Biosolids to Biochar

CNCA Biochar-Urban Forest Strategy

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Prepared for:

CNCA
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NATURE-BASED
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Prepared by:

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1 Introduction

Our approach to socio-economic development has historically been to the detriment of the environment and the rest of the species. For a very long time, human development has depended heavily on intensive resource use. And indeed, while the Human Development Reports have shown the improvements in education, life expectancy, domestic gross product, etc. in parts of the world, it also acknowledges that our influence shapes the natural environment to an alarming extent, destabilising the very systems we depend on for our survival (UNDP, 2020). And with a renewed understanding of the situation, an extensive scientific community has been coming forward with different proposals for the climate crisis. The IPCC, as one of the most comprehensive publications on the matter out there, has indicated two possible paths, both equally valuable for safeguarding the future. First, reduce CO2 emissions on a large scale as soon as possible, and second, deploy a wide range of carbon dioxide removal (CDR) and carbon capture and sequestration (CCS) techniques (Rogelj, et al., 2018). There is a considerable number of challenges for both approaches, ranging from financial, economic, and social issues and debates.

One of the most prominent carbon drawdown technologies emerging in the past years, intensely researched and tested, has been biochar. According to the European Biochar Certification *'Biochar is a porous, carbonaceous material that is produced by pyrolysis of biomass and is applied in such a way that the contained carbon remains stored as a long-term C sink'* (EBC, 2022). By no means a new creation, biochar has a rich history as a soil amendment in agriculture across the globe. However, the interest it raises now for its carbon sequestration potential has increased. With the appropriate technology, the feedstock for biochar production can generally be any organic material. Examples of typical feedstock for biochar include woody biomass (garden and forestry waste, common in Northern countries), food waste, manure, sewage sludge, demolition wood. Naturally, the feedstock is one of the main influencing factors in the properties of the resulting biochar.

The purpose of this report is to serve as an introduction to the topic of sludge derived biochar, some of its physicochemical characteristics and the related possible applications within the urban environment. As much as possible, it is meant to give an overview of the topic, based on the published literature, sludge-char producers' web sources, discussions, and interviews with experts in this domain. The aims of this work are twofold. First, raise awareness and interest in the sludge-char topic, and encourage future research, testing, and development as it is still an emerging subject. And secondly, provide a preliminary market exploration and shortly investigate the potential it can have in the larger carbon sequestration effort.

2 Drivers of sludge-char production

The days of Joseph Bazalgette and the first modern sewer system (Feo, et al., 2014) seem long behind us when we consider the technological advancements in sewer systems and wastewater treatment processes that are available today. Rapid population growth and industrialisation are some of the main factors that brought about these advancements, which in turn, have created great strain on the environment.

Wastewater has been seen for a very long time as an inconvenience rather than an opportunity. And the global standing on wastewater treatment ranges dramatically depending on the location and the socio-economic background of each country. UN-Water estimates that 80% of global wastewater is not adequately treated (UN Water, 2017). This represents a huge risk for the environment as well as human health and well-being. Even if properly treated, there is another environmental challenge. The wastewater treatment operations result in large quantities of sewage sludge which need further processing. Sewage sludge represents up to 40% of the total GHG emissions associated with the operations of the wastewater treatment plant (Callegari & Capodaglio, 2018). For a while, the most common disposal methods have been landfills, incineration (with or without energy recovery), and agricultural applications/land spreading. However, they come with a host of issues (e.g., leaching, water, air, and land pollution) and challenges (e.g., odour management, transport, energy consumption, high costs) (EC, 2001). Depending on the chosen disposal method, as well as the size and location of the wastewater treatment plant, the cost of sewage sludge disposal can represent up to 50% of the operational costs of a water utility company (Cambi, 2021) – in time, that may put pressure on their financial situation.

More sustainable disposal methods through pyrolysis, hydrothermal carbonisation, and anaerobic digestion can add value by recovering nutrients and other compounds, biochar and bioenergy production. This leads to the interest expressed by the scientific community in determining the possible environmental and financial benefits of producing biochar from sewage sludge (Singh, et al., 2020). As discussed, there are generally several drives behind the idea, namely the increasing quantity of sludge (creating handling issues), the high cost of disposal, and the sustainability factor prompting recovery and reuse rather than disposal.

The next chapters will concentrate mainly on the provenience of sewage sludge, its treatment and processing for pyrolysis, and the resulting characteristics of the char. As mentioned, there are other methods of biochar production than pyrolysis, but they are beyond the scope of this report.

2.1 Feedstock and production method

The methods and level of treatment for wastewater depend largely on the size and capabilities of the facilities. Centralised wastewater treatment plants, commonly serving populous urban hubs, have the ability to process larger quantities of wastewater more efficiently. Generally, municipal wastewater and certain industrial streams (limited by national standards on allowable chemicals) are treated together in two or three stages. After screening (to remove large objects from the effluent), primary treatment consists of large sedimentation tanks to separate part of the suspended solids and the liquid, which then passes to secondary treatment. This biological treatment phase may use aerobic or anaerobic digestion to remove as much organic material as possible. Tertiary treatment may include biological or chemical nutrient removal from the effluent, micropollutants removal and disinfection.

This short introduction is necessary to understand the resulting components in sewage sludge. A more specific description of the process is given in Chapter 4. At the end of the treatment process, raw sewage sludge may contain a combination of valuable and harmful components, organic matter, and other elements (Lasaridi, et al., 2018). Besides the useful nutrients (nitrogen, phosphorus, potassium, etc.), there may be other contaminants such as heavy metals (Cr, Ni, Cu, Zn, Cd and Pb), potentially toxic elements (PTEs), polycyclic aromatic hydrocarbons (PAHs), human bacterial pathogens (HBPs) (Singh, et al., 2020), and other microcontaminants (Ratola, et al., 2012). The presence and often the interactions between some of these compounds can lead to harmful effects on the environment (Bondarczuk, et al., 2016). Additionally, there is the real possibility that with an increase in wastewater treatment efficiency, more pollutants will contaminate the sewage sludge (Collivignarelli, et al., 2019) – thus, increasing the need for long-lasting sustainable solutions.

The sewage sludge resulting from the treatment process has different components depending on its provenience (primary, secondary, tertiary sludge). Combined in one stream, the mixed sludge needs further treatment to reduce its water content and prepare it for pyrolysis. By weight, sludge may contain over 90% moisture, in different forms (Chen, et al., 2020). The dewatering process is essential in reducing the amount of sludge, thus, minimizing transportation needs. Current dewatering technologies include chemical preconditioning and electrical mechanical dewatering and subsequent treatments, with plenty of research on the matter (Cao, et al., 2021).

Finally, after drying and crushing them to the necessary size, the biosolids and any additional biomass are ready for pyrolysis – defined as a thermal degradation process which results in varying amounts of biochar, bio-oil, and gases. The advantages of pyrolyzing biosolids can be observed in volume reduction, microorganisms' degradation, pathogens' destruction, useful by-products, and ultimately climate change mitigation (Singh, et al., 2020).

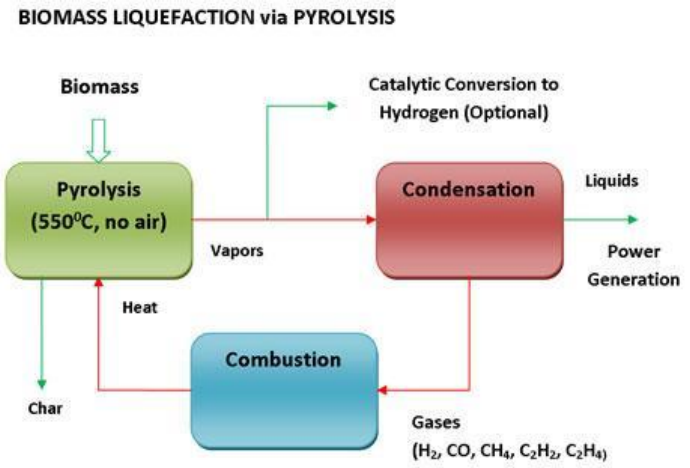

Figure 1: Example of biomass pyrolysis at medium temperature (550° C), the resulting by-products, and their interaction for sustained functioning (Zafar, 2009)

2.2 Sludge char characteristics

Similar to biochar produced from other feedstock, the sludge-char's characteristics are mainly determined by the components and particle size of the feedstock and the pyrolysis conditions, such as temperature, residence time, heating rate and method (Chen, et al., 2020). The choice of input conditions naturally depends on the available technology and resources, but most importantly on the intended biochar application.

- **Biochar yield**. Sludge-char yield decreases as pyrolysis temperature increases, in some examples, decreasing from 72.3% to 52.4% at pyrolyzing temperatures of 300° C and 700° C, respectively (Hossain, et al., 2011). Of note is the conclusion of several studies (Chen, et al., 2019) indicating that co-pyrolysis of sewage sludge and woody biomass yields lower amounts of biochar than sewage sludge alone. However, additional biomass in the process aids in gas generation, which can be harnessed to produce energy (Gopinath, et al., 2021) – so, a careful balance should be considered.
- **Physical characteristics**. Amongst these, porosity and specific surface area are the two most important factors that determine the biochar water retention capabilities (Edeh, et al., 2020). A recent study conducted in Finland, concludes that porosity and specific surface area values of sludge derived biochar were approximately 2-4 times lower than those obtained for wood-based biochar (Turunen, et al., 2021). Unless the pore structure is modified, the study points out that these characteristics greatly affect the usability of the char (ibid.). The electrical conductivity is shown to increase until pyrolysis temperature reaches 500° C, after which it reduces substantially (Singh, et al., 2020).
- **Chemical characteristics**. The ash content in sludge-char has been reported as generally higher than in other biochars (different feedstock). It has also been noticed that the ash content increases with increasing pyrolyzing temperature (Gopinath, et al., 2021). The pH of sludge char (like other biochars) increases with increasing pyrolysis temperature, with some studies placing it between 8.7 to 11.1 (Zhang, et al., 2019).

One of the most important considerations for sludge-char is the fate of the harmful contaminants after pyrolysis. Studies suggest that the concentrations of heavy metals (Pb, Cr, Zn, Cu) increase with higher temperatures. However, the heavy metals are in oxidized form, thus, they are more stable and exhibit lower bioavailability (Gopinath, et al., 2021). Regarding PAHs, there are studies suggesting that their content reduces in the pyrolysis process, however, the trend is decreasing as the temperature increases (A. Zielińska, 2016).

Lastly, depending on the intended use, the characteristics of biochar can be changed or improved by physical activation (using activating agents such as carbon dioxide, air, nitrogen, steam, oxygen (Wang, et al., 2017)) and chemical activation (using inorganic agents – zinc chloride, sulphuric acid, potassium hydroxide, sodium hydroxide, potassium carbonate or organic agents – citric acid (Devi & Saroha, 2017)). Singh, et al. report that the activation process can increase the porosity and the surface area of the sludge-char. Also, it is mentioned that physical activation is more economical and sustainable compared to chemical activation (Singh, et al., 2020).

3 Uses of sludge char

Biochar has long been commended for improving some soil qualities, particularly the structure, texture, porosity, particle size distribution, and density, thus potentially altering their water storage capacity and the nutritional and microbial state (Yuan, et al., 2016). Its application as soil amendment ranges from urban landscaping, sports fields, meadows, and construction soil to roof gardens and walls. It also has numerous other applications in water and stormwater filtering and component in construction materials.

However, due to its feedstock and resulting characteristics, the application of sludge-char in some of these contexts may not be advised without carefully examining the properties of the char and the intended outcomes. Further research, testing outside the laboratory environment and improvements seem to be necessary to adequately determine the benefits and consequences of sludge-char application.

Nevertheless, research suggests that sludge-char application is beneficial in certain areas. There are extensive experiments for the suitability of sludge-char soil applications in agriculture, looking into soil fertility and subsequent crop yield, as well as reducing the amount of needed fertiliser. A 2016 study reported that sludge-char use increased the availability of phosphorus, nitrogen, and exchangeable cations Ca and Mg while decreasing the plant uptake of heavy nutrients (Sousa & Figueiredo, 2015). In the urban environment, the application of sludge-char for parks and urban trees has been studied, and it is indicated that the plant mineral nutrition improves (increases in total soil nitrogen – 1.5 times, organic carbon – 1.9 times, available phosphorus – 5.6 times, and potassium – 0.4 times) (Yue, et al., 2017). The same publication indicates that even though the beneficial effects for the soil grow with higher percentages of sludge-char application, the limit should be observed at 20% due to heavy metal accumulation (ibid.).

Another area of application for sludge-char is wastewater treatment, either municipal or industrial or other such areas in need of remediation. Some studies indicate that this char is more effective than powdered activated carbon for heavy metal (Cd, CU, Zn, Pb) adsorption due to its high pH which converts the metal ions into hydroxide and precipitates on the surface of the sludge-char (Zhou, et al., 2017). It can also be used in the removal of dye due to its pore structure and surface chemistry, certain antibiotics, and other contaminants (Gopinath, et al., 2021).

4 Case studies

As previously mentioned in Chapter 3, the majority of sewage-sludge char production in Europe has been in the experimental and piloting context, the resulting amounts much lower than other types of biochar, as well as the applications somewhat more limited. However, the necessity and the benefits of this sewage sludge disposal method are quite clear, and they have prompted larger undertakings in several parts of the world, which we will concentrate on in this chapter.

4.1 HSY, Ämmässuo eco-industrial treatment centre, Finland

Wastewater situation in the Greater Helsinki area

Finland has developed its biochar production greatly over the past 10 years, with biochar projects in over 10 cities across the country (Nordic Biochar Network, 2021). Such great interest and expertise in the area have increased public awareness and have prompted further research in sludge-char production as well. The Helsinki Region Environmental Services (HSY, abbreviation in Finnish) is Finland's largest water and wastewater operator, waste management facility, and environmental services provider covering the capital's metropolitan area.

The Greater Helsinki area is served by two wastewater treatment plants, Viikinmäki and Suomenoja. The former captures the sewerage from all of Helsinki and seven other municipalities around the capital. 85% of its flow is due to domestic wastewater, amounting to approximately 860 000 inhabitants, while the rest is accounted for by industrial wastewater and other don-domestic sources (HSY, 2018). It is considered the largest facility in the Nordic countries, based on the treated volume and it has been commissioned in 1994, followed by several updates in capacity (ibid.). Suomenoja is located in Espoo, and it treats the city and four other municipalities. Currently, due to population increase in the metropolitan area, the capacity of the plant is under strain. A new wastewater treatment facility has been under work in Blominmäki (due to open in 2022). The new plant is intended to serve 400 000 residents, with a future capacity expansion of up to 1 million people (HSY, 2020).

The treatment process is similar in the two locations, using the activated sludge method. In the pre-treatment stage, the sewage is screened, the sand removed, and there is a preliminary aeration stage to allow aerobic biodegradation of the organic materials. This is followed by the primary sedimentation stage which allows the clumped bacteria and suspended solids to settle, another aeration phase, secondary sedimentation and finally, a biological filter. Phosphorus removal is carried out in two-phase simultaneous precipitation, using ferrous sulphate ($FeSO_4$). The ensuing sediment is bound to the sludge. The nitrogen removal occurs first in the activated sludge process and then in the biological filter (HSY, 2018).

The two wastewater treatment plants in Helsinki adhere to strict environmental standards concerning the amount of nitrogen and phosphorus removed from the wastewater. This is due to the effluent being discharged into the Baltic Sea which is prone to eutrophication. The new plant at Blominmäki proposes to remove 90% of nitrogen and 96% of phosphorus, much higher percentages than required by the EU, national legislation, or HELCOM (HSY, 2020). The high levels of removal from the wastewater in current locations lead to high concentrations of nitrogen and phosphorus in the resulting sludge.

Sludge pyrolysis process

Therefore, since 2016, HSY and their partners have started investigating methods for nutrient recovery, both through further treatment of wastewater as well as sludge pyrolysis (HSY, 2021). The pilot plant, a 10th of the full scale needed, is located at the Ämmässuo eco-industrial centre. The sludge pyrolysis unit is a TECAM model (TECAM, 2020) designed with slight modifications to accommodate HSY's needs and able to provide more accurate data for possible scale-ups.

Currently, the pilot plant is able to process approximately 30 000 tonnes of wet sewage sludge per year. This translates into a rough production of 3 000 tonnes of sludge-char annually. Except for some downtime during the year (accounting for 10% of operational hours) due to technical issues, the plant operates continuously. The step-by-step process is illustrated in Figure 2.

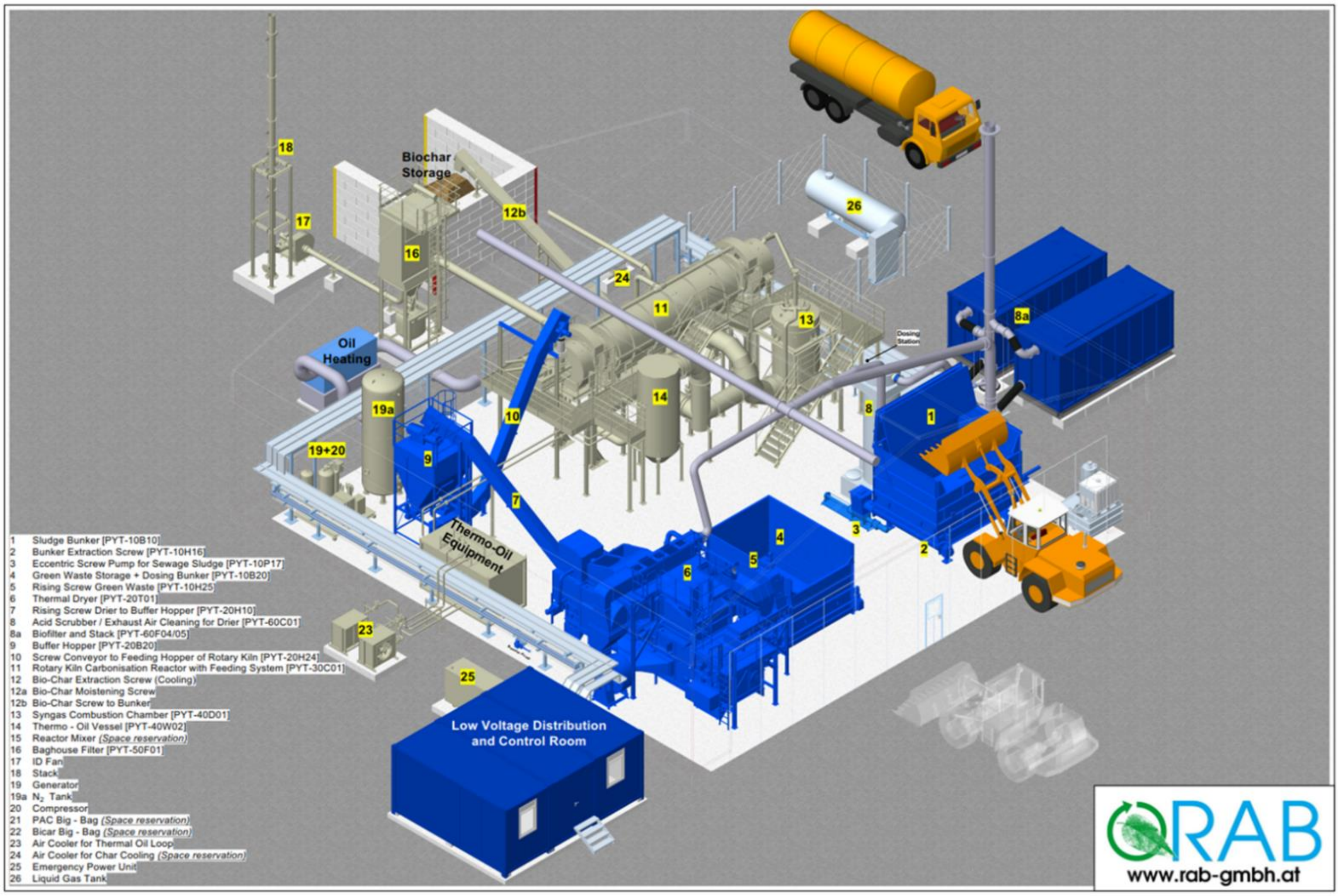

Figure 2: *HSY's sludge pyrolysis pilot plant and the steps of sludge-char production in the unit, described in short below as presented by HSY's R&D portfolio manager and HSY's official website (HSY, 2021b)*

HSY's process involves mixing approximately 20% wood chips (different amounts have been tested) in the sludge pyrolysis process for energy efficiency. The wet sludge and the wood chips are fed into the thermal dryer, which has a moving belt to convey the material to the drying furnace. The heating energy necessary for the process is obtained by combusting the gas, a by-product of pyrolysis. The exhaust air is then treated by an acid scrubber and a biofilter before release to reduce odour.

The pyrolysis unit is a rotary kiln, and it is designed to operate at temperatures ranging from 450° C to 650° C at a set time between 30 and 120 minutes. The sludge-char is cooled with indirect water cooling upon exiting the kiln and it is then transferred by a conveyor to the storage silo. Due to the chosen settings, including the tested temperature ranges, as well as the economic activities in the region, concentrations of heavy metals have been found to be low and not a primary concern. At the moment, the sludge-char does not have official status under Finnish law as biochar, but rather as a waste product. Therefore, its application is limited to compost mixing. The necessary steps have been taken to change its status.

The pilot project for sludge-char has been finalised this year (2022) and the results of the research are soon to be published. HSY's plans for a potential full-scale sludge pyrolysis plant are under consideration, depending on the cost-efficiency of implementing and operating such a project, as well as the overall environmental benefits.

4.2 Other examples across Europe and USA

Several other sludge-char projects are underway across European countries as well as other treatment methods that reduce the environmental impact on the soil, water, and air. The trend toward thermal treatment of sewage sludge has extended, with the Netherlands as a leader (with a 100% thermal treatment rate), followed by Switzerland (97%), Belgium (89%), and Germany (70%) (Schnell, et al., 2020).

In Sweden, Rest till Best (original: Rest till Bäst) is a large project commenced in 2017 and set to come to an end in 2023, designed to develop solutions for a wide range of organic waste (green waste, sludge, seaweed) by producing biochar. It has 15 collaborators, both in the public administration, in universities, as well as private companies (Biokol, 2021) and they have already produced a handbook detailing some of their findings. In 2020, they introduced a lab-scale sludge-pyrolysis unit to study the characteristics of biochar produced from bioagropellets, sludge, and dried green waste. The experiments were carried out with pyrolysis temperatures ranging from 400° C to 900° C, and residence time of 10-20 minutes. Although full results are still to be published, their conclusions have been similar to existing literature, in terms of sludge-char characteristics, heavy metal concentrations, and PAHs content reduction (Fransson, et al., 2020).

In Germany, much like other European countries, sewage sludge has been, for a long time, used in agricultural applications. However, due to public and political attention, the regulations are set to change towards a less harmful practice, with a focus on soil and environmental protection. In terms of sludge pyrolysis, there are two operating Pyreg-designed plants in Linz-Unkel (since 2015) and in Homburg (since 2016). Their operation is similar to the one described for HSY's pilot plant. In Linz-Unkel, the pyrolysis process (taking place at 650° C) reduces the dried sludge by 60% compared to its original volume, while in Homburg (same temperature) by more than 90%. They both function continuously, with energy input from their own operation, being able to process approximately 1000 tonnes of sewage sludge per year individually (Eliquo Stulz, 2018a; Eliquo Stulz, 2018b). There is another sewage sludge pyrolysis unit provided by Pyreg as well attached to the Main-Taunus (district in **Germany**, part of Frankfurt's urban area) municipal wastewater treatment plant (Main-Taunus, 2022). The sludge is first dried and then pyrolyzed at 500° C to 700° C, with the resulting biochar (approximately 15% phosphorus content) used as fertilizer in agriculture. The process is continuous throughout the year, and it is estimated that the unit handles 5000 t of dewatered sludge/year (25% dry matter), resulting in 625 t of biochar/year (Pyreg, 2022).

Since 2018, a combined steam dryer and pyrolysis unit have operated in Odense, **Denmark**, installed by AquaGreen (AquaGreen, 2022). The unit is located near the municipal wastewater treatment plant, which feeds the sludge through a pipe to the steam dryer which in turn, processes the biosolids for pyrolysis and biochar production (AquaGreen, 2019). The unit is self-sufficient as the energy required for the drying process is obtained by burning the gases from the pyrolysis process. Additionally, the excess steam from drying is condensed and used for heating either locally or in the district heating system (ibid.).

There is also an example of a sewage sludge pyrolysis plant from the **USA**, in Redwood City, California, installed by Biotechforce with Pyreg technology. The production process is similar to the other European examples, the biosolids are dried (reducing their mass by 75%) and pyrolyzed (temperature between 350° C and 900° C) resulting in biochar, supported by energy production for the functioning of the unit (Biotechforce, 2022).

5 Market potential

The cost of producing sludge-char, which takes everything into consideration, such as operational cost (acquiring feedstock, transport, production, maintenance, labour, and storage cost) is an essential factor influencing the growth of the market and its long-term sustainability from a business perspective (Singh, et al., 2020). There are several other points to consider regarding sludge-char's place on the market because sometimes there is misunderstanding in the terms *biochar* and *sludge-char*. In some instances, its applications coincide with those of other types of biochar (namely urban soil uses, water and wastewater filtration), but in most cases, it is a separate product with its own characteristics and uses. This means that its market value should be compared to similar products in order to ascertain if it is feasible to produce. For example, a 2018 study estimates that the market price for sludge-char is 246 US $/ton, which is six times lower compared to one direct competitor – activated carbon (estimated at 1500 US $/ton) (Callegari & Capodaglio, 2018).

Further specific studies and projects need to be conducted to try and compile a comprehensive (public) list of costs, perform a cost-analysis of full-scale sludge-char production units, identify the issues and optimize the supply chain (Singh, et al., 2020), while also doing end-user research (to better understand the end customer's concerns and needs). This is a long list of requirements which in time, will most likely be available. However, at the moment, the overall small scale of production does not justify a full market analysis. Currently, there is more emphasis on studying the sludge-char characteristics, the harmful and beneficial impacts it can have if applied in different domains, improvement and further treatment methods. By following the literature, some aspects are still unclear, especially considering that a large number of characteristics have been studied under laboratory conditions, without long-term on-site studies. But careful research is only the first step in further commercial developments (Singh, et al., 2020).

Recent growth in sludge-char popularity has been sustained by the environmental and human well-being considerations, the more stringent sludge disposal regulations, and the higher cost of other disposal methods, rather than demand for sludge-char on the market. There is a lot of investment in this area, both by private and public stakeholders. For example, the Pyrochar project financed by the European Union and addressed to small municipalities (under 10 000 people) that did not have sustainable disposal methods for their sewage sludge operated between 2013 and 2015. Approximately 1.5 million euros have been invested in developing sludge-char solutions in these communities (European Commission, 2016).

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