LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT
School of Energy Systems
Master’s Programme in Circular Economy

Petri-Tapio Heikkonen

Business potential of exporting the Finnish excess of residue nutrients

Examiners: prof. Helena Kahiluoto
M.Sc. Pirjetta Waldén

ABSTRACT

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This master's thesis studied viability of exporting excess residue nutrients from Finland. The study was conducted based on published litterature and results. The use, need and supply of residue nutrients in Finland were evaluated in order to assess the quantity of exportable products. Production and shipping costs and predicted income were defined and Net present value of export was computed in order to evaluate the feasibility of export.

The results suggest that long-distance export of recycling fertiliser from Finland is not economically viable if income is based solely on excess nutrient export but a wider utilisation of residues is required.

TIIVISTELMÄ

LAPPEENRANNAN–LAHDEN TEKNILLINEN YLIOPISTO LUT
School of Energy Systems
Master’s Programme in Circular Economy

Petri-Tapio Heikkonen

Suomen sivuvirtaravinneylijäämän viennin liiketoimintapotentiaali

Diplomityö

2019

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Avainsanat: Kierrätysravinteet, Typpi, Fosfori, NPV

Tarkastajat:	prof. Helena Kahiluoto
	MMM Pirjetta Waldén

Diplomityössä selvitettiin, kuinka kannattavaa ylijäämäisten sivuvirtaravinteitten vienti Suomesta olisi. Tutkimus perustuu tutkimuskirjallisuudesta saatuihin lukuihin. Suomen sivuvirtaravinteitten määrä, käyttö ja tarve selvitettiin vientikelpoisten tuotteitten määrän arvioimiseksi. Tuotanto- ja kuljetuskustannukset sekä arvio saatavasta tulosta määritettiin ja niihin perustuen laskettiin viennin nettonykyarvo kannattavuuden arvioimiseksi.

Tutkimuksen tulosten valossa pelkät lannoitetuotteitten myynnistä saatavat tulot eivät ole riittävät, jotta sivuvirtaravinnevienti olisi taloudellisesti kannattavaa, vaan ravinnesivuvirtojen monipuolisempi hyödyntäminen on välttämätöntä.

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Contents

Symbols and abbreviations

a	year
d	day
ft	foot (30.48 cm)
m-%	mass %
t	tonne (1000 kg)
M	Million
CI	Côte d’Ivoire
DM	dry matter
ET	Ethiopia
FI	Finland
LHV	Lower heating value
NPV	Net present value
PBP	Payback period
UK	The United Kingdom
WWTP	Waste water treatment plant

1 Introduction

The global anthropogenic use of nutrients – especially nitrogen (N) and phosphorus (P) – from edaphic and atmospheric sources have exceeded what is sustainable, the planetary boundaries due to their overuse in developed countries (Kahiluoto et al. 2015). The overuse has led e.g. to eutrophication and damage to vital water ecosystems. However, the spatial distribution of these nutrient flows varies greatly: while developed countries overuse nutrients, developing countries suffer from nutrient deficiency, which has led to erosion, soil degradation, food insecurity and carbon emissions. (ibid.). On one hand, soil fertility should be improved by nutrient inputs in nutrient-poor regions. On the other hand, global use of fertilisers should not increase due to aforementioned excess. A solution would be more equal distribution of nutrients. It is unlikely that agricultural industry in developed countries would decrease use of fertilisers but closing of the nutrient loop and recovery of the nutrients from waste flows might also create business opportunities. Since nutrient use has already exceeded planetary boundaries, the redistribution of nutrients might be plausible through exporting excess nutrients to areas suffering from nutrient-scarcity.

The aim of this thesis is to study the export potential of the possible surplus nutrient residues from Finland to Ethiopia and Côte d'Ivoire. The study examines, to what degree Finland is self-sufficient in nutrients and whether there is a nutrient surplus. The study also aims to find whether there is potential for exporting residual nutrients from Finland and whether this export is economically viable. The export destinations in this study are Ethiopia and Côte d'Ivoire.

Ethiopia and Côte d'Ivoire were chosen because they both have scarcity of nutrients: Ethiopia lacks especially N (Liu et al. 2010, Fig. 2) while Côte d'Ivoire has more scarcity of P (MacDonald et al. 2011, Fig. 1).

When organic waste is treated for fertilising use, it is called *organic* or *recycling fertiliser* in comparison to *synthetic* or *mineral fertiliser*. The biowaste recycled is likely to contain potassium (K), which is also an important nutrient, and the K content will be taken into account, even though global use and flows of K are not on such an unsustainable level as N and P.

There have been several studies regarding nutrient residue flows, both from global perspective and determining specifically those flows in certain areas, e.g. van Dijk et al. (2015) have studied P flows in Europe and Sutton et al. (2013) have analysed the global flows of both N and P.

The main research question is:

What is the business potential of exporting Finnish excess residue nutrients?

The research question is further divided into subquestions:

1. *How much excess residue nutriens are there available in Finland?*
2. *What would be suitable forms for the nutrients to-be-exported?*
3. *What would the shipping costs be?* and
4. *Taking the aforementioned questions into account, would nutrient export be economically feasible?*

1.1 Possible exportable residue-based nutrient sources

1.1.1 Manure

Manure is an inevitable sideflow of animal production and a valuable organic fertilizer. It is a natural fertiliser, and it is regarded in high value – for example in Ethiopia many farmers prefer manure to mineral fertilisers (Kahiluoto et al. 2012). Raw manure, however, is not an optimised fertiliser. N:P ratio of untreated manure is typically 2–4 (e.g. Burton 2007, Table 2), whilst the preferred N:P ratio is between 4 and 9 (TTS 2009). The high phosphorus content of manure has lead to notable phosphorus surpluses on some areas with agriculture focused on animal husbandry and manure as the main fertiliser (Valve et al. 2020, p. 4).

The most limiting factor for export of manure is the transport. Untreated manure is not pleasant to deliver long distances, which causes imbalance even inside Finland, since the need for manure phosphorus is on different areas than where most manure is produced (Marttinen et al. 2017, p. 13). In order to make transport of manure realistic, the absolute minimum requirement is small water content (ibid.).

The nutrient content can be adjusted when refining manure for fertiliser use. Several different technologies exist, one of which is separation to separate the liquid manure, slurry, into solid and liquid fractions. Most of nitrogen will end up into the liquid fraction and phosphorus into solid fraction. (Marttinen et al. 2017, pp. 14–15.) Separation is a very widely used technique to treat manure, the process is relatively easy and cheap and conductible even in relatively small scale, and the results are often satisfying (Burton 2007, p. 208). What makes mechanical separation an attractive alternative, is that manure can be treated locally before transporting further, which reduces transportation costs. Separation does decrease gaseous emissions and smell during storing compared to non-treated manure. Such separating can be done with e.g. a centrifuge or a screw press separator. (Burton 2007; Kässi et al. 2013.)

1.1.2 Biochar

Biochar is a solid product of pyrolysis that is used as soil improvement. It has been found in several studies that adding biochar improves crop yields and carbon sequestration and increases plants' resistance to diseases. (Joseph et al. 2013, pp. 323–324.) Biochar can be manufactured from e.g. wood or grass biomass, sewage sludge, or manure (Shackley et al. 2011, Table 1). The cost of producing biochar varies a lot, which reduces its viability in developed countries (Joseph et al. 2013; Shackley et al. 2011). In developing countries, however, overall scarcity of biomass and the time and recources needed to produce large amounts of biochar are the most limiting factors for biochar use (Joseph et al. 2013, pp. 323–324.).

The exact properties of biochar depend on the material from which it is manufactured, and the manufacturing process (Joseph et al. 2013, p. 324). The porous surface adsorbs different organic and inorganic substances, e.g. nutrients. These substances may create structures resembling galvanic cells, which may allow series of complex redox reactions when the pores are filled with water. (Joseph et al. 2013, p. 325.) Biochar can be mixed with the nutrients in pre- or post-pyrolysis process, during composting or only when adding fertilisers and biochar to soil (Joseph et al. 2013, pp. 323–324). In pre-pyrolysis method a mixture containing nutrients – which can consist solely of nutrient-rich residues – is treated with low-temperature pyrolysis, and in post-pyrolysis method biochar is mixed with for example manure (ibid.). The case assessed in this study will be pyrolysis with manure as feedstock, which is a case of pre-pyrolysis method.

The end-product containing biochar and nutrient-rich biomass is akin to Amazonian *terra preta*, black soil (Glaser et al. 2014), or it can be described as clay-like (Lin et al. 2013, p. 36).

Biochar production by pyrolysis produces also *syngas* as a by-product. Syngas is a mixture mainly of H_2 and CO, which can be combusted as-is or refined into fuels of higher value. (Hlavsová et al. 2014, p. 2.)

1.1.3 Wastewater sludge

Municipal wastewaters are end up in wastewater treatment plants (WWTP) to be treated before being released into water systems. The matter that is removed from wastewater is sludge.

WWTP sludge has high N and P contents, is mainly treated through anaerobic digestion to manufacture biogas and the amount of biogas plants in increasing (Marttinen et al. 2017, p. 17). In Finland using WWTP sludge as fetriliser in only legal after a proper treatment and even then the use is limited (Ministry of Agriculture and Forestry of Finland 2011, 2012, 2013). One factor limiting use of WWTP sludge is that chemically precipitated phosphorus does not suit well for plant fertilising (Marttinen et al. 2017, p. 17). Another, perhaps more important reason are the possible hazardous substances in the sludge. Heavy metals, organic compounds, pathogens and residues of medical substances do appear in wastewater sludge. Although the measured concentrations have been on tolerable – and legal – levels (ibid.), food producers do not want to be associated with such contaminants or simply the thought of wastewater sludge.The wastewater treatment sludge can, however, be treated in order to collect nutrients while leaving other contents of the sludge to be treated by other means (see 1.1.4).

1.1.4 NPHarvest

NPHarvest is a technique developed at Aalto University to treat liquid waste containing high concentrations of N and P. The treatment is conducted using gas permeable hydrophobic membrane. In labotory-scale batch process, 99 % of N and P were removed from reject water and urine and a larger pilot has been able to remove 85 % of N from reject water. (Pradhan et al. 2019, p. 4.) The NPHarvest process produces ammonium sulphate, $(NH_4)_2SO_3$ and P sediment (ibid.). Ammonium sulphate is a salt that can be used as liquid fertiliser or dried to make crystal mineral fertiliser. Dried $(NH_4)_2SO_3$ contains 21 % N. (Pradhan et al. 2018, pp. 1–2.) P sediment can be applied to soil as is (Pradhan et al. 2019, p. 4). However, at the present price-levels, production of both end-products through NPHarvest costs approximately twice as much as industrial production of those (Pradhan et al. 2018, p. 14). Therefore, NPHarvest, while an interesting and potential-rich technique will not be discussed in this study.

2 Material and methods

2.1 Manure

There are differences in nitrogen and phosphorus content of manure between different animal species and even different animal individuals (Marttinen et al. 2017, Table 3). Kaasik (2019) presents methods used in different Baltic Sea countries to define those properties for calculation purposes. Table 1 shows the amounts of different types and total N and P contents of manures from different animal species. In order to evaluate the nutrient contents of each manure types, tables 2, 3 and 4 present amounts of excretion by dairy cows, slaughter pigs and broilers. Nutrient content of each manure type [kg nutrient / t] can be calculated from those data. It will be assumed that the fertilising properties of N and P do not depend on whether it is in liquid or solid fraction.

All numbers t/a	Slurry	Dry manure	Urine	Total	P	N
Cattle	6 770 000	4 680 000	1 010 000	12 460 000	10 300	53 600
Pig	3 320 000	166 000	125 000	3 611 000	2 680	11 100
Poultry	18 000	257 000		275 000	2 390	5 400
Sheep and goat		82 000		82 000	190	720
Horse and pony		686 000	1 000	687 000	510	2 490
Fur		200 000		200 000	3 200	2 260
Total	10 108 000	6 071 000	1 136 000	17 315 000	19 270	75 570

Table 1: Manure production of manure in Finland by livestock and manure type (Marttinen et al. 2017, Table 3).

	Manure [t]	DM [%]	N [kg]	P [kg]	K [kg]
Faeces	16.9	13.5	82.1	20.6	23.6
Urine	9.1	5	68.6	0.7	76.6
Total	26	10	150.7	21.3	100.2

Table 2: Excretion of N, P and K for dairy cows (/cow/a) in Denmark (Kaasik 2019, p. 9).

	Manure [t]	DM [%]	N [kg]	P [kg]
Faeces	0.12	25	0.99	0.48
Urine	0.37	2	1.86	0.15
Total	0.49	7.8	2.85	0.63

Table 3: Calculated excretion of N, P and K content for one slaughter pig (Kaasik 2019, p. 10).

	Manure [t]	DM [%]	N [kg]	P [kg]
Total	3.46	25	31.5	7.3

Table 4: Calculated excretion of N, P and K content for 1000 broilers (Kaasik 2019, p. 10).

2.2 Separation

The nutrient contents of liquid and solid phases depend heavily on, which separation method is used. Using centrifuge, 69 % phosphorus and 32 % nitrogen will end up in the solid fraction, whereas screw press separator separates only 13 % of phosphorus and 8 % of nitrogen are separated into the solid fraction (Kässi et al. 2013, p. 13). It is assumed that potassium is mainly dissolved in water in inorganic form and would behave like soluble nitrogen in terms of separation (ibid.). Thus centrifuge would separate 16 % of potassium into the solid phase (ibid.). Kässi et al. (2013, p. 13) provides no own data about separation of potassium or soluble nitrogen with a screw press, but cites Hjort (2009), who reports that screw press separates 5–18 % of potassium into solid fraction. Since Hjort (2009) also reports that 7–33 % of phosphorus ends up in the solid fraction, but Kässi et al. (2013) gets on 13 %, it can be assumed that the amount of K in solid fraction is closer to the lower limit and 7 % separation efficiency will be used in further calculations.

2.3 Biochar

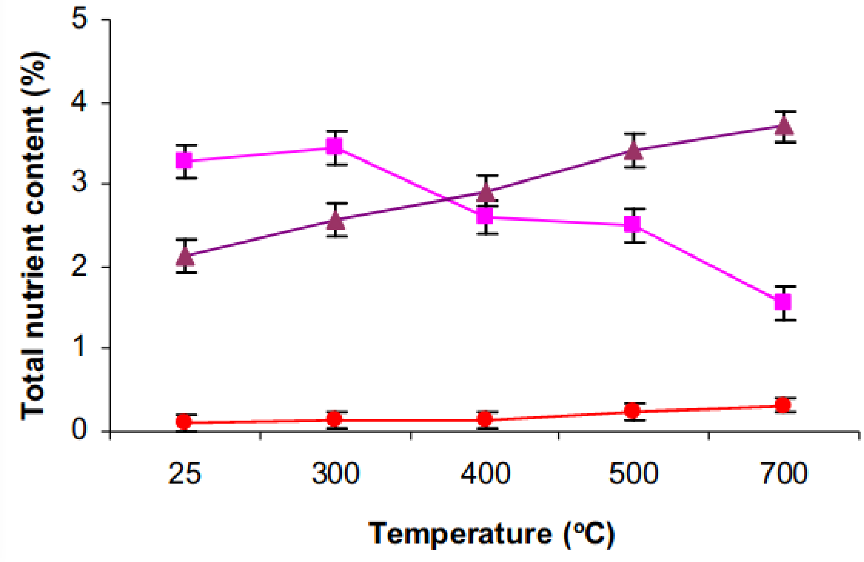

Figure 1: Relative nutrient contents in biochar as function on peak temperature during pyrolysis. Phosphorus is marked with triangles. (Hossain et al. 2010, Figure 2.)

Hossain et al. (2010) have studied the effects of pyrolysis temperature to nutrient properties of biochar produced from sewage sludge. Samples of digested sewage sludge were first pre-treated and pre-dried for two days. The samples were then pyrolysed under controlled conditions with a heating rate of 10° C / min until the peak temperature was reached. (Hossain et al. 2010, p. 224.) Some of the results are presented in Table 5.

	Unit	WW sludge	300° C	400° C	500° C	700° C
Moisture	m-%	7.6	4.3	4.2	3.5	3.4
Ash	m-%	34.0	52.8	63.3	68.2	72.5
C	m-%	32.3	25.6	20.2	20.3	20.4
N	m-%	3.27	3.32	2.40	2.13	1.20
Colwell P	mg/kg	747.5	492.5	740	567.5	527.5
NH_4-N	mg / kg	7275	1175	124.5	25	1.34
NO_3-N	mg / kg	35	0.2	0.2	0.24	0.32
pH		4.42	5.32	4.87	7.27	12
P	m-%	0.92	1.32	2.12	3.32	4.92

Table 5: Contents of some substances and pH in biochar made from wastewater sludge with different peak temperature during the pyrolysis. Mass-percentage of P has been estimated based on Figure 1, others are from Hossain et al. (2010, Table 2).

The amount of Colwell P, phosphorus that is available for plant uptake does vary. The amount of total phosphorus remains approximately constant independent of the temperature, instead. While total phosphorus is not in Hossain et al. (2010, Table 2), it can be estimated from Figure 1. By measuring the figure, it can be seen, that proportional phosphorus content increases by approximately 0.4 %-units. The total mass of biochar yield decreases by over 5 %-units. A plain linear comparison would suggest that the absolute mass of phosphorus increases, which cannot be the case. This can be explained by both the variation in measurements by Hossain et al. and the fact that share of phosphorus is only estimated from a figure.

In a similar matter, while the share of ash content in biochar increases, the amount of ash remains constant during pyrolysis. Thus it can be assumed that the amount of K is constant regardless of the peak temperature of pyrolysis.

The amount of nitrogen decreases and its proportion varies when the peak temperature is increased, which is understandable because nitrogen is in forms that evaporate.

Shackley et al. (2011) have made a thorough review of costs of biochar from different kinds of sources. They, too, have a category for sewage sludge but not for manure, although they have “Poultry litter” as a resource category (Shackley et al. 2011, p. 337, Table 1). While the costs have been assessed from 2011 price level in the United Kingdom, they are a good starting point for evaluating the costs of biochar production. Different costs for biochar produced from sewage sludge through medium-scale and large-scale pyrolyses are presented in Table 6.

Shackley et al. (2011) have gotten even a negative production net cost for large-scale pyrolysis biochar production. However, those calculations include *Renewable obligation certicates (ROCs)*, which are a British system to support renewable energy production (Shackley et al. 2011, p. 342). Similar system for renewable energy production support has existed in Finland, but new power plants can no longer apply to that (Posiva 2019).

Shackley et al. (2011, p. 348) assume that the syngas generated in the pyrolysis process is used to produce electricity. The amount of electricity gained is assumed to be 0.74 MWh / t biochar produced (ibid.). The price of electricity for non-household customers without taxes and levies in the UK was 0.094 EUR / kWh in the first half of 2011 (Eurostat 2019). A net profit 37 GBP / 0.74 MWh is equal to 0.05 GBP / kWh. In 2011, the exchange rate for GBP was 1 EUR = 0.87 GBP (European Central Bank 2019b). Therefore, the net profit of electricity sales would be 0.057 EUR / kWh, and the profit will be assumed to be 60 % of the tax- and levy-free price of the selling price in a syngas powered plant. The levy-free price of electricity for non-household customers was 0.064 EUR / kWh. Assuming the same margin percent, the net profit would be 0.038 EUR / kWh, or 28 EUR / 0.74 MWh as a negative cost of producing 1 t biochar.

Gate fee is a fee that the producer of waste pays the actor taking care of further treatment of the waste when leaving the waste for treatment. Gate fees for non-household biowaste are on average 112 EUR / t in 2019 (calculated from HSY 2019; Kiertokapula 2019). As pyrolysis of manure is a means of biowaste treatment, it is reasonable to assume that the pyrolysis plant is the receiver of the gate fee.

If we assume that the numbers in table 6 apply to Finland bar ROCs and different values for gate fee and selling electricity, it can be estimated that the costs of producing a tonne of biochar from sewage sludge through large-scale pyrolysisi in Finland are 112 EUR / t if electricity is produced for sales and the treatment plant gets the gate fees for feedstock, 10 EUR / t if electricity is not produced or sold, and 102 EUR / t neither of these sources of income are present. The 2011 British prices in GBP have been converted into 2019 euros with exchange rate from 2011, 1 EUR = 0.87 GBP (European Central Bank 2019b) into 2018 purchace power, 1 EUR_{2011} = 1.08 EUR_{2019}, (Statistics Finland 2019). Although these prices should not be taken for granted, it can be assumed that the production cost is low, possibly negative.

It can also be assumed that there are no signicant differences in net energy consumption in regards to the peak temperature of pyrolysis; while higher temperatures require more enrgy, LHV of the gas gained has a linear correlation with the peak temperature (Neves et al. 2011, Equation 13) and the total gas yield increases with the temperature (Neves et al. 2011, Figure 3).

	Medium-scale pyrolysis GBP / t	Large-scale pyrolysis GBP / t	Large-scale in Finland EUR / t
Sales of electricity	−37	−37	−28
ROCs	−74	−74	–
Avoided gate fee	−90	−90	−112
Capital cost	101	45	56
Feedstock	0	0	0
Transport	12	12	15
Storage	15	15	19
Natural gas	11	1	1
Labour	48	4	5
Plant cost	60	6	6
Net cost	52	−109	−38···102

Table 6: Costs of biochar from green waste and sewage sludge produced by medium- and large scale pyrolysis GBP/t (Shackley et al. 2011, pp. 346–347, Tables 9 and 10) and compatible values for large-scale pyrolysis in Finland EUR/t.

Biochar is a part of carbon-sequestration as a long-term carbon storage in soil. Therefore the value of carbon trade could be included when calculating price for biochar. However, the carbon trade value has to take into account several other factors, e.g. CO_2 emissions during manufacture and shipping. Thus, carbon trade is not included in this study.

2.4 Nitrogen and phosphorus balance in Finland

Total nitrogen use in agriculture in Finland is 228 000 t/a. Of that, 76 000 t is from manure, 4 000 t from recycled nutrients, and 148 000 t from synthetic fertilisers (Marttinen et al. 2017, p. 9). Marttinen et al. (2017, p. 11) estimate that total nitrogen content of livestock manure more or less equals the amount of nitrogen from manure-fertilising, i.e. all livestock manure is currently used for fertilising. According to Marttinen et al. (2017, p. 16), 95 % of manure is recycled directly in agriculture, and over 99 % is recycled by some means. Likewise, 100 % of excess grass seem to be recycled, although that is less systematic recycling and more letting grass to decompose on field (ibid.).

	N [t/a]	P [t/a]
Mineral fertilisers	148 000	11 300
Manure	76 000	19 300
Other recycled nutrients	4 000	1 700
Total	228 000	32 300

Table 7: Total annual N and P use in Finland (Marttinen et al. 2017, p. 9).

According to Luonnonvarakeskus (2018), average nitrogen balance in Finland shows 53.7 $\mathrm{kg_N}$/ha surplus. The total field area in Finland is approximately 2.3 M ha, of which 2.0 M ha was used for cultivation in 2015 (Vorne and Karppinen 2017, pp. 18–19). Using these numbers, total amount of excess N can be estimated to 106 000 t/a, or 47 % of the total N used for fertilising.

The phosphorus use by Finnish agriculture is 32 300 t/a. 19 000 t come from manure and the amount of P from artificial fertilisers is 11 300 t. 65 % of P used in fertilising has been recycled as manure and other organic fertilisers. (Marttinen et al. 2017, 9.) Phosphorus use has also become more efficient, partially due to excess P that has accumulated in soil: in some areas annual P balance has been negative (Luonnonvarakeskus 2018). For the whole country, however, the annual P balance has been 2.8–5.1 kg/ha (ibid.). Using the same area of cultivated fields as with N, amount of excess P can be estimated to 11 600 t in 2017, which is approximately the amount of phosphorus from artificial sources.

Van Dijk et al. (2015) presents thorough information about phosphorus flows in all European Union member states. According to supplementary data (van Dijk et al. 2015, Table S5), the amount of excess phosphorus in Finnish agriculture is 18 000 t per year and total phosphorus losses are almost 22 000 t, exceeding slightly the amount of mineral P fertilisers. However, van Dijk's data is relatively old and Luonnonvarakeskus (2018) shows that the amount of P fertiliser use and excess phosphorus have had a declining trend in last years.

According to Marttinen et al. (2017, p. 10), the current use of recycled phosphorus is 21 000 t/a. Ylivainio et al. (2014, p. 18) estimates the need of phosphorus fertilisation in Finland to 8.6 kg_{P}/ha. With 2.0 M ha of cultivated field area, the total need of phosphorus would be approximately 17 000 t/a. Therefore at least 4 000 tonnes of phosphorus would be available for export. Besides that, approximately 5 000 t of recyclable phosphorus is produced but not utilised annually. This amount consists of sludges from wastewater treatment and forest industry and residues from food industry. (Marttinen et al. 2017, p. 10.)

2.5 Current fertiliser prices in target exporting countries

AfricaFertilizer.org is a website that provides information regarding fertiliser statistics and fertiliser market intelligence. The site has regarding e.g. fertiliser production, trade, consumption, prices, and use. (Africa Fertilizer 2019.) The statistics for fertiliser prices in Côte d'Ivoire are from AfrivaFertilizer.org and the values used are the average prices of year 2019 as of October 2019, unless otherwise stated.

According to Heffernan et al. (2012, p. 30), fertiliser prices in Ethiopia are determined by the Ministry of Agriculture and Rural Development (MoARD) in consultation with stakeholders. Agricultural Input Supply Enterprise, as the sole importer, determines costs from the port to cooperative warehouse and the retail prices for farmers are determined by regional MoARD after consulting local cooperatives. Distribution of fertilisers to more remote areas is likely to suffer if the cooperatives do not receive sufficient margins. (ibid.)

2.6 Feasibility analysis

2.6.1 Production costs

Production costs consist of required investments, processing and transport. Besides purchasing and installing the needed machinery, investments include interests and maintenance costs. The main components of processing are costs of electricity and labour. (e.g. Kässi et al. 2013, p. 12, Table 1.) In case of biochar production, the heat for the process is assumed to be produced from natural of biogas and that the processing facility is self-sufficient regarding electricity (Shackley et al. 2011).

Eurostat provides data of electricity prices in EU countries and mean prices for the whole EU. From the first half of 2017 to the first half of 2019 mean prices for non-household consumers in EU have varied between 0.140 and 0.155 EUR/kWh, all taxes and levies included, mean being 0.145 EUR/kWh. During the same time period, the minimum and maximun prices in Finland were 0.083 EUR/kWh and 0.088 EUR/kWh, mean being 0.085 EUR/kWh. (Eurostat 2019.)

In the examples by Kässi et al. (2013, p. 12, Table 1) investment costs include purchase pricee, which are 53 900 EUR for a mobile screw press separator, 23 500 EUR for a stationary screw press separator and 100 000 EUR for a decanter centrifuge. A slurry pump for separator will cost an extra 4 500 EUR. Investment lifetime is assumed to be 12 years. Kässi et al. (2013) use an interest rate of 5 % in their calculations. However presently interest rates are lower, for example Euribor reference rates have been negative since 2015 (Suomen Pankki 2019). Although, during the 12-year investment lifetime it is possible that rates will go up at some point. Banks do not lend money with negative interests either but always add an interest rate margin.

Although there are separators in use in Finland already, the calculations are made under assumption that all separators needed for export are new investments. Some values needed for assessing investment are presented in table 8. The price of a decanter centrifuge is calculated from the price in Jacobsen et al. (2002, p. 38), which is the price in DKR in 2002. The factor for currency conversion is the mean of conversion rates between DKR and EUR in time period 2002-01-29–2019-11-30, 1 EUR = 7.47 DKR (European Central Bank 2019a). The variation in the rate has been very moderate during the whole time and the mean can, thus, be chosen for use. The converted value was then multiplied by 1.25 to get the corresponding value in 2018 money (Statistics Finland 2019).

To estimate the total investment needed, the amount of needed machinery has to be known. Two scenarios for both screw press separator and centrifuge will be assessed: In one it will be assumed that the separators run for 8 h/d and there are 250 working days in a year. In the other, the separators will run all the time throughout the year except during maintenance break. Jacobsen et al. (2002, p. 35) estimate that in the latter case, running time would be 7 000 h/a. When the capacities of separators are known, the total time needed for separation and the amount of separators can be easily calculated.

Besides investment costs, there is also need for operating staff. Kässi et al. (2013, p. 12, Table 1) estimate cost of labour for separation 13 EUR/h. Jacobsen et al. (2002, p. 40) estimate the annual labour costs as 360 000 DKR, which would be 51.43 DKR / h, or 8.63 EUR / h in 2018 price level. It is clear that the cost by Kässi et al. is closer to the actual costs, and likely even that is underestimated.

		Stat. screw press	Centrifuge
Capacity		13 m³/h	7 t/h
Separation efficiency	% into solid fraction	7	17
Electricity consumption		0.29 kWh/m³	2.9 kWh/t
	% DM into solid	33	63
	% N into solid	8	32
	% P into solid	13	69
Cost of separator	EUR	23 500	214 000
Investment lifetime	a	12	20
Cost of slurry pump	EUR	4 500	4 500

Table 8: Efficiencies and costs of screw press separators (Kässi et al. 2013, pp. 12–13) and decanter centrifuge (Jacobsen et al. 2002, p. 38).

As for biochar, the production costs are described in table 6. More detailed background, of which capital and variable costs consist, is presented in Shackley et al. (2011).

2.6.2 Shipping costs

MoveDB.com provides data about shipping costs in containers. The two usual types of containers are 20 ft and 40 ft containers, which can contain loads of 33.1 m³ or 28.2 t and 67.5 m³ or 26.6 t (MoveDB.com 2019). While 40 ft container has larger volume, the maximum mass it can contain is lower than 20 ft container's due to the higher mass of the container itself (ibid.). MoveDB.com does not contain data about shipping from Finland or to Côte d'Ivoire or Ethiopia – obiously there are not data about water transport to a landlocked country. However there are data about shipping costs from the UK to Nigeria and Kenia, which can be utilised to estimate shipping costs (MoveDB.com 2018). The actual cost of water transport from Finland is likely to be higher, due to longer transport distance. In addition to water transport there will be some kind of land (truck) transport at both ends of the transport.

The prices presented in USD will be converted into EUR by using excange rate 1 USD = 0.9 EUR (European Central Bank 2019c).

		to Côte d'Ivoire		to Ethiopia	
Container		20	40 ft	20 ft	40 ft
Cost / container	USD	1 128	1 683	2 024	3 020
Max load	m³	33.1	67.5	33.1	67.5
Max load	t	28.2	26.6	28.2	26.6
Cost	USD / m³	34	25	61	45
Cost	USD / t	40	60	72	114

Table 9: Shipping costs under assumption FI–CI and FI–ET cost approximately same as UK–NG and UK–KE (MoveDB.com 2018).

Table 9 presents the prices for shipping in containers. The actual cost of transport is higher than the values in table 9. These values can still be used to make estimations.

It is easy to calculate, whether the volume or mass limit is to be used when assessing the amount of needed containers. When a products density is known, it can be seen, whether a load of the maximum allowed mass has volume that still fits in the container or vise versa. The limits are 852 kg/m³ for 20 ft container and 395 kg/m³ for 40 ft container. If the density is greater than the limit value, mass is the measure to be used, otherwise it is the volume. In order to estimate the density of manure, DM content needs to be known. The density of DM is 83 kg/m³ (Kässi et al. 2013, p. 16) and the density of the moist content is assumed to be same as that of water, 1 000 kg/m³. The estimated density of biochar, based on Brewer and Levine (2015) is 1 300 kg/m³. When using volume as the measure of load, it has to be taken into account. It will be assumed that manure containers take 10 % of the inside space of a shipping container, and therefore 90 % of the shipping container's volume is available for manure.

In addition to actual transportation, customs and other taxes have to be taken into account, because they do increase the price – or inversely when the retail price is fixed, they decrease the exporter's turnover.

2.6.3 Expected income

Kässi et al. (2013, pp. 6–8) describe how to define prices for different nutrients when prices and nutrient contents of commercial fertilisers are known. The matrix equation for nutrient prices is

$$A^{-1}b = x \tag{1}$$

(Kässi et al. 2013, Equation 1)

where A is matrix of nutrient contents of different fertiliser products and b is a vector of the prices of respective fertiliser products.

$$\begin{bmatrix} F_{1N} & F_{1P} & F_{1K} \\ F_{2N} & F_{2P} & F_{2K} \\ F_{3N} & F_{3P} & F_{3K} \end{bmatrix}^{-1} \times \begin{bmatrix} P_{F1} \\ P_{F2} \\ P_{F3} \end{bmatrix} = \begin{bmatrix} P_N \\ P_P \\ P_K \end{bmatrix} \tag{2}$$

(Kässi et al. 2013, Equation 2)

where F_{nX} is the content of nutrient X in fertiliser F_n, P_{Fn} is the price of fertiliser F_n and P_X is the calculated price for nutrient X.

Potassium is included in the price evaluation since many commercial fertiliser products contain potassium and K content affects the total price of the fertiliser.

Kässi et al. (2013, p. 7) recognise that there are some unexpected and unexplained variation in fertiliser prices and, thus, offer a more flexible variant of the basically same equation in form of ordinary least squares regression (OLS). The equation does not differ notably but it takes into account that nutrient-price relationships are not always strickly linear. The constant term is assumed to be zero, because the price of a fertiliser with no nutrients is assumed to be 0.

$$\begin{bmatrix} F_{1N} & F_{1P} & F_{1K} \\ F_{2N} & F_{2P} & F_{2K} \\ \cdots & \cdots & \\ F_{nN} & F_{nP} & F_{nK} \end{bmatrix}^{-1} \times \begin{bmatrix} P_{F1} \\ P_{F2} \\ \cdots \\ P_{Fn} \end{bmatrix} \sim \begin{bmatrix} P_N \\ P_P \\ P_K \end{bmatrix} + \varepsilon \tag{3}$$

(Kässi et al. 2013, Equation 4)

However, while the prices of nutrients are good guidelines for evaluating prices for the end-product, the price of the fertiliser product is not based solely on those. For example, in biochar, carbon sequestration and soil-enhancement properties create value. Data concerning biochar retail prices are scarce and mostly focused in biochar produced from wood for the U.S. market (see e.g. Campbell et al. 2018). As for manure, at least in Ethiopia manure is preferred to mineral fertilisers even though the nutrient content is usually lower (see 1.1.1).

2.6.4 Investment profitability

Brealey et al. (2017) describe methods to evaluate investment profitability. Two commonly used methods are payback period (PBP) and net present value (NPV).To prevent unnecessary complexity, it is assumed that production and sales of end-products and the retail prices and, thus, annual turnover are constant during the whole evaluation period. Same assumption covers also all costs and, therefore, the net income. In reality all these vary due to several reasons, but predicting those are too complex to be dealt with in this study.

PBP (Equation 4) is used to estimate how long it will take to pay back the investment. If the payback time is shorter than the investment lifetime, the investment is found *possible*.

NPV (Equation 5) is the sum of (possibly varying) annual net incomes during investment lifetime discounted with the interest rate, from with the investment cost is then subtracted. If NPV is positive the investment is profitable. (Brealey et al. 2017, pp. 21–23.)

$$PBP = \frac{I}{N_I} \tag{4}$$

$$NPV = \sum_{k=1}^{m} \left[N_{Ik} \left(1+r\right)^{-k} \right] - I \tag{5}$$

I is total investments, N_I is annual net income – N_{Ik} is that of k:th year – and r in the interest rate. When calculating NPV for biochar, it has to be acknowledged, that the investment costs are already included in net income calculation and, thus the equation for NPV is simply into equation 6.

$$NPV = \sum_{k=1}^{m} N_{Ik} \left(1+r\right)^{-k} \tag{6}$$

The formula for PBP can be further used to calculate the needed net income in order to have payback period equal to or less than the planned lifetime of investment (Equation 7).

$$N_I = \frac{I}{PBP} \tag{7}$$

Likewise, Equation 5 can be used to determine minimum net income to have a positive NPV. The equation is a bit more complicated. Therefore the net income is computed numerically using a Python script.

3 Results

The central results of this study have been gathered in Tables 20, 21 and 22.

3.1 Suitable type of manure

In terms of treatment, the most suitable types of manure for biochar feedstock are those that are rich in nutrients and have relatively low moisture content to begin with. Using values presented in Kaasik (2019, pp. 9–10), it is easy to see that in those terms dry manure of dairy cows is the best raw material for biochar. Cow manure contains 4.9 kg N and 1.3 kg P per tonne. It also contains 1.4 kg K per tonne. Dry matter content of cow faeces is 13.5 %. According to Marttinen et al. (2017, Table 3), the annual production of dry manure from cows is 4.7 million tonnes, which contains (according to Kaasik 2019, p. 9) 22 900 t N, 6 300 tonnes P and 6 500 t K. The amount of P is larger than the amount of exportable excess phosphorus, 4 000 t.

For separation purposes, slurry is the most meaningful raw material. Also, slurry is the type of manure which gains most advantage from separation for transport. Finland's annual cow slurry contains approximately 4 000 t P, which is equal to the amount of excess P. Also the combined amount chicken and pig slurry has almost 4 000 t phosphorus.

The amount of dry manure to contain 4 000 t P is 3 million tonnes, which contains 14 500 t N and 4 100 t K. To have 4 000 t P, approximately 4.6 million tonnes of slurry is needed. That amount of slurry contains 34 000 t N and a bit over 10 000 t K.

3.2 Refining

3.2.1 Separation

The results of separation are presented in table 10. These results suggest that a centrifuge separates much larger amount of P into solid fraction. The centrifuge separates also much larger amount of N into solid fraction, although over two thirds of N remains in liquid fraction. As for screw press separator, 87 % of P remains in liquid fraction. These results suggest

		Centrifuge	Screw press separator
Share of P into solid	%	69.00	13
Share of N into solid	%	32.00	8
Share of K into solid	%	16	7.00
P into solid	t	2 752.55	518.6
N into solid	t	10 794.42	2 698.61
K into solid	t	1 660.53	726.48
P into liquid	t	1 236.65	3 470.60
N into liquid	t	22 938.14	31 033.96
K into liquid	t	8 717.79	9 651.84
DM into solid	m-% of total solids	63	33
Wet weight into solid	m-%	17	7
Liquid fraction	t	3 690 425.54	4 135 055.13
DM in liquid fraction	t	172 738.59	312 796.91
DM in liquid fraction	m-% of liquid fraction	4.7	7.6
Density of liquid fraction	kg/m³	659.1	544.7
Solid fraction	t	755 870.29	311 240.71
DM in solid fraction	t	294 122.47	154 064.15
DM in solid fraction	m-% of solid fraction	38.9	49.5
Density of solid fraction	kg/m³	188.7	154.6
P in solid	m-%	0.4	0.2
N in solid	m-%	1.4	0.9
K in solid	m-%	0.2	0.2
P in liquid	m-%	0.2	1.1
N in liquid	m-%	3.0	10.0
K in liquid	m-%	1.2	3.1

Table 10: Amounts and properties on Finnish cow slurry treated with separation with centrifuge and screw press separator.

that separation of P is much more efficient with centrifuge. On the other hand, if optimisation of liquid fraction is wanted, screw press separator is the better one.

The N:P ratios of centrifuge separated slurry are 3.5 for solid and 15 for liquid fraction. The respective N:P ratios for screw press separated slurry are 4.5 and 9. The N:P ratios fall within the preferred 4–9 in both fractions after screw press separation. Centrifuge results in a low N:P ratio for solid fraction and very high N:P ratio for liquid fraction. Thus, if there are two export destinations, one of which has scarcity of N and the other of P, centrifuge produces more fitting export goods.

3.2.2 Biochar

		Manure	300° C	400° C	500° C	700° C
DM	t	400 306				
Manure with 7.6 % moisture	t	433 232				
Biochar yield	t		289 421.7	254 995.3	231 777.5	209 760.7
Total P	t	3 989.2	3 822.7	3 822.7	3 822.7	3 822.7
Total N	t	22 962.3	9 608.8	6 119.9	4 936.9	2 517.1
Colwell P	t	323.8	213.4	320.6	245.9	228.5
Total K	t	4 138.5	4 138.5	4 138.5	4 138.5	4 138.5
N:P ration		5.8	2.5	1.6	1.3	0.7
pH		4.42	5.32	4.87	7.27	12

Table 11: Amounts of biochar, its N and P contents, and pH after pyrolysis with different peak temperatures.

Even dry cow manure contains high moisture content with only 13.5 % dry matter (Kaasik 2019, p. 9). 3 million tonnes of dry manure contain, thus, 630 000 t solids. In order to reach the starting moisture of sewage sludge, manure has to be predried. After pretreatment manure should contain 7.6 % moisture and have a total mass of approximately 680 000 t. The amounts of biochar produced after different lengths and peak temperatures in pyrolysis are presented in table 11.

With lower peak temperatures, the biochar end-product is more acidic whereas higher temperatures lead to alkalinity. Since the amount of nitrogen decreases when treating temperature is increased, in terms of N lower temperatures are better. This also leads to very low

Fertiliser	2019 Average price in CI [USD/t]
NPK 15 15 15	491
PK 0 23 19 + 6.5 S + 5MgO + 10CaO	492
Urea	486
NPK 12 22 22	558
NPK 15 15 15 + 6 S + 1 B	473
$Ca(NO_3)_2$	486
NPK 12 11 18 + 8 S + 3 MgO	483
NPK 15 9 20 + 9.5 S	599
NPK 14 10 18 + TE	549

Table 12: Prices of different fertiliser products in Côte d'Ivoire (average 2019) (Africa Fertilizer 2019).

Nutrient	Price [USD/kg]
N	1.24
P	0.42
K	1.62
S	0.38

Table 13: Prices of nitrogen, phosphorus, potassium and sulphur

N:P˝ratios when the peak temperature rises. Thus, exporting high-temperature biochar is not meaningful unless the importing country has specifically P scarcity. Besides that, the pH rises along with peak temperature and therefore high-temperature biochar has most value in areas with acidic, P poor soil. Otherwise low-temperature biochar is more optimal product.

3.3 Fertiliser nutrient prices

The average prices for fertilisers in 2019 as for September 2019 in Côte d'Ivoire are presented in table 12. In most of the products "NPK" followed by three numbers tell the percentage of nitrogen, phosphorus and potassium, respectively, in the product. Some fertilisers contain also other nutrients, whose percentages are expressed after the "NPK" statement.

Using Equation 3 and Least Square solver *np.linalg.lstsq* of *NumPy* in a Python script, nutrients got prices presented in table 13.

3.4 Production costs

3.4.1 Separation

		Centrifuge	Screw press
Slurry	t	4 450 000	
Total time needed	h	635 000	155 000
Labour cost	M EUR	1.9	7.6
Cost of electricity	kEUR	1 900	76
Total variable costs	M EUR	9.5	1.95
7 000 h/a			
Machines needed		90	22
Total investment	M EUR	20	1.2
Required net income for $PBP =$ lifetime	kEUR	990	99
Required net income for $NPV > 0$	M EUR	1.6	0.135
Required turnover	M EUR	11.1	2.1
2 000 h/a			
Machines needed		320	77
Total investment	M EUR	69.5	4.2
Required net income for wanted $PBP =$ lifetime	kEUR	3 500	348
Required net income for $NPV > 0$	M EUR	5.6	0.47
Required turnover	M EUR	15	2.4

Table 14: Variable and investment costs for decanter centrifuge and screw press separator and minimum required net income and turnover in order to make profit. Shipping costs are not included.

Production costs including both investment and variable costs are presented in table 14. It can be seen that the investment costs for screw press separators are and order of magnitude less than those for centrifuges. Same is true for variable costs, too. This leads to requirement for 5–6 times bigger sales in order to have a profitable business.

Shipping of separated manure is computed by volume, because the density of screw press separeted solid fraction is 154.6 kg / m^3 and liquid fraction 544.7 kg / m^3. For centrifuge separated manure, the respective densities are 188.7 kg / m^3 and 659.1 kg / m^3. The shipping costs for separeted manure are in table 15. The shipping costs for manure are notable, which is mostly due to high moisture content.

		Côte d'Ivoire	Ethiopia
Solid from screw press	EUR	55 780 000	100 100 000
Liquid from screw press	EUR	210 300 000	377 400 000
Solid from centrifuge	EUR	110 900 000	199 100 000
Liquid from centrifuge	EUR	155 100 000	278 300 000
300° biochar	EUR	11 580 000	22 020 000
500° biochar	EUR	9 271 000	17 636 000
700° biochar	EUR	8 390 000	15 960 000

Table 15: Shipping costs of manure and biochar.

3.4.2 Biochar

Density of biochar is 1 300 kg / m³ and, thus its transport costs are calculated according to mass. Also biochar's shipping costs are in table 15. The shipping costs for biochar are an order of magnitude lower than those of manure, which is understandable since biochar has no to little moisture.

The detailed production costs of biochar are not presented in this study but total costs for 1 t biochar have been presented in table 6. Depending on, whether of not the biochar production yields also other sources of revenue, the total production costs are between16 500 000 and 29 500 000 EUR (see table 16). Under the assumptions of cost structure in table 6, the biochar is obviously feasible if gate fees or electricity production are taken into account as sources of revenue. However, if other sources of revenue are not available, the production costs are high.

Electricity & gate fee	EUR/a	16 500 000
Electricity	EUR/a	21 400 000
Gate fee	EUR/a	2 890 000
No other revenues	EUR	29 500 000

Table 16: Production cost of biochar with 300 ° pyorlysis peak-temperature and different assumptions concerning sources of revenue.

		Centrifuge	Screw press
Solid fraction	USD	17 000 000	4 500 000
Liquid fraction	USD	43 000 000	55 500 000
Total	USD	60 000 000	60 000 000

Table 17: Value of nutrients in solid and liquid fractions separated with centrifuges or screw press separators.

3.5 Predicted turnover

3.5.1 Separation

The values of nutrients according to the recent prices in Côte d'Ivoire (tables 12 and 13) in different fractions are presented in table 17.

3.5.2 Biochar

Pyrolysis peak temperature	Price of nutrients
300 ° C	20 300 000 USD
400 ° C	15 900 000 USD
500 ° C	14 500 000 USD
700 ° C	11 500 000 USD

Table 18: Values of nutrients in biochar after pyrolysis with different peak temperatures.

Biochar nutrient values are presented in table 18. These prices do not take into account the value of the carbon.

3.6 Net income and NPV

By looking the numbers in table 19, it becomes clear that shipping separated manure fraction to Ethiopia or Côte d'Ivoire is by no means profitable, since only the shipping costs are an order of magnitude bigger than potential turnovers. Production costs presented in table 14 are very low compared to shipping costs. Shipping costs could be decreased by drying the manure prior to shipping, but drying would increase production costs due to energy needed. Drying would also decrease the value because some amounts of N will evaporate during the drying process.

		Screw press		Centrifuge	
		Solid	Liquid	Solid	Liquid
Value of nutrients	M EUR	4.27	50.1	15.5	38.3
Shipping to CI	M EUR	50.2	189	99.9	140
Shipping to ET	90.1	340	179	251 EUR	

Table 19: Potential sales and shipping costs for different scenarios for manure.

As for biochar (table 22), it is clear that solely manufacturing and shipping biochar is prejudiced action with over 10 000 000–30 000 000 EUR annual deficit. However, if biochar manufacturer is the receiver of gate fees, net income becomes profitable. If the by-product syngas from pyrolysis is captured an utilised in electricity production and the gate fees are calculated for biochar income, the operation is profitable, with an NPV of 200–300 M EUR.

Available excess P	t/a	4 000
Corresponding amount of slurry	t/a	4 400 000
Corresponding amount of N	t/a	34 000
Corresponding amount of K	t/a	10 000
Separation with centrifuge		
Solid fraction	t/a	756 000
Solid fraction	m^3/a	4 000 000
P	t/a	2 800
N	t/a	10 800
K	t/a	1 700
Liquid fraction	t/a	3 690 000
Liquid fraction	m^3/a	5 600 000
P	t/a	1 200
N	t/a	23 000
K	t/a	8 700
Value of solid fraction	EUR/a	15 500 000
Value of liquid fraction	EUR/a	38 000 000
Total	EUR/a	53 500 000
Variable costs	EUR/a	9 500 000
Capital costs	EUR/a	990 000
Total costs	EUR/a	10 400 000
Net income bar shipping costs	EUR/a	27 600 000
Separation with screw press separation		
Solid fraction	t/a	310 000
Solid fraction	m^3/a	2 000 000
P	t/a	520
N	t/a	2 700
K	t/a	730
Liquid fraction	t/a	4 140 000
Liquid fraction	m^3/a	7 590 000
P	t/a	3 500
N	t/a	31 000
K	t/a	9 700
Value of solid fraction	EUR/a	4 300 000
Value of liquid fraction	EUR/a	49 200 000
Total	EUR/a	53 500 000
Variable costs	EUR/a	1 950 000
Capital costs	EUR/a	99 000
Total costs	EUR/a	2 040 000
Net income bar shipping costs	EUR/a	51 460 000

Table 20: Summary of amounts, compositions, costs and revenues of separated cow slurry.

Available excess P	t/a	4 000
Corresponding amount of slurry	t/a	4 400 000
Corresponding amount of N	t/a	34 000
Corresponding amount of K	t/a	10 000
Production costs		
Incl. sales of electricity & gate fees	EUR/a	16 500 000
Incl. sales of electricity	21 000 000	
Incl. gate fees	EUR/a	2 890 000
Only biochar production	EUR/a	29 500 000
Value of nutrient content	EUR/a	18 200 000
Net income bar shipping costs		
Incl. sales of electricity & gate fees	EUR/a	34 700 000
Incl. sales of electricity	-2 800 000	
Incl. gate fees	EUR/a	21 090 000
Only biochar production	EUR/a	-11 300 000

Table 21: Summary of amount, composition, costs and revenues of biochar from cow manure.

		Shipping to CI	Shipping to ET
Separated manure			
Shipping costs	EUR/a	239 000 000	430 000 000
Centrifuge			
Net income bar shipping costs	EUR/a	27 600 000	
Net income	EUR/a	211 400 000	402 400 000
Screw press separator			
Net income bar shipping costs	EUR/a	51 460 000	
Net income	EUR/a	187540000	378540000
Biochar			
Shipping costs	EUR/a	10 400 000	19 800 000
Net income			
Incl. sales of electricity & gate fees	EUR/a	24 300 000	14 900 000
Incl. sales of electricity	13 200 000	22 600 000	
Incl. gate fees	EUR/a	20 986 000	1 290 000
Only biochar production	EUR/a	11 404 000	31 100 000
NPV (20 year payback time)			
Incl. sales of electricity & gate fees	EUR/a	302 600 000	185 400 000
Incl. sales of electricity	EUR/a	169 500 000	286 600 000
Incl. gate fees	EUR/a	133 500 000	16 340 000
Only biochar production	EUR/a	270 500 000	387 600 000

Table 22: Net incomes and NPV

4 Discussion and conclusions

As it was seen, the value of nutrients in separated manure exceeds the production costs, but the shipping costs exceed the possible income by an order of magnitude. While manure is held in higher value than mineral fertilisers in Ethiopia, it can by no means add the manure's retail value even close to covering the shipping costs. The high shipping costs are due to high moisture content, even in the solid fraction. Whilst the manure could be dried before of after separation, drying would increase energy use and evaporation of N, thus reducing both economic and environmental meaningfulness of manure processing.

Shipping of biochar costs much less than shipping of manure. However, the shipping costs do exceed the value of nutrients in biochar. It is easy to argue that biochar has a value higher than only its nutrient content. The carbon-sequestration and soil enrichment properties are certainly to encrease the retail value of biochar. However, the values of those are not known, and in order to have income exceed the costs, the retail price would likely become too high to afford for farmers in developing countries.

Recovering the syngas by-product from biochar production and using it to produce electricity does increase the income of biochar producer. Yet, the impact of producing and selling electricity is relatively low. What does make manufacturing biochar profitable is to direct the gate fees for manure to biochar producer, which *is* the waste treating operator in this case.

In conclusion, high costs of long-distance shipping make exporting exporting residue nutrients from Finland to Ethiopia or Côte d'Ivoire economically non-viable. Economically, most advantage of recycling fertilisers is gained when transport distances are short. However, biochar production can be very feasible when other sources of income besides sales of biochar is taken into account. Together with positive properties of biochar, this suggests that biochar is the most meaningful product for export.

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