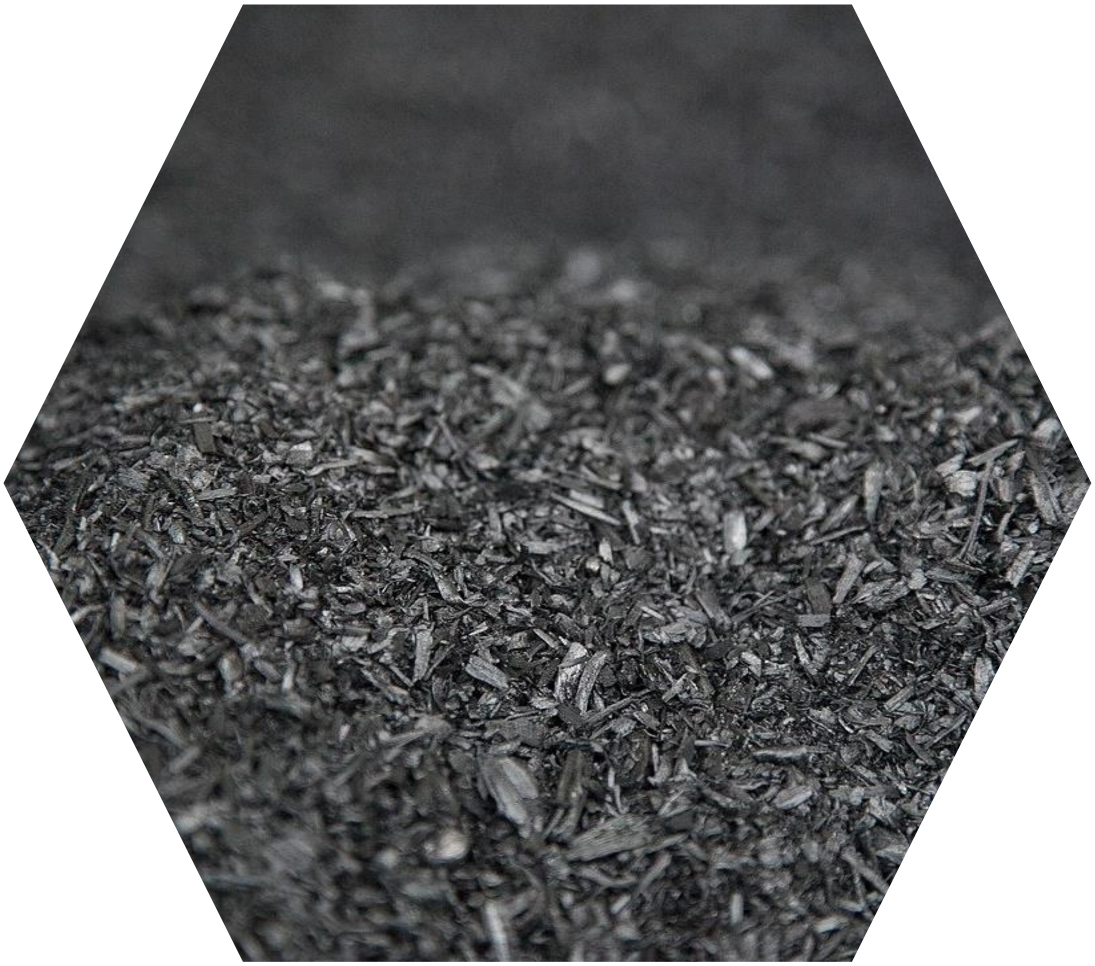
Evaluation of Potential Use Cases of Biochar in Åland
A Preliminary Feasibility Study



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Abstract

A preliminary feasibility study was conducted on the potential use cases of biochar in Åland. Biochar is a carbon-rich solid produced via a high-temperature process called pyrolysis. The research consisted of evaluating existing literature, case studies and field projects on biochar as well as conducting interviews and local field visits. The results of the study indicate that the following are the best potential use cases of biochar on Åland: Feed Additive, Soil Amendment, Nutrient Recovery, and Carbon Sequestration. The report details the motivation behind these results and provides some general recommendations on how the use cases should be implemented. However, further investigations are required to better understand the mechanisms and interactions of biochar as well as the economic feasibility of its implementation on Åland in order to obtain optimum benefits from a technoeconomic perspective.

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1. Background Information

1.1 Introduction to Biochar

Biochar is a carbon-rich solid produced via a process called pyrolysis in which organic matter decomposes at high temperature in a low-to-no oxygen environment. Biochar has numerous properties that make it suitable for a myriad of applications ranging from skin cream to semiconductor material (Schmidt & Wilson, 2014). These properties include a highly porous microstructure, high specific surface area, high cation exchange capacity, neutral-to-alkaline pH range and high fixed carbon content (Gwenzi, Chaukura, Noubactep, & Mukome, 2017). However, as biochar properties are highly dependent upon the type of feedstock and pyrolysis conditions used, and these parameters are highly variable, many different types of biochar can be produced. Consequently, the results obtained from studies with biochar are also highly variable and sometimes contradictory.

Most studies conducted with biochar have been focused on its utilization as a soil amendment. Through this application, biochar has demonstrated its potential to decrease the leaching of nutrients such as phosphate, nitrate and ammonium to local water bodies (Hale et al, 2013). Therefore, biochar can prevent or minimize further eutrophication in water bodies through its application on the farm. Researchers have also demonstrated the potential of biochar to be used in water, storm water and wastewater treatment due to its high surface area and presence of certain functional groups. Biochar has been used as an animal feed additive for many centuries due to its health and environmental benefits (Schmidt et al., 2019).

1.2 General Overview of Mechanisms of Biochar

The porous structure of biochar yields many advantages. The pores can physically trap nutrients and contaminant particles. Furthermore, the high surface area of biochar (which can reach over 500 m^2/g) contains many different functional groups that make it possible for the biochar to participate in a variety of chemical interactions. These chemical interactions are primarily characterized by biochar's cation and anion exchange capacities, CEC and AEC, respectively (Laird & Rogovska, 2015).

The cation exchange capacity (CEC) of biochar represents the biochar's capability to attract cations. Biochar CEC is developed through oxidation reactions that create acidic negatively-charged functional groups on the biochar surface (Ippolito, 2015). Such functional groups can then play key roles in attracting positively charged ions in the soil or water, such as ammonium (NH_4^+) (Laird & Rogovska, 2015). As a result, it can be concluded that biochar aging increases nutrient retention capacity by increasing the density of surface functional groups and the adsorption of organic molecules, which contain nutrients.

The anion exchange capacity (AEC) of biochar corresponds to its ability to hold exchangeable anions. Relevant anions include nitrate (NO_3^-) and phosphate (PO_4^{3-}). Nitrate is retained by biochar primarily through electrostatic forces while phosphate is retained via ligand exchange reactions with the biochar surface functional groups (see Fig. 1) (Laird & Rogovska, 2015).

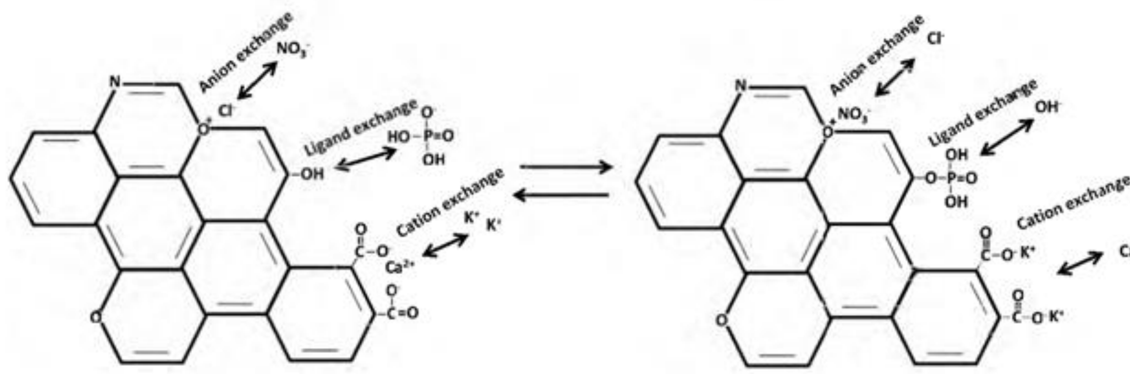

Figure 1. Examples of exchange reactions that can take place on biochar surfaces (Laird & Rogovska, 2015).

However, as biochar contains large amounts of phenolic and carboxylic groups, the biochar itself is typically highly anionic. As a result, it has an excellent ability to attract cations, but limited ability to adsorb anions such as phosphate. Therefore, the biochar may need to be further modified to achieve the desired levels of nutrient recovery. For example, the technique of doping can be used to saturate the biochar with metal cations to enhance its anion adsorption properties. A number of cations have been investigated for doping purposes, with Mg^{2+} and Ca^{2+} being the cheapest and most suitable options found thus far. (Novais, Zenero, Barreto, Montes, & Cerri, 2018).

1.3 Aim and Objectives

The primary objective of this feasibility study was to determine the best potential use cases of biochar on Åland. These use cases were evaluated based on their ability to create circularity and connect people. A secondary objective was to find ways biochar could be used to address the following challenges that Åland is currently facing:

I. Eutrophication

Eutrophication occurs in water bodies that contain an excess of nutrients. It is characterized primarily by algal blooms, which rapidly consume oxygen in the water and consequently lead to the disruption of local ecosystems and death of local fauna. The sources of the excess nutrients vary depending on the location of the water body, but typically include agricultural, groundwater and storm water runoff, fertilizers applied during crop production, and landfill leachate. As eutrophication is a growing problem in the Åland archipelago, it is important to research and implement inexpensive and effective nutrient recovery and water contaminant removal methods.

II. Volatile Climate Conditions

Global climate change has increased extreme hydrological events, which create volatile conditions and uncertainty for agricultural producers. Therefore, it is important to find ways to improve soil resilience to combat the effects of such extreme conditions.

III. Greenhouse Gas Emissions

The United Nations (UN) has committed to reducing climate impact by lowering greenhouse gas emissions in order to keep the global temperature increase from rising above 2°C (Xylia et al., 2019). In 2015, Åland emitted a total of 752,920 tonnes of CO2 equivalents. Therefore, it is important to find ways in which Åland can contribute to attaining the UN goal.

1.4 Scope of Work

A preliminary feasibility study was conducted. Therefore, the scope of work included an evaluation of literature, case studies and existing field projects on biochar. The scope also included a very general evaluation of the technical implementation of biochar pilot studies. However, specifics such as application amounts, equipment design and scalability and creation of sampling plans was not included in this study. Furthermore, the environmental benefits of biochar were only investigated from a general perspective, for example in terms of carbon sequestration. Economic evaluation was not performed. Further evaluation and the conduction of a life cycle assessment is suggested for future work.

It is also important to note that biochar was the focus of the work. The uses of other products of pyrolysis such as gas and oil was not investigated in-depth. However, it is important to consider these products from a circular economy perspective as these products yield added value to the construction of a biochar plant on Åland.

1.5 Current Situation in Åland

In order to determine the best potential use cases for biochar in Åland it was necessary to evaluate the availability of resources and current conditions in Åland. Sections 1.4.1 through 1.4.7 detail the current situation.

1.5.1 Weather

Åland's weather conditions are quite volatile, with mild summers and cold winters. Åland's annual precipitation of about 600 mm is about the same as in the eastern parts of Sweden. However, precipitation can vary greatly from year to year as demonstrated by Table 1, which compares the year 2019 to the year 2018, when Åland experienced a drought.

Table 1. 2018 and 2019 Weather Data (adapted from ÅLANDS HUSHÅLLNINGSSÄLLSKAP, 2020).

	Average temp. ° C (2019)	Average temp. ° C (2018)	Precipitation (mm) (2019)	Precipitation (mm) (2018)
January	-1.10	-0.1	67.50	65.5
February	1.1	-4.6	48.3	21.2
March	1.0	-3.3	66.0	28.7
April	5.3	4.10	15.4	33.3
May	8.9	12.30	41.9	6.30
June	14.9	13.60	23.0	23.80
July	16.1	19.30	47.2	9.70
August	17.2	17.70	82.6	49.40
September	12.5	13.30	129.8	65.80
October	6.7	7.9	77.3	37.7
November	4.1	4.9	114.3	26.7
December	3.2	1.1	101.5	71.8

1.5.2 Current Soil Conditions

The topography of Åland is quite interesting due to the influence of retreating glaciers from the most recent ice age in the island's formation. As a result, soil type can vary from fine sand to clay. In general the conditions in Table 2 describe Åland soil, though exceptions exist.

Table 2. General Soil conditions in Åland (revised from J. Regårdh, personal communication, June 14, 2020).

Parameter	**Status on Åland**
pH	Generally <7 (acidic)
Organic Matter Content	Good
Nutrients	Low in K and Mg
Micronutrients	Low in Mn

The soil is currently treated with chemical fertilizers manufactured by Yara and manure and/or slurry from local farms.

1.5.3 Water conditions

As Åland is part of the Baltic Sea Region and is heavily dependent on the agricultural industry, the Åland water bodies are highly susceptible to eutrophication.

Data on nutrient levels for Brantböle träsk and Bränneriträsk is presented in Table 3. From this data it can be concluded that nitrogen is primarily present in the form of NH_4^+ and NO_2^{3+} while phosphorus is primarily present in the form of PO_4^-.

Table 3. Nutrient concentrations in water samples taken from Brantböle träsk and Bränneriträsk between 2014-2018 (Revised from Cederberg, 2020).

		Phosphorus		Nitrogen					
Lake	Date	Tot.P µg/l	PO4-P µg/l (<5=5)	Tot.N µg/l	NH4-N µg/l	NH4-N µg/l (<10=10)	NO2+3-N µg/l	NO2+3-N µg/l (<5=5)	Alkalinity mmol/l
Brantsböle träsk	1/16/14	33	25	1900	280	280	960	960	2.3
	1/28/15	36	26	2410	400	400	1300	1300	2.4
	1/20/16	19	5	2360			1100	1100	3
	1/23/17	26	<5	2920	630	630	1100	1100	3.2
	1/22/18	40	18	1920	650	650	640	640	3.3
Bränneriträsk	1/16/14	57	32	1910	770	770	120	120	1.4
	1/28/15	59	23	2800	1100	1100	170	170	1.6
	1/20/16	115	63	4180			89	89	1.7
	1/23/17	358	88	5980	18	18	12	12	1.4
	1/22/18	119	20	2284	380	380	22	22	1.4

1.5.4. Greenhouse Gas Emissions

Table 4 below details the Greenhouse Gas (GHG) Emissions on Åland in 2015.

Table 4. Gaseous Air Emissions on Åland in 2015 (in tonnes) (Ålands statistik, ÅSUB, 2019).

Industry, institution	Fossil carbon dioxide (CO_2)	Biogen carbon dioxide (CO_2-bio)	Nitrous oxide (N_2O)	Methane (CH_4)	Sulfur dioxide (SO_2)	Nitrogen dioxide (Laughing gas, NO_2)	Carbon monoxide (CO)	Carbon dioxide-equivalents
Field Cultivation	6 172	3 159	60	497	3	25	77	36 448
Animal husbandry	3 830	1 960	37	308	2	16	48	22 617
horticulture	4 583	2 346	44	369	3	19	57	27 066
Forestry and hunting	406	9	0	0	0	1	9	410
Fishing and aquaculture	7 223	287	0	0	-	121	19	7 298
Food	1 148	222	0	0	4	3	2	1 161
Other industry	6 812	2 833	4	0	16	18	15	7 892
Water and electricity	6 731	56 910	4	278	30	71	83	14 957
construction	6 213	494	0	0	0	38	36	6 262
Trade	541	148	0	0	0	2	2	548
Hotel and rest.	54	20	1	0	0	0	0	239
Other transport	38 463	2 648	1	5	7	161	71	38 898
passenger Shipping	393 453	31 627	10	56	143	4 628	3 269	397 812
freight Shipping	130 188	10 013	3	16	96	1 987	447	131 576
Business Services	5,366	1 083	0	1	1	22	79	5 422
Public administration	3 868	592	0	0	1	19	58	3 911
Training	271	86	0	0	0	1	2	275
Healthcare	892	235	0	0	0	3	5	903
Other service	1 758	383	0	0	0	7	7	1 775
Household	45 724	42 577	2	50	13	137	1 602	47 450
Overall	**663 694**	**157 634**	**167**	**1 582**	**320**	**7 277**	**5 886**	**752 920**

1.5.5 Agriculture

The Åland economy is largely based on agriculture. The use of arable land and agricultural production in Åland in 2019 are depicted in Fig. 2 and 3, respectively.

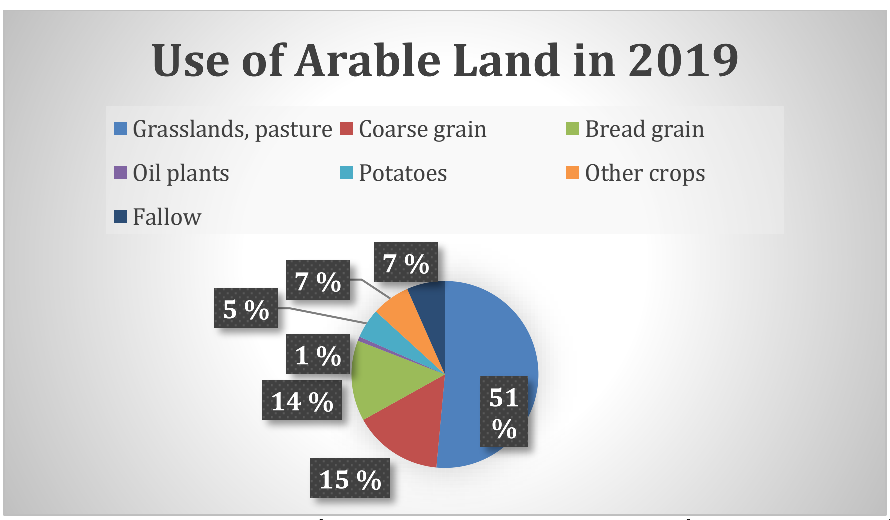

Figure 2. Use of arable land in Åland in 2019 (adapted from Ålands statistik, ÅSUB, 2019).

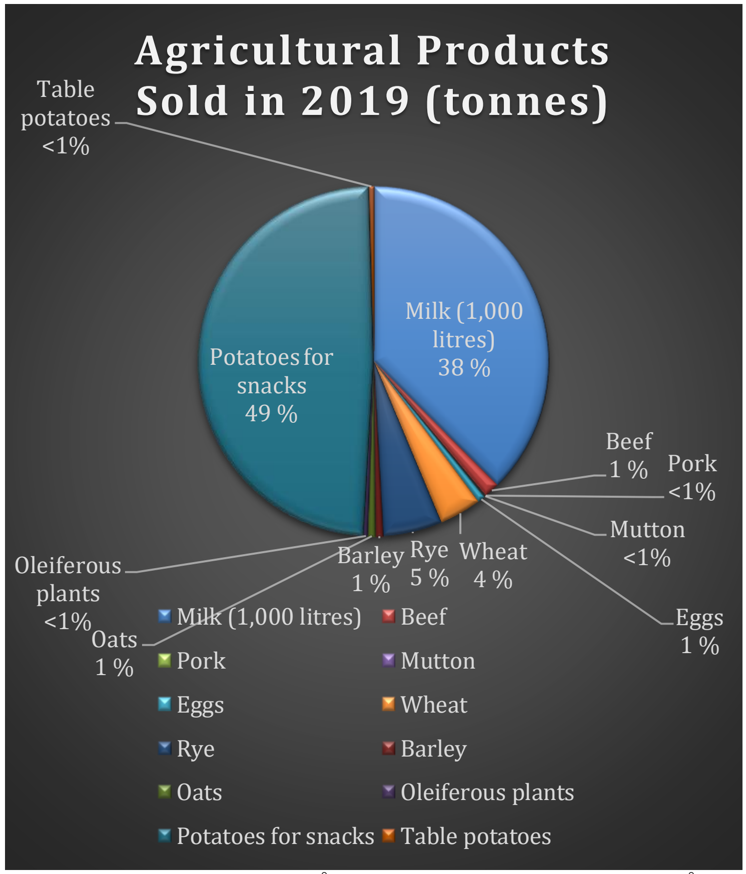

Figure 3. Agricultural production in Åland in 2019 (adapted from Ålands statistik, ÅSUB, 2019).

1.5.6 Fishing

Statistics from the fishing industry are presented in Table 5.

Table 5. Åland Fishing Industry (Ålands statistik, ÅSUB, 2019).

Fish culture	2018
Number of firms	6
Number of units	27
Fish sold, tonnes	5,827
Value of production, 1 000 EUR[1)]	37,117
Number of employed persons[1)]	96

1.5.7 Forestry

The Åland economy is also reliant upon local forestry. Furthermore, the availability of woody biomass is crucial for the production of biochar on the island in the future. Therefore, the availability of wood types and their corresponding volumes in Åland was analyzed. As seen in Table 6, it is apparent that pine composes the largest portion of woody biomass, followed by spruce, birch and other deciduous trees.

Table 6. Wood volumes in Åland (Ålands statistik, ÅSUB, 2019).

Growth		Pine total	Pine logs	Pine pulpwood	Spruce total	Spruce logs	Spruce pulpwood	Birch total	Birch logs	Birch pulpwood	Other deciduous total	Other deciduous logs	Other deciduous pulpwood	All tree species
Brändö	1000 m3/a	164	21	130	36	8	25	81	2	59	177	4	117	459
Eckerö	1000 m3/a	478	83	372	208	66	126	146	11	110	66	5	45	898
Finström	1000 m3/a	485	88	375	232	80	136	163	14	124	95	7	62	975
Föglö	1000 m3/a	661	104	517	216	67	134	139	10	103	123	6	82	1139
Geta	1000 m3/a	274	44	214	91	29	56	60	5	45	36	2	24	461
Hammarland	1000 m3/a	596	107	460	259	85	156	177	14	134	81	5	54	1113
Jomala	1000 m3/a	554	100	428	249	82	149	177	15	135	96	7	64	1076
Kumlinge	1000 m3/a	286	25	232	35	8	25	74	2	53	131	3	86	527
Kökar	1000 m3/a	20	3	14	4	1	3	24	1	17	49	2	30	97
Lemland	1000 m3/a	531	96	410	218	69	133	183	15	138	95	7	64	1028
Lumparland	1000 m3/a	175	28	136	61	20	37	36	3	28	24	1	16	296
Mariehamn-Maarianhamina	1000 m3/a	22	3	17	9	3	5	8	1	6	7	1	4	45
Saltvik	1000 m3/a	550	90	429	196	64	117	127	10	96	74	5	49	947
Sottunga	1000 m3/a	53	8	41	14	4	9	17	1	12	26	1	17	109
Sund	1000 m3/a	463	77	361	178	60	105	108	9	81	65	4	43	813
Vårdö	1000 m3/a	369	56	290	109	33	68	67	5	50	52	3	35	598
Total		5681	933	4426	2115	679	1284	1587	118	1191	1197	63	792	10581
Annual growth volume	1000 m3/a	210			80			70			50			410
Sustainable harvesting volume	1000 m3/a	200	40	140	60	20	20	60		40				320

1.6 Key Stakeholders

The following people/companies/organizations have been identified as potential key stakeholders in the proposed biochar pilot studies:

1. **Carbofex**
   Finnish Biochar manufacturer and proposed supplier of biochar for pilot studies on Åland.
2. **Ålands Landskapsregering**
   The provincial government.
3. **Ålands Vatten**
   In charge of water treatment.
4. **Mariehamns Energi**
   Local energy company. Incorporation of gas and oil products into district heating system could be of interest.
5. **Ålands Fiskodlarförening**
   Local fish production.
6. **Raisioaqua**
   Suppliers of fish feed.
7. **Ålands SkogsIndustrier**
   Forestry Industry
8. **Ålands Hushållningssällskap**
   Serve as advisers to local farmers.
9. **Local Producers**
   Producers such as Orkla and ÅCA.
10. **Farmers**
    Crop, livestock and fish farmers. Can foster collaboration among them.
11. **Lab Analysts**
    Such as ÅMHM and Husö Biologiska.
12. **Citizens**
    The feasibility of such citizen engagement on Åland has been exemplified by previous projects such as Hungry for Saltvik and Kökar's selection into the Clean Energy for EU islands initiative.

2. Methodology

The research conducted can be divided into the following categories:

- Evaluation of case studies and available literature found in online databases
- Evaluation of ongoing field studies with biochar
- Interviews with potential stakeholders, biochar experts and coordinators of current field studies
- Field Visits
  - Two field visits with local farmers were conducted, one in Kökar and one in Hammarland.

3. Proposed Potential Use Cases

The results of the feasibility study indicate that the following are the best potential use cases of biochar in Åland:

- Feed Additive
- Soil Amendment
- Nutrient Recovery
- Carbon Sequestration

It is important to note that the use cases are not mutually exclusive, but rather in many cases overlapping, which is beneficial to attaining the objectives described in Section 1.2. However, for the purposes of this report, the use cases are individually detailed below.

3.1 Feed Additive

3.1.1 Introduction

This concept of using charcoal as a feed additive has been around for many centuries. According to Cato the Elder (234-149 BCE), a charcoal-containing concoction was recommended to sick oxen (Schmidt et al., 2019). Since then, numerous studies have been conducted to investigate the positive effects of biochar on livestock. A comprehensive table of studies and the observed results can be found in Appendix.

3.1.2 Benefits

The largest incentive for using biochar as a feed additive is that it yields immediate and measurable results. Substituting as little as 0.5-1 percent of the total feed with biochar has yielded immediate results (Schmidt et al., 2019).

The benefits of biochar as a feed additive are widespread and can be divided into the categories depicted in Table 7.

Table 7. Environmental, Health, Social and Economic Benefits of Biochar as a Feed Additive (Schmidt et al., 2019).

Environmental	**Health**	**Social**	**Economic**
• Decreased methane emissions from livestock	• Weight gain • Strengthened Immune System • Reduction of hoof diseases • Improved barn hygiene	• Fosters collaboration between farmers • Fewer citizen complaints about odor • Improved meat quality	• Increased profitability due to increased yields

Furthermore, biochar can be used as a feed additive for not only livestock, but also a variety of other animals such as fish, cats and dogs (Schmidt et al., 2019). As a result, this application could also be extended to the fish farming industry.

Using biochar as a feed additive for fish can yield increased weight gain, lower nitrogen excretions and improved water quality (see Table 8).

Table 8. Results of studies using biochar as a feed additive for fish (adapted from Schmidt et al., 2019).

Fish Type	**Daily Biochar intake (% of dry mass fed)**	**Weight Increase (%)**
Flounder	0.5	18
Flounder	1.5	11
Striped Catfish	1	36
Striped Catfish	1	44
Striped Catfish	2	27

3.1.3 Implementation in Åland

It is recommended that the incorporation of biochar as a feed first be implemented for cows as they compose the second largest portion of agricultural production on Åland (see Fig. 3). Furthermore, this has been the most common practice implemented in areas such as Germany, Switzerland and Australia.

Suggested Recipe for Cattle:

- 100-300 g/cow/day
- Interval Diet
    - 3 weeks on
    - 1 week off

The interval diet is recommended as a precaution as the full effects and interactions of biochar are still unknown (Schmidt et al., 2019).

It is recommended that the manure of the cows fed with biochar be sold as a soil amendment to crop farmers on Åland. This not only encourages circularity and collaboration among farmers, but also yields additional benefits to the soil (see Section 3.2.3).

Ideally, the study should be conducted with at least 3-4 crop and dairy farmer pairs. It is recommended that the pairs be spaced out across the Åland mainland and archipelago. Kökar, for example, would be an ideal location to have one of the pairs in the study. It is recommended that the study be initiated during late winter to early spring time as manure spreading is typically conducted in the spring. Therefore, initiating the biochar feeding a few months before manure spreading will ensure that the manure being spread is charged with biochar.

Furthermore, investigations into the use of biochar as a feed additive in fish farming should be continued as well. In particular, Raisioaqua, the primary feed supplier to Åland Fish Farms could be a potential collaborator in trials with biochar supplementation in fish feed. However, further studies on biochar interactions in fish digestive systems need to be conducted prior to the discussion of such a collaboration.

3.2 Soil Amendment

3.2.1 Introduction

Much like using biochar as a feed additive, the concept of using biochar as a soil amendment has also been around for many centuries. Inhabitants of the Amazon Basin used biochar to produce Terra Preta soils, which to this day remain more fertile than soils in surrounding areas (Lehmann, 2015).

Today, as the global population size continues to grow and food scarcity and land availability become more and more prevalent issues, it is of the utmost importance to find ways to increase crop yields and soil fertility. Biochar is one such potential solution.

In their book *Biochar for Environmental Management*, Johannes Lehmann and Stephen Joseph provide a holistic overview of biochar from technical, economic and social perspectives (Lehmann, 2015). They detail the many aspects of biochar in soil amendment applications, including its effects and interactions.

Biochar can undergo many different physical and chemical changes once placed in the soil. The physical processes consist of fragmentation and heteroaggregation. The chemical processes include changes in oxidation state, oxygen and carbon content, pH, CEC and adsorption of natural organic matter. However, at this point in time, a full understanding of all of the mechanisms and interactions of biochar in soil has not been developed. (Lehmann, 2015)

3.2.2 Properties that influence biochar as a soil amendment

Studies have shown that the following properties can influence biochar's success as a soil amendment. However, this is not a comprehensive list.

Feedstock Used

As previously mentioned, the ability to produce biochar from numerous different feedstocks is one factor that contributes to biochar's versatility. This is no exception in the field of biochar as a soil amendment. According to Glaser and Lehr, the direct application of biochar from woody feedstock had no effect on available phosphorus levels in the soil. On the other hand, biochars produced from feedstock that was rich in phosphorus (P) also yielded higher amounts of plant-available P in soils. (Glaser & Lehr, 2019).

Soil pH

The pH of the soil influences the type of biochar that should be used. In general, alkaline biochars benefit acidic soils while acidic biochars benefit alkaline soils (Glaser & Lehr, 2019). Most of the studies that have been conducted in the field of soil amendment have been carried out on weathered, acidic, tropical soils that are low in organic matter and have low cation exchange capacities (Chathurika et al., 2016). This is important to consider in the context of Åland, where although the soils are acidic, they are generally already high in organic matter content.

Amount of Biochar Spread

Biochar application amounts ranging from less than 10 tonnes per hectare (ha) to over 120 tonnes per ha have been studied. Glaser and Lehr recommend using amounts above 10 tonnes per ha, for example, to improve P availability. However, plant biomass decreased when biochar was applied above 60 tonnes per ha. (Glaser & Lehr, 2019).

3.2.3 Benefits

The positive effects of biochar as a soil amendment are summarized in Fig. 4 below.

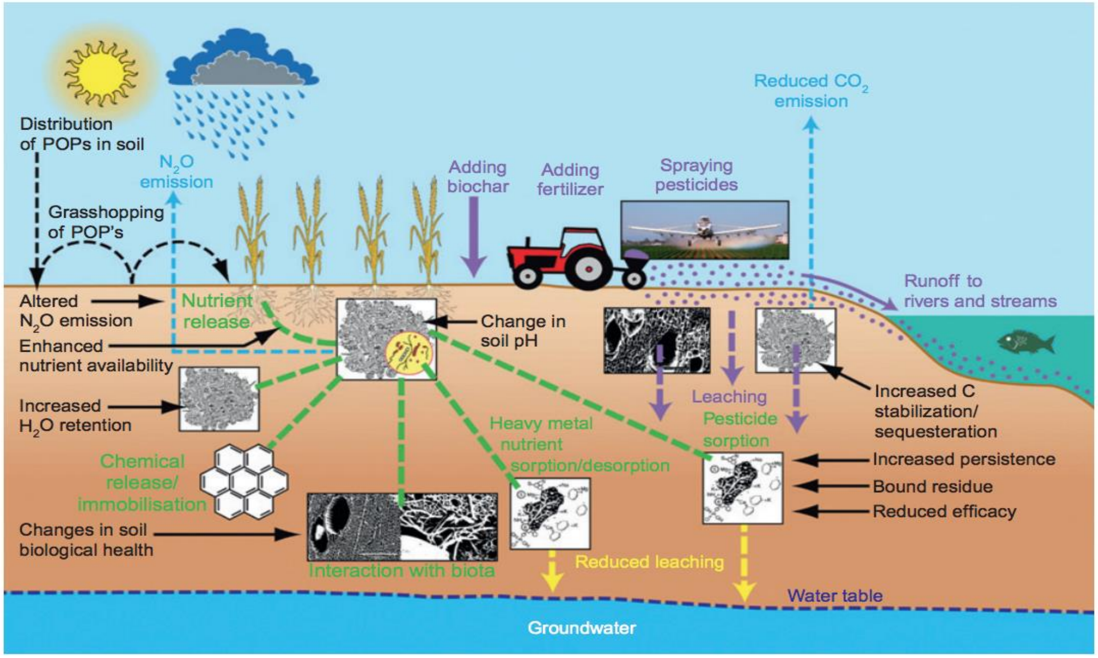

Figure 4. Effects of Biochar as a soil amendment compared to traditional soil amendments (Kookana et al., 2011).

Nutrient Availability

Because biochar usually contains P in relatively larger concentrations compared with the soil, its addition can directly release soluble P and increase available P concentration in amended soils. However, reported effects of biochar have shown variability. In some cases, negative effects have been observed, particularly short-term effects, such as reduced bioavailability of nutrients such as nitrogen and phosphorus. (Chathurika et al., 2016)

Glaser and Lehr used meta-analysis to draw conclusions on biochar effects on phosphorus availability in agricultural soils by comparing 25 published articles. They utilized only studies that used unamended soil as a control and where biochar was fully incorporated into the soil rather than merely spread on the soil surface. Studies included in this meta-analysis ranged from incubation studies of two days up to field studies of five years. (Glaser & Lehr, 2019).

They found that the addition of biochar to agricultural soil increased P availability by a factor of approximately 4.6, regardless of the type of feedstock used (Glaser & Lehr, 2019). The best results were yielded with the following conditions (Glaser & Lehr, 2019):

- biochar application amounts above 10 tonnes per ha
- biochar produced at temperatures less than 600°C significantly
- Application to acid (pH<6.5) and neutral soils (pH 6.5–7.5)

Taken together, this meta-analysis shows that biochar significantly enhances plant-available P in soils amended with biochar for at least five years. For wood-derived biochar, no effect on P bioavailability could be observed and additionally, the level of variety for wood biochar is very small. No significant change of biochar response over time has been observed. Please see Appendix for the studies that were evaluated.

Nutrient Leaching
The increase in nutrient availability to plants is closely tied to an increase in nutrient retention and consequently decrease in nutrient leaching.

The degree of leaching of nutrients from any source is determined by the nutrient source's interaction with the soil. As previously mentioned, biochar's high surface area and porosity yield interactions with soil, such as adsorption, that minimize nutrient leaching. This phenomenon has been observed as early as 1847, when it was recorded that charcoal 'sorbs and condenses the nutritive gases within its pores, to the amount of from 20 to over 80 times its own bulk '. Since then, numerous studies have confirmed this phenomenon (see Appendix). (Lehmann, 2015)

Water Retention
Wang et al, 2019 investigated the impact of biochar on water retention properties in agricultural soils of California in column, lab and field studies. The studies were conducted with sandy and clayey soils, the same soil types that are present on Åland. The researchers observed that only the biochar with higher surface area increased the field capacity of the sandy soil. Neither biochar, altered the field capacity of the higher clay content soil. The best results were yielded from applying particles greater than 1 mm of the porous biochar at greater than 10 tonnes per ha. This biochar improved water retention and increased the soil's resistance to extreme hydrological events such as droughts and floods in the short term. Therefore, this study shows that the impact of biochar on the water retention capacity depends on both the biochar type and soil type. (Wang et at., 2019).

3.2.4 Implementation in Åland

When it comes to designing a plan for implementing biochar as a soil amendment, it is very important to consider the local soil and weather conditions detailed in Sections 1.5.2 and 1.5.3. Since Åland soil varies quite a bit in quality even within small areas of land, it is impossible to predict the exact behavior of biochar in the soil. As a result, small-scale field studies are needed to be able to draw specific quantitative and qualitative conclusions. For a full understanding of the best practices and long-term effects, the studies should be carried out for at least five years.

Since biochar from woody feedstock does not enhance P availability, it is recommended that biochar be incorporated as a soil amendment in conjunction with manure. This is possible to do by using the manure of animals fed with biochar supplements. This is otherwise known as "cascading use of biochar" and is recommended as it integrates the benefits of biochar in both sectors, meanwhile only having to pay the cost of the char once. The biochar is first integrated into the feed. The biochar-enriched manure is then spread on the fields. See figure below.

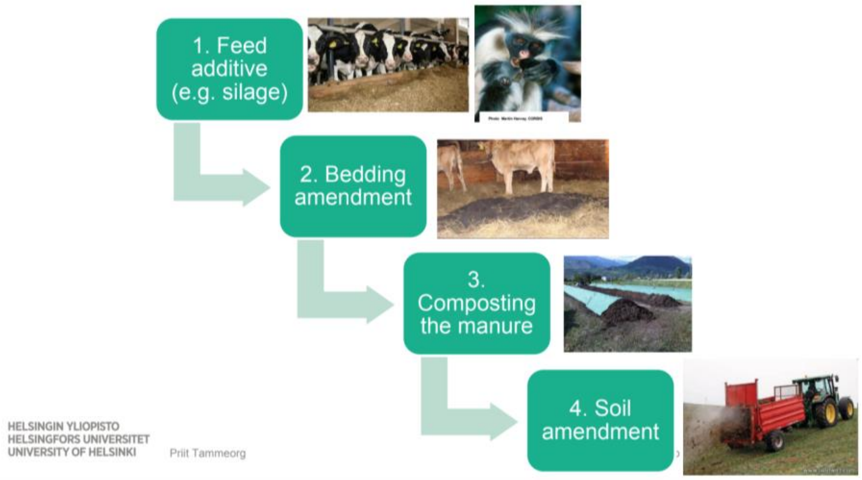

Figure 5. Visual Representation of Cascaded Use of Biochar (adapted from Tammeorg, 2018)

Such a cascading use of biochar can help foster collaboration among local farmers and establish trust.

3.3 Nutrient Recovery

3.3.1 Introduction

While nutrient recovery with biochar is a relatively new concept, it has widespread potential for a variety of applications, including the mitigation of eutrophication. Studies thus far have been conducted primarily on using biochar in storm water, wastewater and groundwater treatment.

3.3.2 Benefits

Several studies have demonstrated biochar's ability to remove phosphorus from aqueous solutions. In general, biochars with high surface areas, high fixed carbon contents and basic pH levels have promoted phosphorus (P) adsorption (Ngatia, Hsieh, Nemours, Fu, & Taylor, 2017).

Saleh, El-Refaey, and Mahmoud studied the removal of ammonium (NH_4^+) ions from synthetic wastewater via the use of peanut hull biochar (PHB) powder as an adsorbent. The results indicated that PHB was a viable, cost effective sorbent material for removing NH4-N from water. Moreover, it was demonstrated that the porous network and functional groups on the biochar surface helped in the irreversible strong retention of NH4-N ions. (Saleh, El-Refaey, & Mahmoud, 2016)

On the other hand, research focusing on nitrate (NO3-) removal has yielded some contradictory results. According to Cheng et al. and Jones et al., biochars produced from wheat straw and hardwood had negligible effects on retaining NO3-. In contrast, Case et al. suggested that NO3- may be held by biochar via physical means rather than ion exchange methods (Case et al., 2012). Prendergast-Miller et al. demonstrated that NO3- was the dominant form of N extracted from biochar and was held via physical entrapment in the pores of the biochar (Prendergast-Miller et al., 2011).

One study evaluated the effectiveness of biochar produced from wood pellets as a filter material for removing mixed contaminants from storm water. The results indicated that effluent nitrate and phosphate concentrations were 86 and 47 percent less than the corresponding influent concentrations.

After filtration, the concentration of heavy metals (Cd, Cr, Cu, Pb, Ni, and Zn) decreased by 18, 19, 65, 75, 17, and 24 percent, respectively. The variation can be explained by the different chemical behaviors of the heavy metals as well as the properties of the biochar. (Reddy, Xie, & Dastgheibi, 2014).

It is important to note that filtering wastewater could contaminate the biochar with heavy metals as well, thereby rendering it unsafe to use for consequent agricultural purposes. On the other hand, dairy effluent or farm residues generally do not contain heavy metals, though further investigation should be conducted for site-specific cases (Foereid, 2015).

3.3.3 Implementation on Åland

It is recommended that nutrient recovery with biochar be implemented in one or more of the following sectors on Åland:

Eutrophic Waters

As it is proposed that nutrients be removed from water bodies to mitigate eutrophication, it is important to investigate the current nutrient availability in Åland swamps and lakes. The following three sites have been proposed as potential sampling sites for conducting biochar nutrient recovery investigations:

1. Brantböle träsk
2. Bränneriträsk
3. Stallhaga träsk

It is best to initiate such projects in the spring, when nutrient levels are the highest as this is when biochar filtration has been shown to be the most effective.

Landfill Leachate and Agricultural Effluents

Capturing nutrients from the digestate of sewage sludge and manures as well as from dairy effluents and landfill leachate are of particular interest to the Åland case, as Åland is heavily reliant upon agriculture. Therefore, using biochar to take advantage of these nutrient-rich streams would increase the degree of circularity attained on Åland. According to Foereid, such biochar applications could also minimize the need for storage of large quantities of digestate and eliminate concerns related to direct digestate spreading (Foereid, 2015).

Tärnebolstad landfill has been proposed as a potential location for testing of recovery from landfill leachate. There is potential for collaboration with the Finström Municipality on this project.

Fish Farming

Collaboration with Ålands Fiskodlarföreninghas been proposed. Further evaluations of current nutrient levels in the fish farms is required.

3.4 Carbon Sequestration

3.4.1 Introduction

In the midst of climate change, finding ways to sequester carbon is of high importance. In 2018, the Intergovernmental Panel on Climate Change (IPCC) included biochar as a "promising negative emission technology" in their special report published on October 8th. This bodes well for funding of biochar research as the Paris Agreement requires the European Union to fund research on such negative emissions technologies. (Schmidt, 2018)

The carbon sink potential of biochar arises from its high fixed carbon content (reaching over 90%). This carbon content is maintained in a relatively high percentage, even over several decades. The Ithaka Institute conservatively estimates that biochars with H : Corg ratio below 0.4 have an average carbon degradation rate of 0.3% per year. This means that one-hundred years after soil application, seventy-four percent of the original fixed carbon is still sequestered in the ground. (EBC, 2020)

The calculation of C-Sink Potential needs to take into account the following (EBC, 2020):

- GHG emissions from production/processing of biomass (in CO2eq)
- GHG emissions from pyrolysis plant (in CO2eq)
- GHG emissions from processing of biochar (in CO2eq)
- Total CO2eq converted to atomic carbon (aka C expenditure)

In addition to the sequestration of carbon in the biochar itself, studies have shown that biochar interactions with the soil can also reduce the organic matter mineralization rate, thereby enhancing levels of native soil carbon levels (Lehmann, 2015).

Using biochar for carbon sequestration also poses high potential for biochar's role in the international carbon market. The continued recognition of biochar as a negative emission technology could lead to government subsidies or compensations, which could serve as an additional incentive to farmers and local industries.

3.4.2 Implementation on Åland

As carbon sequestration is integrated in the aforementioned cascading applications of biochar, it is not necessary to implement any specific measures focused solely on carbon sequestration with biochar. However, to obtain an accurate idea of how much carbon is sequestered, a life cycle assessment (LCA) must be conducted to provide the holistic carbon footprint of biochar. Therefore, it is recommended that such an LCA be conducted in the context of biochar on Åland in the future.

4. Potential Risks and Limitations

After reviewing the case studies, it is evident that the biochar market is still in its preliminary stages. As a result, it is important to address the associated potential risks and limitations.

One major limitation is that to date, the majority of investigations that have been conducted are laboratory scale experiments. In the case of nutrient recovery, these laboratory experiments utilize synthetically constructed waters rather than natural lake/surface/groundwaters. Typically only a few compounds are analyzed at a time and the adsorption capacities of these elements are determined by evaluating the adsorption isotherms and/or kinetics (Gwenzi, Chaukura, Noubactep, & Mukome, 2017). Although comparison of adsorbent performance across several studies is common in literature, there is a lack of standardized experimental conditions such as pH, adsorbate concentration, contact period, etc. As a result, the field of designing and optimizing full-scale, biochar-based water treatment systems remains largely unexplored. There is a need for standardized protocols for the production of biochar and its subsequent application for water treatment. (Gwenzi, Chaukura, Noubactep, & Mukome, 2017). Overall, biochar batch experiments have demonstrated that biochar is capable of absorbing both phosphorus and nitrogen derivatives. However, demonstrating biochar capacity to remove contaminants in real multi-component aqueous solutions at pilot and full scales could be much more challenging given the number of parameters that need to be taken into consideration. Information on the potential environmental and health risks associated with such biochar water treatment is also largely lacking.

Potential risks in terms of soil amendment include that biochar may reduce plant yields and overall growth depending on the type of biochar used and local conditions. Furthermore, there are concerns with contaminants accumulating beyond permissible concentration limits and causing adverse health effects when the crops are consumed. These potential risks need to be evaluated in further research.

Based on the case studies reviewed, using biochar as a feed additive or veterinary treatment has not resulted in any toxic or negative effects on animals or the environment. However, most of the scientific studies that have been conducted have only been performed short-term. Some risks that may be associated with feeding biochar long term include: shifts in the microbial species in the digestive tract and possible adsorption of essential nutrients by the biochar. For this reason, the interval diet is currently recommended.

5. Conclusions and Recommendations

It is recommended that the following pilot studies be run in parallel:

I. Biochar as a Feed Additive and Soil Amendment
   A. Crop-dairy farmer pair I on Mainland
   B. Crop-dairy farmer pair II on Mainland
   C. Crop-dairy farmer pair III on Mainland or Archipelago
   D. Crop-dairy farmer pair IV on Archipelago (i.e. Kökar)
   E. Feed Additive in Fish Farms in collaboration with company (such as Raisioaqua) and/or university

II. Biochar for Nutrient Recovery
   A. One or more of the sites proposed in Section 3.3.3
   B. Tärnebolstad landfill in collaboration with Finström Municipality
   C. Fish farm(s) in collaboration with Ålands Fiskodlarförening

For Pilot Study I, it is recommended that control groups be present in all sectors of the study. Test groups should be relatively small (i.e. 10 cows and 0.1 ha land area per pair).

Although it is not necessarily important to have consistent practices among the various test farms, it is important to keep practices consistent between the control and experimental groups to prevent the influence of confounding variables.

To incentivize farmer participation, it is recommended that monetary compensation be provided to the farmers in exchange for their participation. Although results in the livestock sector are expected to be relatively immediate (within one month of initiating the study), results in the soil amendment sector can take up to 3-5 years.

For Pilot Study II, the following equipment can be utilized in all three nutrient recovery options:

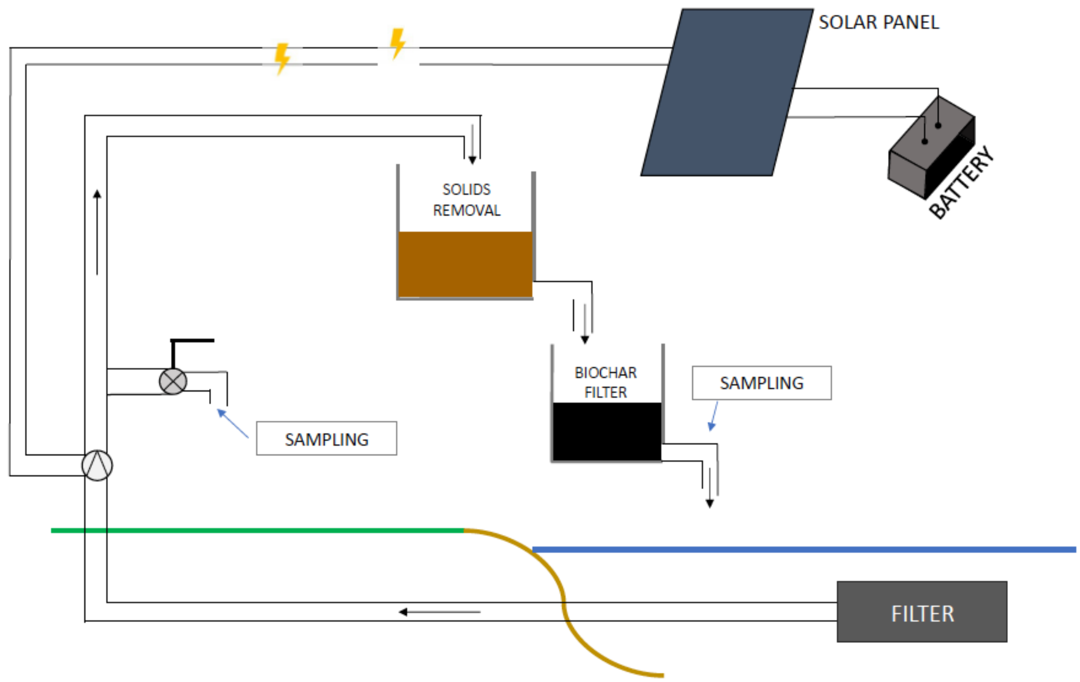

Figure 6. Preliminary Sketch of Proposed Filter System

However, this is merely a preliminary sketch. To initiate these studies, detailed water sampling plans will need to be constructed.

Both studies I and II should be initiated with biochar manufactured by Carbofex. Carbofex is a European Biochar Certificate (EBC)-certified producer of biochar based out of Tampere, Finland. Carbofex biochar is produced from wood chips in an oxygen free environment at 600-700 degrees C (Tukiainen, 2020). The biochar product has a high surface area (>500 m2/g), high fixed carbon content (90-95%), and highly porous structure, properties which make it a highly viable option for use in nutrient recovery (Tukiainen, 2020). The biochar is very low in polyaromatic hydrocarbons, which are toxic. The biochar product is certified for premium and feed applications.

Further research and investigation should be conducted based on current knowledge gaps. More specifically, it is important to further investigate the mechanisms and interactions involved in wood-derived biochar to understand how biochars sorb compounds from eutrophic lake waters and interacts with soil. By doing so, the pilot studies can be optimized to utilize biochar at its maximum potential.

The following are recommended as next steps:

- Evaluate the feasibility of the proposed pilot projects form an economic perspective
- Perform a feasibility study on constructing a biochar plant here on Åland
- Incorporate pyrolysis product applications in the district heating sector
- Conduct a Life Cycle Assessment to assess the overall impact of utilizing biochar from a cradle-to-grave perspective and to compare biochar-based systems with conventional water treatment systems.

Recommended Further Reading:

Nutrient Recovery

Gwenzi, W., Chaukura, N., Noubactep, C., & Mukome, F. N. (2017). Biochar-based water treatment systems as a potential low-cost and sustainable technology for clean water provision. *Journal of Environmental Management, 197*, 732-749. doi:10.1016/j.jenvman.2017.03.087

Animal Feed Additive

Schmidt H-P, Hagemann N, Draper K, Kammann C. (2019). The use of biochar in animal feeding. *PeerJ* 7-7373 DOI 10.7717/peerj.7373

Soil Amendment

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Glaser, B., & Lehr, V. (2019). Biochar effects on phosphorus availability in agricultural soils: A meta-analysis. *Scientific Reports, 9*(1). doi:10.1038/s41598-019-45693-z

Carbon Sequestration

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Appendix.

Table 9. Results of Studies using Biochar as a Feed Additive (adapted from Schmidt et al., 2019).

Animal	Daily BC intake	Feedstock	HTT in °C	Activation	Blend	Weight increase in %	Duration in days	Other results and remarks	Source
Cattle	0.6% of feed DM	Rice hull	700	No		25	98	Reduced enteric methane emissions	*Leng, Inthapanya & Preston (2013)*
Bull	2% of feed DM	Wood	>600	No	Vitamin A	n.s.			*Kim & Kim (2005)*
Cattle	1% of feed DM	Rice husk	>600	No		15	56	15% feed conversion rate increase	*Phongphanith & Preston (2018)*
Goat	1% of body weight	Bamboo		No		20	84	DM, OM, CP digestibility and N retention increased	*Van, Mui & Ledin (2006)*
Goat	1% of feed DM			No		27	90	DM, OM, CP digestibility and N retention increased	*Silivong & Preston (2016)*
Pig	0.3% of feed DM	Bamboo	>600	Yes (900)	Bamboo vinegar	17.5	42	Improved the quality of marketable meat	*Chu et al. (2013c)*
Pig	0.3% of feed DM	Wood		No	Stevia	11		Higher meat quality and storage capacity	*Choi et al. (2012)*
Pig	1%, 3% and 5% of feed DM	Wood	450 °C	No	25% wood vinegar	n.s.	30	Increased duodenal villus height	*Mekbungwan, Yamauchi & Sakaida (2004)*
Pig	1% of DM feed	Wood	>600	No	Lactofermented	n.s.	28		*Kupper et al. (2015)*
Pig	1% of DM feed		>500			20.1	90	20.6% increased feed conversion rate	*Sivilai et al. (2018)*
Poultry	0.2% of DM feed	Wood		No		17	49		*Kana et al. (2010)*
Poultry	0.2% of DM feed	Maize cob		No		6	49	Improved carcass traits	*Kana et al. (2010)*
Poultry	2%, 4%, 8% of feed DM	Citrus wood		No		0	42	Heavier abdomen fat	*Bakr (2007)*
Poultry	2.5%, 5%, 10% of feed DM	Wood		No		0	42	Weight increase up to 28 days but not after 49 days	*Kutlu, Ünsal & Görgülü (2001)*
Poultry	0.3% of feed DM	Wood		No		3.9	140	Reduced mortality by 4%	*Majewska, Pyrek & Faruga (2002), Majewska, Mikulski & Siwik (2009)*
Duck	1% of DM feed	Bamboo	>650	No	Bamboo vinegar	n.s.	49	Intestinal villus height increased	*Ruttanavut et al. (2009)*
Duck	1% of DM feed	Wood		No	Kelp	n.s.	21	Feed conversion rate increased	*Islam et al. (2014)*
Poultry	4% of DM feed	Woody green waste	550	No		n.s.	161	Egg weight increased by 5%; feed conversion ratio by 12%	*Prasai et al. (2016)*
Poultry	1% of DM feed	Rice husk	>550	No		n.s.		Reduced pathogenes in feces	*Hien et al. (2018)*
Poultry	0.7% of DM feed	Wood	>650	No	Lactofermented	n.s.	36		*Kupper et al. (2015)*
Poultry	1% of DM feed	Wood	>650	No	Lactofermented	5	37	Reduced foot pat and hook lesions by 92% and 74%	*Albiker & Zweifel (2019)*
Flounder	0.5% of DM feed	Bamboo		No		18	50	Feed and protein conversion rate increased	*Thu et al. (2010)*
Flounder	1.5% of DM feed	Wood		No	20% wood vinegar	11	56	Highest feed efficiency increase of 10% at 0.5% BC	*Yoo, Ji & Jeong (2007)*
Stripfish	1% of DM feed	Rice husk	>600	No		36	90	Significantly improved water quality	*Lan, Preston & Leng (2018)*
Stripfish	1% of DM feed	Wood		No		44	90	Significantly improved water quality	*Lan, Preston & Leng (2018)*
Carp	0.5%, 1%, 2%, 4% of DM feed	Bamboo		No		n.s.	63	Improved serum indicators	*Mabe et al. (2018)*
Stripfish	2% of feed DM	Bamboo		No	High VOC biochar	27	50	Survival rate increase by 9%	*Quaiyum et al. (2014)*
					Mean	9.9			

Table 10. Summary of the data obtained from 107 pairwise comparisons used in this meta-analysis. X_E represents the mean plant-available phosphorus content of the soil amended with biochar and X_C is the mean plant-available phosphorus content of the un-amended soil. R is the response ratio calculated by X_E/X_C. **(**adapted from Glaser and Lehr, 2019)

Studies	Feedstock	Pyrolysis Temperature [°C]	Amount [Ma ha-1]	Soil pH	Time	Extraction Method	X_E [mg/kg]	X_C [mg/kg]	ln(R)	R
Alotabi & Schoenau, 2016	Oat hulls	450	2.8	7.9	3 years	modified Kelowna extraction	14.5	13.7	0.06	1.06
Bai, Hosseini *et al.* 2014	Poultry litter	500-550	10	n/a	5 years	Bray No. 1	51.6	4.68	2.4	11.03
Bai, Hosseini *et al.* 2014	Green waste	500-550	10	n/a	5 years	Bray No. 1	10	4.68	0.76	2.14
Brantley *et al.* 2016	Poultry litter	500-520	5	6.5	92 days	Mehlich III	1.1	1	0.1	1.10
Brantley *et al.* 2016	Poultry litter	500-520	10	6.5	92 days	Mehlich III	1.3	1	0.26	1.3
Cavoski *et al.* 2016	Olive-mill waste	1100-1200	5	7.5	16 weeks	Olsen	7	7	0	1.00
Chathurika *et al.* 2016	Wood chip	500-650	30	8.0	70 days	Olsen	6.8	7.6	-0.11	0.89
Chathurika *et al.* 2016	Wood chip	500-650	30	7.6	70 days	Olsen	6.8	7.8	-0.14	0.87
Chathurika *et al.* 2016	Wood chip	500-650	15	8.0	70 days	Olsen	7	8.2	-0.16	0.85
Chathurika *et al.* 2016	Wood chip	500-650	15	7.6	70 days	Olsen	7	8.7	-0.22	0.80
Dai *et al.* 2013	Reed	500	20	4.7	100 days	Olsen	37.51	33.73	0.11	1.11
Dai *et al.* 2013	Reed	500	60	4.7	100 days	Olsen	52.38	33.73	0.44	1.55
Studies	Feedstock	Pyrolysis Temperature [°C]	Amount [Ma ha-1]	Soil pH	Time	Extraction Method	X_E [mg/kg]	X_C [mg/kg]	ln(R)	R
Dai *et al.* 2013	Pig manure	500	20	4.7	100 days	Olsen	129.41	33.73	1.34	3.84
Dai *et al.* 2013	Pig manure	500	60	4.7	100 days	Olsen	175.2	33.73	1.65	5.19
Dai *et al.* 2013	Pineapple Peel	500	20	4.7	100 days	Olsen	62.28	33.73	0.61	1.85
Dai *et al.* 2013	Pineapple Peel	500	60	4.7	100 days	Olsen	115.93	33.73	1.23	3.44
Gao *et al.* 2016	Logging residue	500	20	5.9	4 months	$CaCl_2$	10.99	10.34	0.06	1.06
Hossain *et al.* 2010	Wastewater sludge	550	10	4.6	16 weeks	Colwell	56	26	0.77	2.15

Studies	Feedstock	Pyrolysis Temperature [°C]	Amount [Ma ha^{-1}]	Soil pH	Time	Extraction Method	X_E [mg/kg]	X_C [mg/kg]	ln(R)	R
Hunt *et al.* 2013	Dairy manure	350	5	4.5	51 days	modified Mehlich III	25.4	10.3	0.9	2.47
Hunt *et al.* 2013	Dairy manure	700	2.5	4.5	51 days	modified Mehlich III	23.4	10.3	0.82	2.27
Hunt *et al.* 2013	Beef manure	350	4	4.5	51 days	modified Mehlich III	23.2	10.3	0.81	2.25
Hunt *et al.* 2013	Beef manure	700	2.5	4.5	51 days	modified Mehlich III	20.7	10.3	0.7	2.01
Hunt *et al.* 2013	Chicken manure	350	2	4.5	51 days	modified Mehlich III	21.8	10.3	0.75	2.12
Hunt *et al.* 2013	Chicken manure	700	1.5	4.5	51 days	modified Mehlich III	19.9	10.3	0.66	1.93
Hunt *et al.* 2013	Turkey manure	350	1.5	4.5	51 days	modified Mehlich III	20.5	10.3	0.69	1.99
Hunt *et al.* 2013	Turkey manure	700	1.5	4.5	51 days	modified Mehlich III	19.7	10.3	0.65	1.91
Hunt *et al.* 2013	Pig manure	350	1.5	4.5	51 days	modified Mehlich III	19.6	10.3	0.64	1.90
Hunt *et al.* 2013	Pig manure	700	1	4.5	51 days	modified Mehlich III	20.7	10.3	0.70	2.01
Jin *et al.* 2016	Pig manure	400	10	6.3	98 days	Olsen	87.2	20.9	1.43	4.17
Jin *et al.* 2016	Pig manure	400	30	6.3	98 days	Olsen	141.6	20.9	1.91	6.78
Jin *et al.* 2016	Pig manure	400	10	5.0	98 days	Olsen	44.5	12.2	1.29	3.65
Jin *et al.* 2016	Pig manure	400	30	5.0	98 days	Olsen	109.6	12.2	2.20	8.98
Marchetti & Castelli 2013	Wood chip	420	10	8.2	90 days	Olsen	26	26	0	1.00
Marchetti & Castelli 2013	Swine solids	420	10	8.2	90 days	Olsen	60.1	26	0.84	2.31
Naggar et al. 2015	Conocarpus wood waste	400	20	8.5	90 days	AB-DTPA	0.57	0.32	0.58	1.78
Novak *et al.* 2009	Peanut hull	400	40	5.9	2 days	Mehlich I	104	5.9	2.87	17.63
Novak *et al.* 2009	Peanut hull	500	40	5.9	2 days	Mehlich I	85	5.9	2.67	14.41
Novak *et al.* 2009	Pecan shell	350	40	5.9	2 days	Mehlich I	71	5.9	2.49	12.03

Studies	Feedstock	Pyrolysis Temperature [°C]	Amount [Ma ha^{-1}]	Soil pH	Time	Extraction Method	X_E [mg/kg]	X_C [mg/kg]	ln(R)	R
Novak *et al.* 2009	Pecan shell	700	40	5.9	2 days	Mehlich I	71	5.9	2.49	12.03
Novak *et al.* 2009	Switch grass	250	40	5.9	2 days	Mehlich I	74	5.9	2.53	12.54
Novak *et al.* 2009	Switch grass	500	40	5.6	2 days	Mehlich I	94	5.9	2.77	15.93
Novak & Buscher 2013	Peanut hull	400	40	5.6	120 days	Mehlich I	39	29	0.30	1.34
Novak & Buscher 2013	Peanut hull	500	40	5.6	120 days	Mehlich I	33	29	0.13	1.14
Novak & Buscher 2013	Hard wood	700	40	5.6	120 days	Mehlich I	22	29	-0.28	0.76
Novak *et al.* 2014	Peanut hull	400	40	5.6	127 days	Mehlich I	36	27	0.29	1.33
Novak *et al.* 2014	Peanut hull	500	40	5.6	127 days	Mehlich I	28	27	0.04	1.04
Novak *et al.* 2014	Pecan shell	350	40	5.6	127 days	Mehlich I	24	27	-0.12	0.89
Novak *et al.* 2014	Pecan shell	700	40	5.6	127 days	Mehlich I	31	27	0.14	1.15
Novak *et al.* 2014	Poultry litter	350	40	5.6	127 days	Mehlich I	393	27	2.68	14.56
Novak *et al.* 2014	Poultry litter	700	40	5.6	127 days	Mehlich I	714	27	3.28	26.44
Novak *et al.* 2014	Switch grass	250	40	5.6	127 days	Mehlich I	29	27	0.07	1.07

Studies	Feedstock	Pyrolysis Temperature [°C]	Amount [Ma ha^{-1}]	Soil pH	Time	Extraction Method	X_E [mg/kg]	X_C [mg/kg]	ln(R)	R
Novak *et al.* 2014	Hard wood waste	500	40	5.6	127 days	Mehlich I	22	27	-0.2	0.81
Novak *et al.* 2015	Pig solids	350	10	6.5	124 days	Mehlich I	155	21	2.00	7.38
Novak *et al.* 2015	Pig solids	350	20	6.5	124 days	Mehlich I	212	21	2.31	10.10
Novak *et al.* 2015	Pig solids	350	40	6.5	124 days	Mehlich I	490	21	3.15	23.33
Olmo *et al.* 2014	Olive-tree pruning	450	40	8.2	7 months	Olsen	21	12.8	0.5	1.64
Partey *et al.* 2014	Mixed hardwood	500	5	6.1	1 year	Olsen	5.6	5.4	0.04	1.04

Parvage *et al.* 2013	Wheat residue	500	20	6.4	16 hours	WSP	4.43	2.76	0.47	1.61
Parvage *et al.* 2013	Wheat residue	500	20	6	16 hours	WSP	1.55	1.11	0.33	1.40
Parvage *et al.* 2013	Wheat residue	500	20	6.2	16 hours	WSP	0.95	0.66	0.36	1.44
Parvage *et al.* 2013	Wheat residue	500	20	6.6	16 hours	WSP	5.25	4.74	0.10	1.11
Parvage *et al.* 2013	Wheat residue	500	20	5.4	16 hours	WSP	7.61	3.96	0.65	1.92
Parvage *et al.* 2013	Wheat residue	500	20	7.7	16 hours	WSP	0.53	0.15	1.26	3.53
Parvage *et al.* 2013	Wheat residue	500	20	6.2	16 hours	WSP	1.14	1.2	-0.05	0.95

Studies	**Feedstock**	**Pyrolysis Temperature [°C]**	**Amount [Ma ha^{-1}]**	**Soil pH**	**Time**	**Extraction Method**	**X_E [mg/kg]**	**X_C [mg/kg]**	**ln(R)**	**R**
Parvage *et al.* 2013	Wheat residue	500	20	5.9	16 hours	WSP	7.23	6.03	0.18	1.20
Parvage *et al.* 2013	Wheat residue	500	20	5.9	16 hours	WSP	0.09	0.06	0.41	1.50
Parvage *et al.* 2013	Wheat residue	500	20	5.3	16 hours	WSP	1.17	0.63	0.62	1.86
Parvage *et al.* 2013	Wheat residue	500	20	5.3	16 hours	WSP	0.12	0.12	0	1
Warren *et al.* 2009	Cattle bone	400	7.6	7.9	145 days	Olsen	44.7	56.6	-0.04	0.96
Warren *et al.* 2009	Cattle bone	400	7.6	6.1	145 days	Olsen	68.7	50.2	0.31	1.37
Warren *et al.* 2009	Cattle bone	400	7.6	6.8	145 days	Olsen	41.2	39.2	0.05	1.05
Warren *et al.* 2009	Cattle bone	400	7.6	8.3	145 days	Olsen	14.9	13.4	0.11	1.11
Warren *et al.* 2009	Cattle bone	400	7.6	7.4	145 days	Olsen	25.6	13.9	0.61	1.84
Warren *et al.* 2009	Cattle bone	400	7.6	5.0	145 days	Olsen	70.8	5.3	2.59	13.36
Warren *et al.* 2009	Cattle bone	400	7.6	5.5	145 days	Olsen	127.8	67.7	0.64	1.89
Warren *et al.* 2009	Cattle bone	400	7.6	5.0	145 days	Olsen	65	1.4	3.84	46.43
Warren *et al.* 2009	Cattle bone	400	7.6	5.4	145 days	Olsen	47.1	12.1	1.36	3.89

Studies	Feedstock	Pyrolysis Temperature [°C]	Amount [Ma ha⁻¹]	Soil pH	Time	Extraction Method	X_E [mg/kg]	X_C [mg/kg]	ln(R)	R
Warren *et al.* 2009	Cattle bone	400	7.6	5.1	145 days	Olsen	44	12.8	1.23	3.44
Warren *et al.* 2009	Cattle bone	400	7.6	8.8	145 days	Olsen	13.1	11	0.17	1.19
Warren *et al.* 2009	Cattle bone	400	7.6	3.4	145 days	Olsen	146.7	11.2	2.57	13.10
Wu *et al.* 2014	Furfural residue	300	4.5	8.3	56 days	Olsen	7.43	3.34	0.80	2.22
Wu *et al.* 2014	Furfural residue	300	4.5	8.3	56 days	Olsen	12.42	3.34	1.31	3.72
Xu *et al.* 2015	Peanut shell	550	9.2	5.5	163 days	Olsen	3	4.8	-0.47	0.63
Xu *et al.* 2015	Peanut shell	550	9.2	5.5	163 days	Olsen	7.2	6.1	0.17	1.18
Zhai *et al.* 2015	Maize straw	400	40	6.4	42 days	Olsen	12	3	1.39	4.00
Zhai *et al.* 2015	Maize straw	400	75	6.4	42 days	Olsen	27	3	2.20	9.00
Zhai *et al.* 2015	Maize straw	400	150	6.4	42 days	Olsen	46	3	2.73	15.33
Zhai *et al.* 2015	Maize straw	400	40	8.3	42 days	Olsen	53	13	1.41	4.08
Zhai *et al.* 2015	Maize straw	400	75	8.3	42 days	Olsen	93	13	1.97	7.15
Zhai *et al.* 2015	Maize straw	400	150	8.3	42 days	Olsen	137	13	2.36	10.54

Studies	Feedstock	Pyrolysis Temperature [°C]	Amount [Ma ha⁻¹]	Soil pH	Time	Extraction Method	X_E [mg/kg]	X_C [mg/kg]	ln(R)	R
Zhao *et al.* 2014	Maize straw	500	10	8.6	14 days	Olsen	10.96	10	0.09	1.10
Zhao *et al.* 2014	Maize straw	500	20	8.6	14 days	Olsen	13.2	10	0.28	1.32
Zhao *et al.* 2014	Maize straw	500	40	8.6	14 days	Olsen	15.46	10	0.44	1.55
Zhao *et al.* 2014	Maize straw	500	95	8.6	14 days	Olsen	25.36	10	0.93	2.54
Zhao *et al.* 2014	Maize straw	500	10	5.3	14 days	Olsen	6.94	6.02	0.14	1.15
Zhao *et al.* 2014	Maize straw	500	20	5.3	14 days	Olsen	8.16	6.02	0.30	1.36

Zhao *et al.* 2014	Maize straw	500	40	5.3	14 days	Olsen	7.91	6.02	0.27	1.31
Zhao *et al.* 2014	Maize straw	500	95	5.3	14 days	Olsen	12.7	6.02	0.75	2.11
Zong *et al.* 2016	Wheat straw	500	40	5.0	180 days	Olsen	20.37	7.18	1.04	2.84
Zong *et al.* 2016	Wheat straw	500	75	5.0	180 days	Olsen	43.5	7.18	1.80	6.06
Zong *et al.* 2016	Wheat straw	500	115	5.0	180 days	Olsen	63.24	7.18	2.18	8.81
Zong *et al.* 2016	Wood chips	500	40	5.0	180 days	Olsen	14.26	7.18	0.69	1.99
Zong *et al.* 2016	Wood chips	500	75	5.3	180 days	Olsen	18.05	7.18	0.92	2.51

Studies	**Feedstock**	**Pyrolysis Temperature [°C]**	**Amount [Ma ha^{-1}]**	**Soil pH**	**Time**	**Extraction Method**	**X_E [mg/kg]**	**X_C [mg/kg]**	**ln(R)**	**R**
Zong *et al.* 2016	Wood chips	500	115	5.0	180 days	Olsen	21.12	7.18	1.08	2.94
Zong *et al.* 2016	Wastewater sludge	500	40	5.0	180 days	Olsen	23.5	7.18	1.19	3.27
Zong *et al.* 2016	Wastewater sludge	500	75	5.0	180 days	Olsen	55.11	7.18	2.04	7.68
Zong *et al.* 2016	Wastewater sludge	500	115	5.0	180 days	Olsen	122.5	7.18	2.84	17.06

Table 11. Biochar effects on nutrient leaching (adapted from Laird & Rogovska, 2015).

Biochar	*Soil characteristics*	*Observations*	*Citations*
Commercially produced from mixed feedstock of fruit trees, ~500°C	Silty clay loam (field experiment)	72% decrease in NO_3^- leaching, no effect on NH_4^+ leaching.	Ventura et al (2013)
Maize stover, 600°C	Aeric Endoaquepts fine-loamy soils (field experiment)	82% reduction in NO_3^- leaching at 100% recommended fertilization rate; no effect at reduced (50%) fertilization rate.	(Guerena et al, 2013)
Peanut hall, 600°C	Sandy soil (laboratory)	34 and 14% reduction in NO_3^- and NH_4^+ leaching; 39% increase in P leaching.	(Yao et al, 2012)
Brazilian pepperwood, 600°C	Sandy soil (laboratory)	30 and 35% reduction in NO_3^- and NH_4^+ leaching; 21% reduction in P leaching.	
Locally produced mixed wood, ~500–700°C	Typic Haplustox clay soil (field experiment)	Leaching varied within the rooting zone. At 1.2 M depth Ca^{2+}, Mg^{2+}, K^+, NO_3^- and Sr^{2+} leaching decreased by 14, 22, 31, 2 and 14%, respectively, while no effect of biochar was observed for NH_4^+ and P.	(Major et al, 2012)
Switchgrass at 250°C	Xeric Haplocalcids loamy soil (laboratory)	27, 27 and 88% reduction in cumulative leaching of Ca, Mg and NO_3^-, respectively; 47% increase in K leaching; no effect on P leaching.	(Ippolito et al, 2012)
Switchgrass at 500°C		67% reduction in cumulative leaching of NO_3^-; 267 and 172% increase in K and P, respectively; no effect on Ca and Mg leaching.	
Switchgrass at 250°C	Xeric Haplocambids silty soil (laboratory)	32, 28 and 72% reduction in Ca, Mg and NO_3^-, respectively; no effect on K and P leaching.	
Switchgrass at 500°C		10, 11 and 152% increase in Mg, K and P leaching, respectively; 37% reduction in NO_3^- leaching.	
Bagasse at 800°C	Clay soil (laboratory)	5% reduction in NO_3^- leaching.	(Kameyama et al, 2012)
Mixed wood at 475°C	Silty and sandy soils (laboratory)	No effect on P and NO_3^- leaching	(Borchard et al, 2012)
Jarrah wood at 600°C	Sandy soil (lysimeter pots)	28% reduction in NO_3^- leaching	(Dempster et al, 2012)
Bamboo at 600°C	Sandy silt (laboratory)	15% reduction in NH_4^+ leaching at the subsurface 10–20cm depth.	(Ding et al, 2010)
Mixed wood at ~550°C	Typic Hapludolls fine loamy soil (laboratory)	74, 14, 28, 35 and 26% increase in leaching of K, Mg, Zn, Ca and total N, respectively; no effect on P, Cu, Mn, Na, B and Si leaching.	(Laird et al, 2010a)[1]
Pecan shells at 700°C	Typic Kandiudults fine loamy soil (laboratory)	206 and 110 % increase in K and Na leaching, respectively; 35 and 78% decrease in P and Zn leaching; no effect on Ca, Mg and S leaching.	(Novak et al, 2009a)[2]

1 Difference in cumulative leaching between control and columns amended with the highest rate (2% w/w)
2 Differences in leaching between control and columns amended with the highest rate of biochar after 67-day incubation period