The Utilization of Industrial By-products as Soil Conditioners and Fertilizers in Non-food Potato Production

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Peatlands require soil improvement to be suitable for cultivation. Creating eco-friendly and cost-effective carbon sinks in peatlands originated from peat production has several benefits. For this purpose various valuable biomass can be used by utilizing industrial by-products also as soil conditioners and fertilizers. For example, the addition of such materials has potential to transform peat bogs, which otherwise would slowly release methane, into productive cultivated areas. The rehabilitation of peat bogs from unused land into various agricultural and forestry areas is also a viable business activity. The examined industrial by-products could have many agricultural applications in non-food potato production, wherein monoculture causes problems such as condensed soil, lost humus or soil organic matter, and reduced nutrient retention capacity, leading to increased leaching of nutrients and negative impacts on the environment. Five industrial by-products were examined in this study as soil conditioners and fertilizers: fiber sludge, biocarbon, hygienic biodigestate, paper mill sludge, and gypsum waste. Based on the results of a nutrient content analysis, hygienic biodigestate and fiber sludge were the most effective fertilizers.

Keywords: Soil conditioner; Fertilizer; Fiber sludge; Paper mill sludge; Biocarbon; Biodigestate; Gypsum; Non-food production; Peat bog; Carbon sink

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INTRODUCTION

The Earth's population is increasing by up to 200,000 people per day, while the amount of available land for food production is decreasing. When salinization and soil desertification occur, as well as rising water levels in coastal areas, formerly arable land is converted to bioenergy production. However, the current global trend is to move from fossil raw materials towards a bio-economy, increasing the need for fields and woodlands. Thousands of hectares of peatlands are removed from peat production annually, and in Finland, an estimated 50,000 hectares of land have become non-productive. Most of the areas that no longer produce peat are located in southern, central, and northern Ostrobothnia. However, peatlands require soil improvements to be suitable for all kinds of cultivation uses (Myllys 1996).

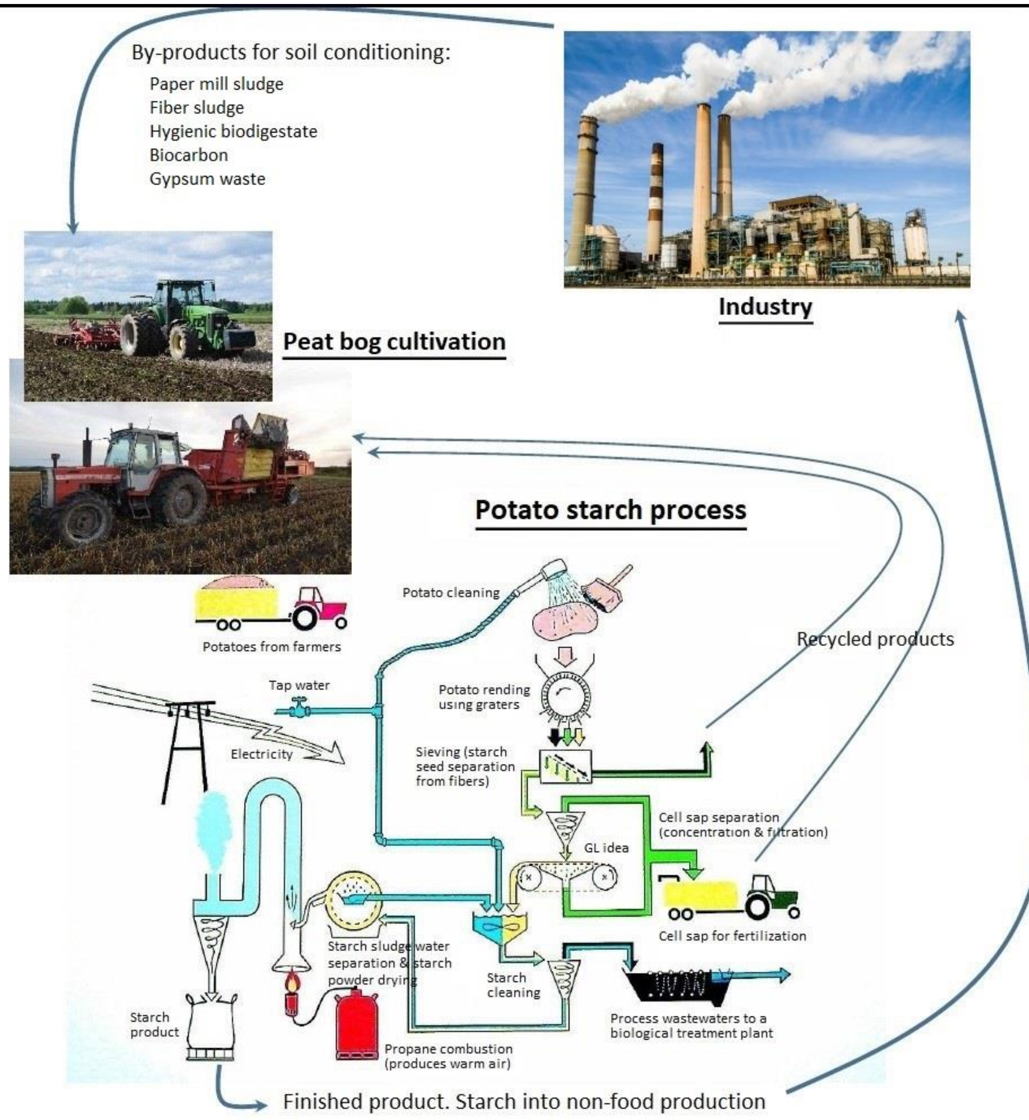

Fig. 1. The circular economy cycle of non-food potato production

Peatlands cover only 3% of the Earth's land surface, but boreal and subarctic peatlands store about 15% to 30% of the world's soil carbon as peat (Limpens *et al*. 2008). Despite covering less than 3% of the Earth's land surface, boreal and subarctic peatlands store between 270 TgC and 370 TgC (1 TgC = 10^{12} g of carbon) as peat (Turunen *et al.* 2002), which would also amount to 34% to 46% of the 796 TgC currently held in the atmosphere as CO_2 (Solomon *et al*. 2007). These massive deposits are the legacy of peatlands acting as sinks of atmospheric carbon dioxide (CO_2) for millennia, but they also illustrate the potential for large CO_2 and methane (CH_4) fluxes into the atmosphere or dissolved carbon (DC) into rivers if peatland carbon stores were to be destabilized by global warming, and changes in land use are not made. Until now, peatlands have contributed to global cooling on the millennium scale (Frolking and Roulet 2007), and undisturbed peatlands are likely to continue functioning as net carbon sinks despite the large interannual variability of individual peatlands (Moore *et al*. 1998).

Soil improvement aims to improve water conductivity and water retention, improve nutrient retention, adjust the soil's pH by liming, and utilize recycled nutrients. In non-food production (Fig. 1), recycled nutrients could be used increasingly in the future according to the circular economy principle. The intensification of agriculture by the use of high-yielding crop varieties, fertilization, irrigation, and pesticides has contributed substantially to the tremendous increases in food production over the past 50 years. Land conversion and intensification, however, also alter biotic interactions and patterns of resource availability in ecosystems and can have serious local, regional, and global environmental consequences. The use of ecologically sound management strategies can increase the sustainability of agricultural production while reducing off-site consequences (Matson *et al*. 1997).

A new innovation in this ongoing project is to introduce eco-friendly and cost-effective materials that can serve as carbon sinks. These are added to peatlands that no longer produce peat. Various types of valuable biomass that are available from industrial by-products can be used as soil conditioners and fertilizers. The carbon sink potential of peatlands depends on the balance of carbon uptake by plants and microbial decomposition. Both of these processes' rates will increase with global warming. The present-day global sink will increase slightly until around the year 2100 but decline thereafter. Peatlands will remain a carbon sink in the future, but their response to warming will switch from a negative to a positive climatic feedback (*i.e*., decreased effectiveness as a carbon sink with warming) at the end of the twenty-first century (Gallego-Sala *et al*. 2018). The potential benefits of carbon sink activity are as follows:

1. It changes peat bogs that slowly release methane into productive cultivated areas while creating valuable new carbon sinks by also increasing the biomass that is required for a long growth period (Lai 2009).

2. Pre-treating soils for cultivation is easy, as they have no trees, roots, or stones. The areas are also large. Thus, splitting them into different uses is easy, including experimental areas that could simultaneously involve both agricultural and forest cultivation.

3. It is potentially an eco-friendly, materially efficient, and cost-effective way to utilize various industrial by-products in accordance with the current European Union (EU)/Finland National Waste Strategy, as well as granulated products (*e.g*., bio ash, bio-sludge, and gypsum waste-based materials). By using legislation that will evolve in the future, this list will also include materials that are currently classified as waste (Karvonen *et al*. 2011). Consequently, the topic is central to circular economic thinking.

4. Through the conversion of former peatlands, more farming areas will become available for the needs of a strongly evolving bio-economy and expanding bio-refinery plants that are partially foreign-owned. These needs include different fibrous and potato starch-based products, of which new ones include textiles and plastic substitutes. Additionally, the quality of fiber- and starch-based products depends decisively on, among other things, what kind of wood the products are made of, where the trees are grown, and what kinds of fertilizer are used to grow the tree. Wood formation is attributed to many factors, including site, environmental, and stand conditions, as well as management, genetics, and age (Zobel and van Buijtenen 1989; Saranpää 2003). Therefore, one must strive to use the correct amount and type of fertilizer. This innovation presumably has a notable impact on the quality of the fiber material used in the manufacture of future products.

5. The rehabilitation of peat bogs from unused land to various agricultural and forestry areas will also be a viable business activity due to the increased value of the soil. Peatlands

can provide income and other benefits to local communities by supporting forestry and agricultural cultivation under wet conditions, and cultivation can occur wherever there are marketable plants and animals living in wet conditions. This can produce biomass for bioenergy, feed for livestock, fibre, building materials, and even food (Joosten *et al*. 2016).

6. Rehabilitating peat bogs for the sole production of thermal energy, for example by rapid growth or the current cultivation of willows, does not create carbon sinks in the affected areas, as was noted last year in Finland's successful negotiations on intensifying the felling of forests in the EU.

7. The creation of new carbon sinks can also be considered as being important for general climate policy reasons, in accordance with the EU's climate policy strategy and other related objectives.

8. The implementation of this new carbon sink objective requires a wide range of experts to succeed. The design and implementation of projects must be performed by various university and vocational institutions and research institutes, as well as by large energy companies, municipal parties, and, especially, new environmental firms that deal with granulation, drying technology, and humus removal from natural water bodies.

In potato production, monocultures are common in Finland, with the main reasons being economic: Potato production farms specialize in potato production, farms have the entire machine chain, and markets are built solely for potato production (Tuomisto 2011). Furthermore, the mass of potatoes transported from the fields is large, so potato cultivation has been concentrated close to economic centers (Myyrä 2001; Tuomisto and Huitu 2008; Tuomisto 2011). However, monocultures create problems, including increased plant pest and disease activity, condensed soil, loss of humus or the soil's organic matter, and weakened soil nutrient retention, resulting in nutrient leaching, environmental damage, and economic losses (Lemola *et al*. 2000). Hence, the concentration of localized environmental damage can be considerable.

Environmental hazards can be reduced by using appropriate soil conditioning agents, such as paper mill sludge, native fiber sludge, and biotechnologically modified fiber sludge, along with other fiber sludge-based products in general, because their chemical purity can be considered a viable option. In the soil structure, between the soil particles, remaining bonds (such as hydrogen bonds), play an essential role in helping potato plants access water and nutrients. Usable water for plants is bound to the medium-sized pores, while macroscopic pores are filled with air and allow for plant root growth. In the saturated state, pores are filled with water. When soil is drying, the large pores empty first, followed by the small pores. In small pores, water movement is weak (Boone *et al.* 1978; van Loon and Bouma 1978). In sand, the groundwater capillary rise is strong. Potatoes are grown mainly in coarse soils with an abundance of large pores, and in potato production, the soil needs organic matter. Therefore, one alternative with a strong likelihood of success in potato production is applying biotechnologically modified fiber sludge enhanced with appropriate nutrients to the soil, where it operates as a soil conditioning agent and fertilizer. Additionally, fiber sludge degrades slowly and functions as a breeding ground (Kuokkanen *et al*. 2015). The application of biotechnologically modified fiber sludge is currently being researched, and results will be published in the near future. In this study, however, only native fiber sludge was tested as a soil conditioner. Five different industrial by-products were tested in this study as soil conditioners: fiber sludge, biocarbon, hygienic biodigestate, paper mill sludge, and gypsum waste.

Soil Conditioners

Gypsum is commonly used in the manufacture of plasterboard, soil conditioner, fertilizer, cement, building coatings, alabaster (glass-like material frequently used for ornamental purposes), medical-grade plaster, and other products. Approximately 20 million m^2 or 200,000 tons of plasterboard is produced in Finland each year. Between 14,000 tons and 20,000 tons of gypsum waste (Fig. 2) is generated in Finland each year; presently, only a small fraction of it is recycled.

Fig. 2. Gypsum waste

The rest was previously placed in landfills (the current waste tax is 70 €/t). At the beginning of 2016, the situation changed as gypsum could no longer be placed in landfills in Finland. As a soil conditioner, gypsum works on the ground so that it dissolves in the earth's barrier layer, where it changes the soil's properties. Gypsum does not bind to phosphorus, but phosphorus remains in use for various plants (Ekholm *et al*. 2010). Gypsum increases the solubility of the soil due to soluble sulfate (SO_4^{2-}), binds earth particles with Ca-bridges, and enhances phosphate retention in ground particles. In this case, the soil remains in the field, erosion decreases, and less phosphorus is flushed from the fields.

Wood fiber sludge is generated as a by-product of the pulp and paper industry in Finland at the rate of approximately 750,000 tons per year. In the past, wood fiber sludge was either combusted or landfilled. The amount sent to landfills has decreased because wood waste is currently subject to a waste tax (now 70 € / wet waste ton), which also applies to industrial landfills (Kuokkanen *et al*. 2018). For energy production, fiber sludge is not a very efficient fuel due to its high moisture content (typically 80% to 90%). Wood fiber contains fewer nutrients, but it has a considerable amount of slowly biodegradable organic matter. By spreading this by-product on the fields, more organic matter is absorbed into the soil, improving the structure of low-loam clay land. In field soil, fiber improves microbial conditions, retains moisture, and increases biological activity. In the autumn, carbonaceous wood fiber binds nitrogen to the soil and, thus, reduces nitrogen leaching. An innovative approach is being developed in which the fiber sludge by-product of the pulp industry is utilized as a new kind of soil conditioner for potato production, which would have a fertilizing, liming, and aerating effect (Kuokkanen *et al*. 2018). The effect of this biotechnologically modified fiber sludge (Fig. 3b) is based on a cost-effective enzymatic treatment of native wood fiber sludge (Fig. 3a) in which the fiber cluster is chemically opened, providing a greater reaction surface for various applications *via* binding (Kuokkanen *et al.* 2018). Various recent fiber sludge applications include binding agents for combustion pellets used in the energy industry, bedding pellets used on horse farms, a binding component of granulated soil conditioners in agricultural and forestry farming, and as such in soil conditioners. In addition there are efficient and ecological dust binding agents for various purposes, for example, road building and horse fields (Kuokkanen *et al*. 2018) and horse stables. The suitability of new eco-efficient materials as raw materials for these granulated symbiosis products in non-food potato cultivation with peat bogs has also been studied in the ongoing project. Furthermore, this research will be extended in the future to corresponding forestry projects.

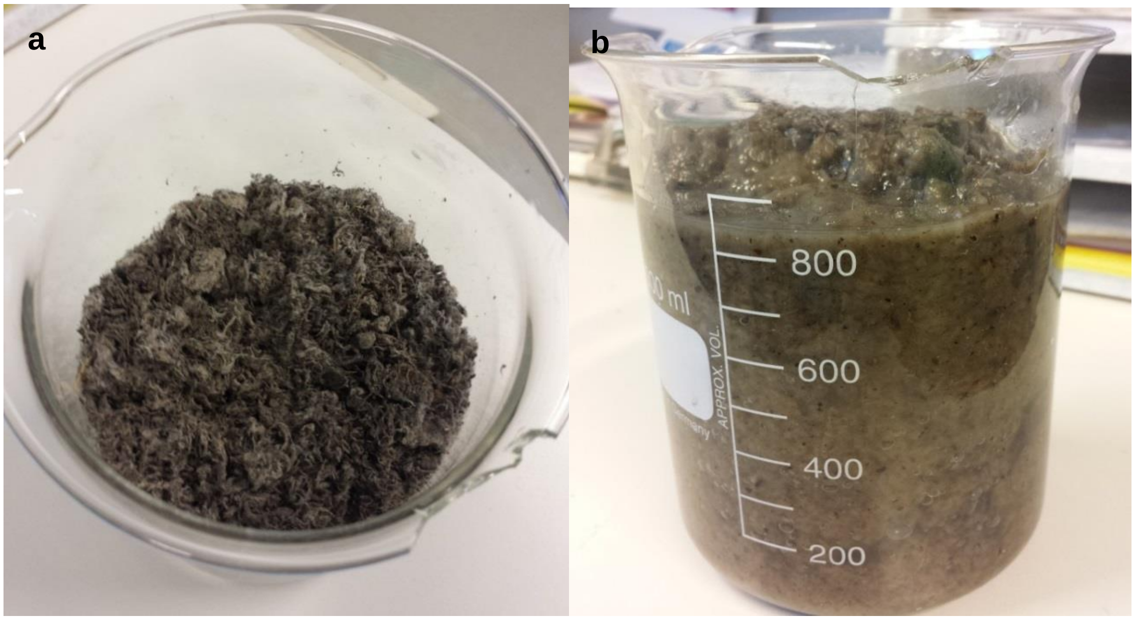

Fig. 3. Native (a) and biotechnologically modified (b) wood fiber sludge (Kuokkanen *et al.* 2018)

Paper mill sludge is the primary sludge from the mechanical pre-clarification of paper mill wastewater treatment, consisting of both organic and inorganic materials (Pöykiö *et al*. 2009). Typically, a paper mill produces sludge at the rate of 20,000 tons per year to 30,000 tons per year (Kuokkanen *et al*. 2008). The organic substances are mainly wood and lignin fibers, in addition to additives used in papermaking and fillers, such as latex and various adhesives. Paper mill sludge has a distinct liming effect and, thus, allows the peatland to import mineral matter to improve peat crops and the heat economy. This type of sludge contains very few nutrients but is rich in slowly biodegradable organic matter. Paper mill sludge is expected to improve the soil structure in the field by improving the water conductivity and water absorption capacity, enhancing microbiological conditions, increasing the mineral and humus content (lignin), reducing nutrient leaching (especially potassium and nitrogen), reducing soil compaction, improving soil structure and malleability, reducing erosion, binding carbon, and binding excessive nitrogen to sulfates and peatlands (Kuokkanen *et al*. 2008).

Fig. 4. Hygienic biodigestate

Hygienic biodigestate is the slurry that is hygienized residual fraction of organic matter from a biogasification plant (Fig. 4). The primary wet digestate solid content is only approximately 3%. The sludge produced by centrifuging is approximately 30% solid content. In this study, the latter digestate, or hygienic biodigestate, was examined.

In the biogas process, the nitrogen of the input material is mineralized into ammonium nitrogen, with a large part of phosphate into phosphate phosphorus, which are useful forms for plants (Möller and Müller 2012; Liu and Chen 2014). In addition to the nutrients, the treatment residue contains non-degradable organic matter that is important for soil microbiology. It is possible to further dry and granulate the solid matter fraction to approximately 30% solid content sludge. A primary hygienic digestate solution can be spread onto fields in a liquid form. Because biodigestion plants are currently being built in Finland at an accelerating pace, the utilization of waste digestate and the development of granulated symbiosis products made from it are becoming even more important. Therefore, the use of such products as soil conditioners and fertilizers in peat bogs can be predicted to increase.

Biocarbon is a testable soil conditioner (Fig. 5), and there is currently lively research activity to develop new, cost-effective products with it.

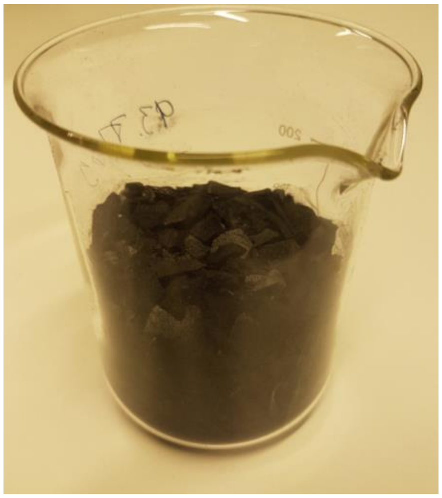

Fig. 5. Biocarbon sample

Biocarbon is a thermally treated biomass-based product. Under this definition, torrefied biomass, slow or rapid pyrolysis-generated charcoal, and residual carbon from the biogasification of wood can be calculated (Tuomikoski 2014). The impact of biocarbon on soil depends on the soil type. The positive effect of biocarbon is indicated by changes in soil acidity. In acidic soils, it increases pH and increases cation exchange, thus improving both soil and crop quality (van Zwieten *et al*. 2010).

Biocarbon's uses are very diverse. It can be used, for example, as fuel and energy in households and as soil improvers and active carbon in agriculture. One interesting application in Finland is the production of biocarbon from unutilized forest biomass to partly or completely replace coke used in blast furnaces, both as a reducing agent and as an energy source (Suopajärvi 2014). In this case, biocarbon production would increase greatly, at a rate of at least tens of thousands of tons and up to approximately 400,000 tons per year for one blast furnace.

EXPERIMENTAL

Materials and Methods

Experimental setup

Potato field tests were performed by following the test sample table (Table 1) and test field map (Fig. 6). Tests were performed in Seinäjoki, Finland, in former peatland. In the first stage, the peatland was plowed, and then soil conditioners were planted in the ground as shown in Table 1. The test implementation is presented below. All plots were fertilized with the same amount of basic fertilizer before planting, except reference sample 3001. The test field map is presented in Fig. 6.

Table 1. Test Samples and Soil Conditioner Amounts

Sample	Soil Conditioner
3001	Control, no fertilization
3002	Control
3003	Control + veil cover
3004	Gypsum waste (3 kg/m^2)
3005	Biocarbon (3 kg/m^2)
3006	Fiber sludge (15 kg/m^2)
3007	Paper mill sludge (15 kg/m^2)
3008	Paper mill sludge (15 kg/m^2) + veil cover
3009	Paper mill sludge (15 kg/m^2) + gypsum waste (3 kg/m^2)
3010	Hygienic biodigestate (0.5 kg/m^2)
3011	Paper mill sludge (3 kg/m^2)

Test implementation

The experimental model consisted of block randomized plots, with 3 replicates. Subplot gross was 4.8 m × 8 m and net area was 1.6 × 5 m and whole test area was 159 m × 8 m, so combined it was 1272 m^2. The used potato variety was Hankkijan Tanu (early starch potato) and planting density was 28 / 80 cm. Basic fertilization information were as following: Concentrated potato juice 7 m^3/ha N70 P15 K189 and granular phosphorus fertilizer 200 kg/ha (N2 P18) (Except sample 3001) and soil nutrition as follows: Terric Histosol pH 5.0, P 3.6, K 50, Mg 250.

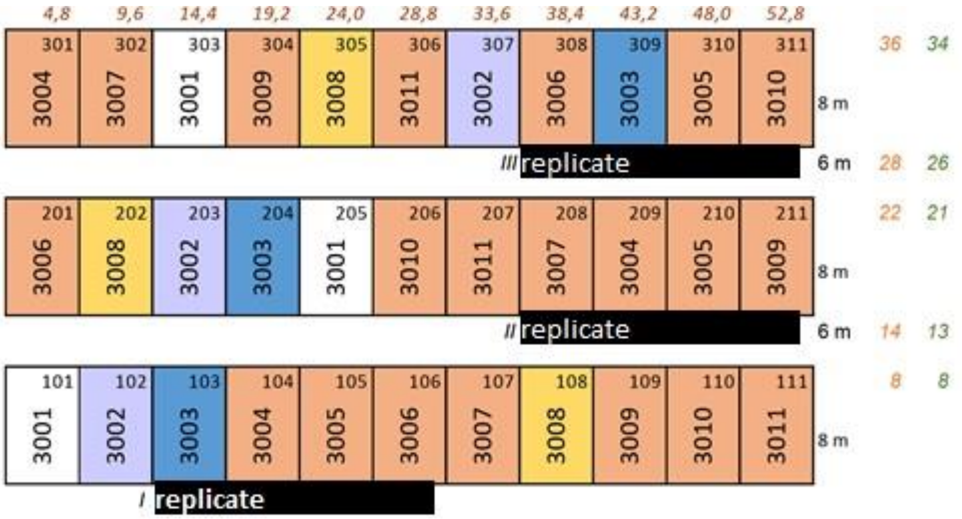

Fig. 6. Field map of planted soil conditioners in 3 replicates (I, II, and III)

Moisture Content Measurement

Moisture content was measured according to the ISO 589 (2008) and CEN/TS 14774-1 (2004) standards. According to ISO 589 (2008), the samples were dried overnight to a constant mass (16 h to 24 h) in a drying oven at 105 °C ± 2 °C. According to CEN/TS 14774-1 (2004), the samples were dried to a constant mass (up to 24 h) in a drying oven and immediately weighed when hot.

Elemental Analysis

The samples were extracted with MARS5 microwave wet combustion equipment (Berkeley, CA, USA) using the EPA-3051 standard method (2007). Measurements were performed with a commercial plasma emission spectrometer (ICP-OES; Perkin-Elmer, Waltham, MA, USA), and the results were calculated against the sample’s dry weight (at 105 °C).

Run-off Experiments

In the run-off experiments, the water blank sample was obtained from rainwater collected in the Potato Research Institute’s test field in Seinäjoki, Finland. A control plot sample was collected as run-off from the control plot (treatment 3002). The run-off experiments were performed at the Research Unit of Sustainable Chemistry at Oulu University (Oulu, Finland). The run-off tests from the test plots were performed by measurements taken from sampling tubes drilled into the ground. Monitoring was conducted prior to soil conditioning (*i.e.*, before the addition of soil conditioners) and continued after soil conditioning. The results could be compared to a blank water sample, in which case, it was possible to detect the potential removal of the components in different test plots and a control sample plot. In this study, dissolved organic carbon, total nutrients, phosphates (also filtered), major alkali and earth alkaline metals (K, Ca, Mg, Na), and major metals and heavy metals were monitored. The gypsum-treated plot’s sulfate levels were also monitored.

Biodegradation Tests

Soil samples (approximately 700 g) with an 80% moisture content were first weighed and measured in 1.5-L bottles using OxiTop® Control B6M instrumentation (WTW, Weilheim, Germany) (Vähäoja 2006; Roppola 2009). A 50-mL beaker filled with a 1 M sodium hydroxide solution was placed on a holder. The bottles were held in an incubation cabinet at a temperature of 20.0 °C ± 0.2 °C for 60 d. The amount of soil conditioners added to the samples was 300 mL.

Table 2. Amounts of Soil Conditioners Added in the Liquid Phase

Soil Conditioner	Added Amounts
Hygienic biodigestate	0.38 g and 0.24 g
Gypsum waste	3.83 g and 4.15 g
Biocarbon	0.42 g and 3.89 g
Fiber sludge	0.72 g and 0.46 g
Paper mill sludge	3.61 g and 1.77 g

The BOD OxiTop apparatus for solid phase measurements is fully automated, and it only measures the difference in partial oxygen pressure $\Delta p(O_2)$ (hPa); from this value, the degree of biodegradation (%) could be calculated as previously presented (Vähäoja 2006; Roppola 2009). The BOD OxiTop apparatus for the liquid phase also measures the pressure and calculates the BOD value (mg/L) (Roppola 2009). The amounts of soil conditioners added for measurements in the liquid phase, wherein 100 mL of water was added, are presented in Table 2. Nutrients and bacteria were added to the solution in which the soil conditioner sample was placed. This dilution water contained, in addition to bacteria, nitrogen as ammonium, calcium, magnesium, iron, and a phosphate buffer. A large amount of gypsum waste was added due to the low carbon content of the sample. Various amounts of paper mill sludge and biocarbon were added to the sample because the amount of organic carbon in the biocarbon was unknown. Additionally, there was a large amount of pulp in the paper mill sludge sample, so various amounts of sample were added.

RESULTS AND DISCUSSION

Physical and Chemical Properties of Soil Conditioners

In this study, five different industrial by-products (hygienic biodigestate, biocarbon, paper mill sludge, fiber sludge, and gypsum waste) were tested as soil conditioners, and their physical and chemical properties were examined. The physical and chemical properties of the tested soil conditioners are presented in Table 3. The nitrogen and phosphorus concentrations of hygienic biodigestate and fiber sludge were greater than in other samples, indicating that they had a strong fertilizer effect, both in a solution and bound. Although gypsum waste contained the lowest amount of nitrogen and phosphorus, it may have had a weak fertilizing effect. Hygienic biodigestate, fiber sludge, and gypsum waste had the greatest sulfate concentrations, which also affects fertilization. Calcium concentrations are greatest in naturally Ca-rich components of paper mill sludge and gypsum waste. Hygienic biodigestate had the greatest concentrations of copper and iron, though copper and iron metal concentrations of fiber sludge were greater than in other samples, and gypsum waste had a moderately high concentration of iron. Among the other nutrient metals, potassium and manganese concentrations were high in hygienic biodigestate, biocarbon, and fiber sludge, while the magnesium concentration was high in every soil conditioner except biocarbon.

Table 3. Physical and Chemical Properties of the Tested Soil Conditioners

Component	Unit	Hygienic Biodigestate	Biocarbon	Paper Mill Sludge	Fiber Sludge	Gypsum Waste
Dry matter	%	27	97	68	46	63
Total N	mg/kg	28 000	3 800	2 900	22 000	640
Total N, dissolved	mg/kg	520	2	36	1 500	19
P, dissolved	mg/kg	4.40	6.90	4.00	4.90	0.46
Phosphorous	mg/kg	45 000	730	200	2 900	77
Dissolved organic carbon (DOC)	mg/kg	570	220	2 100	1 200	140
Total organic carbon (TOC)	%	17	76	5.3	24	0.74
Sulfate	mg/kg	19 000	< 53	< 50	24 000	16 000
Arsenic	mg/kg	< 3	< 3	< 3	< 3	< 3
Boron	mg/kg	12 000	17	16	12	25
Calcium	mg/kg	18 000	10 000	170 000	22 000	160 000
Cadmium	mg/kg	< 0.5	< 0.5	< 0.5	1.2	< 0.5
Cobolt	mg/kg	5	1	< 1	10	3
Chromium	mg/kg	140	< 1	6	59	110
Copper	mg/kg	270	4	3	80	10
Iron	mg/kg	150 000	48	760	28 000	11 000
Mercury	mg/kg	0.27	< 0.01	< 0.01	0.11	0.10
Potassium	mg/kg	5 600	2 400	93	2 300	780
Magnesium	mg/kg	3 500	710	1 400	4 300	2 800
Manganese	mg/kg	300	290	53	240	91
Molybdenum	mg/kg	6	< 1	3	6	< 1
Sodium	mg/kg	4 000	< 10	190	560	460
Nickel	mg/kg	14	1	2	34	8
Lead	mg/kg	16	< 3	< 3	17	5
Sulfur	mg/kg	12 000	31	630	20 000	110 000
Antimony	mg/kg	< 5	< 5	< 5	< 5	< 5
Selenium	mg/kg	< 3	< 3	< 3	< 3	< 3
Tin	mg/kg	20	< 0.2	0	3	1
Thallium	mg/kg	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Zinc	mg/kg	410	190	14	340	52

When observing harmful elements in the results in Table 3, it can be noted that arsenic concentrations were less than the limit of determination. Cadmium concentrations were moderately high in fiber sludge but below the acceptable limit for agricultural use as a fertilizer, which is 1.5 mg/kg. Limits for agricultural and forestry use (Finnish Ministry of Agriculture and Forestry 2011) are presented in Table 4.

Table 4. Limits for Agricultural and Forestry Use (Finnish Ministry of Agriculture and Forestry 2011)

Element	Limit Value of Utilization as Forest Fertilizer (mg/kg)	Limit Value of Utilization as Agricultural Fertilizer (mg/kg)
Cadmium (Cd)	15	1.5
Copper (Cu)	700	600
Lead (Pb)	150	100
Chromium (Cr)	300	300
Zinc (Zn)	4500	1500
Arsenic (As)	30	25
Nickel (Ni)	150	100
Mercury (Hg)	1.0	1.0

As presented in Table 3, all the results were under the limit values presented in Table 4. The hygienic biodigestate had a slight amount of mercury, and the concentration of chromium was moderately high in hygienic biodigestate and gypsum waste. This result may be due to impurities in the gypsum waste sample.

Run-off Experiments

Run-off results of the examined soil conditioners are presented in Table 5. As shown in the table, all soil conditioners except paper mill sludge had lower pH values compared to the blank water sample. Nitrogen concentrations were increased in all test plots, indicating that none of these soil conditioners could retain nitrogen in the soil. With the fiber sludge treatment, dissolved phosphorus was retained in the soil, in contrast to the total phosphorus value. This may be due to phosphorus adsorption into fiber sludge pores. Gypsum waste seemed to hold some organic carbon in the soil, which is a positive function for a soil conditioner, in contrast to the other tested soil conditioners. Paper mill sludge seemed to hold sulfate in the ground when compared to the control sample. Potassium was flushed from the ground with every studied soil conditioner. Calcium, iron, and magnesium were flushed from gypsum waste and fiber sludge in large quantities. Iron levels were increased in the run-off water sample of paper mill sludge. In all the samples, there was no mercury, selenium, tin, or thallium (Hg, Se, Sn, Tl) detected; the results were below measurement values or negligible. Compared to a control sample, a large amount of manganese was flushed from all the samples except the biocarbon. Gypsum waste and fiber sludge held the nickel in the ground very well. Sulfur was flushed in large amounts from gypsum waste and fiber sludge. Zinc infiltrated into the ground with every examined soil conditioner, as well as the control sample.

By observing the nutrients' solubilities and comparing the results shown in Tables 3 and 5, some interesting notes concerning the fertilizing effect can be made. All the examined soil conditioners held nitrogen very well and contained large amounts of bound nitrogen except gypsum waste, which only contained 640 mg/kg nitrogen. In the hygienic biodigestate, there was a large amount of solid phosphorus, and only a small amount was flushed out; all the other soil conditioners hold phosphorus very well.

Table 5. Run-Off Experiment Results for the Blank Sample and Different Test Plots

Analysis	Unit	Water Blank Sample	Run-off 3002 Control	Run-off 3004 Gypsum Waste	Run-off 3005 Biocarbon	Run-off 3006 Fiber sludge	Run-off 3007 Paper Mill Sludge	Run-off 3010 Hygienic Biodigestate
Electrical conductivity, 25°C	mS/m	3.5	15	113	26.8	96.5	14.6	25.7
pH value, 25 °C		6.5	4.3	3.9	4.1	3.7	6	4.6
Total N	µg/L	830	6 600	4 800	18 000	17 000	8 200	18 000
Total N, dissolved (0.45 µm)	µg/L	830	6 400	4 200	16 000	12 000	6 600	16 000
P, dissolved (0.45 µm)	mg/L	0.052	0.14	0.017	0.58	0.11	0.3	1.9
Total P	mg/L	0.056	0.14	0.048	0.65	0.3	0.42	1.9
Dissolved organic carbon (DOC)	mg/L	4	113	28.7	117	86.1	186	106
Total organic carbon (TOC)	mg/L	4	120	34.3	120	100	190	110
Sulfate	mg/L	1.1	25	560	37	390	9.7	33
Arsenic	µg/L	0.34	2.9	0.79	1.7	2.5	3.8	1.8
Boron	µg/L	10	15	14	19	21	9	16
Calcium	mg/L	4	15	160	23	96	24	25
Cadmium	µg/L	0.72	0.07	0.13	0.25	0.31	0.05	0.05
Cobolt	µg/L	0.07	2.1	6	1.6	16	3.4	1.9
Chromium	µg/L	0.2	4.7	1.8	5.9	4.8	11	5.8
Copper	µg/L	5.3	4	2.3	5.4	8.4	3.3	4.1
Iron	µg/L	69	2 600	4 100	2 200	11 000	5 600	1 600
Mercury	µg/L	< 0.05	< 0.05	< 0.05	< 0.05	0.12	< 0.05	< 0.05
Potassium	mg/L	0.57	5.7	15	14	27	13	13
Magnesium	mg/L	0.23	4.8	35	7.1	30	6.6	7.2
Manganese	µg/L	3	100	4 900	320	3 400	960	960
Molybdenum	µg/L	1	1.1	0.9	0.9	0.9	0.8	1.3
Sodium	mg/L	0.17	0.65	1.7	0.85	6.6	1.8	1.6
Nickel	µg/L	0.4	120	5.4	150	17	49	49
Lead	µg/L	0.78	1.2	0.53	7.9	1.7	1.8	1.5
Sulfur	mg/L	0.97	9.1	200	13	150	4.8	12
Antimony	µg/L	0.64	1.5	1	0.91	0.85	0.7	0.36
Selenium	µg/L	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.3	0.3
Tin	µg/L	0.4	0.4	0.3	0.3	0.4	0.4	< 0.2
Thallium	µg/L	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Zinc	µg/L	340	9.7	38	13	74	20	23

Biodegradation Tests

As shown in Table 6, the degree of biodegradation in the hygienic biodigestate was very low (almost 0); it had already been biodegraded in an anaerobic treatment, and the remaining matter biodegrades very slowly. Gypsum waste was a heterogeneous sample due to the cardboard coating of the gypsum, which resulted in a difference in biodegradation results in the solution. Biocarbon biodegraded only 0.7% and thus it can be regarded as a practically non-biodegradable substance. Fiber sludge biodegraded 15.9% during 34 d of measurements. Paper mill sludge biodegraded only 1.4% and is very slowly biodegradable.

Table 6. Biodegradation Degrees of Soil Conditioners

Soil Conditioner	Biodegradation Degree in Solution (%)
Hygienic biodigestate	0.05
Gypsum waste	6.9 and 0
Biocarbon	0.7
Fiber sludge	15.9
Paper mill sludge	1.4

CONCLUSIONS

1. By utilizing industrial by-products as soil conditioners and fertilizers, it was possible to create eco-friendly and cost-effective carbon sinks in peatlands that have been used in the past for peat production.
2. Based on the nutrient content, hygienic biodigestate and fiber sludge were the most effective fertilizers studied. However, these results should be compared to the yield results, which will be published elsewhere in the future.
3. When observing harmful elements, only the cadmium concentration was moderately high (1.2 mg/kg) in fiber sludge, and this can be explained by its raw material (*i.e.*, trees) being raised in Finnish soil. However, it was under the acceptable limit for agricultural use as a fertilizer, which is 1.5 mg/kg.
4. All soil conditioners except the paper mill sludge lowered the pH values of run-off water compared to a blank water sample. Paper mill sludge raised the pH values of run-off water.
5. Potassium was flushed from the ground with every studied soil conditioner.
6. All the biodegradation tests conducted in the solid phase showed that the examined soil conditioners did not degrade at all during the 90-day measurement period. This result means that these materials containing a granulated soil conditioner or fertilizer compounds, which are currently in common use (*e.g.*, in Finland), do not degrade mechanically and can stay in the ground for a long period.
7. Biodegradation tests in the liquid phase showed that the hygienic biodigestate and biocarbon did not degrade at all during the 34-day measurement period, while the fiber sludge slightly degraded (15.9%). The gypsum waste and paper mill sludge proved to be practically non-biodegradable, although gypsum waste contained very small amounts of organic impurities originating from cardboard coatings, which caused slight biodegradation.
8. The surface area of a soil conditioner was very important in terms of dissolution and biodegradation. Thus, a larger surface area enabled better solubility compared to a smaller surface area.
9. It is very reasonable to carry out further tests to observe long-term effects (*i.e.*, 3 y to 5 years) in peat bogs and potato fields.

10. It would be reasonable to carry out tests to find a mixture of different soil conditioners, wherein the positive effects of examined soil conditioners are combined.

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