Biochar-Urban Forestry Strategy

FOR THE GREATER HELSINKI AREA, FINLAND

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Biochar feedstock assessment in the Greater Helsinki area

1 Introduction

This report is prepared as part of an explorative study of the use of biochar in the Greater Helsinki area. The work has been conducted in collaboration with the City of Helsinki and the Carbon Neutral Cities Alliance CNCA.

1.1 Feedstock availability: an overview

Biochar can be produced from multiple different sources including wastewater sludge, construction wood, demolition wood, municipal mixed biowaste, garden waste, green waste, grass and reed trimmings, manure, restaurant waste, and waste from food production. The feedstock used in the production has a significant impact on the quality and properties of the biochar. Other important factors that affect the quality and properties of the biochar are the pre-treatment of feedstock and the processing conditions.

In the Helsinki area, the following feedstocks are considered most relevant: wastewater sludge, construction and demolition wood, municipal mixed biowaste, garden waste, and green waste. These feedstocks were chosen based on the annual amounts produced, data availability and former known usage as a feedstock for biochar production. The identified flows and potential for biochar production are presented in Figure 1. These flows vary in terms of the accuracy of data. They will be investigated in more detail later in this report.

Restaurant and cafeteria waste along with waste from food production, even if presented as an option, were left out of the scope of this article for the reasons of data availability. The potential of these waste flows is estimated to be relevant for biochar production, but the lack of publicly available data limits the estimation of these feedstocks. Coastal and grass trimmings and manure, even if presented as an option, were left out of the scope of this assessment.

In the case of wastewater sludge and biowaste, the mass data can be considered fairly reliable, as the numbers are provided by HSY and are measured more accurately. In the case of wood waste and green waste the masses provided are mainly based on estimations, as waste collectors in the Helsinki area seldom weigh their waste flows but instead approximate the volumes based on experience. For these flows, we aim to provide a rough ballpark estimation for the upper limits of the potential feedstock, and these estimations should be further validated throughout the project.

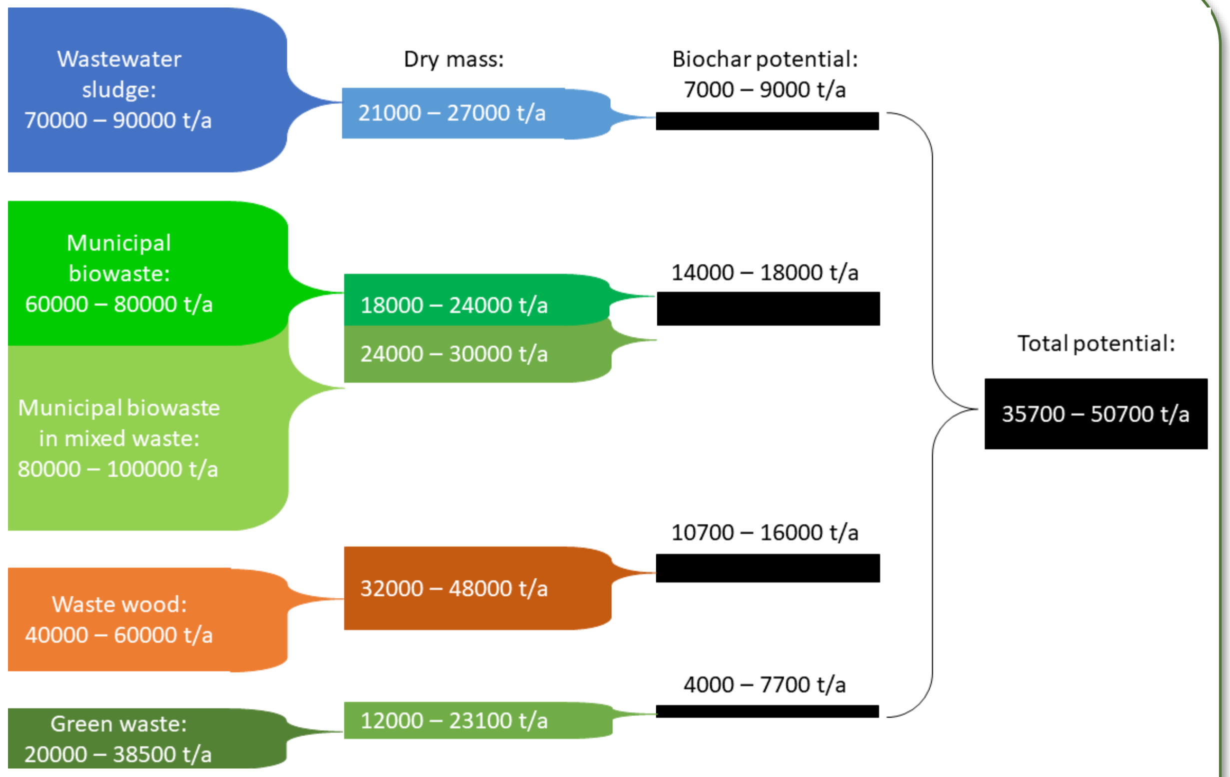
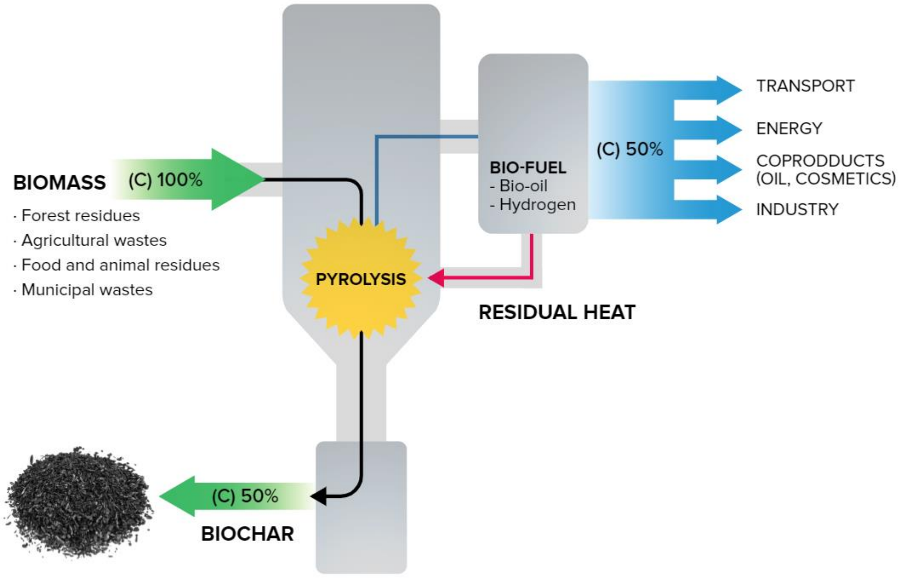


Figure 1. Flowchart of the identified potential feedstocks for biochar production. The numbers are based on the amounts of current source-separated waste flows. For example, the biowaste flow could potentially more than double with improved separation. Figures for the green waste are for the City of Helsinki whereas the other figures are for the greater Helsinki area.

1.2 Pyrolysis: basic principles of the process of producing biochar from organic matter

Biochar can be produced by pyrolysis, a thermochemical decomposition process with the absence or restricted amounts of oxygen (O_2). Typically, the process takes place at temperatures between 500-1100 K. The amounts of volatile gases (CO, CO_2, H_2O, H_2) and oils produced in the process is dependent on the processing temperature and amount of oxygen allowed to the reaction mixture, with lower oxygen levels resulting in fewer by-products and higher biochar yields (Lehmann & Joseph, 2015). A schematic picture of the biochar production process is shown in Figure 2 below.

The biochar potential presented in this report is calculated with the cautious rule of thumb estimation that one unit of solid dry biomass is converted into 1/3 mass equivalent of biochar. The actual amount of biochar produced, and the ratio of the captured carbon is dependent on the quality of the feedstock as well as the processing conditions, as stated above. The potential for CO_2-sequestration can be derived from the stoichiometry of a burning reaction and is 1:3½ per mass unit of biochar with up to 5w-% of impurities. CO_2 is sequestered in cases where instead of incinerating a waste flow (such as waste wood) it is turned into biochar, capturing some of the carbon to its solid form.



Source: International Biochar Initiative, Johannes Lehmann and Valoral Advisors.

Figure 2. Schematic diagram of the production of biochar (Garzaron & Viton, 2021). In this scenario, half of the carbon from the feedstock ends up in the biochar product, while the rest goes to the oils and volatile gases produced.

2 Estimations of potential feedstock flows for biochar production

2.1 Wastewater sludge

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 non-domestic sources (HSY, 2021 a.). 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, 2021 a.).

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, 2021 a.).

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, 2022). The high levels of removal from the wastewater lead to high concentrations of nitrogen and phosphorus in the resulting sludge. One of the reasons for HSY to use pyrolysis is to remove /break apart organic residues of e.g., medicament and other harmful substances. This aims to increase the further use of sludge to produce biochar or soil amendment.

HSY imposes strict regulations on the industrial and non-domestic sewage flows, under the Industrial Wastewater Agreement (HSY & FIWA, 2018). The Finnish Industrial Wastewater Guide mentions that a utility is allowed to refuse the connection of a property that could impact the good functioning of their wastewater treatment process (ibid.). If the industrial flow contains contaminants or harmful substances, there is a need for pre-treatment. In short, the quality of the sludge produced by the wastewater treatment plants in the Helsinki area is not affected by the provenance of the sewage. The resulting sludge is, in theory, of consistent quality.

Annual flow: 70 000 – 90 000 t/a (HSY, 2020 a.) → dried sludge roughly 30% of wet mass
Biochar potential: 7 000 – 9 000 t/a

- The wastewater sludge is produced in two different WWTFs (roughly 1/3 & 2/3 flow (HSY, 2020 a.)).
- Currently, HSY's sludge char pilot is able to process around 30 000 t/a of wet sludge from the Suomenoja WWTF.
- Current production is roughly 3 000 t/a of sludge char annually.
- Production volumes depend on the ratio of sludge to wood chips, the current process uses around 20% of wood chips by dry mass.
- Organic residues from medicaments have been found to be low, and due to the economic activities of the region, the concentrations of heavy metals are low as well.

2.2 Biowaste digestate and compost material

The main authority responsible for collecting mixed solid biowaste within the Greater Helsinki area is HSY. The presented amount consists of source-separated biowaste that is roughly divided in half between domestic households and the public sector. Although a significant amount of solid mixed biowaste is successfully source-separated, a large portion of it still ends up in the mixed waste bins. According to HSY's statistics, biowaste accounts for around 30% of the annual 270 000 – 300 000 tons of mixed waste, totalling an additional 80 000 – 100 000 t/a of biowaste (HSY, 2020 b.), which is illustrated in Figure 3 below. However, the increased biowaste feedstock could be counteracted by the reduction of food waste, a goal that many public and private actors are committed to.

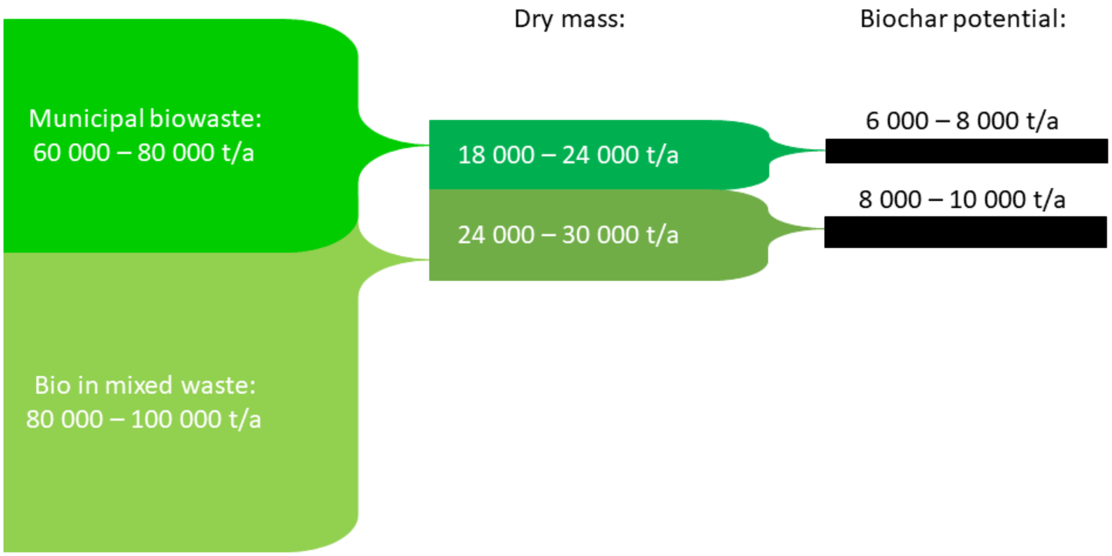


Figure 3. HSY statistics on municipal biowaste and biowaste in mixed waste. Better sorting of biowaste could more than double biowaste digestates biochar potential.

The bio-based side-streams from the private sector would be a good topic for future research. For example, the waste production of coffee roasteries in the Helsinki area could be investigated in the future, as the coffee grindings can be used to produce more homogenous biochar in terms of quality and structure.

Current annual flow: 60 000 – 80 000 t/a (HSY, 2021 b.)
→ dried biomass roughly 30% of wet mass
Biochar potential: 6 000 – 8 000 t/a

- Pyrolyzed biowaste digestate contains traces of phosphorus and nitrogen that are beneficial to growing plants.
- Better performance in the collection of municipal biowaste could significantly increase the biochar potential up to 14 000 – 18 000 t/a.

2.3 Construction wood waste

It is estimated that the annual volume of wood waste on the national level in Finland is around 250 000 t/a (Häkämies, et al., 2019). We can assume that roughly 20-25% of this is produced within the Greater Helsinki area, and the HSY statistics support this estimation (HSY, 2021 b.). Some uncertainty is caused by private waste collectors that sometimes transport waste wood further distances outside of the Greater Helsinki area.

The waste wood is by far the hardest feedstock to estimate, as the collection and disposal of waste wood is highly privatized and not coordinated by any central authority. Nevertheless, waste wood has also great potential as feedstock for biochar, as pyrolysis of wood produces homogenous biochar in terms of quality and structure.

It should also be noted that clean wood waste is already in high demand. For example, the earlier mentioned HSY Sludge Char-pilot project currently uses wood chips in the process, and many other industrial actors compete for clean wood waste to be used in their processes.

Annual flow: 40 000 – 60 000 t/a (Häkämies, et al., 2019)→ dried wood mass roughly 80% of wet mass
Biochar potential: 10 700 – 16 000 t/a

- Greater variation in reliability compared to other feedstocks, caused by dependency on ongoing projects
- However, an urban environment does always produce some amount of wood waste related to repairs, restoration, demolition, and new construction projects

2.4 Green & garden waste

This stream is difficult to estimate because it ends up in many destinations by several different contractors, and also because not all of the growth of organic matter is collected away, but instead is left on site. Many estimations are also done based on volume as it is easier to estimate by heart, and these values must then be converted into mass units.

Green areas contribute to around 40% of the City of Helsinki's 21 380 ha land area, and about half of the green areas are forests (City of Helsinki, 2013). Most of this green area, 7041 ha, is managed by Helsinki's Office of Built Environment (HSY, 2021 c.), which constitutes about 85% of the total green areas of Helsinki. Biomass can be harvested from forested areas.

Currently, it is estimated that Southern Finnish urban forests produce on average around 4 m^3/ha/a of biomass, which takes into account that these forests are relatively old and not managed to maximize the yield. This means that in addition to the collected biomass some 17 100 m^3/a of biomass from urban forests would be available theoretically within the City of Helsinki, which translates to roughly 8 500 t/a using an average density of 500 kg/m^3 for the wood mass. This theoretical figure is supported by our interview with the Forest Official of the City of Helsinki, who confirmed that the amount of wood

Helsinki sells annually is between 13 800 – 15 000 m^3/a, which translates to approximately 6 900 – 7 500 t/a (Koskikallio, 2022). It should be noted that a large share of wood must be left to the forests, as urban forests are also subject to biodiversity management, which requires decaying wood, as well as recreational use.

The other green areas produce biomass as well, but estimates are scarce. The average yield of cost-effective, low productivity soilage production is 6 t/ha/annually and it is probably a lot higher than the amount of biomass an urban green space can produce. By using this overscale figure and an area estimate of 4 000 ha to calculate an upper range estimate we land on 24 000 t/a, a theoretical upper limit for the wet mass of green waste produced by the non-forested city green areas. By estimating a dry mass of 30%, similar to municipal biowaste, we land on a dry mass of 7 200 t/a. In reality, this figure seems to be significantly lower than this theoretical upper limit would suggest and does not consider the fact that leaving some of the cuttings on the field has some nutritional benefits to the ecosystem.

Annual flow: *Combined mass of biomass from green areas*: 20 000 – 38 500 t/a
(HSY, 2021 b.; HSY, 2021 c.; Viskari, et al., 2021)
→ wet mass can vary depending on the *wood mass/cuttings* -ratio
→ to simplify, our estimation for dried mixed garden waste is 60% of the wet mass
Biochar potential: 4 000 – 7 700 t/a

- Includes twigs, trunks, stumps, cuttings, and mowing

Biochar benefits and potential applications in the Greater Helsinki area

3 Introduction

Historically, the purpose of biochar has been limited to soil amendment in agricultural activities, especially in tropical climates where the product has been first observed. However, as the awareness of carbon mitigation and sequestration technologies spread over time, so did the emphasis placed on biochar. This report proposes to investigate different applications of biochar relevant to the urban environment, specifically for the Greater Helsinki area. It also endeavours to determine realistic volumes of biochar that could potentially be used, thus linking to previous research into feedstock potential and production capacity in Helsinki.

Generally, the applications of biochar have been long researched in agriculture, applied as a raw soil amendment capable of retaining nutrients and water, thus leading to an increase in crop yields. Studies show that by applying fertiliser in combination with biochar, there was a 15% average yield increase compared to the same fertilization technique without the biochar (Schmidt, et al., 2021). More recently, efforts have been made to move in a different direction and combine biochar with compost, fertiliser, or even manure to be applied on agricultural land to lower the overall GHG emissions (Kammann, et al., 2017). However, the benefits of biochar use in the urban environment are a somewhat newer pursuit, generating a lot of research in academic circles, driven as well by the environmental and economic value of the material. In the urban environment, biochar has been established as a carbon sequestration method, as well as a useful tool for climate adaptation objectives. Biochar can be used as an ingredient in manufactured soil, as a contaminated soil remediation method, in filtering systems, construction materials additive (for example, concrete, asphalt, or mortar), electronics component and other technologies (Azzi, 2021).

The practical applications are widely dependent on the location, availability, and characteristics of the available biochar. That is why for the Greater Helsinki area, this report has identified the following use categories, expanded upon in later chapters: soil amendment in urban vegetation planting, new soil component, stormwater and wastewater filtering material, and a component of blue-green-grey infrastructure solutions. The amount of biochar used has also been of interest. To constitute a viable carbon sequestration method and help meet the environmental targets of the city (City of Helsinki, 2018), the volumes of biochar must be substantial.

3.1 Physical and chemical properties of biochar

Depending on the source of the definition, biochar represents an umbrella term for a multitude of carbonized bio-based materials (Azzi, 2021). For the purpose of this report, there are several cumulative conditions to be met in order for a bio-based material to be considered biochar. Having a clear definition of the term is essential for quality purposes and ensuring that the term *sustainable material* is applied correctly. Following certain guidelines in biochar production ensures carbon efficiency and a reduced environmental footprint.

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).

Generally, considering the production possibilities and feedstock in the Greater Helsinki area, the terms mentioned in the definition above are applicable.

The two main deciding factors for the physicochemical properties of biochar are the feedstock options and the pyrolysis conditions – heating rate and temperature of pyrolysis. These properties then in turn determine the stability of the biochar and thus, its longevity in the soil (Crombie, et al., 2013). Pyrolysis occurs at temperatures between 300° C and 700° C in limited oxygen conditions (Ippolito, et al., 2020). The heating rate, and the temperature range, affect the amount of biochar produced. Slower heating rates and lower temperatures (300° – 500° C) lead to a higher yield of solids (biochar) – approximately 30% of input.

Whereas higher heating rates and higher temperatures (600^{o} – 700^{o} C) favour the production of by-products and only around 10% yield of biochar (Pokharel et al., 2020).

However, studies show that temperature remains the factor with the strongest effect on biochar composition. By increasing the pyrolysis temperature - the stability, specific surface area, pore-volume, C content, and pH also increase. For instance, the specific surface area is related to nutrients and contaminants retention; while pore volume affects water availability (Ippolito, et al., 2020). Depending on the intended biochar application, these factors must be considered in the production process to ensure the benefits of the final product.

3.2 Biochar density for measurements

There are three different values when referring to the 'density' of a porous material. There is the bulk density (defined by the volume of the container used to measure the sample, including pore space *in* and *between* the particles), the envelope density (which considers each particle, but not the pore space between them), and the skeletal density (excludes both *intra*- and *inter*- pore space and only deals with the solid material) (Brewer, et al., 2014). The density of biochar is a useful point to remember especially when considering the material across several different fields. Bulk density is usually the most relevant parameter, both for producers (who need to report the value for voluntary biochar quality standards e.g., EBC, IBI-BS) and the buyers who are interested in storing options (Guo, 2020). For reference, it is estimated that the bulk density of biochar varies between 0.09 tonnes/m^3 to 0.5 tonnes/m3 (Lehmann & Joseph, 2015).

Familiarity and convenience might play a role in how the biochar is measured, as well as the intended purpose. For instance, in research and academic writing, biochar is usually expressed as mass. It is a straightforward way of conveying the quantities and the input/output relationship. It is also easier to measure an exact mass rather than a volume for small amounts of biochar (Brewer & Levine, 2015). Also, for the carbon credits market, biochar requires mass-based accounting. However, in the industrial, commercial, and green infrastructure/construction spheres biochar is mostly sold based on volumes. That is because biochar has a low bulk density, and its volume is a limiting factor compared to its weight.

In this report, biochar quantities will be reported as a volume because the applications in the Greater Helsinki area generally involve large quantities applied as soil amendment or biofilter.

4 Potential applications of biochar in Greater Helsinki

The use options and volumes of biochar use will depend on the physical environment. The estimates for the Greater Helsinki area are summarised in Table 1 including estimates for both a conservatively low estimate and a maximum figure which would be the result of large-scale utilization of biochar in this option. The conservative estimate has been obtained by considering the current biochar practices in the city, the least amount of added biochar (by volume), lower soil thickness for a specific application, etc. For the maximum figure, future developments have been regarded, as well as maximum volume and thickness. The annual values have been obtained by proposing a maintenance or renewal rate of biochar application. The table also includes considerations on the quality of biochar for particular applications, based on the European Biochar Certification (Appendix).

Table 1: *Biochar applications in the Greater Helsinki area, with volume estimations and potential, and biochar certification class (according to European Biochar Certification – see Appendix for limit values of common parameters)*

	Applications	Details	References	Biochar estimated amount (volume)		Biochar Certification Class/ Feedstock option
				Minimum (m^3/year)	Maximum (m^3/year)	
Mixed in with soil	Tree planting	City of Helsinki: 1 000 trees/year[1]; 8 m3 - 25 m3 - soil volume/tree; 5% - 20% recommended biochar by volume [2] (10% chosen)	[1]Interview, City of Helsinki representative [2]Embrén, Bjorn. 2016. "Planting Urban Trees with Biochar." Biochar Journal.	800	2 500	Traditionally, woody biomass. **EBC-Urban** (limits PAHs, thus biochar can act as net adsorber)
	Roof gardens & green walls	Greater Helsinki area (90 000 m2 of green roofs, with 3 000 000 m2 potential)[3]; 100 mm (0.1 m) thickness of soil layer; 30% biochar by volume[4]; 10% increase rate/year	[3]HSY. 2016. "Green roofs in the Helsinki Metropolitan Area." Open Data Finland. Ulkoinen lähde: Paikkatietohakemisto.	270 (total 2 700 m3)	9 000 (total: 90 000 m3)	**EBC - Agro, EBC - AgroOrganic** (meets EU fertilizer regulations & organic production)
	Sport fields	2 000 000 m2 (200 ha) neighbourhood sport fields, football, ice-skating etc.[5]; 0.4 m thickness soil layer; 5% biochar by volume[6]; 10% -15% maintenance rate	[5] Lipas.fi. 2021. University of Jyväskylä - Lipas - Statistics. https://lipas.fi/tilastot. [6]Estimation QS. n.d. How To Build a Football Field for your Professional Club, Community or Backyard – Natural Grass and Artificial Turf Pitch. https://estimationqs.com/how-to-make-a-football-field/.	4 000 (total 40 000 m3)	6 000 (total 60 000 m3)	**EBC-Urban / EBC - Agro** (both can be used for urban soil applications)
	Soil fill/structural soil	Park maintenance/ vegetated roadside/ bioswale/ embankment/private garden use; 200 000 m3 Helsinki - 475 000 m3 (/year) Greater Helsinki area soil producers report[7]; 10% biochar by volume	[7] Ruokavirasto. 2021. "LANNOITEVALMISTEIDEN VALMISTUS." Helsinki, Finland	20 000	47 500	**EBC - Urban**
	Meadows & agricultural land	4 200 000 m2 (420 ha) under City of Helsinki administration[8]; 300 mm (0.3 m) topsoil layer; 5% - 10% biochar by volume[9]; 10% maintenance rate	[8]2019. NATURE AND GREEN AREAS » NATURE MAINTENANCE » MEADOWS AND AGRICULTURAL LAND.https://www.hel.fi/helsinki/en/housing/nature/maintenance/meadows-agricultural/. [9] McLaughlin, Hugh, and Keegan Pyle. 2016. "Practical Applications of Biochar in the Landscape." Ecological Landscape Alliance.	6 300	12 600	**EBC - Agro, EBC - AgroOrganic** (meets EU fertilizer regulations & organic production)
Filters	Stormwater filter	Stormwater retention basins; biofiltration systems; contaminated stormwater filtration (test sites: Maunulanpuro 700 m2, Otsolahti 1000 m2[10] - estimated 10 new basins/year); soil thickness 0.5 m - 1 m; biochar by volume 10%	[10] Peltosaari et al. 2020. Storm water management in the city of Helsinki.30.6.https://www.bsrwater.eu/news/storm-water-management-helsinki.	85	1170	**EBC - Urban** (helps filtration, prevents surface and ground water contamination)
Other uses	Concrete/tiles/plaster	Biochar replaces part of the cement (2-10%) in the mix[11]; 50% biochar, 30% sand and 20% clay for plaster mix [12]	[11] Draper, Kathleen, and Hans-Peter Schmidt. 2021. Urban Bioenergy-Biochar: An Opportunity Assessment for Municipalities. Biochar, Bioenergy, Ithaka Institute for Carbon Intelligence. [12] Schmidt et al. 2014. "The use of biochar as building material." Biochar Journal.			**EBC - BasicMaterial** (guarantees sustainbily produced material, for non-soil applications)
	Insulating material	Thickness up to 200 mm, can replace Styrofoam [12]				
	Deposit	Unused biochar amount collected in a central storage				
				31 455	**78 770**	*BC (2012-2022) 'European Biochar Certificate - Guidelines for a Sustainable Production of Biochar.' European Biochar Foundation (EBC), Arbaz, Switzerland. (http://european-biochar.org). Version 10.0 from 1st Jan 2022

4.1 Biochar in soil applications

The threat of climate change in the urban environment brings varied and unprecedented consequences to the infrastructure and inhabitants. Often, due to the inherent nature of a city (high-density population, intense activity, developed grey infrastructure) the effect of extreme weather conditions is accentuated – be it flooding, drought, storms, etc. On the other hand, cities and urban activities are major contributors to greenhouse gas emissions, an estimated 75% of the global CO_2 emissions arise in the cities according to the UNEP (UNEP, 2022). Thus, cities constitute a focal point. They have a great potential for action and results, by implementing emission reduction strategies, carbon drawdown programmes, or blue-green-grey sustainable infrastructure projects.

Biochar in urban tree planting

Following this logic, the benefits of developing green areas in the urban environment are well-known for the mental and physical health of the inhabitants (Bennett & Jones, 2018), the cultural essence of a city, supporting biodiversity (Filazzola et al., 2019), as well as aiding in CO_2 emissions reductions. However, like any development project, the process of building and planting trees in the urban environment comes with its own emissions. A study in the Helsinki area estimates that the newly planted trees need approximately 30 years before the initial emissions are offset and they start the net CO_2 sequestration (Riikonen et al., 2017). As a way to offset the initial emissions or to compensate, biochar could be mixed in the soil of urban trees. This has been identified as one benefit of using biochar in urban tree planting, in addition to other soil-related benefits.

The urban environment is rather harsh for plants, due to its higher rates of air and soil pollution, drought exposure, and soil compaction. In some cases, growing conditions for trees and other perennial plants are less than ideal. They suffer from reduced soil volumes, improper water filtration, and unreliable soil quality. Thus, adding biochar to granular topsoil can prevent excess settling and compaction, as well as provide a nutrient and water retention layer (Embrén, 2016). Literature suggests that between 5% - 20% of biochar should be added to the soil mix (ibid.).

In the City of Helsinki, there are approximately 1 000 large trees planted every year and between 4 000 and 10 000 forest seedlings in green areas around the city. There is evidence of growing demand to increase tree planting (Hämäläinen, 2020), however, that is highly dependent on available resources and space.

Biochar in urban roof gardens, rain beds, and green walls

Roof gardens and green walls have a long history of usage in the urban environment spanning thousands of years (Abass, et al., 2020). In each climate zone, the concept has been adapted accordingly, with varying degrees of popularity over the years. Green infrastructure is a powerful climate adaptation and mitigation tool in urban resilience plans, as described in Helsinki's climate change adaptation policies (City of Helsinki, 2019). Generally, vegetated roofs, walls, and rain beds are included under the umbrella term 'blue-green infrastructure' because their purpose is two-fold: as part of the stormwater management system, they retain water and help manage urban runoff levels; and as green areas, they help maintain the local biodiversity (Filazzola et al., 2019), and add to human health and well-being benefits.

In this report, we have chosen to focus mainly on green roofs because they present a higher growth potential in the Helsinki region (HSY, 2016). The benefits of developing green solutions for roofs are best represented by the three sustainability pillars. From the environmental standpoint, roof gardens have a cooling effect on the surroundings, thus, lowering the urban heat island effect. From the economic view, they act as insulators for buildings, lowering the heating/cooling needs and saving on energy costs. Lastly, they are aesthetically pleasing and act as a relaxing green area for people, covering the social benefits.

However, green roofs are part of the built environment, and they require careful planning and construction. The structure of a green roof contains several layers of substrate, including a waterproofing layer (most common a bitumen membrane), a drainage layer with a filter, sometimes combined with a rainwater storage tank, and the growing medium which should be light-weight and help with drainage (Setherton, 2022). Therefore, there is an added permanent load to any building and their structural integrity must be assessed in advance. Another impediment to green roofs, especially in the Nordic climate is represented by the repeated freezing/thawing cycles and the temperature variations. They could be detrimental to the waterproofing layer, increase maintenance needs, as well as harm any non-native plants (Andenæs, et al., 2018).

There are several studies in the past years indicating that biochar use in roof gardens improves soil quality, by increasing the porosity and the soil moisture, regulating the pH values, improving the nutrient and water holding capacity, and reducing the soil's bulk density (Cao, et al., 2014) – an important benefit because the same area could be covered by a thicker soil layer without adding weight to the structure. Additionally, there is evidence of increased microbial diversity in the soil due to increased levels of carbon and phosphorus from the added biochar (Chen, et al., 2021). There are ongoing studies into the characteristics of biochar suitable for green roofs due to its ability to affect the runoff quality and quantity, especially concerning nutrient leaching (Kuoppamäkia, et al., 2015).

Depending on the vegetation type from grass to small trees, the growing medium can vary between 25 – 1000 mm. Most roof gardens in the urban environment should be as self-sufficient as possible and extensive planting, especially in the Nordic climate would not be sustainable in the long term. Literature indicates that 30% biochar mix by volume in the substrate increases the plant-available water, while 40% biochar mix significantly increases the water holding capacity, therefore the optimal choice for stormwater retention (Cao, et al., 2014). Thus, in this report, a substrate of 100 mm of 30 % biochar mix has been assumed (Table 1), to support small to medium local vegetation.

Biochar in sports fields

A green and vibrant city, Helsinki is covered by 40% green spaces out of its total land area (City of Helsinki, 2013). Half of that area is forested, and approximately 200 ha are devoted to neighbourhood sports fields (relaxing and entertaining spots for the inhabitants rather than highly maintained professional pitches), skating rinks, golf courses, football/tennis/baseball pitches etc. (Lipas.fi, 2021).

These are high traffic areas, which require certain soil conditions in order to maintain their intended uses over time. Some pitches may also require more careful planning of the substrate to allow for proper water drainage and limit soil movements. Under the natural grass turf, it is ideal to include a highly permeable rootzone layer (approximately 300 mm) and a coarse subbase (approximately 100 mm) (Estimation QS, n.d.). Mixing biochar with the sand in the rootzone layer can lead to faster drainage while improving the water retention and availability for the turf above. Similarly, biochar in the coarse subgrade layer aids in water drainage, lessening the reliance on drainpipes (Major, 2010). Finally, there may be a financial and/or aesthetic reason for utilising biochar in sports pitches (both professional turfs and neighbourhood fields) due to prolonged serviceability. The grass turf has access to the necessary nutrients and water to endure longer into the season with lower maintenance/ fertilizer needs.

The urban environment is constantly developing and changing; thus, the construction industry is an important pillar of any city. The total turnover in Finland for the broad construction sector in 2020 has been EUR 70.8 billion, an increase of 66.8% since 2010 (European Commission, 2021). Considerable growth has been reported for the southern capital region, with plans to develop the industry while reducing GHG emissions and implementing social changes (affordable housing, reducing homelessness, etc.) (ibid.).

Biochar in construction (road and railway embankments, structural soils, bioswales)

The IPCC recognizes biochar as a viable option for carbon sequestration, indicating that the stored carbon can remain in the soil between decades and centuries depending on the soil's type and management and the biochar's production temperature (IPCC, 2018). Thus, one option to advance Helsinki's climate action plan and develop its carbon-storing capacity would be to include biochar in new soils. New soils produced in the Helsinki Metropolitan area would include approximately 10% mix of biochar by volume and their usage would remain unchanged. In this scenario, the benefits of biochar in soil applications take a secondary place, being replaced by the carbon sequestration function.

For example, one possible storage for the biochar, suggested by the International Biochar Initiative is in the substrate soil layer under buildings, roads, etc. (Major, 2010). Most of the time, before an infrastructure or urban development project can commence, there are extensive earthworks on the site. One of the first steps, after the geotechnical investigations of the site, is removing the top layer of soil because of its organic content, poor engineering qualities, contamination and so forth. A layer of biochar or biochar/soil mix in these conditions could represent a significant use in the urban environment.

However useful as a carbon-storing solution, it would be desirable for biochar to serve other purposes in its application to account for the investment. In the construction industry, as an amendment to new soils, biochar could also be useful to improve soil engineering properties. The applications range from road and railway embankments, landfill cover, bioengineered slopes, etc. The geotechnical properties of the soil in these structures require careful design, and the long-term effect of biochar application has not been studied as thoroughly as its agricultural uses (Hussaina et al., 2019).

Biochar in landscaping (meadows)

Inside the city borders, Helsinki has large areas classified as recreational meadows, traditionally cultivated agricultural lands, and pastures - approximately 420 ha. The areas are maintained by the Urban Space and Landscape planning authority together with city residents and any other relevant associations. They are mainly used to grow domestic grains, sunflowers, wildflowers and peas, for the residents' own use or for animal grazing (City of Helsinki, 2019). Their purposes are mainly to serve as a connection to nature for the residents, and maintain traditional agricultural practices alive, as some areas (such as the Haltiala farm (City of Helsinki, 2021)) are part of Finland's cultural heritage.

As discussed in chapter 3.1, biochar soil applications in this setting would enhance the microbial biodiversity of the soil, increase the water holding capacity, retains minerals in plant available form, and thus, aid in maintaining plant diversity and health. The diversity of species is especially relevant in meadows and unregulated fields to maintain their character and usefulness. If one species becomes predominant (as is the tendency with time), the biodiversity resilience of the area is lowered (Nyblom, et al., 2010). One species is vulnerable to disease and extreme weather phenomena, and it risks destruction. Many species react differently and can endure.

The meadows and agricultural lands in the City of Helsinki represent a significant biochar application opportunity. They are able to generate large biochar volume demands estimated in Table 1, especially with a demand for repeated applications over the years.

4.2 Biochar in filters and blue-green-grey infrastructure

The blue-green-grey infrastructure shows a growing trend in the urban environment, advancing the climate change mitigation and adaptation plans (City of Helsinki, 2019). Blending the built and natural environments is a challenging task, considering the already existing infrastructure and the substantial investments necessary to renew and innovate said infrastructure. Biochar could prove a useful tool in certain sectors such as water and wastewater treatment and stormwater management due to its ability to act as a filter. There are advancements in both sectors and already several projects are being tested in the Greater Helsinki area for stormwater filtration basins using biochar.

Biochar in wastewater treatment

Studies suggest that biochar could be used at different stages of the wastewater treatment process (summary of the applications – Figure 1 (Pokharel et al., 2020)) to improve the efficiency of activated sludge treatment and nutrient recovery. The innovation factor for this application is the cascading effect of biochar use. Biochar added during the secondary treatment in the aeration tank improves the efficiency of the process (increasing the settling ability of the sludge by adsorption of inhibitors and toxic compounds). While in the tertiary treatment, biochar adsorbs nutrients (nitrogen and phosphorus in particular). These improvements enhance the quality of the resulting biosolids which in turn, could be used to produce nutrient-enriched biochar.

In itself, this biochar application does not predict substantial volume uses. However, the interest in Helsinki for sludge derived biochar (sludge-char) has been growing recently, due to HSY's test pilot facility (HSY, 2022). Accordingly, there is an opportunity for biochar use in the wastewater treatment sector to increase the efficiency and streamline the process.

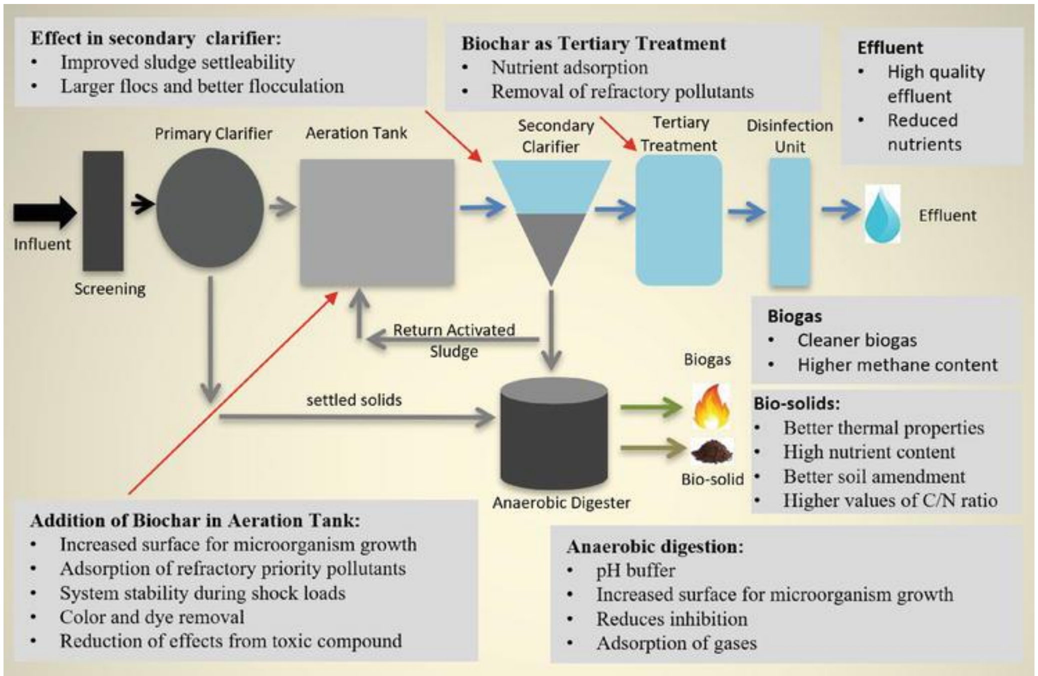


Figure 4: *Schematic view of the effects of biochar use in the wastewater treatment process (Pokharel et al., 2020)*

Biochar in stormwater retention basins

In 2018, the City of Helsinki developed an Integrated Stormwater Management Program (City of Helsinki, 2018), as part of the climate change adaptation plans. Based on the continuous growth of the city and the evolving legislation, the reasoning of the plan is twofold. It first takes into account the growth of the urban sphere, the expansion of the inner city and the development of smaller centres, thus, leading to a denser city with more impermeable surfaces. Secondly, it considers the forecasted effects of climate change consisting of more extreme weather events (more rainfall in the winter, dry periods followed by heavy rainfall during the summer period). Thus, the stormwater flow rates increase, potentially overwhelming the combined sewer system, endangering the health of the residents, and creating the possibility of flash floods.

The management program also draws special attention to utilizing stormwater as a resource in the urban environment, rather than an inconvenience. However, that implies that the quality of the water becomes a concern. Suspended solids binding nutrients, heavy metals, and hazardous substances from industrial activity that might reach the waterways are especially harmful (Peltosaari et al., 2020). Green solutions for infrastructure are preferable and indeed, they are an integral part of Helsinki's urban planning strategy (iWater, 2016). Thus, Helsinki has already started to implement small and medium scale sustainable stormwater filtration solutions.

1. Otsolahti is a shallow bay in Tapiola, Espoo which has suffered from eutrophication over the years, affecting its recreational use (Itämerihaaste, 2019). The filtration solution has been implemented next to the bay in order to reduce the stormwater load and prepare for changes in the area. The basin is approximately 1000m^2 with the biofiltration (composed of sand and biochar) completely underground due to space restrictions.

2. Another biofiltration system (700m^2), located in Maunulanpuito park, filters stormwater from an industrial area through a sedimentation basin with the bottom lined with biochar, crushed aggregate, and vegetation to bind nutrients and heavy metals (Peltosaari et al., 2020). This solution filters the water before reaching a brook with significant flora and fauna.

3. Part of the stormwater flow from Pasila is filtered through an underground stream system and a sedimentation basin with biochar filtration before it enters the wider system in Töölönlahti bay.

These biofiltration systems are proof of the city's commitment to investing in sustainable solutions. They also represent significant opportunities for biochar application, in light of future developments in the area (an estimated 10 new stormwater filtration basins per year).

4.3 Other special uses of biochar

Safely storing biochar

Depending on the supply and demand relationship in the Greater Helsinki area, there may be a need to deposit biochar in large quantities until it can be used profitably. As a fast-developing sector, the biochar production capacity and its applications may not be in synch yet, depending on the market. The UN classifies biochar as a Class 4 Dangerous Good, regarding storage and transport (UN, 2005). It represents a fire hazard in confined spaces because its particles in combination with air can form explosive mixtures. Freshly produced biochar rapidly sorbs oxygen and moisture (an exothermic process), potentially leading to high temperatures and self-ignition (Major, 2010). Several methods of prevention are suggested by the International Biochar Initiative: adding certain chemicals to decrease flammability (e.g., boric acid, ferrous sulphate), storing and transporting biochar in an oxygen-free environment (ibid.)

Biochar in construction materials

Integrating biochar in construction materials can have numerous benefits, both from an environmental standpoint as well as from an engineering perspective. The construction industry in Finland seeks to regulate and reduce their CO_2 emissions (Kuittinen & Häkkinen, 2020), thus, biochar as a carbon sequestration method can help minimize the emissions. On the other hand, biochar has a low thermal conductivity, and it has high water holding capacity, meaning that it can be used to insulate buildings and regulate humidity (Schmidt et al., 2014). It can be used both on the inside and outside walls of a building, in a cement mix, additive to bricks or plaster, or with clay.

The effort to develop carbon negative concrete has been growing rapidly in recent years. One concrete example comes from Norway, where Snøhetta (together with Skanska and several other partners) have developed and tested *biocrete* – a mix of concrete and biochar (obtained from construction wood waste) (Snøhetta, 2022). Their tests and projects are ongoing, but this is an example of a large investment in biochar and its use in construction materials.

Biochar awareness

Raising awareness and presenting biochar use benefits to a wider public could advance the whole sector. This application possibility is not likely to require large volumes of biochar, thus it has not been explored in detail in this report. However, more exposure could lead to lower prices on the Finnish market and wider applications of biochar in the urban environment. Therefore, there are several areas that could be shortly proposed in this report: art installations made of biochar powder as part of landscaping projects, sculptures, everyday household items, demonstrations, and workshops for city inhabitants, etc.

5 Conclusion

The report presents the results of collecting information about the feedstock available for biochar production in the Greater Helsinki area. It also gives an overview of biochar applications in the context of the urban environment. There are numerous other feedstock flows and prospective applications, however, the ones presented in this report have been deemed to be the most relevant, scalable, and accessible (publicly available data). The figures should be regarded as estimates, and they are subject to changes based on ongoing projects and future development of the market.

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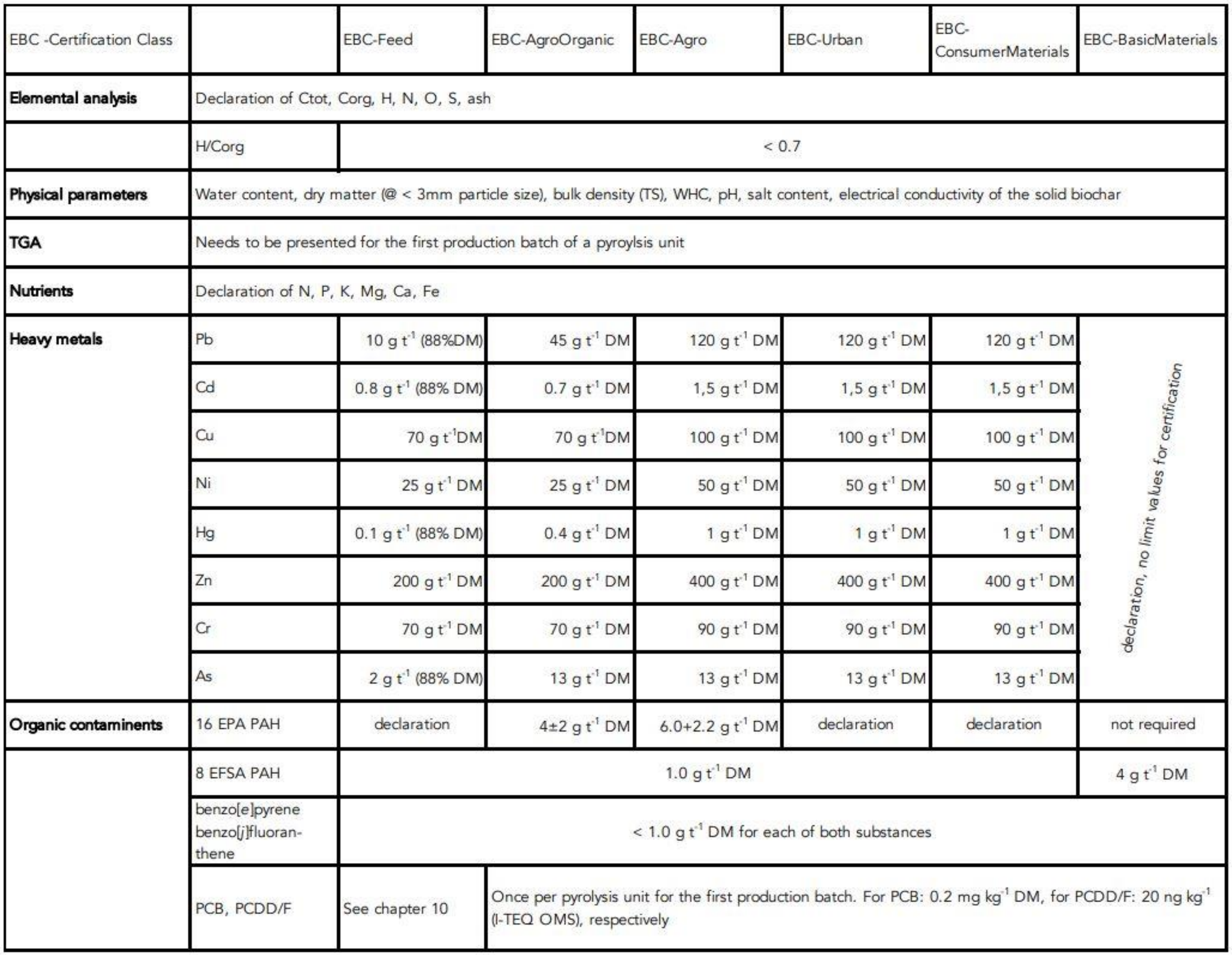
Appendix

Table A: *European Biochar Certification class and the relevant limit values analysis (EBC, 2022) referred in Table 1*



EBC -Certification Class		EBC-Feed	EBC-AgroOrganic	EBC-Agro	EBC-Urban	EBC-ConsumerMaterials	EBC-BasicMaterials
Elemental analysis	Declaration of Ctot, Corg, H, N, O, S, ash						
	H/Corg	< 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	Needs to be presented for the first production batch of a pyroylsis unit						
Nutrients	Declaration of N, P, K, Mg, Ca, Fe						
Heavy metals	Pb	10 g t^{-1} (88%DM)	45 g t^{-1} DM	120 g t^{-1} DM	120 g t^{-1} DM	120 g t^{-1} DM	*declaration, no limit values for certification*
	Cd	0.8 g t^{-1} (88% DM)	0.7 g t^{-1} DM	1,5 g t^{-1} DM	1,5 g t^{-1} DM	1,5 g t^{-1} DM	
	Cu	70 g t^{-1}DM	70 g t^{-1}DM	100 g t^{-1} DM	100 g t^{-1} DM	100 g t^{-1} DM	
	Ni	25 g t^{-1} DM	25 g t^{-1} DM	50 g t^{-1} DM	50 g t^{-1} DM	50 g t^{-1} DM	
	Hg	0.1 g t^{-1} (88% DM)	0.4 g t^{-1} DM	1 g t^{-1} DM	1 g t^{-1} DM	1 g t^{-1} DM	
	Zn	200 g t^{-1} DM	200 g t^{-1} DM	400 g t^{-1} DM	400 g t^{-1} DM	400 g t^{-1} DM	
	Cr	70 g t^{-1} DM	70 g t^{-1} DM	90 g t^{-1} DM	90 g t^{-1} DM	90 g t^{-1} DM	
	As	2 g t^{-1} (88% DM)	13 g t^{-1} DM	13 g t^{-1} DM	13 g t^{-1} DM	13 g t^{-1} DM	
Organic contaminents	16 EPA PAH	declaration	4±2 g t^{-1} DM	6.0+2.2 g t^{-1} DM	declaration	declaration	not required
	8 EFSA PAH	1.0 g t^{-1} DM					4 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	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				