGreen, Dall Energy, Frichs Pyrolysis and Organic Fuel Technology. Responses were received from the first four companies. In addition to potential plants from the Danish technology providers, there are – to the best of our knowledge, currently only two relevant biomass plants in operation in Denmark – the Harboøre gasifier and the Skive Gasifier. These are described briefly below, and in combination with the overview of the plants produced by the Danish technology developers, this should give a nearly complete overview of the plants currently deployed and under development in Denmark.

6.3.1 The Harboøre gasifier

As mentioned in the historical milestones, the Harboøre Gasifier has been in operation since 1995, converting wood chips to heat and power, tar and ash/char. The gasifier is an air-blown updraft gasifier of 5.2 MW thermal input capacity, that converts wood chips into producer gas which is cleaned and used as fuel in two gas engines with generators producing electricity and heat for the grid. As part of the gas cleaning, tar is condensed out and collected. Approximately 400 tons of tar is collected every year, and used on-site as fuel in an oil–boiler for peak load operation in cold periods. Various experiments with increased-value use of the tar as raw material for fuel production have been conducted over the years. However, none of these projects had led to a commercial breakthrough on this site. The ash/char product is returned to local forests where the wood for the plant is harvested. The Harboøre gasifier is designed for unattended operation and has achieved far more than 100,000 hours of continuous operation[191].

6.3.2 The Skive gasifier

The gasifier in Skive is a bubbling fluidized bed gasifier, converting wood pellets to heat and power and carbon-rich solid residue. The plant produces approximately 6 MW power and 11.5 MW heat from conversion of gas from the gasification of approximately 20 $\text{MW}_{\text{Thermal capacity}}$ wood pellets. The gas is converted after cleaning (tar reformer, cooler, filter, and scrubber) in a combination of gas boilers and gas engines. The investment decision for the plant in Skive was taken in 2005, but due to various operational issues, the full capacity of the plant was not reached until around 2013-14. There have been various experiments with the gas from the Skive gasifier, with the most ambitious being a campaign with Haldor Topsøe to synthesize gasoline. The gasifier is not designed for optimized quality of the char/ash products, which is currently used as boosters to facilitate waste incineration in a near-by waste-to-energy plant[192].

6.3.3 Stiesdal SkyClean – status and perspectives

SkyClean is one of four technology solutions in the Stiesdal cooperation[193]. Stiesdal SkyClean delivers pyrolysis plants for pelletized biomass based on an up-draft fixed-bed design. An illustration of the SkyClean process design is provided in Figure 30.

The main focus is currently on pyrolysis of biogas digestate and cereal straw while next-phase development targets wood (both in pellets and in chips), grass pulp pellets from green bio-refineries etc. One of the unique selling points of the SkyClean setup is the design for operation on pelletized biomass. Initially, this may seem like a process drawback as it increases costs of biomass pre-treatment. However, in the longer term, the focus on pelletized biomass increases the process flexibility and robustness substantially, because biomass fuel variation and feeding problems are among the most dominant issues related to the development of new processes for biomass processing. In addition to development of the pyrolysis process, SkyClean is also integrating systems for drying and pelletizing in full-scale plants.

First-generation SkyClean plants are built with combustion of the complete pyrolysis gas product stream to produce high-temperature heat for industrial processes. However, the company is already engaged in development projects and processes related to advanced energy utilization including production of bio-oil, methane, and methanol.

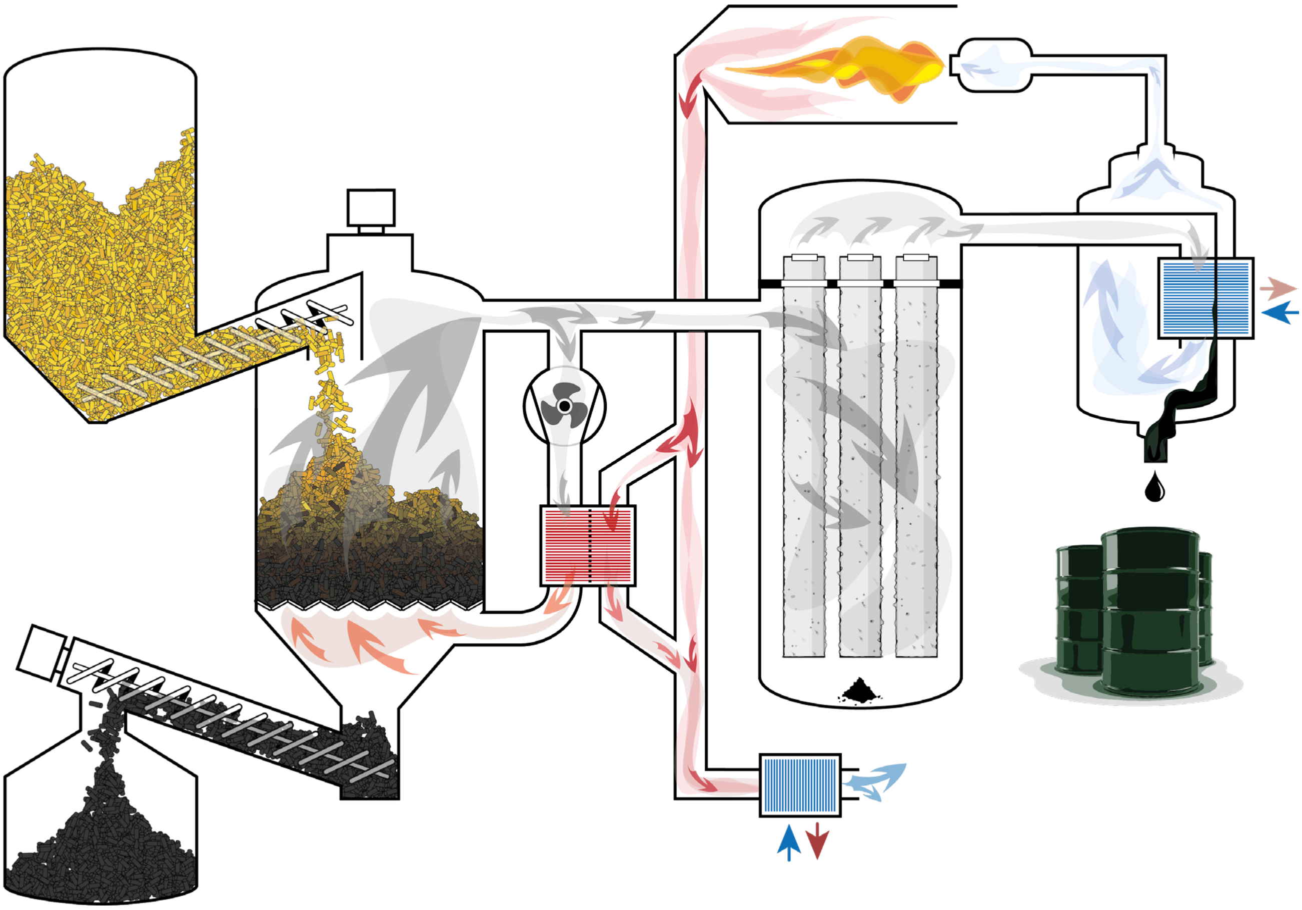

Figure 30: *Simple illustration of the SkyClean pyrolysis process design including pelletized feedstock and an up-draft, fixed-bed pyrolysis reactor. There are variations of the plant design depending on gas/oil end-use. This is an example with production of oil and heat. Illustration by the author.*

Presently, SkyClean has built two pilot scale plants (200 kW thermal fuel capacity) in Brædstrup, Denmark, a large demonstration scale plant of 2 MW thermal fuel capacity in Green Lab Skive, Denmark and has recently commenced construction of the first commercial-scale plant of 20 MW thermal fuel capacity in Vrå, Denmark. Many hours of operation have been obtained on various fuels in the first pilot facility and several successful campaigns on straw pellets have been completed with gas flaring in the 2 MW unit. The 2 MW unit was recently fitted with a boiler and will now start producing heat for a neighboring biogas upgrading plant. At the same time, the unit will start converting biogas digestate from biogas plants instead of straw.

The heat provided will be used to regenerate the amines used to scrub CO_2 from the biogas. Pictures of the 2 MW plant are provided in Figure 31.

A comparable setup is planned for the coming 20 MW unit in Vrå. At this facility, the biogas plant will provide dewatered digestate to be dryed and pelletized before pyrolysis. The energy from the pyrolysis gas will fuel the drying process, which is based on a pressurized steam drying concept. After drying, 150 °C heat can be recovered from the pressurized steam, and this will be used to regenerate the amines in the gas upgrading. It is expected that the energy produced from pyrolysis of the complete quantity of digestate from the biogas will match almost 1:1 the energy needed for the amine recovery. The 20 MW plant in Vrå is expected to be completely installed and in operation during the second half of 2023.

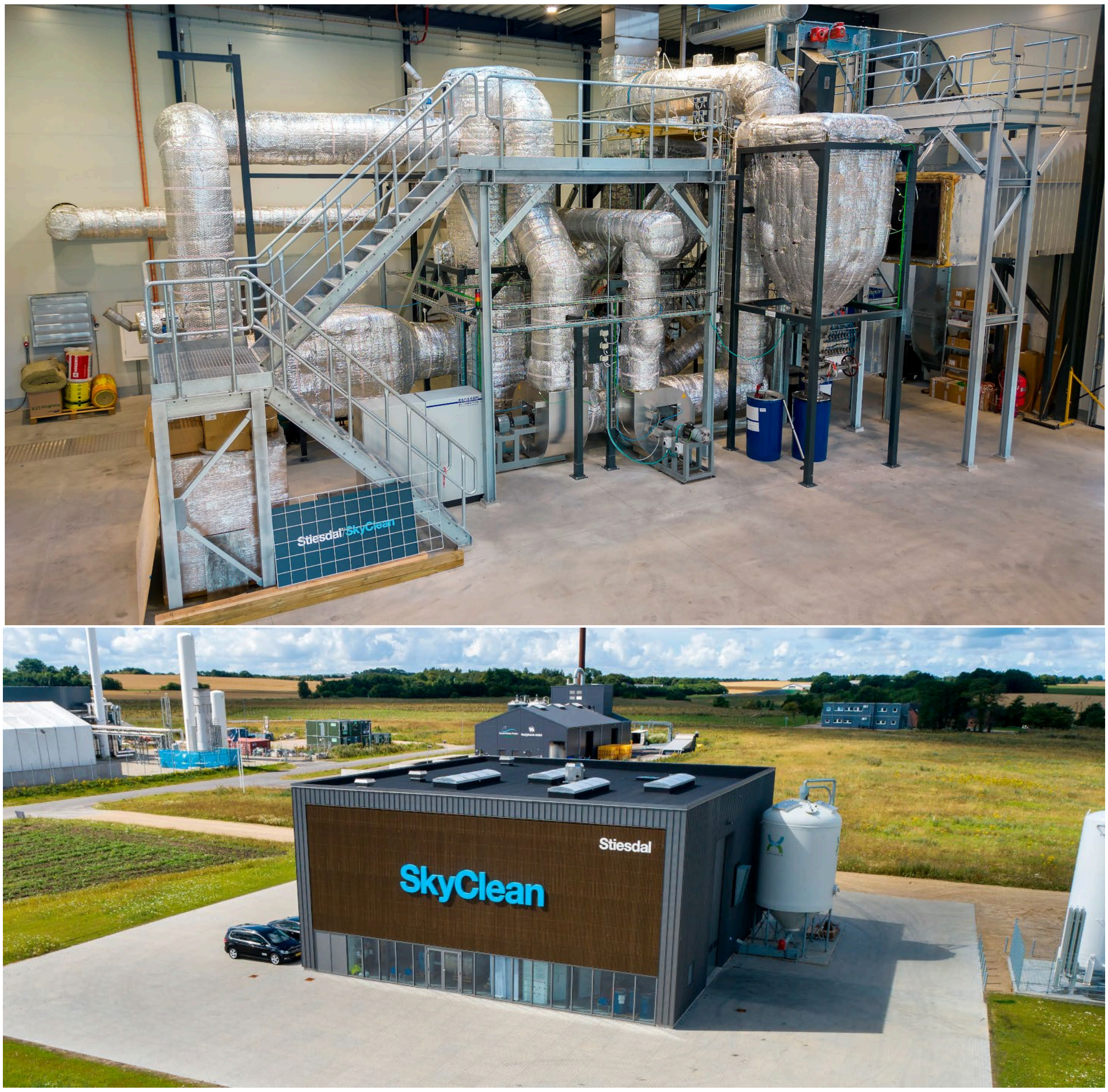

Figure 31: *Pictures of the 2 MW SkyClean plant in GreenLab Skive. © Stiesdal SkyClean.*

Dialogues involving several additional 20 MW plants are currently in various stages of the planning process mainly targeting biogas digestate as feedstock. Following the initial focus on biogas digestate and production of heat for amine recovery, it is expected that a series of plants will be built for treatment of straw, wood, grass pulp, and other agricultural residues in connection with production of heat for other industrial processes, district heating plants or CHP plants. The first SkyClean plant producing advanced fuels from biomass pyrolysis is expected to be deployed during 2024. In total, it is the ambition and aim of SkyClean to produce about 90 plants in Denmark before 2030 as preparation for international deployment. This could contribute substantially to mitigation of climate change and non-fossil energy production. The company has a keen focus on export, especially markets in EU and the US are of interest.

Biochar from SkyClean plants is not yet commercially available, but currently reserved for tests and trials in various R&D projects. During 2023, the company will open options for commercial sale of phosphorus-rich biochar from digestate fibers as well as carbon credits based on PyCCS effects of the company's operations and agricultural use of the biochar.

6.3.4 AquaGreen – status and perspectives

AquaGreen develops stand-alone systems for dry biomass pyrolysis as well as integrated systems with steam drying and pyrolysis for treatment of wet biomasses like sewage sludge, manure fibers etc.[194]. An illustration of the integrated system is provided in Figure 32.

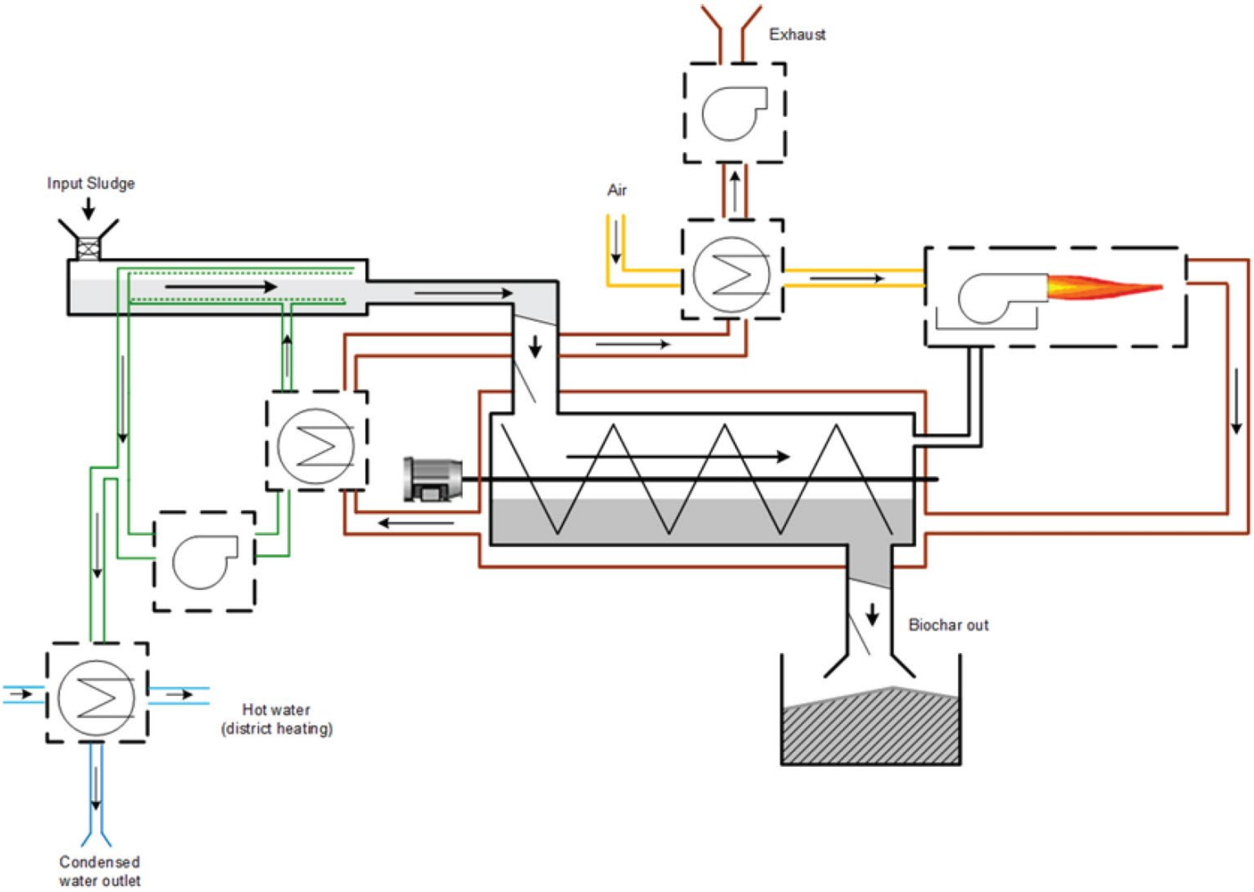

Figure 32: *Simple illustration of AquaGreen's integrated system for steam drying and pyrolysis of wet biomasses like sewage sludge. Green is the steam cycle (dryer), and red is the pyrolysis section. Yellow is pre-heating of air for the gas burner © AquaGreen*

AquaGreen started out with focus on fish manure and aquaculture sludge in Norwegian fish farming. From there, the company shifted attention to treatment of sludge from municipal wastewater. The focus today is still primarily on treatment of sludge and the company has built its first plants in Denmark and is now looking at accelerating deployment in both Denmark, Sweden, and Italy. In addition, AquaGreen is also developing equipment for stand-alone pyrolysis of dry biomass as well as post-process treatment of both biochar (physical activation) and pyrolysis gas (char-bed tar-cracking).

Presently, AquaGreen has one integrated full-scale steam-drying and pyrolysis plant in operation on sewage sludge from municipal waste-water treatment in Fårevejle under Odsherred Utility Company in Denmark while another plant is well under way at Søndersø Wastewater Treatment Plant under VandCenterSyd Utility Company, Denmark. These are plants of the HECLA type and both plants have a thermal capacity of 0.6 MW based on fuel input (HHV). A picture of the HECLA plant in Fårevejle is provided in Figure 33.

Figure 33: *Picture of AquaGreen HECLA plant for steam drying and pyrolysis of sewage sludge in Fårevejle, Denmark. Picture is taken during construction. Today the plant is in full operation. © AquaGreen*

In addition to the two full-scale HECLA plants, the company sold a demonstration plant for VA Syd, located in Ellinge in Sweden with separate electrically heated steam dryer and high-temperature pyrolysis oven for research purposes. This plant will also operate on sewage sludge. Finally, the company sold a stand-alone 1 MW pyrolysis plant for BMG in South Africa that will operate on agricultural waste as well as three stand-alone, electrically heated dryers for the Norwegian aquaculture industry.

AquaGreen and Odsherred Utility Company are now selling sludge biochar as a product. The biochar produced at the plant in Fårevejle is sold to the company Milford that produces nutrient-rich soil for urban green zones and urban tree planting. Other companies within soil manufacturing have shown large interest as well.

AquaGreen expects that ca. 100 HECLA type plants for sludge treatment and stand-alone pyrolysis plants for dry biomass will be built and sold in the next 5 years. Most of the biochar from these plants is expected to be used for amendment in agricultural soil or in soil manufacturing. On the energy-side, it is expected that heat will be the main product in most cases, but also that advanced gas use for engines or synthesis may be realized within a 5-year horizon. On the market level, the next phase development will also include an R&D focus on expanding the equipment portfolio to be able to treat various manure fiber products, digestate fibers, grass pulp from green biorefineries etc.

6.3.5 MASH Makes – status and perspectives

MASH Makes[195] is a Danish-Indian technology development company that develops and builds systems for biomass pyrolysis and biomass gasification. The development is conducted in Denmark and India, but the deployment focus is on the Global South, particularly Africa and Asia, in areas where quantities of unused biomass are high and the soil quality is low so that genuine soil enhancement effects can be documented from the biochar use.

Currently (November 2022), MASH Makes has constructed two pilot-scale plants. One of the plants is a full-scale dedicated pyrolysis pilot plant built and operated in India. The plant runs continuously and can handle an input of 10 tons per day, with 30% conversion to biochar and 20% bio-oil. A picture of the plant in India is provided in Figure 34.

In addition, the company has constructed one gasifier pilot plant in Denmark, which is currently located at Risø where it is undergoing improvements and developments. The gasification technology deployed by MASH Makes is a redesign of the TwoStage Down-draft gasifier developed at DTU MEK/KT, built in various scales including the "Viking Gasifier" located at DTU Risø Campus[196].

Figure 34: *Picture of the MASH Makes pyrolysis plant in India. © MASH Makes.*

MASH Makes is now ramping up its deployed capacity and has started construction of its first commercial 20 MW facility, which will also be in India. An illustration of such a facility is provided in Figure 35. This up-scaled plant consists of four pyrolysis units running continuously in parallel. The plant can treat 76 tons of feedstock (un-specified agricultural residues) per day. The outputs from this facility will be approximately 23 tons of biochar and 16 tons of bio-oil per day. Production is expected to start by the end of Q1 2023. It is expected that additionally, three similar facilities will be set up by the end of 2023. From this point on, it is the strategic aim of the company to double the number of facilities each year, ending up with at least 50 comparable facilities being built over the next 5 years. It is the plan to construct the first plants in India, followed by other countries in Southeast Asia, Africa, and North America. The accumulated PyCCS capacity of MASH Makes' strategic 5-year aim is sequestration of 1 million tons of CO_2e per year.

Figure 35: *Project visualization of a MASH Makes 20 MW pyrolysis facility. © MASH Makes.*

The company has ongoing activities related to optimizing char-use efficiency. These include both plant pot experiments and field trials. A dose-response experiment in pots has shown good growth response to increasing doses of the produced biochar, especially when the char was mixed with vermicompost.

Next-phase developments in regard to end-use of MASH biochar include e.g.

- Field trials with high biochar application rates on different plant species in water-stressed soils, which is a major focus of the company's activities and planning
- Large-scale demonstrations of biochar use to validate soil effects in a practical, agricultural context and under varying fertilizer regimes
- Collaboration with Indian NGOs working on afforestation projects to study the effect of biochar on tree health in a series of new afforestation projects including test and development of biochar use in regions with semi-arid soils, where it was earlier not possible to grow any trees
- Development of biochar-based fertilisers
- Use of biochar as a building material to manufacture bricks and as an additive in concrete.

Finally, MASH Makes has been very active within development of private markets for carbon removal. The company is in dialogue with multiple carbon removal marketplaces for the development of projects that would market and sell PyCCS credits. In October 2022, MASH Makes and carbon credit marketplace Carbonfuture signed a five-year purchase agreement to deliver 50,000 ton of CO_2e from MASH's pyrolysis projects in India[197], and the company expects that all their future projects will involve production and selling of PyCCS credits on private economic markets.

MASH Makes defines some of the most important drivers behind the company's development and growth plans in the coming years to be i) the growing market for carbon removal credits, and ii) the huge markets developing for bio-based fuels in sectors such as the marine industry.

6.3.6 Dall Energy – status and perspectives

Dall Energy[198] has a long history, developing new biomass energy technologies to the global market with focus on heat production or combined heat and power production based on local biomasses. The company has built six full-scale plants in Denmark, France and the US based on a patented and well-proven biomass furnace design that combines updraft gasification with gas combustion. However, in a pyrolysis context, the company departs in a new direction – towards the Low Temperature Circulating Fluidized Bed (LT-CFB) gasifier design, originally developed and constructed at increasing capacity from 50 kW to 500 kW at DTU and later built in a 6 MW unit at Asnæs power plant (the Pyroneer) in collaboration with Ørsted, DFBT etc. The design of the LT-CFB has undergone continuous development for many years. An illustration of the LT-CFB gasifier design for the period 2012-18 is provided in Figure 36. More information about this technology can be found in the proposed references[199].

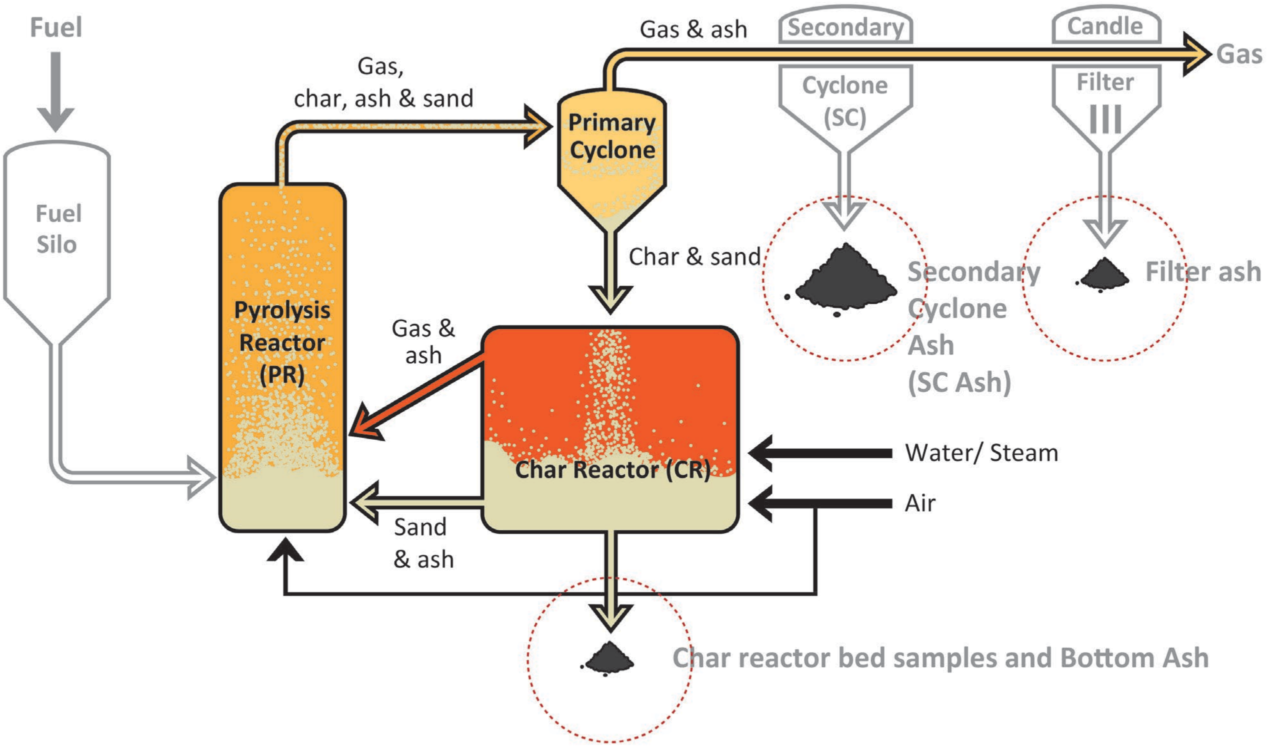

Figure 36: *Simple illustration of the LT-CFB gasifier design as it was developed at DTU KT until 2018. Illustration by the author.*

Today, only a pilot-scale facility of 100 kW located at DTU KT, Risø campus still exists. A picture of this unit is provided in Figure 37. However, the situation is about to change as Dall Energy received funding for a new generation of LT-CFB plants in Denmark.

Figure 37: *Picture of the only LT-CFB unit (100 kW at DTU KT, Risø Campus) currently existing. Picture taken in 2012 during installation of the ceramic candle filter (to the right). By the author.*

In the summer of 2022, Dall Energy was approved funding from ”Pyrolysepuljen” to a proposed project with the overall aim to establish a ”Large-scale fluid-bed pyrolysis plant (Project title: ”Stor-skala fluid-bed pyrolyseanlæg”). The plant design will be based on the former development of the LT-CFB gasifier, but with more focus on production of biochar and on designing a system that may convert biomass fuels with as much as 80% moisture. The project has now been initiated and Dall Energy is currently working with the other project partners to determine project details related to plant capacity and size, location, biomass availability and characteristics etc. It is expected that the plant will be located in the south-western part of Denmark and have a capacity of 5-10 MW based on fuel input. The plant is expected to operate on a mixture of different local biomass resources, predominately sewage sludge, biogas digestate fibers, industrial organic waste etc. Initially, the plant will be built for production of biochar and heat for district heating. However, later in the project it will be investigated how the process gas can be upgraded and used for higher-value purposes. The plant is expected to be in operation from 2024-25.

6.3.7 Frichs Pyrolysis - status

No input for this section was received from the company, but some information about a large project with Frichs Pyrolysis was found from the company website[200] and a presentation from the seminar “Biochar Onwards 2022+” from Roskilde University in June 2022. Frichs obtained 18.6 mio. DKK in funding from Pyrolysepuljen to construct a 2 MW unit of the company’s electrically heated flash pyrolysis plant for treatment of pre-dried chicken manure from the egg-producer Springkilde Eggs.

Frichs Pyrolysis previously developed their technology based on an American design heated by combustion of the produced gas or by oil burners. However, the new design is electrically heated which makes operation and maintenance much simpler. The new plant operates at temperatures around 800 °C and with retention times around 1 second. The gas is subsequently cleaned and converted to heat and power in a gas engine. The reactor design is based on indirectly heated entrained flow methodology in multi-layered pipes, and according to the company the design is very energy efficient with very low energy consumption and parasitic loss[201]. The company obtained a patent on their reactor design in 2022. As with all the Pyrolysepulje projects, the plant has to be in operation before the end of 2025. A picture from the construction of a Frichs demonstration plant is provided in Figure 38.

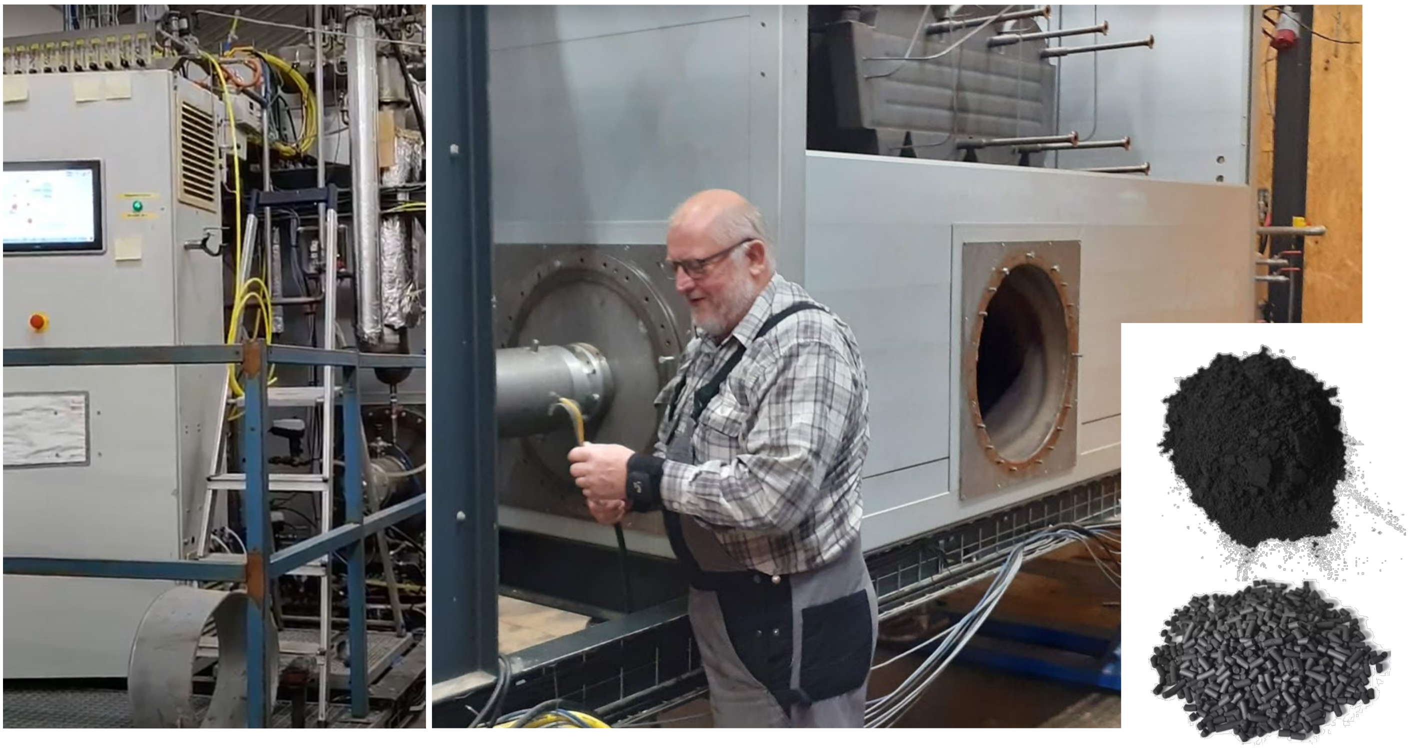

Figure 38: *Pictures from construction of a Frichs Pyrolysis Flash pyrolysis demonstration plant and of two biochar products from the processing of different biomasses. © Frichs Pyrolysis*

6.3.8 Organic Fuel Technology - status

No information for this section was received from the company and it was not possible to compile any status on activities by Organic Fuel Technology. The following information is retrieved from the company’s website[202]. OFT develops and produces plants for biomass pyrolysis based on a patented micro-wave reactor design where the biomass is treated at 325 °C and a small over-pressure of 20 mbar. According to the company, the OFT plant is safer and mechanically cheaper than conventional systems due to the reduced temperature. An illustration is provided in Figure 39.

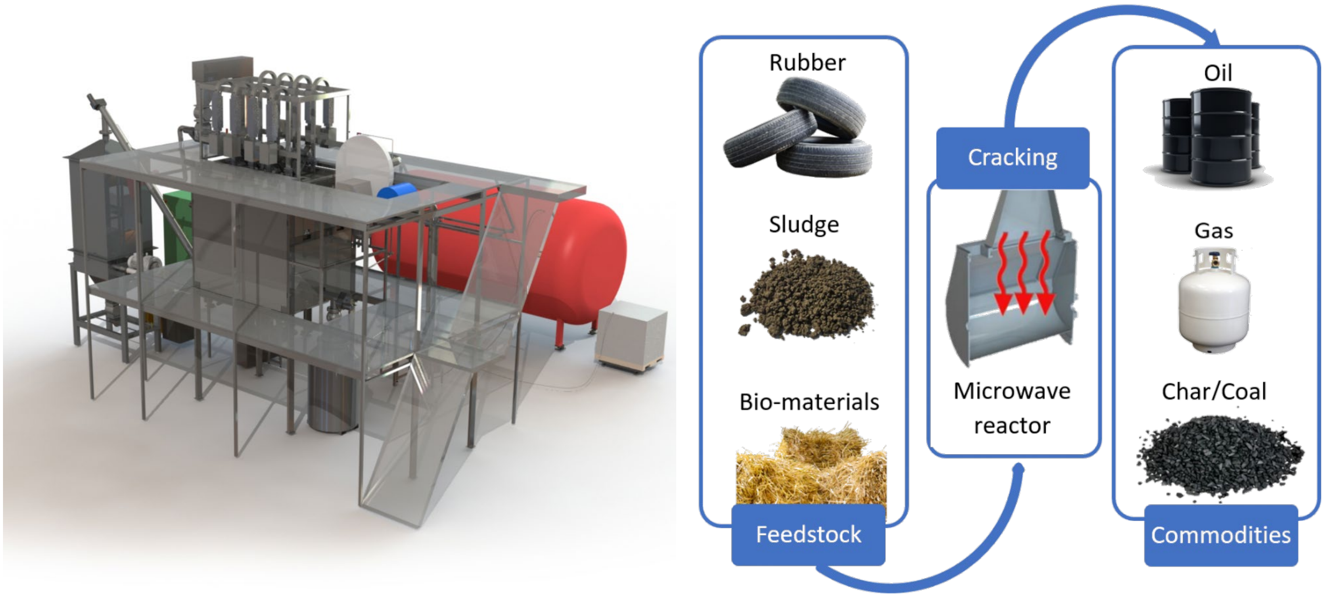

***Figure 39:** Computer rendered illustration of the OFT8 plant design and simple schematics. According to the company website, the OFT8 plant can process 600 kg organic waste per hour*[203]*. © Organic Fuel Technology.*

7 Risks, gaps and barriers going forward

Development towards a new pyrolysis-oriented sector is fast and accelerating. However, past experiences from bio-based innovation processes on e.g. ethanol production, thermal gasification, biogas and heat/CHP plants have shown that there are many delays, obstacles and barriers along the development and implementation pathways and that not all technologies make it to a break-through. This chapter aims to illuminate known risks and downsides, present identified knowledge gaps and showcase some of the current barriers existing towards further development and implementation.

There are substantial commercial and political expectations related to impact and value creation from biomass pyrolysis. In a Danish context there is a keen focus on potential climate effects of amending biochar to soil, and in the current implementation scheme, many barriers will be related to scaling, validating and monetizing these effects. However, realizing the potential climate effects on a large scale will also bring about environmental effects in the soil and adjacent ecosystems on a correspondingly large scale. As many of these effects are expected to be highly irreversible, "now" may be the only chance to develop the knowledge required to fill the current gaps and make the plans for robust, reasonable and long-term sustainable implementation of a Danish pyrolysis sector.

This is not an exhaustive list – far from it, and it can be expected to expand continuously with further development and implementation efforts. The focus in this short chapter will be mainly related to production and use of biochar in an agricultural soil context as this is foreseen to be the first large market for Danish biochar use – and one where the irreversibility of biochar amendment may become the biggest issue if not sufficiently investigated. Other specific knowledge gaps, risks and issues will relate to the use of biochar in other circumstances as well as to the use of the other pyrolysis products.

7.1 Risk assessment and potential downsides

There are both risks and negative effects related to production and use of biochar. Some of these can be avoided and some are already addressed in legislation and certification. Nevertheless, there are risks related to knowledge gaps that must be addressed. Generally, the focus up until now has been mainly on short-term effects and on impacts of various well-established physical and chemical properties of biochar. The focus on identification and mitigation of adverse effects is not new. Below are highlights of a risk assessment cited from the summary of a large review study published by Verheijen et al. under the Joint Research Centre (JRC) back in 2010[204]:

- ***"The use of biochar analogues for assessing effects of modern biochars is very limited:*** *Charcoal in Terra Preta soils is limited to Amazonia and has received many diverse additions other than charcoal. Pyrogenic biochar is found in soils in many parts of the world but are of limited feedstock types and pyrolysis conditions.*
- ***Soil loss by erosion:*** *Top-dressing biochar to soil is likely to increase erosion of the biochar particles both by wind (dust) and water. Many other effects of biochar in soil on erosion can be theorized, but remain untested at present.*
- ***Soil compaction during application****: Any application carries a risk of soil compaction when performed under inappropriate conditions. Careful planning and management could prevent this effect.*
- ***Risk of contamination****: Contaminants (e.g. PAHs, heavy metals, dioxins) that may be present in biochar may have detrimental effects on soil properties and functions. The occurrence of such compounds in biochar is likely to derive from either contaminated feedstocks or the use of processing conditions that may favor their production. Evidence suggests that a tight control over*

the type of feedstock used, and lower pyrolysis temperatures (<500°C) may be sufficient to reduce the potential risk for soil contamination.

- ***Residue removal**: Removal of crop residues for use as a feedstock for biochar production can forego incorporation of the crop residue into the soil, potentially leading to multiple negative effects on soils.*
- ***Occupational health and fire hazards**: Health hazards (e.g. from dust exposure) and fire hazards associated with the production, transport, application and storage of biochar need to be considered when determining the suitability for biochar application. In the context of occupational health, tight health and safety measures need to be put in place in order to reduce such risks. Some of these measures have already proved adequate.*
- ***Reduction in earthworm survival rates (limited number of cases):** High biochar application rates of >67 t ha^{-1} (produced from poultry litter) were shown to have a negative effect on earthworm survival rates, possibly due to increases in pH or salt levels"*

This list from the JRC report is still – at least to a very large extent, representative for the current focus on negative effects of biochar use. Especially the risk of contamination, the negative effects of residue removal, fire hazards and potential negative effects on soil life are still issues of concern. However, in 2022 there are also new points on the list as described in the following, and some of the points on the 2010 list have been removed or modified.

In a more recent critical review by Godlewska et al. from 2021 called "The dark side of the black gold: Ecotoxicological aspects of biochar and biochar-amended soils", it was concluded that in most cases, the application of biochar into soil does not have a toxic effect and that the use was often found to positively "*stimulate plants, bacteria activity and invertebrates*". However, in the same study several problematic examples of biochar application were identified and overall, the risks and downsides are found in this study to be controlled by the biochar type and quality under dominance by i) type of biomass feedstock, ii) the applied pyrolysis temperature profile and iii) contaminants content in the char. In some cases, it is found that otherwise positive characteristics of the biochar (i.e. pH effects and electrical conductivity) may cause negative effects when improperly managed, while more classic issues like the content of polycyclic aromatic hydrocarbons and heavy metals are found to (still) dominate the risks and downsides related to biochar toxicity[205].

In another critical review from the same year by Martin Brtnicky et al., it is also concluded that the findings are often very mixed, and sometimes ranging from the negative to the positive. However, some general issues are identified including indications that:

- Application of high doses of biochar in clay soils may decrease available water content
- Surface application of biochar to sandy soils may increase erosion and particle emissions
- Large biochar application rates may increase soil salinity and decrease fertility in alkaline soils due to nutrient precipitation from pH increases
- biochar use may decrease the effectiveness of (agro)chemicals
- the role of toxic substances in applied biochar can have "*adverse effects on reproduction, growth, and DNA integrity of earthworms* [and] *effects on soil microbiome such as a shift in the fungi-to-bacteria ratio*"[206].

Based on the highly diverse effects identified, Brtnicky et al. propose development and adoption of a more comprehensive regulatory framework that considers a broader range of positive and negative effects of biochar in a holistic assessment.

The findings in the "Knowledge Synthesis on Biochar in Danish Agriculture" published by Lars Elsgaard and his colleagues from Aarhus University, support and elaborate on many of these risks and concerns. Here are some highlights from the report, that all point towards increased risks and negative effects at very large biochar application rates[207]:

- **About impact on soil salinity** (page 58): Adding large amounts of biochar to soil, may also bring large amounts of un-regulated elements – like potassium, that may to some extent be water soluble and thus increase the salt levels and the electrical conductivity in soil water. The salt level will impact plant water uptake and may induce salt stress and reduce yield of many different (most) crops. In many cases, regulation of other biochar elements will prevent excessive K application, but in any case, it should be avoided to distribute more than the typical crop requirement of 50-100 kg K/ha/year.
- **About impact on soil life** (page 66+): High biochar amendment levels may also induce harmful effects on soil life while lower dosing of the same biochar may have none or even positive effects. Negative effects have been reported repeatedly at amendment levels of 50 t/ha or above. At large dosing rates, the toxic effects of the biochar itself may exceed the positive effects of toxin adsorption that occur also at lower concentrations and end up harming various micro-organisms.
- **About excessive application rates:** The report from AU also describes some negative results from Kalundborg in 2011 and 2012 where yields of maize were reduced by 22-25% in two different field tests after treatment with biochar at large applications rates of 50 t/ha. However, there is no detailed description of expected mechanisms or references for further knowledge[208].

The risk of negative effects from high biochar application rates on plant yield is corroborated by other studies as well. In a review from Osman et al. from 2022, it is discussed how un-mixed biochars with low nutrient content are unsuited as fertilizers due to the requirement for large application rates. It is argued that in general, application of high rates of biochar (>50 t/ha) will impose substantial economic burdens on the farmer from the expensive application procedure while having a *"detrimental effect on the soil microbial community, impairing its fertility. Moreover, it inhibits plant germination and early growth in the soil when applied at such high rates"*[209].

Overall, there are categories of negative effects that may be controlled and some that cannot.

- Effects related to biochar content of toxins and pollutants can be controlled and optimized by e.g.
    - i) selecting proper biomass fuels to avoid e.g. heavy metals and
    - ii) conducting biomass pyrolysis in well-designed – and controlled, plants to avoid production of PAH's and dioxins.
- Effects related to pH-modification, soil salinity and electrical conductivity may be controlled by avoiding large application rates of biochar with considerable amounts of e.g. potassium. From several different sources, it seems that considerable caution should be taken if considering distributing amounts of 50 t/ha or higher.
- Effects related to e.g. water retention and -permeability, soil density and -structure etc. may be partially controlled by matching soil type, biochar type, biochar particle size distribution and application rates.
- Effects related to adsorption of nutrients and to some extent agro-chemicals may be controlled or at least improved by char pre-treatment, co-application or proper timing. Some of the negative (as well as the positive) effects of biochar application may be short-lived. The most immediate effect to mitigate with timing in this way could be the biochar nutrient sponge effect. This effect is most prominent immediately after uncharged biochar is amended to soil with available nutrients, and the negative effect may be expected to level off with establishment of suitable equilibriums. It may be possible to utilize this effect as an advantage instead of a disadvantage, if the uncharged biochar is applied in the autumn to boost/replace cover crops to fix soil nutrients until spring growth. In regard to timing, Ahmad Khan investigated the use of biochar in wheat production in a calcareous soil and found that biochar increased the effects of the co-applied nitrogen fertilizers

and gave substantial increases in grain protein content, yield of grain and straw and total N concentration and uptake in all plant parts. However, it was also found that the 2nd year effects were significantly better than 1st year effects[210].

Despite the many mitigation options, there are also some effects that cannot be controlled with the current level of knowledge as there are substantial gaps herein. This can relate to a site-specific context with a given soil + biochar + crop + agricultural practice + climate etc. that has not been assessed and documented yet. Or it can relate to treatments after the first and second year which are rarely investigated. Or it can relate to long-term effects. Or cocktail effects. Or…

7.1.1 Non-soil negative effects

The type, number and magnitude of both positive and negative effects will depend on the site-specific context of the biochar production and use system. As mentioned, this cannot be regarded as neither fool-proof nor one-size-fits-all. The wider the system, the larger the number of direct and indirect effects. Here are some examples of risks and negative effects that should be taken into consideration:

- **N-losses:** Nitrogen is lost in pyrolysis as atmospheric N_2. This is typically regarded as a drawback as nitrogen is an important nutrient. However, there may also be cases with positive effects from removal of nitrogen and reduced leaching hereof.
- **SPK-losses:** Sulphur can also be released in quite large amounts during pyrolysis. This can be a drawback or benefit depending on the use case. A small fraction of the biomass phosphorus and potassium may also be lost, especially at high pyrolysis temperatures. This is typically a downside.
- **Nutrient losses in non-soil biochar applications:** If the biochar is used in systems where it does not eventually end up in soil then the non-renewable nutrients in the biochar herein will often be lost from the circular bio-economy context and this is generally not sustainable. Ideally, only biochar with low nutrient content (e.g. from wood or woody biomasses) or biochar from polluted biomasses should be used in systems without a soil end-of-life situation.
- **Emissions from production:** Dust, particles, gases, fumes, vapors, noise, odorants etc. may cause local problems around the pyrolysis plant. Proper biomass selection and handling, well-designed plants and regulation can reduce/prevent these effects.
- **Biomass is a limited resource:** Using biomass for pyrolysis only to sequester carbon and profit from PyCCS effects may have overall negative effects on the full system. Energy use should be optimized. Biomass should be selected carefully. Pyrolysis of biomass and application of biochar should ideally lead to an increased biomass productivity to facilitate the circular bio-economy. Use of char in well-assessed use contexts and systems and preferable on depleted, arid and/or degraded soils may boost this effect.
- **Biogenic carbon will be a limited resource:** In a non-fossil system with substantial human activity, there may be a deficit of biogenic carbon. Especially if soil productivity is not maintained, and the current rate of development is not reversed. Simple systems for biomass pyrolysis and direct biochar soil amendment in large scale may not be sufficiently efficient for such a system. Especially, if the char amendment does not increase soil quality and biomass production. In such cases, cascade and use-re-use systems with many tiers and loops should be developed to increase carbon efficiency, and both pyrolysis and biochar can play a major role in this context as well. This is discussed in section 5.3.5
- **PyCCS is a limited effect:** Both biomass and pyrolysis plant capacity are limited resources, making PyCCS a limited effect. According to IPCC, carbon-capture technology like biomass pyrolysis is needed to secure a net drain of carbon/greenhouse gases from the atmosphere after 2050. This will be difficult if the biomass resource and pyrolysis plant capacity is locked in long-term contracts

and compensation structures related to compensation mechanisms in e.g. agriculture, industry or air-traffic. Strategic and sustainable governance is required to prevent this situation. Climate crisis mitigation targets and funding options need to separate sink effects from other mitigation measures. This could be done by dividing targets and resources into at least 4 different categories where transfers and overlaps are not allowed. These should include e.g.:

    - **Energy use reduction** e.g. energy savings, changes of habits
    - **Fossil fuel use substitutions** e.g. in energy production
    - **Emission prevention** e.g. biomass stabilization, CH_4/N_2O-prevention
    - **Carbon sequestration** e.g. via PyCCS, build-up in biological systems, materials etc.

- A mitigation model of this sort is required to reduce the risk of biochar production and use ending up as a simple compensation mechanism used to facilitate business-as-usual. A comparable approach is supported by the European Biochar Industry Consortium. The organization works for this approach to become an integrated part of near-future EU legislation related to certification of carbon removals.

It is not unlikely that increasing the knowledge base further will foster possibilities to avoid/ reduce/mitigate more of the negative effects currently related to biochar production and use. In the following section, a list of identified knowledge gaps related to production and use of biochar are therefore presented.

7.2 Knowledge gaps

The knowledge base and number of scientific publications on production and use of biochar increases exponentially. At the same time, new processes, new char-use schemes, new integrated systems, new sector involvements etc. are under constant development. At the same time, many effects from biochar use – especially related to use in soil systems, are highly context dependent. As a result, the assessment matrix required to cover the variations and fill relevant knowledge gaps is practically without end. In this section, a brief status and assessment of recent developments is made. It is possible to establish an initial overview of the central topics governing the knowledge gaps currently assessed in Danish R&D by assessing the list of ongoing R&D projects in 6.2.2. This list indicates that there is a lot of focus on the lack of knowledge concerning

i) climate effects,
ii) soil enhancement effects
iii) technical development of fuel production and up-scaling.

To elaborate on current knowledge gaps, an analysis of knowledge gaps performed by Verheijen et al. for the Joint Research Centre back in 2010[211] is compared to a very recent assessment of relevant knowledge gaps performed by Elsgaard et al. for Aarhus University and the Danish Agricultural Agency[212] and supplemented by a few additional findings.

In Table 5, the primary gaps identified in the JRC report in 2010 are summarized.

Table 5: *Knowledge gaps identified in report from Joint Research Council back in 2010. Cited directly as published in Verheijen et al. (2010) except for internal references that are deleted*[213]

Knowledge gap	Description
Empirical evidence is extremely scarce for many modern biochars in soils under modern arable management	Biochar analogues do not exist for many feedstocks, or for some modern pyrolysis conditions. Biochar can be produced with a wide variety of properties and applied to soils with a wide variety of properties. Some short term (1-2 yr) evidence exists, but only for a small set of biochar, environmental and soil management factors and almost no data is available on long term effect.
C Negativity	The carbon storage capacity of biochar is widely hypothesized, although it is still largely unquantified and depends on many factors (environmental, economic, social) in all parts of the life cycle of biochar and at the several scales of operation.
Effects on N cycle	N_2O emissions depend on effects of biochar addition on soil hydrology (water-filled pore volume) and associated microbial processes. Mechanisms are poorly understood and thresholds largely unknown.
Biochar Loading Capacity (BLC)	BLC is likely to be crop as well as soil dependent leading to potential incompatibilities between the irreversibility of biochar once applied to soil and changing crop demands.
Environmental behaviour mobility and fate	The extent and implications of the changes that biochar undergoes in soil remain largely unknown. Although biochar physical-chemical properties and stabilization mechanisms may explain biochar long mean residence times in soil, the relative contribution of each factor for its short- and long-term loss has been sparsely assessed, particularly when influenced by soil environmental conditions. Also, biochar loss and mobility through the soil profile and into the water resources has been scarcely quantified and transport mechanisms remain poorly understood
Distribution and availability of contaminants (e.g. heavy metals, PAHs) within biochar	Very little experimental evidence is available on the short- and long-term occurrence and bioavailability of such contaminants in biochar and biochar-enriched soil. Full and careful risk assessment in this context is urgently required, in order to relate the bioavailability and toxicity of the contaminant to biochar type and 'safe' application rates, biomass feedstock and pyrolysis conditions, as well as soil type and environmental conditions
Effect on soil organic matter dynamics	Various relevant processes are acknowledged but the way these are influenced by combinations of soil-climate-management factors remains largely unknown
Pore size and connectivity	Although pore size distribution in biochar may significantly alter key soil physical properties and processes (e.g. water retention, aeration, habitat), experimental evidence on this is scarce and the underlying mechanisms can only be hypothesized at this stage
Soil water retention/availability	Adding biochar to soil can have direct and indirect effects on soil water retention, which can be short or long lived, and which can be negative or positive depending on soil type. Positive effects are dependent on high applications of biochar. No conclusive evidence was found to allow the establishment of an unequivocal relation between soil water retention and biochar application
Soil compaction	Various processes associated with soil compaction are relevant to biochar application, some reducing others increasing soil compaction. Experimental research is lacking. The main risk to soil compaction could probably be reduced by establishing a guide of good practice regarding biochar application
Priming effect	Some inconclusive evidence of a possible priming effect exists in the literature, but the evidence is relatively inconclusive and covers only the short term and a very restricted sample of biochar and soil types
Effects on soil megafauna	Neither the effects of direct contact with biochar containing soils on the skin and respiratory systems of soil megafauna are known, nor the effects or ingestion due to eating other soil organisms, such as earthworms, which are likely to contain biochar in their guts
Hydrophobicity	The mechanisms of soil water repellency are understood poorly in general. How biochar might influence hydrophobicity remains largely untested
Enhanced decomposition of biochar due to agricultural management	It is unknown how much subsequent agricultural management practices (planting, ploughing, etc.) in an agricultural soil with biochar may influence (accelerate) the disintegration of biochar in the soil, thereby potentially reducing its carbon storage potential
Soil CEC	There is good potential that biochar can improve the CEC of soil. However, the effectiveness and duration of this effect after addition to soils remain understood poorly
Soil Albedo	That biochar will lower the albedo of the soil surface is fairly well established, but if and where this will lead to a substantial soil warming effect is untested

Some of the gaps identified in 2010 have been addressed in substantial experimental campaigns since then, and many studies have been conducted to expand the knowledge related to e.g. “Distribution and availability of contaminants (e.g. heavy metals, PAHs) within biochar”, “Soil water retention/availability”, “Priming effect” and “Soil CEC”. However, even within these focal areas, there are still gaps in the available knowledge. And, as previously mentioned, new gaps have been identified during the assessment of new knowledge and as a result of the continued development of new products, processes and possibilities. Table 6 presents an overview of some of the knowledge gaps that have been identified in recent years. To make it possible to compare with Table 5, the focus is on the technical and natural science aspects off biochar use in an agricultural context.

Table 6: *Knowledge gaps related to use of biochar in agricultural soil, identified in Elsgaard et al. (2022) “Knowledge Synthesis on Biochar in Danish Agriculture”*[214] *(referred to in the table as KS), alongside a few additional references from 2021 and 2022*

Knowledge gap	Description
Generally about effects of biochar on soil microbial communities	Several studies show that effects of biochar application of soil microbial communities are generally positive expressed through e.g. a higher microbial biomass production, microbial diversity (e.g. DNA mapping) and/or activity levels. However, there are also several studies that show negative effects on e.g. the levels of microbial community diversity or inhibition of various community functions. The complex dynamics and interactions between soil, biochar, nutrients, water and microorganisms makes this a challenging and very interesting field of research. Taking this one step further, adding plants or context will further increase the complexity and the size of the knowledge gaps [KS page 66-69].
Biochar as microorganism habitat	The image of large particles of biochar amended to agricultural soil to function as a terrestrial coral reef to shelter various microorganism cultures is exciting and positive. Microorganisms play a key role in agriculture and many different types of organisms are added to soil to promote plant growth through various interactions with soil and plants. However, to this date there is very limited knowledge about how and when and under which conditions biochar may have positive effects in this regard. Increasing knowledge in this regard may help boost positive effects of biochar use as well as open new business opportunities within optimization and design of biochar products for soil life enhancement [KS page 66-69].
Effects on earthworms	From no effects to negative effects to positive effects: There is a substantial lack of robust knowledge and guidelines related to biochar use and effects on earthworms and other macro- (and meso-) fauna. In a review by Brtnicky et al. (2021), it was concluded that “*The effects of biochar on earthworm survival, growth reproduction, and behavior were found to be contradictory), which illustrates that the understanding of biochar-organism interactions is still incomplete. Similarly, conflicting results have been found for other groups of organisms*.” [215] Studies on the use of wheat straw biochar on agricultural fields in mid Zealand, Denmark with moderate biochar application rates (up to 16 t/ha in total over 3 consecutive years) showed that the biochar application gave measurable positive effects on bacteria populations, but no apparent – positive or negative, effect on the population of earthworms.[216]
Aging of biochar	Effects related to aging of biochar – either in soil or before soil amendment, are not very well understood but may be very important to be able to analyze, evaluate and use results from many different studies of biochar application. In a comprehensive review from 2021, Joseph et al. *“describe three stages of reactions of biochar in soil: dissolution (1– 3 weeks); re-active surface development (1– 6 months); and aging (beyond 6 months). As biochar ages, it is incorporated into soil aggregates, protecting the biochar carbon and promoting the stabilization of rhizodeposits and microbial products.”*[217] Elsgaard et al. describe the aging process as a combination of physical, biological and chemical effects that foster a wide range of potential alterations of biochar structure and the effect of biochar on the environment. The biochar will undergo both physical changes (i.e. breaking, filling, transportation), chemical changes (i.e. changes in cation-exchange-capacity and variety of functional surface groups, decreasing adsorption strength etc.) and even biological changes (e.g. by formation of bio-film on the surface) during these interactions with the environment [KS page 72, 218]. Due to the temporal dynamics of all these interactions between biochar and the soil environment, it important to begin to include a stronger perspective of time in effect assessments and not simply expect that a given effects of biochar in soil – positive or negative, is static and semi-permanent.

Adsorption of agrochemicals	Biochar has been found to absorb and stabilize various pollutants and toxins in soil[219]. However, biochar in agricultural soil may also absorb agrochemicals. This may have benefits related to avoided leaching, but it may also lead to a reduced effect of the given chemical (fungicide, pesticide, nitrification inhibitors etc.). These effects are not very well understood [KS page 69-73] and need to be further investigated, especially if biochar is used in conventional farming systems.
Leaching of biochar into aquatic environments	Biochar amended to agricultural soil may end up in aquatic environments, suspended in water and moved via drains or surface runoff. This may be particularly relevant for amendment of smaller biochar particles or aged biochar that has undergone physical degradation. Several studies have been performed on the potential negative effects of biochar leaching, but there are substantial gaps in the existing knowledge. Current results indicate that there is a risk of different harmful effects of biochar on e.g. fish, phytoplankton and different plants, but these studies are not studies of biochar leached into aquatic environments after being amended to soil, but simply studies of putting biochar into water with various aquatic organisms [KS page 72-73]. As with any other biochar effect, the type of biochar (biomass + pyrolysis process) will also play a significant role with regard to risks from leaching of biochar. Biochar containing toxins – from the biomass, pyrolysis process or from adsorption in the soil, will naturally bring these toxins to the aquatic environments even though the solubility of these toxins may be altered in the processes.
Effects on N_2O emissions	According to Elsgaard et al., there is a lack of evidence and robust results when it comes to effects of biochar on N_2O emissions from Danish field conditions [KS page 91]. Many studies have been conducted on the international scene, but they are often difficult to compare. And it is also difficult to transfer the often very specific and isolated results to another context or to field conditions. Assessment of this matter is important in Denmark where N_2O emissions are abundant due to widespread, intensive agriculture. There is a big focus on this topic in Danish R&D projects (section 6.2.2) and tasks related to N_2O emissions from soil with biochar are included in several projects e.g. STABIL, MitiChar, SkyClean Scale-Up and the new DFF project "Optimization of biochar properties for maximum reduction of N_2O emissions from agricultural soils".
Effect of biochar derived dissolved organic matter	In a study from 2021, Sun et al. discuss the potential issues of biochar derived dissolved organic matter (DOM), and stresses the need for an improved understanding of this field of interest. The authors find that DOM may be rapidly mobilized when amending biochar to soil and that this dissolved organic matter is an important component for soil physics, soil biology and the fate of contaminants. Negative effects of unsuited and/or polluted biochar DOM arise from toxicity, competitive sorption, blockage effect, and solubilization that may lead to e.g. mobilization of contaminants, nitrogen immobilization and inhibition of microbial activity and plant growth. However, in other cases biochar DOM may have more or less the opposite positive effect range and the matter needs to be further investigated[220, KS page 104].

The knowledge gaps described in the table above relate to both positive and negative effects of biochar use and to understanding of effects on both the mechanistic level and in a site-specific context. The majority of analytical studies on biochar effects conducted so far, has been short (max. 1-2 years), and many of them have been conducted under lab conditions. This approach may provide both screening-type results for inspiration and broad assessments as well as appropriate conditions for test and validation of established hypotheses. In addition, the assessment matrix related to soil application of biochar is HUGE due to the high context dependency and interdependent effects between biomass, pyrolysis process, soil, plant and growth conditions. As a result, the efforts on the short term and lab scale level need to be continued. However, these efforts are rarely possible to reproduce robustly under real, full-scale conditions. In addition, it is very hard to make robust long-term assessments based only on results from short-term studies.

In future analytical programs, a special emphasis should therefore be put on initiating and maintaining long-term experiments across different scales and contexts - from the controlled and decoupled experiment in the lab to the fully situated everyday-use on a farm, and from broad screenings to deep analysis. Long-term experiments take – well, a long time, and with the rapid development and large focus, such activities should ideally have been initiated years ago.

In addition, both the "old" and "new" assessment of knowledge gaps, indicate that there is a severe lack of knowledge related to evaluation of biochar effects, when these are considered in the light of a more praxis-near perspective e.g.

- Any effect considered in a truly long-term experiment under natural climatic conditions
- Any effect considered under influence of real, agricultural practice and farming systems over several years and crop rotation schemes
- Any effect considered under application of different types of biochar to the same soil over time
- Any effect considered outside a business-as-usual context, under influence of a changing system (both socio-technical changes and ecological and climatic changes)

Assessing effects of biochar use in a sufficiently situated context to provide such knowledge requires a new type of biochar-related research, and development activities involving e.g. fully embedded – and long term, large-scale case studies. Some examples of what questions to answer in a practical, fully context-specific situation – preferably over time, could include e.g.

- Assessment of when to apply biochar in crop rotation.
    - Use as instead of – or in combination with cover crops, to valorize biochar nutrient sponge effect and limit negative effect hereof on yield of primary crops?
    - Or use in large amounts in deep soils?
    - Or use little by little over time e.g. in manure?
- Determine practical balance between amending untreated organic material to the soil and amending biochar to the soil to improve soil biome conditions and integrity
- Assess needs and requirements related to nutrient quantity, quality and closed/narrow loop-systems in full scale and under influence of biochar use.
    - Reduce input of fertilizers – quality and/or quantity?
    - Avoid leaching?
    - Increase yield and/or robustness of production (yield over time)?
    - Preserve and prioritize critical resources?

It may be that modelling can help provide at least parts of the answers for such questions – or at least expand the applicability hereof, if the models are properly validated.

However, with the current rate of development, it may also be that before academia has found the requested answers, there will be front-runner farmers enacting biochar use on large scale and searching for the answers themselves. To utilize this momentum, it could prove valuable to seek ways to support and follow such farmers, establish structures for knowledge exchange and foster innovation in living laboratories.

Finally, due to the specificity and context dependence of many biochar related effects, it is paramount to make broad/inclusive/holistic impact assessment studies – especially in the larger, expensive studies with high path dependency once initiated. Such studies should address a broad range of effects of biochar use – both positive and negative, in relation to value creation and damage on both economy, environmental and social indicators. Increasing the perspective and scope also increases cost and resource requirements, but it will similarly increase robustness of results and conclusions and decrease the time needed to reach sound conclusions. The time argument could be the most urgent in the current situation. This urgently calls for greater collaboration and more interdisciplinary assessment programs in the coming phase of development.

7.2.1 Knowledge gaps related to non-soil system impact and continuous development

When expanding the perspective beyond in-soil effects, then the landscape of required assessment efforts to fill the emerging knowledge gaps grows accordingly. Here, a few examples of knowledge gap categories are provided related to non-soil system impact and future developments:

- Operation stability, emission measurements and variation in char quality and characteristics from various full-scale technologies and assessment of this variation on system performance and – effects
- In-depth case studies on value creation and impact from context-specific full-scale plant with mature value chains
- Effects and value of biochar and pyrolysis liquids in various products and construction materials
- Feasibility of heavy metal polluted biomass pyrolysis at elevated temperatures and assessment of the effect of heavy metal volatilization and staged re-condensation on system performance and value creation
- Effect of large-scale nutrient mobilization via pyrolysis and production of biochar-based fertilizers with input materials and use across sectors
- Storage emissions and safety hazards
- Optimized design of full value chain for biochar-based nutrient filters for use as fertilizers
- Optimized system and post-process treatment of biochar for gas and odor filter applications
- Assessment of expected changes in biomass availability from changes in e.g. food consumption, animal production, climate change impact, development of a circular bio-economy, land-use policies and requirements for biodiversity and wilding, other forms of energy production and resource procurement etc.
- Integration of pyrolysis technology and energy production options in dynamic energy system modelling
- Planning and R&D in relation to energy production:
    - How to move from simple energy use (heat) to more advanced energy use (fuels) and further to even more advanced uses (materials, chemicals etc.)
    - How to integrate with other technologies for synergetic effects
    - How and where to deploy plants to optimize value creation
- How to implement production and use of biochar in a Danish context under EU fertilizer and energy regulation, coming Taxonomy/Ecodesign requirements etc.
- Assessment of new options for system integration and synergy in bio-refinery and/or industrial symbiosis contexts e.g. Biogas + Pyrolysis + PtX + Green Bio-refinery + composites + ???
- Development of robust frameworks and detailed case examples of future biomass cascade use systems with extreme carbon-use-reuse efficiency and closed loops of critical raw materials
    - 1st generation cascade systems: Waste/by-products are valorized in other value chains
    - 2nd generation cascade systems: Input is waste/by-products and all waste/by-products are valorized in other value chains
- Innovation projects for new char end uses to substitute fossil-based products and systems
- Innovation projects for new oil, gas and wood vinegar end-uses to substitute fossil-based products and systems
- …

7.3 Barriers going forward

In this last section of the report, some examples of barriers towards further development and/or implementation of a pyrolysis sector in Denmark are presented. Some of these barriers are fully identified while some have characteristics related to a lack of knowledge.

- There is a need for lighthouse projects that illuminate the process of implementation, spear-head critical issues and questions, help mature value chains, and validate feasibility at commercial scale and over time

- Processes and organs need to be established to approve and use Danish biochar under national and EU fertilizer regulation
- Processes and organs need to be established to approve and use liquid products from Danish biomass pyrolysis biochar under national and EU chemical/energy/material regulation
- Insufficient knowledge and awareness among central stakeholders i.e. farmers, consultants, biomass distributors, politicians etc.
- There are huge variations in data results and it is difficult to determine which potential effects are more generally applicable and which are more context dependent
- Further validation of use and boundary conditions for simple-to-measure proxy parameters for e.g. carbon stability, emission reductions, soil effects etc. for biochar produced from relevant Danish biomass feedstock under Danish field and climate conditions
- Integration between PyCCS and CCS and alignment of support-measures
- A climate tax in agriculture has to be settled to valorize e.g. biomass stabilization
- Pyrolysis is cross-sectoral and the value propositions are difficult to integrate in current full-system energy modelling
- It is a substantial barrier that there is currently many different overlapping standards and certification schemes being developed by different organizations e.g. EBC, Puro and VCS. These methodologies are similar in some regards and different in others, and it is not in all cases clear and transparent what the reasons behind the differences is and what the effect of it may be. It would benefit the development with increased alignment hereof.
- There is a lack of consistent, political visions for development of a circular bio-based economy including planning of land use in Denmark 2030 and 2050
- There is currently a lack of incentives in Denmark for agricultural biochar end use. Long-term, site-specific use at scale combined with mature mechanisms for monetizing the PyCCS effect in different taxation and certification schemes is needed.
- There is no catalogue of potential ownership/agency configurations, robust business models or cost-benefit analysis for agricultural stakeholders to investigate when considering options to engage in production and use of biochar
- Detailed and robust multi-criteria analysis and/or life cycle assessment studies need to be showcased to identify relevant potential positive >< negative effects and optimization options related to particularly i) climate impact, ii) ammonia emissions, iii) eutrophication, iv) soil toxicity, v) crop yield and vi) overall revenue
- Options to export Danish nutrient rich biochar in a development aid program to increase crop yields in areas with arid/depleted/infertile soils and insufficient nutrient and water availability
- Established long-term scheme for how and when climate impact effects from production and use of biochar is registered and accounted for at different governance levels (product, farm, organization, municipality, region, country, sector, etc.)
- Stable support schemes for R&D and for deployment may reduce critical barriers as previously observed in histories of biogas and bioethanol in Denmark[221]
- Focus on nutrient purification and carbon sink potential in organic agriculture or other consumer-goods oriented certification scheme
- Clarification on and robust frameworks for how to calculate, monitor, distribute, anchor and certify various effects (positive and negative) across the many different stakeholders/organizations/sectors involved in the many new, entangled value chains of the circular bio-economy of tomorrow.
- …

8 Literature, notes and links

---

[1] Elsgaard et al. (2022) *Knowledge synthesis on biochar in Danish agriculture*, found at https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport208.pdf

[2] There are also other definitions that are both broader (e.g. no limitations on use) or narrower (only char used in biological systems, typically soil).

[3] i) Cornel University (n.d.) *Terra Preta de indio*, found at https://www.css.cornell.edu/faculty/lehmann/research/terra%20preta/terrapretamain.html
ii) Cornel University (n.d.) *Biochar soil management*, found at https://www.css.cornell.edu/faculty/lehmann/research/biochar/biocharmain.html

[4] Scopus website Home, found at https://www.scopus.com/home.uri

[5] EBI market report 2021-2022, found at https://www.biochar-industry.com/2022/european-biochar-market-report-2021-2022-available-now/

[6] Official Journal of the European Union (2021) *Commission Delegated Regulation (EU) 2021/2088 of 7 July 2021 amending Annexes II, III and IV to Regulation (EU) 2019/1009 of the European Parliament and of the Council for the purpose of adding pyrolysis and gasification materials as a component material category in EU fertilising products (Text with EEA relevance)*, found at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R2088

[7] Official Journal of the European Union (2021) *Commission Implementing Regulation (EU) 2021/1165 of 15 July 2021 authorising certain products and substances for use in organic production and establishing their lists (Text with EEA relevance)*, found at https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A32021R1165

[8] Elsgaard et al. (2022) *Knowledge synthesis on biochar in Danish agriculture*, found at https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport208.pdf

[9] European Biochar Certificate (n.d.) *EBC guidelines & documents*, found at https://www.european-biochar.org/en/ct/2-EBC-guidelines-documents

[10] IPCC (2022*) Climate Change 2022, Mitigation of Climate Change - Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, found at https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_FinalDraft_FullReport.pdf e.g. section 7.4.3.2

[11] IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use - Appendix4: Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development*, found at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch02_Ap4_Biochar.pdf

[12] Compensate (2022) *Biochar evaluation criteria to help Compensate select the most sustainable projects on the market*, found at https://www.compensate.com/articles/biochar-evaluation-criteria-to-help-select-sustainable-projects

[13] Puro.earth (n.d.) *CORC Supplier Listing, sort by "Biochar"*, found at https://puro.earth/CORC-co2-removal-certificate/?carbon_removal_method%5B0%5D=7363

[14] Carbonfuture website home, found at https://www.carbonfuture.earth/

[15] (Danish) Ministry of Climate, Energy and Utilities (2021) *Klimaprogram 2021*, found at https://kefm.dk/Media/637684923696666735/Klimaprogram%202021%20(DIGITAL).pdf (in Danish)

[16] Brice R. Mbodiam @ Business in Cameroon (2021) *COP 26: Cameroon becomes first country in the world to integrate biochar into its climate strategy*, found at https://www.businessincameroon.com/environment/1111-12048-cop-26-cameroon-becomes-first-country-in-the-world-to-integrate-biochar-into-its-climate-strategy

[17] Danish Municipal climate plans E.g. Køge municipality found at https://www.koege.dk/klimaplan (in Danish), Holbæk municipality, found at https://holbaek.dk/media/yodbvj0t/holbaek-2050-handleplan-vejen-mod-en-klimaneutral-kommune.pdf (in Danish), and Thisted municipality for Thy as geografical area, found at

---

https://www.thisted.dk/~/media/ESDH/committees/217/2252/Punkt_101_Bilag_1_Bilag_1_Klimastrategi_for_Thy_som_geografi_forslag.ashx (in Danish)

[18] Netzero press release (2022) *NetZero delivers its first carbon removal credits to BCG as part of a newly announced long-term purchase agreement*, found at https://netzero.green/news/press-releases/PR-NetZero-20221104-EN.pdf

[19] E.g. i) Tumurulu et al. (2021) *Biomass Torrefaction Process, Product Properties, Reactor Types, and Moving Bed Reactor Design Concepts*, found at https://www.frontiersin.org/articles/10.3389/fenrg.2021.728140/full and
ii) Lei Shang phd thesis (2012) *Upgrading Fuel Properties of Biomass by Torrefaction*, found at https://backend.orbit.dtu.dk/ws/portalfiles/portal/56263668/Ph.d.+thesis+-+Lei+Shang%2C+klar+til+trykkeri.pdf

[20] E.g. i) Chen et al. (2015) *Characterization of solid and liquid products from bamboo torrefaction*, found at https://www.sciencedirect.com/science/article/abs/pii/S0306261915003062,
ii) Chen et al. (2021) *Comprehensive research on the solid, liquid, and gaseous products of rice husk and rice straw torrefaction*, found at https://pubs.rsc.org/en/content/articlelanding/2021/se/d0se01701a and
iii) Daniel et al. (2021) *Upgrading the Strategy of Multistage Torrefaction Liquid by the Selective Oxidation Reaction Route Using a Reusable MgO-Based Au/Al2O3 Catalyst*, found at https://pubs.acs.org/doi/10.1021/acs.energyfuels.1c02362

[21] IEA Bioenergy task 34 (2008) *Biomass Pyrolysis*, found at https://www.ieabioenergy.com/wp-content/uploads/2013/10/Task-34-Booklet.pdf

[22] E.g. i) Thomsen et al. (2011) *The potential of pyrolysis technology in climate change mitigation – influence of process design and –parameters, simulated in SuperPro Designer Software*, found at https://forskning.ruc.dk/da/publications/the-potential-of-pyrolysis-technology-in-climate-change-mitigatio,
ii) IEA Bioenergy task 34 (2008) *Biomass Pyrolysis*, found at https://www.ieabioenergy.com/wp-content/uploads/2013/10/Task-34-Booklet.pdf,
iii) Wang et al. (2020) A Review of Recent Advances in Biomass Pyrolysis, found at https://pubs.acs.org/doi/10.1021/acs.energyfuels.0c03107,
iv) Hu et al. (2019) *Biomass pyrolysis: A review of the process development and challenges from initial researches up to the commercialisation stage*, found at https://www.sciencedirect.com/science/article/abs/pii/S209549561830901X,
v) Fahmy et al. (2018) *Biomass pyrolysis: past, present, and future*, found at https://link.springer.com/article/10.1007/s10668-018-0200-5,
vi) Lehmann & Joseph (2015) *Biochar for Environmental Management - Science, Technology and Implementation 2nd Edition*, can be bought at https://www.routledge.com/Biochar-for-Environmental-Management-Science-Technology-and-Implementation/Lehmann-Joseph/p/book/9780367779184, An open pre-print of the 2009 version of the book can be found here https://www.css.cornell.edu/faculty/lehmann/publ/First%20proof%2013-01-09.pdf
vii) International Biochar Initiative (n.d.*) Overview of IBI publications*, found at https://biochar-international.org/ibi-publications/,
viii) ithaka institute for carbon strategies (2022) *The most important scientific publications of the Ithaka Institute*, found at https://www.ithaka-institut.org/en/publications and
ix) Puig-Arnavat et al. (2019) *Pyrolysis and Gasification of Lignocellulosic Biomass*, found at https://link.springer.com/chapter/10.1007/978-3-030-10961-5_4

[23] i) Thomsen et al. (2015) *Screening of various low-grade biomass materials for low temperature gasification: Method development and application*, found at https://forskning.ruc.dk/da/publications/screening-af-en-r%C3%A6kke-forskellige-lav-v%C3%A6rdi-biomasse-br%C3%A6ndsler-ti and
ii) Thomsen & Martin (2022) *Screening af kulstoflagring og energipotentiale fra pyrolyse af kommunale biomasser: Metodetest og indledende forsøg*, found at https://forskning.ruc.dk/da/publications/screening-af-kulstoflagring-og-energipotentiale-fra-pyrolyse-af-k (in Danish)

[24] Pictures from i) Interreg ØKS project Grater Bio publication Thomsen & Martin (2022) *Screening af kulstoflagring og energipotentiale fra pyrolyse af kommunale biomasser: Metodetest og indledende forsøg*,

---

found at https://forskning.ruc.dk/da/publications/screening-af-kulstoflagring-og-energipotentiale-fra-pyrolyse-af-k (in Danish) and from ii) Thomsen et al. (2017) *Changes imposed by pyrolysis, thermal gasification and incineration on composition and phosphorus fertilizer quality of municipal sewage sludge*, found at https://forskning.ruc.dk/da/publications/changes-imposed-by-pyrolysis-thermal-gasification-and-incineratio. Willow char picture from un-published project on water filtration.

[25] ECN (n.d.) *Phyllis2 database, char search*, found at https://phyllis.nl/Browse/Standard/ECN-Phyllis#char

[26] ECN (n.d.) *Phyllis2 database, char search*, found at https://phyllis.nl/Browse/Standard/ECN-Phyllis#char

[27] Thomsen et al. (2015) *Screening of various low-grade biomass materials for low temperature gasification: Method development and application*, found at https://forskning.ruc.dk/da/publications/screening-af-en-r%C3%A6kke-forskellige-lav-v%C3%A6rdi-biomasse-br%C3%A6ndsler-ti

[28] Thomsen et al. (2015) *Screening of various low-grade biomass materials for low temperature gasification: Method development and application*, found at https://forskning.ruc.dk/da/publications/screening-af-en-r%C3%A6kke-forskellige-lav-v%C3%A6rdi-biomasse-br%C3%A6ndsler-ti

[29] Thomsen et al. (2015) *Screening of various low-grade biomass materials for low temperature gasification: Method development and application*, found at https://forskning.ruc.dk/da/publications/screening-af-en-r%C3%A6kke-forskellige-lav-v%C3%A6rdi-biomasse-br%C3%A6ndsler-ti

[30] Thomsen et al. (2015) *Screening of various low-grade biomass materials for low temperature gasification: Method development and application*, found at https://forskning.ruc.dk/da/publications/screening-af-en-r%C3%A6kke-forskellige-lav-v%C3%A6rdi-biomasse-br%C3%A6ndsler-ti

[31] Thomsen et al. (2015) *Screening of various low-grade biomass materials for low temperature gasification: Method development and application*, found at https://forskning.ruc.dk/da/publications/screening-af-en-r%C3%A6kke-forskellige-lav-v%C3%A6rdi-biomasse-br%C3%A6ndsler-ti

[32] ECN (n.d.) *Phyllis2 database category "European Biochar Certificate"*, found at https://phyllis.nl/Browse/Standard/ECN-Phyllis#char

[33] Meiwa co. (n.d.) *Product declaration: Drought Hero: Special biochar product, making dryland agriculture more resilient to water deficiency*, found at http://www.unido.or.jp/en/technology_db/5250/

[34] Tomczyk et al. (2020) *Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects*, found at https://link.springer.com/article/10.1007/s11157-020-09523-3#Tab1

[35] Cheng and Li (2018) *Preparation and Application of Biochar-Based Catalysts for Biofuel Production*, found at https://www.mdpi.com/2073-4344/8/9/346

[36] Biochars can be both physically and chemically activated to increase SSA and other performance characteristics. Activation processes can include e.g. gasification with steam or CO_2, acid washing, ozone treatment and more. See e.g. i) Sakhiya et al. (2020) *Production, activation, and applications of biochar in recent times*, found at https://link.springer.com/article/10.1007/s42773-020-00047-1 and ii) Sajjadi et al. (2018) *A comprehensive review on physical activation of biochar for energy and environmental applications*, found at https://par.nsf.gov/servlets/purl/10091642

[37] ECN (n.d.) *Phyllis2 database, char search*, found at https://phyllis.nl/Browse/Standard/ECN-Phyllis#char

[38] E.g. i) Andreas Nordin's mater thesis (2015) *Heavy Metal Removal From Sewage Sludge By Pyrolysis Treatment*, found at http://www.diva-portal.org/smash/get/diva2:902689/FULLTEXT01.pdf,
ii) Raheem et al. (2022) *Roles of Heavy Metals during Pyrolysis and Gasification of Metal-Contaminated Waste Biomass: A Review*, found at https://pubs.acs.org/doi/10.1021/acs.energyfuels.1c04051,
iii) Liu et al. (2020) *Transformation of Heavy Metals during Pyrolysis of Predried Dyeing Sludge,* found at https://pubs.acs.org/doi/10.1021/acs.energyfuels.9b03050,
iv) He et al. (2022) *A state-of-the-art review of the fate of heavy metals and product properties from pyrolysis of heavy-metal(loid)-enriched biomass harvested from phytoextraction*, found at https://aiche.onlinelibrary.wiley.com/doi/10.1002/ep.13979?af=R and
v) Tobias Thomsen's thesis (2016) *Closing the Loop - Utilization of Secondary Resources by Low Temperature Thermal Gasification*, found at https://rucforsk.ruc.dk/ws/portalfiles/portal/66911184/Tobias_P_Thomsen_2016_Closing_the_Loop_phd_thesis_Online_version.pdf

[39] Tobias Thomsen phd thesis (2016) *Closing the Loop - Utilization of Secondary Resources by Low Temperature Thermal Gasification*, found at

---

https://rucforsk.ruc.dk/ws/portalfiles/portal/66911184/Tobias_P_Thomsen_2016_Closing_the_Loop_phd_thesis_Online_version.pdf

[40] Thomsen et al. (2017) *Changes imposed by pyrolysis, thermal gasification and incineration on composition and phosphorus fertilizer quality of municipal sewage sludge*, found at https://www.sciencedirect.com/science/article/pii/S0301479717304206

[41] Müller-Stöver et al. (2021) *Increasing plant phosphorus availability in thermally treated sewage sludge by post-process oxidation and particle size management*, found at https://www.sciencedirect.com/science/article/abs/pii/S0956053X2030605X

[42] Vandermoere et al. (2021) *Soil phosphorus (P) mining in agriculture – Impacts on P availability, crop yields and soil organic carbon stocks*, found at https://www.sciencedirect.com/science/article/abs/pii/S0167880921003649

[43] Talboys et al (2016) Struvite: a slow-release fertiliser for sustainable phosphorus management? found at https://link.springer.com/article/10.1007/s11104-015-2747-3

[44] ECN (n.d.) *Phyllis2 database category "European Biochar Certificate"*, found at https://phyllis.nl/Browse/Standard/ECN-Phyllis#char

[45] European Biochar Certificate (2022) *Guidelines for a Sustainable Production of Biochar v. 10.1*, found at https://www.european-biochar.org/media/doc/2/version_en_10_1.pdf

[46] i) European Biochar Certificate (n.d.) *EBC guidelines & documents*, found at https://www.european-biochar.org/en/ct/2-EBC-guidelines-documents and ii) European Biochar Certificate (2022) *C-sink*, found at https://www.european-biochar.org/en/c-sink

[47] European Biochar Certificate (2022) *Guidelines for a Sustainable Production of Biochar v. 10.1*, found at https://www.european-biochar.org/media/doc/2/version_en_10_1.pdf

[48] European Biochar Certificate (2022) *Positive list of permissible biomasses for the production of biochar v. 10.1*, found at https://www.european-biochar.org/media/doc/2/positivlist_en_2022_1_v10_1.pdf and ii) European Biochar Certificate (2022) *Guidelines for a Sustainable Production of Biochar v. 10.1*, found at https://www.european-biochar.org/media/doc/2/version_en_10_1.pdf

[49] EUR-LEX (2019) *Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 (Text with EEA relevance)*, found at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02019R1009-20221003

[50] European Biochar Certificate (2022) *Guidelines for a Sustainable Production of Biochar v. 10.1*, found at https://www.european-biochar.org/media/doc/2/version_en_10_1.pdf

[51] European Biochar Certificate (2022) *Guidelines for a Sustainable Production of Biochar v. 10.1*, found at https://www.european-biochar.org/media/doc/2/version_en_10_1.pdf

[52] EUR-LEX (2019) *Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 (Text with EEA relevance)*, found at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02019R1009-20221003

[53] The European Biochar Industry Consortium (EBI) website home, found at https://www.biochar-industry.com/

[54] European Sustainable Phosphorus Platform (ESPP) website home, found at https://www.phosphorusplatform.eu/

[55] Official Journal of the European Union (2021) *Commission Implementing Regulation (EU) 2021/1165 of 15 July 2021 authorising certain products and substances for use in organic production and establishing their lists (Text with EEA relevance)*, found at https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A32021R1165

[56] Many examples of studies that vary in both topic and assessment method. See e.g.
i) Puig-Arnavat et al. (2019) *Pyrolysis and Gasification of Lignocellulosic Biomass*, found at https://link.springer.com/chapter/10.1007/978-3-030-10961-5_4,
ii) Nguyen & Clausen (2019) *Techno-economic analysis of polygeneration systems based on catalytic hydropyrolysis for the production of bio-oil and fuels*, found at

---

https://www.sciencedirect.com/science/article/pii/S0196890419301220?via%3Dihub,
iii) Kofler & Clausen (2022) *Exergy-based comparison of three wheat straw based biorefineries*, found at https://backend.orbit.dtu.dk/ws/portalfiles/portal/284696434/Manuscript_Rene_Kofler_rev.pdf,
iv) Bakari et al. (2020) *Simulation and optimisation of the pyrolysis of rice husk: Preliminary assessment for gasification applications*, found at https://www.sciencedirect.com/science/article/pii/S0165237020303119?via%3Dihub,
v) Varma et al. (2019) *Pyrolysis of wood sawdust: Effects of process parameters on products yield and characterization of products*, found at https://www.sciencedirect.com/science/article/pii/S0956053X19302296?via%3Dihub,
vi) Kataria et al. (2022) *A system level analysis of pyrolysis of cotton stalk biomass*, found at https://www.sciencedirect.com/science/article/pii/S2214785321077361,
vii) Chen et al. (2018) *Mobile Autothermal Pyrolysis System for Local Biomass Conversion: Process Simulation and Techno-Economic Analysis*, found at https://pubs.acs.org/doi/10.1021/acs.energyfuels.7b03172 and
viii) Tobias Pape Thomsen (2021) *Climate Footprint Analysis of Straw Pyrolysis & Straw Biogas - Assessment of the Danish climate crisis mitigation potential of two new straw management options*, found at https://forskning.ruc.dk/da/publications/klimaaftryk-fra-anvendelse-af-halm-i-pyrolyse-og-biogas-en-analys

[57] i) Btg Bioliquids website home, found at https://www.btg-bioliquids.com/ and
ii) IEA task 34 (n.d.) *Task 34: Direct Thermochemical Liquefaction*, found at https://task34.ieabioenergy.com/biofuels/

[58] Phil Z @ Linkedin (2015) *Swedish university first to produce renewable fuel (DME) from pyrolysis bio-oil*, found at https://www.linkedin.com/pulse/swedish-university-first-produce-renewal-fuel-dme-from-zoldak-/

[59] See examples of this development in E.g.
i) Raymundo et al. (2019) *Deoxygenation of Biomass Pyrolysis Vapors via in Situ and ex Situ Thermal and Biochar Promoted Upgrading*, fount at https://pubs.acs.org/doi/10.1021/acs.energyfuels.8b03281,
ii) Kumar et el (2019) *Enhanced bio-oil deoxygenation activity by Cu/zeolite and Ni/zeolite catalysts in combined in-situ and ex-situ biomass pyrolysis*, found at https://www.sciencedirect.com/science/article/pii/S0165237018311318,
iii) Valle et al. (2022) *Role of zeolite properties in bio-oil deoxygenation and hydrocarbons production by catalytic cracking*, found at https://www.sciencedirect.com/science/article/pii/S0378382021004136,
iv) Eschenbacher et al. (2022) *Enhancing bio-oil quality and energy recovery by atmospheric hydrodeoxygenation of wheat straw pyrolysis vapors using Pt and Mo-based catalysts*, found at https://orbit.dtu.dk/en/publications/enhancing-bio-oil-quality-and-energy-recovery-by-atmospheric-hydr ,
v) Eschenbacher et al. (2020) *Deoxygenation of wheat straw fast pyrolysis vapors over Na-Al2O3 catalyst for production of bio-oil with low acidity*, found at https://orbit.dtu.dk/en/publications/deoxygenation-of-wheat-straw-fast-pyrolysis-vapors-over-na-alsub2 and for an overview and introduction, see the thesis: vi) Jundong Wang (2022) *Catalytic hydro-deoxygenation of bio-oil from biomass pyrolysis : comprehension of reaction pathways*, found at https://tel.archives-ouvertes.fr/tel-03517330/document

[60] E.g. i) Simonsen et al. @ IEA Bioenergy: Task 39 (2021) *Progress towards biofuels for marine shipping - Status and identification of barriers for utilization of advanced biofuels in the marine sector*, found at https://www.ieabioenergy.com/blog/publications/progress-towards-biofuels-for-marine-shipping/,
ii) Frederic Meyer @ Total Energies (2021) *Why Biofuels are Critical In Shipping's Future Fuel Mix*, found at https://marinefuels.totalenergies.com/news/blog/why-biofuels-are-critical-in-shippings-future-fuel-mix,
iii) Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (2022) *Bio-oils*, found at https://www.zerocarbonshipping.com/energy-carriers/bio-oils/?section=regulation and
iv) Tan et al. (2021) *Biofuel Options for Marine Applications: Technoeconomic and Life-Cycle Analyses*, found at https://pubs.acs.org/doi/10.1021/acs.est.0c06141

[61] See e.g. this review article Machado et al. (2022) *Bio-Oil: The Next-Generation Source of Chemicals*, found at https://www.mdpi.com/2624-781X/3/1/9/htm

[62] Clausen et al. (2020) *Grøn skibsfart kræver grønt brændstof. Hvordan kommer vi i gang*?, found at https://videnskab.dk/forskerzonen/teknologi-innovation/groen-skibsfart-kraever-groent-braendstof-hvordan-kommer-vi-i-gang (in Danish)

---

[63] i) ETIA EcoTechnologies (n.d.) *Pyrolysis process for biomass and waste*, found at https://etia-group.com/operations-for-thermal-processing/pyrolysis/ and ii) Biogreen (n.d.) *The pyrolyzer Spirajoule*, found at https://www.biogreen-energy.com/spirajoule

[64] Frichs Pyrolysis website home, found at https://www.frichs-pyrolysis.dk/

[65] Organic Fuel Technology website home, found at https://www.organicfueltechnology.com/

[66] Often relatively large plants see e.g. IEA HPT (n.d.) *Annex 58: High-Temperature Heat Pumps Mechanical vapor recompression for drying process at Hadano water treatment center*, found at https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2022/07/casehadano-city.pdf

[67] Can be both very small and large plants see e.g. Dryingmatter website home, found at https://www.dryingmatter.com for a Danish case

[68] AquaGreen (n.d,) *Sustainable biomass treatment*, found at http://aquagreen.dk/technology/

[69] E.g. i) Giulia Ravenni phd thesis (2018) *Application of biomass char to tar conversion and producer gas upgrading to syngas*, found at https://backend.orbit.dtu.dk/ws/portalfiles/portal/204575062/Final_thesis_fil_fra_trykkeri_Giulia_Ravenni.pdf,
ii) Ravenni et al. (2020) *Residual gasification char applied to tar reforming in a pilot-scale gasifier: Performance and evolution of char properties for perspective cascade uses*, found at https://orbit.dtu.dk/en/publications/residual-gasification-char-applied-to-tar-reforming-in-a-pilot-sc and
iii) Xu et al. (2020) *Mini-Review on Char Catalysts for Tar Reforming during Biomass Gasification: The Importance of Char Structure*, found at https://pubs.acs.org/doi/full/10.1021/acs.energyfuels.9b03725

[70] Lehmann & Joseph (2015) *Biochar for Environmental Management - Science, Technology and Implementation 2nd Edition*, can be bought at https://www.routledge.com/Biochar-for-Environmental-Management-Science-Technology-and-Implementation/Lehmann-Joseph/p/book/9780367779184, An open pre-print of the 2009 version of the book can be found here https://www.css.cornell.edu/faculty/lehmann/publ/First%20proof%2013-01-09.pdf

[71] ii) Cornel University (n.d.) *Biochar soil management*, found at https://www.css.cornell.edu/faculty/lehmann/research/biochar/biocharmain.html

[72] ii) Cornel University (n.d.) *Biochar soil management*, found at https://www.css.cornell.edu/faculty/lehmann/research/biochar/biocharmain.html

[73] Elsgaard et al. (2022) *Knowledge synthesis on biochar in Danish agriculture*, found at https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport208.pdf

[74] Joseph et al. (2021) *How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar*, found at https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12885

[75] Assessment of persistence level drivers by Wang et al. (2016) *Biochar stability in soil: meta-analysis of decomposition and priming effects*, found at https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12266

[76] i) Method overview by Budai et al. @ IBI (2013) *Biochar Carbon Stability Test Method: An assessment of methods to determine biochar carbon stability*, found at https://www.biochar-international.org/wp-content/uploads/2018/06/IBI_Report_Biochar_Stability_Test_Method_Final.pdf and
ii) Wang et al. (2022) *Stability of biochar in mineral soils: Assessment methods, influencing factors and potential problems*, found at https://www.sciencedirect.com/science/article/pii/S0048969721058678?via%3Dihub.
iii) Recent model update by Woolf et al. (2021) *Greenhouse Gas Inventory Model for Biochar Additions to Soil*, found at https://cpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/8/7329/files/2021/11/EST-55-14795-14805-2021-Woolf.pdf. iv) Assessment of persistence level drivers by Wang et al. (2016) *Biochar stability in soil: meta-analysis of decomposition and priming effects*, found at https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12266

[77] Thomsen & Martin (2022) *Screening af kulstoflagring og energipotentiale fra pyrolyse af kommunale biomasser: Metodetest og indledende forsøg*, found at https://forskning.ruc.dk/da/publications/screening-af-kulstoflagring-og-energipotentiale-fra-pyrolyse-af-k (in Danish)

[78] Taghizadeh-Toosi et al. (2014*) C-TOOL: A simple model for simulating whole-profile carbon storage in temperate agricultural soils*, found at https://pure.au.dk/portal/en/publications/ctool(ec9459f6-e147-4ac5-ae9f-dd5670ee514f).html

---

[79] Carbon-persistence levels for carbon-sequestration calculations obtained from C-tool modelling in REF1: Knudsen M. T. et al. (2018) *Inkludering af jordens kulstofændringer i livscyklusvurderinger (LCA)*. AU. Found at https://www.landbrugsinfo.dk/-/media/landbrugsinfo/public/3/b/f/oe-18-3854-inkld-af-jordenskulstofaendr-i-lca-mtk.pdf, REF2: Hansen J. H. (2016) *Kulstof i jorden*. SDU. Found at https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjm04arqaX6AhWMQ_EDHSSfDloQFnoECAYQAQ&url=https%3A%2F%2Fwww.sdu.dk%2F-%2Fmedia%2Ffiles%2Fom_sdu%2Fcentre%2Flifecycleengineering%2Fgrass_to_biogas_seminar%2F12_julie_houge_hansen_kulstof_i_jorden_konsekvenser_ved_hoest_og_forskellig_energianvendelse.pdf&usg=AOvVaw0wH18ORgEJGz3sm0JLmxAu and PYR: Sigurjonsson et al. (2015) *Climate effect of an integrated wheat production and bioenergy system with LT-CFB*. DTU. Found at https://backend.orbit.dtu.dk/ws/portalfiles/portal/127845871/article_postprint_Climate_effect_of_an_integrated_wheat_production_and_bioenergy_system_with_Low_Temperature_Circulating_Fluidized_Bed_gasifie.pdf

[80] Tobias Pape Thomsen (2021) *Climate Footprint Analysis of Straw Pyrolysis & Straw Biogas - Assessment of the Danish climate crisis mitigation potential of two new straw management options*, found at https://forskning.ruc.dk/da/publications/klimaaftryk-fra-anvendelse-af-halm-i-pyrolyse-og-biogas-en-analys

[81] Cayuela et al. (2014) *Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis*, found at https://www.sciencedirect.com/science/article/pii/S0167880913003496

[82] Sánchez-García et al. (2014) *Biochar increases soil N2O emissions produced by nitrification-mediated pathways*, found at https://www.frontiersin.org/articles/10.3389/fenvs.2014.00025/full

[83] Borchard et al. (2019) *Biochar, soil and land-use interactions that reduce nitrate leaching and N2O emissions: A meta-analysis*, found at https://www.sciencedirect.com/science/article/pii/S0048969718339330

[84] Duan et al. (2018) *Field-aged biochar stimulated N2O production from greenhouse vegetable production soils by nitrification and denitrification*, found at https://www.sciencedirect.com/science/article/pii/S0048969718322423

[85] E.g. i) Rittl et al. (2021) *High Application Rates of Biochar to Mitigate N2O Emissions From a N-Fertilized Tropical Soil Under Warming Conditions*, found at https://www.frontiersin.org/articles/10.3389/fenvs.2020.611873/full,
ii) Sánchez-García et al. (2014) *Biochar increases soil N2O emissions produced by nitrification-mediated pathways*, found at https://www.frontiersin.org/articles/10.3389/fenvs.2014.00025/full
iii) Zhang et al. (2021) *Biochar Mitigates N2O Emission of Microbial Denitrification through Modulating Carbon Metabolism and Allocation of Reducing Power*, found at https://pubs.acs.org/doi/10.1021/acs.est.1c01976, and
iv) Zhang et al. (2021) *The effect of long-term biochar amendment on N2O emissions: Experiments with N15-O18 isotopes combined with specific inhibition approaches*, found at https://www.sciencedirect.com/science/article/pii/S0048969720380645

[86] Animal feed e.g.: i) Schmidt et al. (2019) *The use of biochar in animal feeding*, found at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6679646/,
ii) Gerlach and Schmidt (2014) *The use of biochar in cattle farming*, found at https://www.biochar-journal.org/en/ct/9, and
iii) Man et al. (2020) *Use of biochar as feed supplements for animal farming*, found at https://www.tandfonline.com/doi/abs/10.1080/10643389.2020.1721980?journalCode=best20,
Composting e.g.: i) Chen et al. (2017) *Effects of different types of biochar on methane and ammonia mitigation during layer manure composting*, found at https://www.sciencedirect.com/science/article/pii/S0956053X17300144,
ii) Harrison et al. (2022) *Dairy Manure Co-composting with Wood Biochar Plays a Critical Role in Meeting Global Methane Goals*, found at https://pubs.acs.org/doi/10.1021/acs.est.2c03467,
iii) Sonoki et al. (2012) *Influence of biochar addition on methane metabolism during thermophilic phase of composting*, found at https://onlinelibrary.wiley.com/doi/abs/10.1002/jobm.201200096, and
iv) Cao et al. (2019) *Mitigation of ammonia, nitrous oxide and methane emissions during solid waste composting with different additives: A meta-analysis*, found at https://www.sciencedirect.com/science/article/pii/S095965261932253X

---

[87] Henriksen et al. (2019) *Reduktion af landbrugets klimaaftryk ved termisk pyrolyse af afgrøderester og organiske gødningsfraktioner*, found at https://forskning.ruc.dk/da/publications/reduktion-af-landbrugets-klimaaftryk-ved-termisk-pyrolyse-af-afgr (in Danish)

[88] Baronti et al. (2022) *Long term effect of biochar on soil plant water relation and fine roots: Results after 10 years of vineyard experiment*, found at https://www.sciencedirect.com/science/article/abs/pii/S0048969722053244?via%3Dihub

[89] Kahn et al. (2022) *Biochar Optimizes Wheat Quality, Yield, and Nitrogen Acquisition in Low Fertile Calcareous Soil Treated With Organic and Mineral Nitrogen Fertilizers*, found at https://www.frontiersin.org/articles/10.3389/fpls.2022.879788/full

[90] Kätterer et al. (2022) *Maize grain yield responses to realistic biochar application rates on smallholder farms in Kenya*, found at https://link.springer.com/article/10.1007/s13593-022-00793-5

[91] E.g. i) Danso et al. (2019) *Impact of rice straw biochar and irrigation on maize yield, intercepted radiation and water productivity in a tropical sandy clay loam*, found at https://www.sciencedirect.com/science/article/abs/pii/S0378429019302953?via%3Dihub and
ii) Danso et al. (2019) Effect of rice straw biochar and irrigation on growth, dry matter yield and radiation-use efficiency of maize grown on an Acrisol in Ghana, https://onlinelibrary.wiley.com/doi/10.1111/jac.12383

[92] Elsgaard et al. (2022) *Knowledge synthesis on biochar in Danish agriculture*, found at https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport208.pdf

[93] E.g.
i) Zhencai et al. (2013) *Direct and Indirect Short-term Effects of Biochar on Physical Characteristics of an Arable Sandy Loam*, found at https://journals.lww.com/soilsci/Abstract/2013/09000/Direct_and_Indirect_Short_term_Effects_of_Biochar.2.aspx, Bruun et al. (2014) *Biochar amendment to coarse sandy subsoil improves root growth and increases water retention*, found at https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/sum.12102

[94] Bruun et al. (2021) *Ash and biochar amendment of coarse sandy soil for growing crops under drought conditions*, found at https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/sum.12783

[95] Hansen et al. (2017) *The effects of straw or straw-derived gasification biochar applications on soil quality and crop productivity: A farm case study*, found at https://www.sciencedirect.com/science/article/pii/S0301479716308258?via%3Dihub

[96] Elsgaard et al. (2022) *Knowledge synthesis on biochar in Danish agriculture*, found at https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport208.pdf, section 7.7, page 105. No reference to original data source.

[97] AU staff (2016) *Potatoes and biochar are not friends*, previously found at https://dca.au.dk/en/current-news/news/show/artikel/kartofler-og-biochar-er-ikke-gode-venner-1, but now (24-11-2022) only available at https://spudsmart.com/potatoes-biochar-not-friends/

[98] Yang et al. (2022) *Interactions between biochar, arbuscular mycorrhizal fungi and photosynthetic processes in potato (Solanum tuberosum L.)*, found at https://www.sciencedirect.com/science/article/pii/S0048969721067255?via%3Dihub

[99] Jeffery et al. (2017) *Biochar boosts tropical but not temperate crop yields*, found at https://iopscience.iop.org/article/10.1088/1748-9326/aa67bd

[100] Elsgaard et al. (2022) *Knowledge synthesis on biochar in Danish agriculture*, found at https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport208.pdf, section 7.7, page 104-105

[101] Elsgaard et al. (2022) *Knowledge synthesis on biochar in Danish agriculture*, found at https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport208.pdf

[102] Lehmann & Joseph (2015) *Biochar for Environmental Management - Science, Technology and Implementation 2nd Edition*, can be bought at https://www.routledge.com/Biochar-for-Environmental-Management-Science-Technology-and-Implementation/Lehmann-Joseph/p/book/9780367779184, An open pre-print of the 2009 version of the book can be found here https://www.css.cornell.edu/faculty/lehmann/publ/First%20proof%2013-01-09.pdf

[103] E.g. i) Humberto Blanco-Canqui (2017) *Biochar and Soil Physical Properties*, found at https://acsess.onlinelibrary.wiley.com/doi/full/10.2136/sssaj2017.01.0017,
ii) Bruun et al. (2014) *Biochar amendment to coarse sandy subsoil improves root growth and increases*

---

water retention, found at https://bsssjournals.onlinelibrary.wiley.com/doi/abs/10.1111/sum.12102,

iii) Imparato et al. (2016*) Gasification biochar has limited effects on functional and structural diversity of soil microbial communities in a temperate agroecosystem*, found at https://www.sciencedirect.com/science/article/pii/S0038071716300748,

iv) Lehmann et al. (2011) *Biochar effects on soil biota – A review*, found at https://www.sciencedirect.com/science/article/pii/S0038071711001805,

v) Hansen et al. (2016) *Effects of gasification biochar on plant-available water capacity and plant growth in two contrasting soil types*, found at https://www.sciencedirect.com/science/article/pii/S0167198716300265,

vi) Schmidt et al. (2021) *Biochar in agriculture – A systematic review of 26 global meta- analyses*, found at https://onlinelibrary.wiley.com/doi/epdf/10.1111/gcbb.12889,

vii) Joseph et al. (2021) *How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar*, found at https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12885,

viii) El-Naggar et al. (2019) *Biochar application to low fertility soils: A review of current status, and future prospects*, found at https://www.sciencedirect.com/science/article/pii/S0016706118309686?via%3Dihub,

ix) Razzaghi et al. (2020) *Does biochar improve soil water retention? A systematic review and meta-analysis*, found at https://www.sciencedirect.com/science/article/pii/S0016706119322153?via%3Dihub, and

x) Tesfaye et al. (2020) *Could biochar amendment be a tool to improve soil availability and plant uptake of phosphorus? A meta-analysis of published experiments*, found at https://link.springer.com/article/10.1007/s11356-021-14119-7

[104] Ye et al. (2019) *Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls*, found at https://bsssjournals.onlinelibrary.wiley.com/doi/abs/10.1111/sum.12546

[105] E.g. i) Sun Cha et al. (2016) *Production and utilization of biochar: A review*, found at https://www.sciencedirect.com/science/article/abs/pii/S1226086X16301472?via%3Dihub,

ii) Kasey Johnston's thesis (2018) *The Production, Characterization, and Upgrading of Biochars into Activated Carbon*, found at https://digitalcommons.library.umaine.edu/cgi/viewcontent.cgi?article=1337&context=honors,

iii) Sajjadi et al. (2018) *A comprehensive review on physical activation of biochar for energy and environmental applications*, found at https://par.nsf.gov/servlets/purl/10091642,

iv) Ajay Dalai (2008) *Steam and KOH activation of biochar: Experimental and modeling studies*, found at https://www.academia.edu/14233003/Steam_and_KOH_activation_of_biochar_Experimental_and_modeling_studies

v) Gale et al. (2021) *Physiochemical Properties of Biochar and Activated Carbon from Biomass Residue: Influence of Process Conditions to Adsorbent Properties*, found at https://pubs.acs.org/doi/10.1021/acsomega.1c00530,

vi) de Medeiros (2020) Effect of biochar and inoculation with Trichoderma aureoviride on melon growth and sandy Entisol quality, found at https://www.cropj.com/medeiros_14_6_2020_971_977.pdf,

vii) Efthymiou et al. (2018) Augmentation of the phosphorus fertilizer value of biochar by inoculation of wheat with selected Penicillium strains, found at https://www.sciencedirect.com/science/article/abs/pii/S0038071717305977?via%3Dihub,

viii) Laghari et al. (2021) *Evaluation of Biochar Post-Process Treatments to Produce Soil Enhancers and Phosphorus Fertilizers at a Single Plant*, found at https://link.springer.com/article/10.1007/s12649-021-01358-5,

ix) Tu et al. (2020) *Biochar and bacteria inoculated biochar enhanced Cd and Cu immobilization and enzymatic activity in a polluted soil*, found at https://www.sciencedirect.com/science/article/pii/S0160412019340759

x) Tony Callaghan @ SoilFixer (2020) *How to Activate and Inoculate Biochar*, found at https://www.soilfixer.co.uk/Biochar-activation-inoculation and

xi) biochar.co.uk (2020) *One, five and fifteen day inoculated biochar-compost seed germination trial*, found at https://biochar.co.uk/biochar-inoculation-vs-germination-trial/,

[106] E.g. i) Sørmo et al. (2021) *Stabilization of PFAS-contaminated soil with activated biochar*, found at https://www.sciencedirect.com/science/article/pii/S0048969720375653,

ii) Zhang & Liang (2022) *Performance of different sorbents toward stabilizing per- and polyfluoroalkyl*

---

substances (PFAS) in soil, found at https://www.sciencedirect.com/science/article/pii/S2666765722000527,

iii) Lahori et al. (2019) *Stabilization of toxic metals in three contaminated soils by residual impact of lime integrated with biochar and clays*, found at https://link.springer.com/article/10.1007/s11368-019-02453-w,

iv) Ren et al. (2020) *Performance of the emerging biochar on the stabilization of potentially toxic metals in smelter- and mining-contaminated soils*, found at https://link.springer.com/article/10.1007/s11356-020-07805-5, and

v) Guo et al. (2020) *Biochar-Facilitated Soil Remediation: Mechanisms and Efficacy Variations*, found at https://www.frontiersin.org/articles/10.3389/fenvs.2020.521512/full,

[107] E.g. i) Zhao et al. (2022) *Biochar-Based Fertilizer Improved Crop Yields and N Utilization Efficiency in a Maize–Chinese Cabbage Rotation System*, found at https://www.mdpi.com/2077-0472/12/7/1030

ii) Ndoung et al. (2021) *A scoping review on biochar-based fertilizers: enrichment techniques and agro-environmental application*, found at https://www.cell.com/heliyon/fulltext/S2405-8440(21)02576-7?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS2405844021025767%3Fshowall%3Dtrue,

iii) Liu et al. (2019) Impact of Application of Biochar-Based Fertilizer on the Content of Phosphorus and Potassium in Soil, found at https://iopscience.iop.org/article/10.1088/1755-1315/252/5/052064/pdf,

iv) Wang et al. (2022) *Biochar-based slow-release of fertilizers for sustainable agriculture: A mini review*, found at https://www.sciencedirect.com/science/article/pii/S2666498422000230,

v) Gao et al. (2022) *A critical review of biochar-based nitrogen fertilizers and their effects on crop production and the environment*, found at https://link.springer.com/article/10.1007/s42773-022-00160-3 and

vi) Melo et al. (2022) *Biochar-based fertilizer effects on crop productivity: a meta-analysis*, found at https://link.springer.com/article/10.1007/s11104-021-05276-2

[108] E.g. Chen et al. (2012) *Fuel-N Evolution during the Pyrolysis of Industrial Biomass Wastes with High Nitrogen Content*, found at https://www.mdpi.com/1996-1073/5/12/5418

[109] Elsgaard et al. (2022) *Knowledge synthesis on biochar in Danish agriculture*, found at https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport208.pdf, page 101

[110] E.g. i) Li et al. (2017) *Plant Availability of Phosphorus in Five Gasification Biochars*, found at https://www.frontiersin.org/articles/10.3389/fsufs.2017.00002/full,

ii) Glaser & Lehr (2019) *Biochar effects on phosphorus availability in agricultural soils: A meta-analysis*, found at https://www.nature.com/articles/s41598-019-45693-z and

iii) Bornø et al. (2018) *Contrasting effects of biochar on phosphorus dynamics and bioavailability in different soil types*, found at https://www.sciencedirect.com/science/article/pii/S0048969718303255

[111] E.g. i) Li et al. (2017) *Availability of potassium in biomass combustion ashes and gasification biochars after application to soils with variable pH and clay content*, found at https://www.tandfonline.com/doi/abs/10.1080/03650340.2017.1414198?journalCode=gags20,

ii) Laghari et al. (2021) *Evaluation of Biochar Post-Process Treatments to Produce Soil Enhancers and Phosphorus Fertilizers at a Single Plant*, found at https://link.springer.com/content/pdf/10.1007/s12649-021-01358-5.pdf,

iii) Hien et al. (2021) *Enhancing soil water holding capacity and provision of a potassium source via optimization of the pyrolysis of bamboo biochar*, found at https://link.springer.com/article/10.1007/s42773-020-00071-1 and

iv) Wiinikka et al. (2017) *Fate of inorganic elements during fast pyrolysis of biomass in a cyclone reactor*, found at https://www.sciencedirect.com/science/article/pii/S0016236117305550?via%3Dihub

[112] E.g. i) Wiinikka et al. (2017) *Fate of inorganic elements during fast pyrolysis of biomass in a cyclone reactor*, found at https://www.sciencedirect.com/science/article/pii/S0016236117305550?via%3Dihub

ii) Zhao et al. (2018) *Effect of pyrolysis temperature on sulfur content, extractable fraction and release of sulfate in corn straw biochar*, found at https://pubs.rsc.org/en/content/articlehtml/2018/ra/c8ra06382f and

iii) Cheah et al. (2014) *Speciation of Sulfur in Biochar Produced from Pyrolysis and Gasification of Oak and Corn Stove*, found at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4123929/

[113] i) Gatiboni et al. (2020) *Editorial: Legacy Phosphorus in Agriculture: Role of Past Management and Perspectives for the Future*, found at https://www.frontiersin.org/articles/10.3389/feart.2020.619935/full and

---

ii) Vandermoere et al. (2021) *Soil phosphorus (P) mining in agriculture – Impacts on P availability, crop yields and soil organic carbon stocks*, found at https://www.sciencedirect.com/science/article/abs/pii/S0167880921003649?via%3Dihub

[114] E.g. i) Talboys et al (2016) Struvite: a slow-release fertiliser for sustainable phosphorus management? found at https://link.springer.com/article/10.1007/s11104-015-2747-3 and
ii) Ye at al (2019) *Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls*, found at https://bsssjournals.onlinelibrary.wiley.com/doi/abs/10.1111/sum.12546

[115] Ye at al (2019) *Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls*, found at https://bsssjournals.onlinelibrary.wiley.com/doi/abs/10.1111/sum.12546

[116] E.g. i) Wang et al. (2022) *Biochar-based slow-release of fertilizers for sustainable agriculture: A mini review*, found at https://www.sciencedirect.com/science/article/pii/S2666498422000230,
ii) Wang et al. (2021) *Biochar composites: Emerging trends, field successes and sustainability implications*, found at https://bsssjournals.onlinelibrary.wiley.com/doi/full/10.1111/sum.12731 and
iii) Osman et al. (2022) *Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review* , found at https://link.springer.com/article/10.1007/s10311-022-01424-x

[117] Many relevant sources e.g. i) Bloomberg Cities Network (2019) *Solution Spotlight: Turning garden waste into a carbon sink in Stockholm*, found at https://bloombergcities.jhu.edu/news/solution-spotlight-turning-garden-waste-carbon-sink-stockholm,
ii) Bloomberg Cities Network (2017) *Stockholm Biochar Project, a Mayors Challenge winner, opens its first plant | Bloomberg Philanthropies*, found at https://bloombergcities.jhu.edu/news/stockholm-biochar-project-mayors-challenge-winner-opens-its-first-plant-bloomberg,
iii) Mattias Gustafsson @ EcoTopic (2019) *Climate positive energy*, found at https://www.hamk.fi/wp-content/uploads/2019/04/Mattias-Gustafsson-pieni.pdf,
iv) International Biochar Initiative (2021) *STOCKHOLM BIOCHAR STUDY TOUR – PRESENTATIONS*, found at https://biochar-international.org/stockholm-biochar-study-tour-presentations/,
v) Bjorn Embrén (2016) *Planting Urban Trees with Biochar*, found at https://www.biochar-journal.org/en/ct/77 and
vi) Trees and Design Action Group (2015) *The Stockholm Solution - an integrated approach to trees and infrastructure in the urban realm*, found at https://www.youtube.com/watch?v=MojlKaAKeh8

[118] Aalto University (2020) *Hiilipuisto - Carbon Park*, found at https://www.aalto.fi/en/department-of-architecture/hiilipuisto-carbon-park

[119] Bloomberg Cities Network (2019) *Inspired by Stockholm's success, a U.S. city goes big on biochar*, found at https://bloombergcities.jhu.edu/news/inspired-stockholms-success-us-city-goes-big-biochar

[120] E.g. i) Fransson et al. (2019*) Biochar in urban applications*, found at https://dc.engconfintl.org/biochar_ii/15/,
ii) Kathrin Weber (2020) *How Cities Can Use Biochar to Build Carbon Sinks*, found at https://blog.sintef.com/sintefenergy/bioenergy/how-cities-can-use-biochar-to-build-carbon-sinks/,
iii) Charlotta Liukas (2020) *How to use biochar for structured soil plant beds in urban areas*, found at https://medium.com/carboculture/how-to-use-biochar-for-structured-soil-plant-beds-in-urban-areas-8a45108e799,
iv) Corenthin Chassouant (2019) *Introduction: potential use of biochar in the horticulture and urban farming industry*, found at https://horti-generation.com/potential-use-of-biochar-in-horticulture/,
v) Charles Hegberg (2020) *Introduction: Biochar uses in the Urban Landscape*, found at https://biochar-us.org/presentation/introduction-biochar-uses-urban-landscape,
vi) Huang & Gu (2019) *Effects of Biochar on Container Substrate Properties and Growth of Plants—A Review*, found at https://www.mdpi.com/2311-7524/5/1/14,
vii) Nordic Biochar Network (2021) *Video presentations from Previous Workshop "Biochar for Green Cities"*, found at https://www.nordicbiochar.org/biochar/workshops/ and
viii) Song et al. (2020) *Biochar for urban agriculture: Impacts on soil chemical characteristics and on Brassica rapa growth, nutrient content and metabolism over multiple growth cycles*, found at https://www.sciencedirect.com/science/article/abs/pii/S0048969720322592,

---

[121] E.g. i) Sun Cha et al. (2016) *Production and utilization of biochar: A review*, found at https://www.sciencedirect.com/science/article/abs/pii/S1226086X16301472?via%3Dihub,
ii) Osman et al. (2022) *Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review*, found at https://link.springer.com/article/10.1007/s10311-022-01424-x,
iii) Bartoli et al. (2020) *A Review of Non-Soil Biochar Applications*, found at https://www.mdpi.com/1996-1944/13/2/261 and
iv) Schmidt & Wilson (2014) *The 55 uses of biochar*, found at https://www.biochar-journal.org/en/ct/2

[122] E.g. Nordic Biochar Network (2022) *Biocrete – Carbon Negative concrete*, found at https://www.youtube.com/watch?v=QYotVrybTao,

[123] E.g. i) Mohan et al. (2006) *Pyrolysis of Wood/Biomass for Bio-oil: A Critical Review*, found at https://pubs.acs.org/doi/10.1021/ef0502397,
ii) Pienihäkkinen et al. (2022) *Improving Fast Pyrolysis Bio-Oil Yield and Quality by Alkali Removal from Feedstock*, found at https://pubs.acs.org/doi/10.1021/acs.energyfuels.1c04331,
iii) Prabir Basu (2018) *Biomass Gasification, Pyrolysis and Torrefaction Practical Design and Theory (3rd edition)*, found at https://www.sciencedirect.com/book/9780128129920/biomass-gasification-pyrolysis-and-torrefaction
iv) Koos Overwater (2019) *Advanced Biofuels from Fast Pyrolysis Bio-Oil*, found at https://ec.europa.eu/info/sites/default/files/20_koos_overwater.pdf,
v) Tan et al. (2021) *Biofuel Options for Marine Applications: Technoeconomic and Life-Cycle Analyses*, found at https://pubs.acs.org/doi/10.1021/acs.est.0c06141
vi) Anthony Bridgewater (2004) *Biomass fast pyrolysis*, found at https://www.researchgate.net/publication/270464333_Biomass_fast_pyrolysis,
vii) Peter Arendt Jensen (2013) *Liquid Fuel Production by Fast Pyrolysis of Biomass*, found at https://backend.orbit.dtu.dk/ws/portalfiles/portal/59449597/Liquid_Fuel_Production.pdf,
viii) Conrad et al. (2021) *Improved fast pyrolysis bio-oils from straw and miscanthus by fractionated condensation*, found at https://aiche.onlinelibrary.wiley.com/doi/10.1002/ep.13708,
ix) Btg Bioliquids website home, found at https://www.btg-bioliquids.com/,
x) IEA task 34 (n.d.) *Task 34: Direct Thermochemical Liquefaction*, found at https://task34.ieabioenergy.com/biofuels/,
xi) Phil Z @ Linkedin (2015) *Swedish university first to produce renewable fuel (DME) from pyrolysis bio-oil*, found at https://www.linkedin.com/pulse/swedish-university-first-produce-renewal-fuel-dme-from-zoldak-/
xii) Raymundo et al. (2019) *Deoxygenation of Biomass Pyrolysis Vapors via in Situ and ex Situ Thermal and Biochar Promoted Upgrading*, found at https://pubs.acs.org/doi/10.1021/acs.energyfuels.8b03281,
xiii) Kumar et al. (2019) *Enhanced bio-oil deoxygenation activity by Cu/zeolite and Ni/zeolite catalysts in combined in-situ and ex-situ biomass pyrolysis*, found at https://www.sciencedirect.com/science/article/pii/S0165237018311318
xiv) Valle et al. (2022) *Role of zeolite properties in bio-oil deoxygenation and hydrocarbons production by catalytic cracking*, found at https://www.sciencedirect.com/science/article/pii/S0378382021004136,
xv) Eschenbacher et al. (2022) *Enhancing bio-oil quality and energy recovery by atmospheric hydrodeoxygenation of wheat straw pyrolysis vapors using Pt and Mo-based catalysts*, found at https://orbit.dtu.dk/en/publications/enhancing-bio-oil-quality-and-energy-recovery-by-atmospheric-hydr ,
xvi) Eschenbacher et al. (2020) *Deoxygenation of wheat straw fast pyrolysis vapors over Na-Al2O3 catalyst for production of bio-oil with low acidity*, found at https://orbit.dtu.dk/en/publications/deoxygenation-of-wheat-straw-fast-pyrolysis-vapors-over-na-alsub2,
xvii) Jundong Wang's thesis (2022) *Catalytic hydro-deoxygenation of bio-oil from biomass pyrolysis : comprehension of reaction pathways*, found at https://tel.archives-ouvertes.fr/tel-03517330/document
xviii) Simonsen et al. @ IEA Bioenergy: Task 39 (2021) *Progress towards biofuels for marine shipping - Status and identification of barriers for utilization of advanced biofuels in the marine sector*, found at https://www.ieabioenergy.com/blog/publications/progress-towards-biofuels-for-marine-shipping/,
xix) Frederic Meyer @ Total Energies (2021) *Why Biofuels are Critical In Shipping's Future Fuel Mix*, found at https://marinefuels.totalenergies.com/news/blog/why-biofuels-are-critical-in-shippings-future-fuel-mix,

---

xx) Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (2022) *Bio-oils*, found at https://www.zerocarbonshipping.com/energy-carriers/bio-oils/?section=regulation and
xxi) Kari Tiilikkala (2012) Chemical Composition of Birch Wood Slow Pyrolysis Products, found at https://www.researchgate.net/publication/253337329_Chemical_Composition_of_Birch_Wood_Slow_Pyrolysis_Products

[124] i) "Wood Vinegar and Biochar in Agriculture - How to Improve Crop Quality While Reducing Dependence on Agricultural Chemicals". Kishimoto Sadakichi, Tsuyoshi Hirowaka, Joseph Stephen, Gabi Paananen and Helen Gould. 2015. Published on research gate. No direct link available and
ii) Makoto Ogawa @ Japan Biochar Association (n.d.) *Introduction to the Pioneer Works of Charcoal Uses in Aguriculture, Forestry and Others in Japan*, found at https://biochar.jp/en/biochar-in-japan/

[125] In addition to the two sources mentioned in the previous end-note, also e.g.
i) Yang et al. (2016) *Chemical Composition, Antioxidant, and Antibacterial Activity of Wood Vinegar from Litchi chinensis*, found at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6274201/,
ii) Bouket et al. (2022) *In Vitro Evaluation of Wood Vinegar (Pyroligneous Acid) VOCs Inhibitory Effect against a Fungus-like Microorganism Ovatisporangium (Phytopythium) Isolate Recovered from Tomato Fields in Iran*, found at https://www.mdpi.com/2073-4395/12/7/1609/htm,
iii) Marleena Hagner's thesis (2013) *Potential of the slow pyrolysis products birch tar oil, wood vinegar and biochar in sustainable plant protection - pesticidal effects, soil improvement and environmental risks*, found at
https://www.biochar.info/docs/wood-vinegar/Potential-of-birch-tar-oil-wood-vinegar-in-sustainable-plant-protection.pdf,
iv) Zhu et al. (2021) *Wood Vinegar as a Complex Growth Regulator Promotes the Growth, Yield, and Quality of Rapeseed*, found at https://www.mdpi.com/2073-4395/11/3/510/htm,
v) Lu et al. (2019) *Effect of Pyrolysis Temperature on the Characteristics of Wood Vinegar Derived from Chinese Fir Waste: A Comprehensive Study on Its Growth Regulation Performance and Mechanism*, found at https://pubs.acs.org/doi/10.1021/acsomega.9b02240 and
vi) Nordic Biochar Network (2022) *Biochar byproduct: pyrolysis liquids – the forgotten business*, found at https://www.youtube.com/watch?v=FYL7MzRPe1g

[126] Theodore P. Kaye (1997) *Pine Tar; History And Uses*, found at https://www.maritime.org/conf/conf-kaye-tar.php

[127] E.g. i) Czernik & Bridgwater (2004) *Overview of Applications of Biomass Fast Pyrolysis Oil*, found at https://pubs.acs.org/doi/pdf/10.1021/ef034067u
ii) Hagner et al. (2010) *Effects of birch tar oils on soil organisms and plants*, found at
https://www.researchgate.net/publication/42377674_Effects_of_birch_tar_oils_on_soil_organisms_and_plants,
iii) Tiilikkala et al. (2010) *History and Use of Wood Pyrolysis Liquids as Biocide and Plant Protection Product*, found at
https://www.researchgate.net/publication/274861748_History_and_Use_of_Wood_Pyrolysis_Liquids_as_Biocide_and_Plant_Protection_ProductHistory_and_Use_of_Wood_Pyrolysis_Liquids_as_Biocide_and_Plant_Protection_Product
iv) Sayed et al. (2018) *Insecticidal activity of bio-oils and biochar as pyrolysis products and their combination with microbial agents against agrotis ipsilon (Lepidoptera: Noctuidae)*, found at
https://www.researchgate.net/publication/325138644_Insecticidal_activity_of_bio-oils_and_biochar_as_pyrolysis_products_and_their_combination_with_microbial_agents_against_agrotis_ipsilon_Lepidoptera_Noctuidae
v) Marleena Hagner's thesis (2013) *Potential of the slow pyrolysis products birch tar oil, wood vinegar and biochar in sustainable plant protection - pesticidal effects, soil improvement and environmental risks*, found at
https://www.biochar.info/docs/wood-vinegar/Potential-of-birch-tar-oil-wood-vinegar-in-sustainable-plant-protection.pdf and
vi) Ren et al. (2020) *Performance of bitumen coating sheet using biomass pyrolysis oil*, found at https://www.tandfonline.com/doi/full/10.1080/10962247.2019.1705434

[128] Czernik & Bridgwater (2004) *Overview of Applications of Biomass Fast Pyrolysis Oil*, found at

---

https://pubs.acs.org/doi/pdf/10.1021/ef034067u

[129] E.g. i) Britta Scholze’s thesis (2002) *Long-term Stability, Catalytic Upgrading, and Application of Pyrolysis Oils -*
Improving the Properties of a Potential Substitute for Fossil Fuels, found at https://d-nb.info/967136490/34,
ii) Nam et al. (2020) *Chemical composition of pyrolysis oil through thermal decomposition of sugarcane biomass*, found at https://onlinelibrary.wiley.com/doi/pdf/10.1002/vjch.202000077,
iii) IEA Bioenergy Task 34: Direct Thermochemical Liquefaction (n.d.) *Pyrolysis Bio-oil*, found at https://task34.ieabioenergy.com/bio-oil/,
iv) Ringer et al. (2006) Large-Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis, found at https://www.nrel.gov/docs/fy07osti/37779.pdf,
v) Haoxi et al. (2019) *A Comprehensive Characterization of Pyrolysis Oil from Softwood Barks*, found at https://www.osti.gov/servlets/purl/1606833,
vi) Lyu et al. (2015) *Estimation and comparison of bio-oil components from different pyrolysis conditions* , found at https://www.frontiersin.org/articles/10.3389/fenrg.2015.00028/full and
vii) Fagernäs et al. (2012) *Chemical Composition of Birch Wood Slow Pyrolysis Products* , found at https://pubs.acs.org/doi/10.1021/ef2018836

[130] E.g. i) Pighinelli et al. (2014) *Evaluation of Brazilian biomasses as feedstocks for fuel production via fast pyrolysis*, found at https://www.sciencedirect.com/science/article/pii/S0973082614000441?via=ihub,
ii) Jin et al. (2012) *Characteristics of Gases From Co-Pyrolysis of Sawdust and Tires*, found at https://www.tandfonline.com/doi/full/10.1080/15435075.2011.625585?scroll=top&needAccess=true,
iii) Morgan et al. (2015) *Fast Pyrolysis Behavior of Banagrass as a Function of Temperature and Volatiles Residence Time in a Fluidized Bed Reactor*, found at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4550300/,
iv) Costa et al. (2022) *Slow pyrolysis of cork granules under nitrogen atmosphere: by-products characterization and*
their potential valorization, found at https://www.biofueljournal.com/article_145622_41ed9fa1c864f66ffb83aaae113e4bed.pdf and
v) Pandey et al. (2019) *Fast Pyrolysis of Poultry Litter in a Bubbling Fluidised Bed Reactor: Energy and Nutrient Recovery*, found at https://www.mdpi.com/2071-1050/11/9/2533

[131] Werner et al. (2022) *Potential of Land-Neutral Negative Emissions Through Biochar Sequestration*, found at https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021EF002583

[132] Tobias Pape Thomsen (2021) *Climate Footprint Analysis of Straw Pyrolysis & Straw Biogas - Assessment of the Danish climate crisis mitigation potential of two new straw management options*, found at https://forskning.ruc.dk/da/publications/klimaaftryk-fra-anvendelse-af-halm-i-pyrolyse-og-biogas-en-analys page 7-8

[133] Azzi et al. (2021) *Assessing the diverse environmental effects of biochar systems: An evaluation framework*, found at https://www.sciencedirect.com/science/article/pii/S0301479721002164

[134] E.g. i) Matuštík et al. (2020) Life cycle assessment of biochar-to-soil systems: A review, found at https://www.sciencedirect.com/science/article/abs/pii/S0959652620310453,
ii) Azzi et al. (2021) *Assessing the diverse environmental effects of biochar systems: An evaluation framework*, found at https://www.sciencedirect.com/science/article/pii/S0301479721002164,
iii) Thers et al. (2019) Biochar potentially mitigates greenhouse gas emissions from cultivation of oilseed rape for biodiesel, found at https://www.sciencedirect.com/science/article/abs/pii/S0048969719312495?via%3Dihub,
iv) Leppäkoski et al. (2021) *Assessing the Carbon Footprint of Biochar from Willow Grown on Marginal Lands in Finland*, found at https://www.mdpi.com/2071-1050/13/18/10097 and
v) Owsianiak et al. (2021) *Environmental and economic impacts of biochar production and agricultural use in six developing and middle-income countries*, found at https://www.sciencedirect.com/science/article/abs/pii/S0048969720359842?via%3Dihub

[135] Matuštík et al. (2020) Life cycle assessment of biochar-to-soil systems: A review, found at https://www.sciencedirect.com/science/article/abs/pii/S0959652620310453

[136] Thomsen & Ahrenfeldt (2013) *Scenario based assessment of domestic biomass potential and technical application for energy production in Denmark – now and near future: ForskNG 10689 - Detailed analysis of*

---

bio-SNG technologies and other RE-gases. Final report of work package 1, found at https://forskning.ruc.dk/da/publications/scenario-based-assessment-of-domestic-biomass-potential-and-techn

[137] Rasmussen et al. (2022) *Scenarier for anvendelse af biomasseressourcer i fremtidens produktionssystemer for fødevarer, energi og materialer inden for rammerne af gældende politik for landbrug, miljø, klima, natur og energi*, found at https://fvm.dk/fileadmin/user_upload/FVM.dk/Dokumenter/Foedevarer/AAU_Scenarier_for_anvendelse_af_biomasseressourcer_i_fremtidens_produktionssystemer.pdf (in Danish)

[138] Larsen et al. (2018) *Life cycle assessment comparing the treatment of surplus activated sludge in a sludge treatment reed bed system with mechanical treatment on centrifuge*, found at https://www.sciencedirect.com/science/article/pii/S0959652618305122?via%3Dihub

[139] System Analysis @ Danish Energy Agency (2022) *Klimastatus og –fremskrivning 2022 (KF22): Landbrugsprocesser*, found at https://ens.dk/sites/ens.dk/files/Basisfremskrivning/kf22_sektornotat_10b_landbrugsprocesser.pdf (in Danish)

[140] About the STABIL project, found at https://plen.ku.dk/forskning/plante--og-jordvidenskab/soil-fertility/stabil/

[141] Cordell & White (2014) *Life's Bottleneck: Sustaining the World's Phosphorus for a Food Secure Future*, found at https://www.annualreviews.org/doi/10.1146/annurev-environ-010213-113300

[142] European Commission (2020) *Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions - Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability*, found at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0474&from=EN

[143] Manfred Klinglmair's thesis (2016) *Anthropogenic phosphorus flows in Denmark - Quantification and critical analysis*, found at https://backend.orbit.dtu.dk/ws/portalfiles/portal/125595474/Manfred_Klinglmair_PhD_Thesis_Online_version.pdf

[144] E.g. i) Nordic Biochar Network (2022) *Piloting sludge pyrolysis – Sludge char research and the new pilot facility in Helsinki region*, found at https://www.youtube.com/watch?v=DLabXSHNfwI,
ii) Ni et al. (2020) *Microplastics Mitigation in Sewage Sludge through Pyrolysis: The Role of Pyrolysis Temperature*, found at https://pubs.acs.org/doi/10.1021/acs.estlett.0c00740,
iii) Longendyke et al. (2021) *PFAS fate and destruction mechanisms during thermal treatment: a comprehensive review*, found at https://pubs.rsc.org/en/content/articlelanding/2022/em/d1em00465d/unauth,
iv) Kleantha Pillay's master thesis (2001) *Pyrolysis of chlorinated organic chemicals*, found at https://researchspace.ukzn.ac.za/handle/10413/5875,
v) Mosko et al. (2021) *Effect of pyrolysis temperature on removal of organic pollutants present in anaerobically stabilized sewage sludge*, found at https://www.sciencedirect.com/science/article/pii/S0045653520332793

[145] E.g. i) Andreas Nordin's mater thesis (2015) *Heavy Metal Removal From Sewage Sludge By Pyrolysis Treatment*, found at http://www.diva-portal.org/smash/get/diva2:902689/FULLTEXT01.pdf,
ii) Raheem et al. (2022) *Roles of Heavy Metals during Pyrolysis and Gasification of Metal-Contaminated Waste Biomass: A Review*, found at https://pubs.acs.org/doi/10.1021/acs.energyfuels.1c04051,
iii) Liu et al. (2020) *Transformation of Heavy Metals during Pyrolysis of Predried Dyeing Sludge,* found at https://pubs.acs.org/doi/10.1021/acs.energyfuels.9b03050,
iv) Wang et al. (2021) *Speciation and environmental risk of heavy metals in biochars produced by pyrolysis of chicken manure and water-washed swine manure*, found at https://www.nature.com/articles/s41598-021-91440-8 and
v) He et al. (2022) *A state-of-the-art review of the fate of heavy metals and product properties from pyrolysis of heavy-metal(loid)-enriched biomass harvested from phytoextraction*, found at https://aiche.onlinelibrary.wiley.com/doi/10.1002/ep.13979?af=R

[146] E.g. i) Tobias Thomsen's thesis (2016) *Closing the Loop - Utilization of Secondary Resources by Low Temperature Thermal Gasification*, found at

---

https://rucforsk.ruc.dk/ws/portalfiles/portal/66911184/Tobias_P_Thomsen_2016_Closing_the_Loop_phd_thesis_Online_version.pdf and
ii) Thomsen et al. (2022) *Growth, Resources and the Circular Economy*, found at https://forskning.ruc.dk/da/publications/growth-resources-and-the-circular-economy

[147] See e.g. Thomsen et al. (2017) *Changes imposed by pyrolysis, thermal gasification and incineration on composition and phosphorus fertilizer quality of municipal sewage sludge*, found at https://forskning.ruc.dk/da/publications/changes-imposed-by-pyrolysis-thermal-gasification-and-incineratio

[148] Hanserud et al. (2017) *Redistributing Phosphorus in Animal Manure from a Livestock-Intensive Region to an Arable Region: Exploration of Environmental Consequences*, found at https://www.mdpi.com/2071-1050/9/4/595

[149] E.g. i) Pan et al. (2019) *Achievements of biochar application for enhanced anaerobic digestion: A review*, found at https://www.sciencedirect.com/science/article/pii/S096085241931288X?via%3Dihub and
ii) Osman et al. (2022) *Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review*, found at https://link.springer.com/article/10.1007/s10311-022-01424-x

[150] E.g. i) Hwang et al. (2018) *Efficacy of Different Biochars in Removing Odorous Volatile Organic Compounds (VOCs) Emitted from Swine Manure*, found at https://pubs.acs.org/doi/10.1021/acssuschemeng.8b02881,
ii) Sobol et al. (2022) *Biochar as a Sustainable Product for the Removal of Odor Emissions - Mini Literature Review*, found at https://revistadechimie.ro/pdf/10%20LUKASZ%204%2022.pdf,
iii) Meiirkhanuly et al. (2020) *Mitigation of Gaseous Emissions from Swine Manure with the Surficial Application of Biochars*, found at https://www.mdpi.com/2073-4433/11/11/1179,
iv) Zhu et al. (2021) *Reducing odor emissions from feces aerobic composting: additives*, found at https://pubs.rsc.org/en/content/articlehtml/2021/ra/d1ra00355k,
v) Milan & Garcia–Perez (2021) *Development of Engineered Biochar Cocktails for Odor Removal in Composting Facilities*, found at https://s3.us-west-2.amazonaws.com/wp2.cahnrs.wsu.edu/wp-content/uploads/sites/32/2021/10/Development-of-Engineered-Biochar-Cocktails-for-Odor-Removal-in-Composting-Facilities.pdf and
vi) Ro et al. (2021) *Pilot-scale H2S and swine odor removal system using commercially available biochar*, found at https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1546&context=hruskareports

[151] i) Baltrėnas et al. (2015) *A biochar-based medium in the biofiltration system: Removal efficiency, microorganism propagation, and the medium penetration modeling*, found at https://www.tandfonline.com/doi/full/10.1080/10962247.2016.1162227,
ii) Shahraki & Mao (2022) *Biochar application in biofiltration systems to remove nutrients, pathogens, and pharmaceutical and personal care products from wastewater*, found at https://acsess.onlinelibrary.wiley.com/doi/full/10.1002/jeq2.20331,
iii) Amirbekov (2021) *HCH Removal in a Biochar-Amended Biofilter*, found at https://www.mdpi.com/2073-4441/13/23/3396 and
iv) Das et al. (2019) *Performance of a compost and biochar packed biofilter for gas-phase hydrogen sulfide removal*, found at https://www.sciencedirect.com/science/article/pii/S0960852418315852?via%3Dihub

[152] i) Gwenzi et al. (2017) *Biochar-based water treatment systems as a potential low-cost and sustainable technology for clean water provision*, found at https://www.sciencedirect.com/science/article/pii/S030147971730302X?via%3Dihub,
ii) Inyang et al. (2015) *The potential role of biochar in the removal of organic and microbial contaminants from potable and reuse water: A review*, found at https://www.sciencedirect.com/science/article/pii/S0045653515003161?via%3Dihub,
iii) Zhang et al. (2020) *Evaluating biochar and its modifications for the removal of ammonium, nitrate, and phosphate in water*, found at https://www.sciencedirect.com/science/article/pii/S0043135420308393?via%3Dihub and
iv) Wei et al. (2018) *Biochar-based functional materials in the purification of agricultural wastewater:*

Fabrication, application and future research needs, found at https://www.sciencedirect.com/science/article/pii/S0045653517321719?via%3Dihub,

[153] BIOCIRC website home, found at https://biocirc.dk/

[154] E.g. Bolwig et al. (2019) *Bioøkonomiens maskinrum - DTU Sektorudviklingsrapport*, found at https://rucforsk.ruc.dk/ws/portalfiles/portal/66911780/108657_sektorudviklingsrapport_bio_net.pdf page 16 (in Danish)

[155] Det nationale bioøkonomipanel (2022) *Anbefalinger: Bioressourcer til grøn omstilling*, found at https://fvm.dk/fileadmin/user_upload/FVM.dk/Dokumenter/Foedevarer/Anbefalinger_fra_Det_Nationale_Biooekonomipanel_28092022.pdf (in Danish)

[156] Rasmussen et al. (2022) *Scenarier for anvendelse af biomasseressourcer i fremtidens produktionssystemer for fødevarer, energi og materialer inden for rammerne af gældende politik for landbrug, miljø, klima, natur og energi*, found at https://fvm.dk/fileadmin/user_upload/FVM.dk/Dokumenter/Foedevarer/AAU_Scenarier_for_anvendelse_af_biomasseressourcer_i_fremtidens_produktionssystemer.pdf page 52 (in Danish)

[157] Bolwig et al. (2019) *Bioøkonomiens maskinrum - DTU Sektorudviklingsrapport*, found at https://rucforsk.ruc.dk/ws/portalfiles/portal/66911780/108657_sektorudviklingsrapport_bio_net.pdf page 13 (in Danish)

[158] i) Jens Mathiasen (2018) *Trætjære og gas holder Harboøre varm*, found at https://www.skovdyrkerne.dk/fileadmin/user_upload/Nord-Ost/dokumenter/56_Skovdyrkerne_NORDOEST.pdf (in Danish) and
ii) Harboøre Varmeværk webiste home, found at http://harvarme.dk/ (in Danish)

[159] BlackCarbon (2012) *News*, found at http://www.blackcarbon.dk/News

[160] Aarstiderne (n.d.) *Aarstidernes tidslinje*, found at https://www.aarstiderne.com/om-aarstiderne/baggrund-og-tal/aarstidernes-tidslinje (in Danish)

[161] i) State of Green (2012) *DONG Energy Turns Biowaste into Green Energy with New Gasification Plant*, found at https://stateofgreen.com/en/news/dong-energy-turns-biowaste-into-green-energy-with-new-gasification-plant/ and
ii) CPH post online (2014) *DONG closes down high-profile gasification plant*, found at https://cphpost.dk/?p=3416

[162] E.g. i) Hansen et al. (2017) *The effects of straw or straw-derived gasification biochar applications on soil quality and crop productivity: A farm case study*, found at https://www.sciencedirect.com/science/article/pii/S0301479716308258?via%3Dihub and
ii) Veronika Hansens phd thesis (2015) *The Effect of Gasification Biochar on Soil Carbon Sequestration, Soil Quality and Crop Growth*, info – but no download at https://plen.ku.dk/ansatte/?pure=en%2Fpublications%2Fthe-effect-of-gasification-biochar-on-soil-carbon-sequestration-soil-quality-and-crop-growth(b557aa45-1b64-46b3-b084-9ccbb0c2b292).html

[163] Research output overview from Ulrik Birk Henriksen, Senior Researcher, Department of Chemical and Biochemical Engineering, CHEC Research Centre, Technical University of Denmark, found at https://orbit.dtu.dk/en/persons/ulrik-birk-henriksen/publications/

[164] Esben Bruun's phd thesis (2011) *Application of Fast Pyrolysis Biochar to a Loamy soil - Effects on carbon and nitrogen dynamics and potential for carbon sequestration*, found at https://core.ac.uk/download/pdf/13747999.pdf

[165] i) Twitter-post from "Landbrug og Fødevarer" (L&F) 4/10-22, handing out biochar samples to Danish politicians, found at https://twitter.com/spisekammeret/status/1577174793287127040 (in Danish),
ii) L&F (2022) *Ny pyrolyseteknologi kan halvere landbrugets klimaaftryk og lave grønne PtX-løsninger*, found at https://lf.dk/biokul?email (in Danish),
iii) L&F (2022) *Fjern barrierer for at sikre tempo i udrulning af pyrolyse*, found at https://lf.dk/aktuelt/nyheder/2022/september/fjern-barrierer-for-at-sikre-tempo-i-udrulning-af-pyrolyse (in Danish) and
iv) L&F (2022) *Nyt udspil fra Landbrug & Fødevarer: Vi skal luge ud i bureaukratiet*, found at https://lf.dk/aktuelt/nyheder/2022/september/udspil-fra-lf-fra-bureaukrati-til-klimahandling (in Danish)

[166] Elsgaard et al. (2022) *Knowledge synthesis on biochar in Danish agriculture*, found at https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport208.pdf

---

[167] (Danish) Ministry of Climate, Energy and Utilities (2021) *Klimaprogram 2021*, found at https://kefm.dk/Media/637684923696666735/Klimaprogram%202021%20(DIGITAL).pdf (in Danish)

[168] i) European Commission (2021) *NextGenerationEU: European Commission endorses Denmark's €1.5 billion recovery and resilience plan*, found at https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3024,
ii) European Commission (2021) *ANNEX to the Proposal for a Council Implementing Decision on the approval of the assessment of the recovery and resilience plan for Denmark*, found at https://ec.europa.eu/info/system/files/com-2021-326_annexe_en.pdf page 11 ("Brown refineries" is an invented DK term that essentially means "pyrolysis plants") and
iii) Danish Energy Agency (2022) *Tilskud til projekter, som fremmer teknologier til reduktion af drivhusgasudledningen inden for landbrugssektoren (Pyrolysepuljen 2022)*, found at https://ens.dk/ansvarsomraader/forskning-udvikling/tilskud-til-projekter-som-fremmer-teknologier-til-reduktion-af (in Danish)

[169] Harald Bier, Head of Office and EBI Consortium during the presentation "From a national to an EU perspective – biochar and carbon markets EBI presentation" given at the seminar "Pyrolysis and Biochar Onwards 2022+ - recent developments and near-future perspectives on Danish, Nordic and EU-Level" at Roskilde University June 23rd 2022. https://biochar-international.org/event/pyrolysis-and-biochar-onwards-2022-perspectives-on-danish-nordic-and-eu-level/

[170] E.g. i) Compensate (2022) *Biochar evaluation criteria to help Compensate select the most sustainable projects on the market*, found at https://www.compensate.com/articles/biochar-evaluation-criteria-to-help-select-sustainable-projects,
ii) Puro.earth (n.d.) *CORC Supplier Listing, sort by "biochar"*, found at https://puro.earth/CORC-co2-removal-certificate/?carbon_removal_method%5B0%5D=7363 and
iii) Carbonfuture.earth website home, found at https://www.carbonfuture.earth/

[171] Carbonfuture (2022) *PRESS RELEASE - MASH Makes and Carbonfuture partner to provide unprecedented 50,000 tonnes of effective carbon removal*, found at https://uploads-ssl.webflow.com/602d30e6f6c4e88604042643/634d0d4ede70c7d08ea6ca9f_Mash%20Makes%20and%20Carbonfuture%20partner%20to%20provide%2050000%20tonnes%20of%20CO2e.pdf

[172] Puro.earth (n.d.) *CORC Supplier Listing, sort by "biochar"*, found at https://puro.earth/CORC-co2-removal-certificate/?carbon_removal_method%5B0%5D=7363, price at 14/11-2022

[173] FabLab RUC website home, found at https://fablab.ruc.dk/

[174] E.g. i) Sommer & Smith (2021) *Debat - Forskere er "dybt bekymrede": Ensidigt fokus på pyrolyse overser alternativ teknologi*, found at https://www.altinget.dk/foedevarer/artikel/forskere-er-dybt-bekymrede-ensidigt-fokus-paa-pyrolyse-overser-alternativ-teknologi (in Danish),
ii) AU BCE (2022) *Hydrothermal Liquefaction*, found at https://bce.au.dk/en/research/key-areas-in-research-and-development/process-and-materials-engineering/hydrothermal-processing/research/hydrothermal-liquefaction
iii) AU CHEM (2022) *Biofuel and Hydrothermal Liquification*, found at https://chem.au.dk/en/research/research-areas-and-groups/analyticalchemistry/ac3/information-for-prospective-students/biofuel-and-hydrothermal-liquification,
iv) Rosendahl et al., EU project 2017-2021, *Hydrothermal Liquefaction: Enhanced performance and feedstock flexibility for efficient biofuel production*, found at https://vbn.aau.dk/en/projects/hydrothermal-liquefaction-enhanced-performance-and-feedstock-flex,
v) AAU Energy (2022) *News: Final Press Release – NextGenRoadFuels*, found at https://www.energy.aau.dk/2022-10-28-htl-biorefinery-n47529 and
vi) Thomas Helmer Pedersen (n.d.) *Spildevandsslam i flymotoren*, found at https://www.danva.dk/media/6407/thomas-helmer-pedersen_aau.pdf (in Danish)

[175] Nordic Biochar Network website home, found at https://www.nordicbiochar.org/

[176] Food & Bio Cluster Denmark (2022) *Opstart af Dansk Pyrolyse- og Biokulnetværk*, found at https://foodbiocluster.dk/nyheder/opstart-af-dansk-pyrolyse--og-biokulnetvaerk?Action=1&M=NewsV2&PID=44109 (the network does not have a dedicated website yet, the link is for the kick-off event. In Danish).

---

[177] i) L&F (2022) *Fjern barrierer for at sikre tempo i udrulning af pyrolyse*, found at https://lf.dk/aktuelt/nyheder/2022/september/fjern-barrierer-for-at-sikre-tempo-i-udrulning-af-pyrolyse (in Danish),
ii) L&F (2022) *Pyrolysenetværk hilser biokulsyntese velkommen som et godt indledende skridt på vejen*, found at https://lf.dk/aktuelt/nyheder/2022/oktober/pyrolysenetvaerk-hilser-biokulsyntese-velkommen-som-et-godt-indledende-skridt-paa-vejen (in Danish) and
iii) Emma Lauridsen (2022) *Nyt netværk skal skubbe på udrulningen af pyrolyse-projekter*, found at https://agriwatch.dk/Nyheder/Industrien/article14432183.ece (in Danish)

[178] The Energy Technology Development and Demonstration Programme (EUDP) (2021) *The SkyClean EUDP project*, found at https://www.energiteknologi.dk/en/node/16258

[179] The Energy Technology Development and Demonstration Programme (EUDP) (2020) *Sustainable and flexible production of maritime fuel from biomass*, found at https://eudp.dk/en/node/15917

[180] AgriFoodTure Innomission partnership (2022) *The MitiChar project*, found at https://agrifoodture.com/projects/mitichar/

[181] KU PLEN (n.d.) *The STABIL project*, found at https://plen.ku.dk/forskning/plante--og-jordvidenskab/soil-fertility/stabil/

[182] Nordic Biochar Network (2020) *The Grass Biochar project*, found at https://www.nordicbiochar.org/2020/06/21/grass-biochar/

[183] KU PLEN (n.d.) *The BioAdapt project*, found at https://plen.ku.dk/forskning/plante--og-jordvidenskab/soil-fertility/biochar-as-a-tool-for-climate-adaptation-in-crop-production-on-coarse-sandy-soil-bioadapt/

[184] SkyClean (2022) *The SkyClean Scale-up project*, found at https://www.stiesdal.com/wp-content/uploads/2022/06/Stiesdal-pressemeddelelse-om-tildeling-af-midler-fra-Pyrolysepuljen-28.06.22.pdf

[185] Danish Energy Agency (2022) *Pyrolysepuljen: Tre projekter modtager 194 mio. kr. til grøn omstilling af dansk landbrug*, found at https://ens.dk/presse/pyrolysepuljen-tre-projekter-modtager-194-mio-kr-til-groen-omstilling-af-dansk-landbrug (in Danish)

[186] Danish Energy Agency (2022) *Pyrolysepuljen: Tre projekter modtager 194 mio. kr. til grøn omstilling af dansk landbrug*, found at https://ens.dk/presse/pyrolysepuljen-tre-projekter-modtager-194-mio-kr-til-groen-omstilling-af-dansk-landbrug (in Danish)

[187] Danmarks Frie Forskningsfond, DFF (2022) *Projekter vi har finansieret -> Project: Optimization of biochar properties for maximum reduction of N2O emissions from agricultural soils*, found at https://dff.dk/forskningsprojekter?instrument:list=all&filed_method:list=ac3ueprpg1&b_start:int=20&period:list=njmlyyjx2g&SearchableText

[188] AU DCA (2022) *Jern og biokul kan til sammen være en ny metode til af afbøde pesticidudvaskning (the Novel rhizosphere-activated hydroxyl radical oxidation of pesticides, OHiROOT project)*, found at https://dca.au.dk/aktuelt/nyheder/vis/artikel/jern-og-biokul-kan-til-sammen-vaere-en-ny-metode-til-af-afboede-pesticidudvaskning (in Danish)

[189] ShippingLab (n.d.) *Partners*, found at https://shippinglab.dk/about/partners/

[190] CIP fonden website home, found at https://cipfonden.dk/ (in Danish)

[191] i) Jens Mathiasen (2018) Trætjære og gas holder Harboøre varm, found at https://www.skovdyrkerne.dk/fileadmin/user_upload/Nord-Ost/dokumenter/56_Skovdyrkerne_NORDOEST.pdf (in Danish),
ii) Harboøre Varmeværk webiste home, found at http://harvarme.dk/ (in Danish) and
iii) Ahrenfeldt et al. (2013) *Biomass gasification cogeneration – A review of state of the art technology and near future perspectives,* found at https://www.sciencedirect.com/science/article/abs/pii/S135943111100737X

[192] i) Torben Skøtt (2014) *Skive Fjernvarme kan lave benzin til hele byen*, found at https://www.forgasning.dk/sites/default/files/pdf/Forgasningsanlaeg_skive_FiB14_48.pdf (in Danish),
ii) Jens Utoft (2008) *Skive fremstiller selv gassen til el- og fjernvarmeproduktionen*, found at https://www.forgasning.dk/sites/default/files/pdf/Skive_biokraftvarmevaerk_gasteknik08_1.pdf (in Danish),

---

iii) Bjørn Kock Sørensen (2007*) Skive bygger Europas største forgasningsanlæg*, found at https://ing.dk/artikel/skive-bygger-europas-storste-forgasningsanlaeg-82162 (in Danish) and
iv) Energysupply (2017) *Skive Fjernvarme viser sin forgasnings-succes frem*, found at https://www.energy-supply.dk/article/view/562296/skive_fjernvarme_viser_sin_forgasningssucces_frem (in Danish)

[193] Stiesdal (n.d.) *The SkyClean technology explained*, found at https://www.stiesdal.com/the-skyclean-technology-explained/

[194] AquaGreen website home, found at https://aquagreen.dk/

[195] MASH makes website home, found at https://www.mashmakes.com/

[196] E.g. i) Gøbel et al. (2004) *Status - 2000 Hours of Operation with the Viking Gasifier*, found at https://backend.orbit.dtu.dk/ws/portalfiles/portal/3265885/rome2004_O1-5.pdf, and
ii) Ahrenfeldt et al. (2013) *Biomass gasification cogeneration – A review of state of the art technology and near future perspectives,* found at https://www.sciencedirect.com/science/article/abs/pii/S135943111100737X

[197] Carbonfuture (2022) *PRESS RELEASE - MASH Makes and Carbonfuture partner to provide unprecedented 50,000 tonnes of effective carbon removal*, found at https://uploads-ssl.webflow.com/602d30e6f6c4e88604042643/634d0d4ede70c7d08ea6ca9f_Mash%20Makes%20and%20Carbonfuture%20partner%20to%20provide%2050000%20tonnes%20of%20CO2e.pdf

[198] Dall Energy website home, found at https://dallenergy.com/en_gb/

[199] E.g. i) Tobias Thomsen phd thesis (2016) *Closing the Loop - Utilization of Secondary Resources by Low Temperature Thermal Gasification*, found at https://rucforsk.ruc.dk/ws/portalfiles/portal/66911184/Tobias_P_Thomsen_2016_Closing_the_Loop_phd_thesis_Online_version.pdf
ii) Peder Stoholm (2010) *DONG Energy satser på forgasning*, found at https://www.forgasning.dk/sites/default/files/pdf/Forgasningsanlaeg_Dong_FiB10_31.pdf (in Danish),
iii) Hafthor Ægir Sigurjonsson's phd thesis (2016) *Modeling and Evaluation of Bioenergy and Agriculture System Integration*, found at https://orbit.dtu.dk/en/publications/modeling-and-evaluation-of-bioenergy-and-agriculture-system-integ,
iv) Eschenbacher et al. (2020) *Catalytic upgrading of tars generated in a 100 kWth low temperature circulating fluidized bed gasifier for production of liquid bio-fuels in a polygeneration scheme*, found at https://orbit.dtu.dk/en/publications/catalytic-upgrading-of-tars-generated-in-a-100kwth-low-temperatur,
v) Giulia Ravenni's phd thesis (2018) Application of biomass char to tar conversion and producer gas upgrading to syngas, found at https://orbit.dtu.dk/en/publications/application-of-biomass-char-to-tar-conversion-and-producer-gas-up and
vi) Nielsen et al. (2005) *The LT-CFB gasifier: First test results from the 500 kW test plant*, found at https://orbit.dtu.dk/en/publications/the-lt-cfb-gasifier-first-test-results-from-the-500-kw-test-plant

[200] Frichs Pyrolysis (n.d.) *Pyrolysis gasification of manure*, found at https://www.frichs-pyrolysis.dk/445514334.html

[201] Danish Energy Agency (2022) *Pyrolysepuljen: Tre projekter modtager 194 mio. kr. til grøn omstilling af dansk landbrug*, found at https://ens.dk/presse/pyrolysepuljen-tre-projekter-modtager-194-mio-kr-til-groen-omstilling-af-dansk-landbrug (in Danish)

[202] Organic Fuel Technology (n.d.) *Technology*, found at https://www.organicfueltechnology.com/technology/

[203] Organic Fuel Technology (n.d.) *Products*, found at https://www.organicfueltechnology.com/products/

[204] Verheijen et al. (2010) *Biochar Application to Soils - A Critical Scientific Review of Effects on Soil Properties, Processes and Functions*, found at https://publications.jrc.ec.europa.eu/repository/handle/JRC55799

[205] Godlewska et al. (2021) *THE DARK SIDE OF BLACK GOLD: Ecotoxicological aspects of biochar and biochar-amended soils*, found at https://www.sciencedirect.com/science/article/abs/pii/S0304389420318227?via%3Dihub

[206] Brtnicky et al. (2021) *A critical review of the possible adverse effects of biochar in the soil environment*, found at https://www.sciencedirect.com/science/article/abs/pii/S0048969721038286?via%3Dihub

[207] Elsgaard et al. (2022) *Knowledge synthesis on biochar in Danish agriculture*, found at https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport208.pdf

---

[208] Elsgaard et al. (2022) *Knowledge synthesis on biochar in Danish agriculture*, found at https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport208.pdf

[209] Osman et al. (2022) *Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review*, found at https://link.springer.com/content/pdf/10.1007/s10311-022-01424-x.pdf

[210] Kahn et al. (2022) *Biochar Optimizes Wheat Quality, Yield, and Nitrogen Acquisition in Low Fertile Calcareous Soil Treated With Organic and Mineral Nitrogen Fertilizers*, found at https://www.frontiersin.org/articles/10.3389/fpls.2022.879788/full

[211] Verheijen et al. (2010) *Biochar Application to Soils - A Critical Scientific Review of Effects on Soil Properties, Processes and Functions*, found at https://publications.jrc.ec.europa.eu/repository/handle/JRC55799

[212] Elsgaard et al. (2022) *Knowledge synthesis on biochar in Danish agriculture*, found at https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport208.pdf

[213] Verheijen et al. (2010) *Biochar Application to Soils - A Critical Scientific Review of Effects on Soil Properties, Processes and Functions*, found at https://publications.jrc.ec.europa.eu/repository/handle/JRC55799

[214] Elsgaard et al. (2022) *Knowledge synthesis on biochar in Danish agriculture*, found at https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport208.pdf

[215] Brtnicky et al. (2021) *A critical review of the possible adverse effects of biochar in the soil environment*, found at https://www.sciencedirect.com/science/article/abs/pii/S0048969721038286?via%3Dihub

[216] Hansen et al. (2017) *The effects of straw or straw-derived gasification biochar applications on soil quality and crop productivity: A farm case study*, found at https://www.sciencedirect.com/science/article/pii/S0301479716308258?via%3Dihub

[217] Joseph et al. (2021) *How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar*, found at https://onlinelibrary.wiley.com/doi/epdf/10.1111/gcbb.12885?src=getftr

[218] Xiang et al. (2021) *Potential hazards of biochar: The negative environmental impacts of biochar applications*, found at https://www.sciencedirect.com/science/article/pii/S0304389421015764

[219] E.g. Sørmo et al. (2021) *Stabilization of PFAS-contaminated soil with activated biochar*, found at https://www.sciencedirect.com/science/article/pii/S0048969720375653?via%3Dihub

[220] Sun et al. (2021) *Roles of biochar-derived dissolved organic matter in soil amendment and environmental remediation: A critical review*, found at https://www.sciencedirect.com/science/article/abs/pii/S1385894721019732?via%3Dihub

[221] E.g. i) Thomsen et al. (2019) *Maabjerg Bioenergy Center: Development of technical solutions, politics and business concepts across 20 years*, found at https://forskning.ruc.dk/da/publications/maabjerg-bioenergicenter-udvikling-af-tekniske-l%C3%B8sninger-politik- and

iii) Mark Booker Nielsen (2022) *Identifying Challenges and Drivers for Deployment of Centralized Biogas Plants in Denmark*, found at https://www.mdpi.com/2071-1050/14/13/8021/htm