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Mobile-manufactured biochar in mine closure, costly yet carbon-negative – A techno-economic and life cycle assessment of growing media value chains

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ABSTRACT

This concept case explored a circular bioeconomy-based value chain to produce new high-quality growing media to be used in mine closures. Our specific interest was in the production of biochar from waste wood using the mobile pyrolysis unit and use of biochar as a supplement in mine closure growing media. A life cycle costing (LCC) and environmental impact assessment (LCA) was conducted for the production and value chain of four different growing media solutions based on mixtures of composted sewage sludge (COM), fly ash (ASH), peat, till, and waste-wood-based biochar (BC).

The application of wood waste biochar to compost-till growing media (10 % by volume) increased the costs by 51–71 % (BC-COM-TILL, €28.60 m^{-3}). The most affordable scenario was based on compost, ash and till (€16.76 m^{-3}). Environmental impacts were acknowledged in the costs according to their carbon dioxide equivalent (CO_2eq) emissions assessed in LCA (€52.56 CO_2eq t^{-1}). Accounting for the long-term carbon storage capabilities of the materials, the emissions were highest in peat and till based solution (74.7 kg CO_2eq m^{-3}), and lowest in the most expensive solution with biochar (-49.7 kg CO_2eq m^{-3}). The biochar-based solution turned into a carbon sink with negative CO_2eq emissions.

The study 1) highlighted the lower emissions of growing medias based on circular bioeconomy-based solutions compared to peat used in the traditional growing media solution; 2) showed that the climate emissions of biochar-based growing media were negative; 3) indicated that the price of biochar-based growing media was high, while suggestions were made to moderate the cost. The positive effects of biochar on the plant growth in mine areas have been documented elsewhere, but not acknowledged in this study's environmental or economic results.

1. Introduction

The green transition to an economy independent of fossil fuels triggers ore resource mining. In 2023, the European Commission released its proposal for a new EU raw materials initiative, known as the Critical Raw Materials Act (CRMA) (European Commission, 2024). Strategic raw materials are essential for example for the green transition, digitalization and defense industry needs. The target includes opening new mines across Europe and extracting minerals from the waste of decommissioned mines. Due to the geological features of Nordic regions, there is a high prospectivity potential for critical raw materials. For example, Finland's mineral deposits make it the world's 13th most attractive country (1st in Europe) for mining investments (Yunis and Aliakbari, 2021). Currently, 44 mines operate in Finland, producing over 100 million tons of waste rocks and tailings that need enclosure annually (Kaivosteollisuus, 2022). Similar increasing mining activity trends have been reported in other northern latitude countries like Sweden and Canada, as well as globally (Yunis and Aliakbari, 2021).

Coinciding with increasing metal demand, the EU is committed to energy saving and a reduction of greenhouse gas (GHG) emissions by at least 55 % by 2030 from 1990 levels (European Commission, 2019). EU policy therefore encourages member states to adopt a circular economy,

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which means keeping the value of products, materials, and resources in the economy as long as possible and minimizing end waste generation (European Commission, 2015a). However, for example in Finland less than one percent of total mining site extraction is recycled or recovered (Statistics Finland, 2019), revealing that the mining industry faces challenges in contributing to the circular bioeconomy.

Without proper waste management including a closure process, mine residues can pollute soil and water systems through acid run-off and the release of heavy metals (Tolvanen et al., 2019). Today, mining waste site emissions are typically reduced by sealing the waste rock with a thick layer of till (0.20–180 cm), or geopolymer structures and applying a thin layer of organic topsoil to promote revegetation. In large-scale open-pit mines, waste rock dumps can span thousands of hectares and reach hundreds of meters in height. Sealing these dumps requires a substantial amount of virgin soil material for the cover structure, particularly in humid climates and when dealing with sulphidic waste rock (Heikkinen et al., 2008). Although significant volumes of glacial tills and peat are typically removed and stored during the construction stage of the tailings management facility (TMF) (Dillon et al., 2004), virgin soil materials are limited resources, with a low regeneration rate (McBratney et al., 2014).

The topsoil used for covering is often nutrient-poor, which slows down revegetation and hinders plant growth. One currently used solution to enhance vegetation development in mine covers is using locally dumped low-fertility peat as an organic amendment applied above the soil layer before the sowing of seeds (Heikkinen et al., 2008). However, peat-based growing media (digging and decomposition of peat) is a source of GHG emissions (Pohjola, 2014). With increasingly stringent GHG emission regulations and emission allowances (Ulrich et al., 2022), alternative covering materials with feasible costs and lower environmental impacts in covering waste rock sites are urgently needed.

Circular-bioeconomy-based solutions could provide new types of growing media utilizing local side streams or waste biomasses in mine closures instead of virgin peat. High organic matter and nutrient content, combined with a low cost, can make sewage sludge compost a potential soil amendment for use in large restoration areas (Pérez-Gimeno et al., 2019; Heiskanen et al., 2022). Wood ash from industrial heat and power plants may also be a feasible growth media component for use in mine closures, as it contains valuable plant nutrients and improves soil pH and plant growth (Mayer et al., 2022). Similarly, due to its unique physicochemical properties, such as its high surface area and porous structure, biochar is a sustainable and versatile material for environmental remediation. Biochar's effect on soil structure, water and nutrient retention properties and microbial activity (Kabir et al. 2023) can help mitigate the adverse effects of soil degradation (Rasa et al., 2018; Turunen et al., 2020). Biochar has been shown to improve crop plant growth especially in agricultural conditions (Chan and Xu, 2009; Liu et al., 2017; Maroušek et al., 2019), but it has also proven to have potential as the growth media component to improve plant rehabilitation in mine closures (Smart et al., 2015; Heiskanen et al., 2020; Hagner et al., 2021). However, its effectiveness and ecological impact in soil environments can vary depending on a combination of interacting factors (Kabir et al., 2023).

Process of soil carbon sequestration intends removing CO2 from the atmosphere and storing it within the soil. As a chemically stable aromatic material highly resistant to microbial decomposition, biochar also contributes to long-term carbon sequestration (Maroušek et al., 2019; Bekchanova et al., 2024), and reduces NH3 and GHG emissions (Xiao et al., 2017), thus having high potential to reduce the mine closure carbon footprint (Fawzy et al., 2022; Ulrich et al., 2022; Ruett et al., 2024). However, mechanisms of biochar affecting soil GHG emissions and carbon sequestration depend on several factors such as biomass feedstock type, pyrolysis conditions and soil characteristics (Wang et al., 2023).

Different closure strategies' cost and environmental impacts vary widely (Heikkinen et al., 2008). Although waste biomasses are reported to be among the most suitable feedstocks for biochar production (Matuštík et al., 2022), the price of the new alternative cover material is critical for large-scale implementation. A better understanding of the production costs and potential benefits of new circular bioeconomy-based solutions are therefore needed. There is a lack of studies focusing on the value chain for producing mine closure growing media from waste biomass, including biochar, despite research on the environmental and economic performance of biochar production in other industries, e.g. in agriculture (Zilberman et al., 2023) and steel industry (Ibitoye et al., 2024).

In this study, we demonstrated a value chain in which circular bioeconomy-based waste biomasses were used as growing media substrates to be applied in mine closures in Northern Finland. The overall aim was to conduct a techno-economic life cycle costing (LCC) and environmental life cycle assessment (LCA) for the value chain to support mine industry actor's decision-making process. Four different growing media compositions to be utilized in mine closure and rehabilitation solutions were considered. LCC considered all the cost factors related to the optional solutions during their operational lifetime, and these are complemented by analyzing the environmental impacts (LCA) and further calculating the environmental LCC (E-LCC), including the externalities likely to manifest themselves as actual costs (costs of emission allowances) for the relevant industry.

The specific aim was to compare the closure scenarios containing local side stream materials (sewage sludge, fly ash, wood waste biochar) to till and peat that represented a traditional closure solution. The study also emphasized the production of biochar from waste wood using the mobile pyrolysis unit and the costs and environmental impact of using biochar as a supplement in mine closure growing media. The overall hypothesis of the study was that circular bioeconomy-based solutions would result in the lower emissions compared to peat as a traditional growing media solution, while the costs were expected to increase depending on side or waste streams used.

2. Methods

2.1. Study site

We evaluated the techno-economic and environmental feasibility of the value chain of four different growing media used in mine closure solutions. The data was based on real-life demonstration, where raw material owners, processing and transportation companies as well as mining company were involved. The concept case was assessed for the Boliden Kevitsa Mining Oy open pit mine, which represents one of the world's largest nickel reserves, estimated to be 128 million tons of ore grading 0.2 % nickel (Berthet, 2022). The site is in the municipality of Sodankylä, northern Finland (67°41′38″N 26°55′41″E) (Fig. 1). Its commercial production started in 2012, and its annual production of waste rock is approximately 26 tons (Berthet, 2022). The site represents mining in Arctic areas, where geological resources attract international companies due to the availability of geodata, a skilled workforce, infrastructure, and established legal processes (Noras, 2016).

2.2. Scenario definition and system boundaries

Four mine closure scenarios were assessed with the volumetric composition of the components in the growing media mixtures as follows:

(i) COM-TILL: 50 % till and 50 % composted sewage sludge;
(ii) COM-ASH-TILL: 50 % till, and 50 % composted sewage sludge and fly ash (3 ‰);
(iii) COM-BC-TILL: 50 % till, 40 % composted sewage sludge, and 10 % waste wood-based biochar; and
(iv) PEAT-TILL: 50 % peat, and 50 % till.

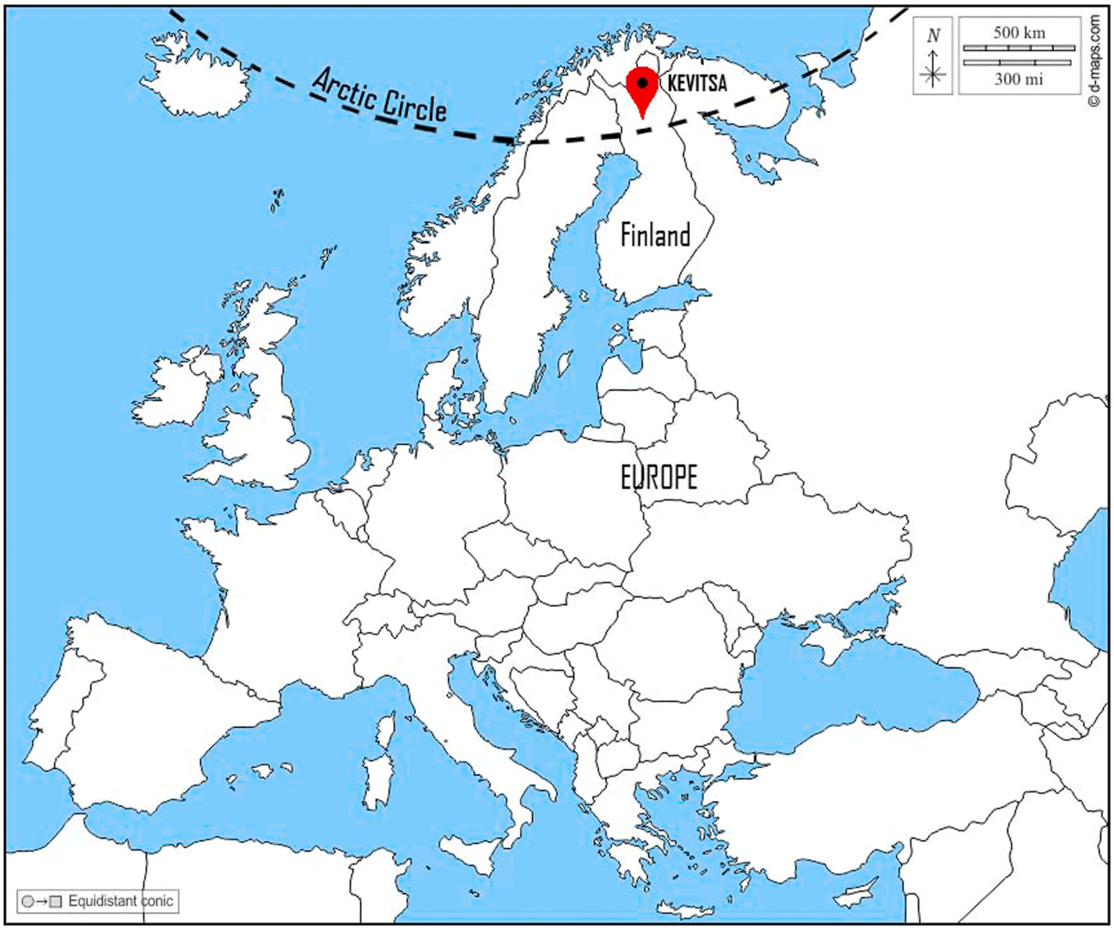

Fig. 1. Location of case study area (Kevitsa mine) in Finland. (Modified map from source: https://d-maps.com).

A thin layer of growing media, usually peat (5–10 cm), is used in mine reclamation areas in harsh arctic environments when recovering natural vegetation after large soil disturbances. In our circular bioeconomy-based closure scenarios, composted sewage sludge was used instead of peat. This thin growth layer has moderate nutriet content adequate for several arctic plant species. Ash was used in one scenario to improve nutrient balance of growing media. Used ash concentration (3000 kg/ha) is a typical dose in ash fertilization of mineral soil forests, but it is usually only effective when nitrogen is abundant (Saarsalmi and Kukkola 2009). Here it was combined with compost addition providing nitrogen. In biochar scenario, biochar concentration was selected according to our previous experiments (Hagner et al. 2021; Heiskanen et al. 2020, 2022) showing that application of 10 % biochar enhances vegetation development. In this case study, it is assumed that all used materials (sewage sludge compost, ash and biochar) meet the limit values of current EU Fertilizing Product Regulation (2019/1009) having no risks to the environment.

System boundaries and value chain of the closure scenarios in LCA and LCC were assessed according to the flowchart in Fig. 2. Ash and compost were supplied as by-products of energy production and sewage treatment, from the closest abundant source, whereas till and peat were sourced from natural deposits closest to the reclamation area. After production, the supply chain for the materials started with the loading of the components from storage and ended with the application of the ready-made growing media at the mine site. Assumed supply chain distances are shown in Table 2. Market values were used to estimate the production cost of fly ash, compost, till, and peat and it was assumed to represent the cost allocation of production of these goods. Similar approach was used by Ruett et al. (2024). Production of biochar was modelled to acquire production cost of biochar.

Fig. 3 illustrates the biochar production, from recycled wood to the ready-made component, ready to be delivered and mixed with compost.

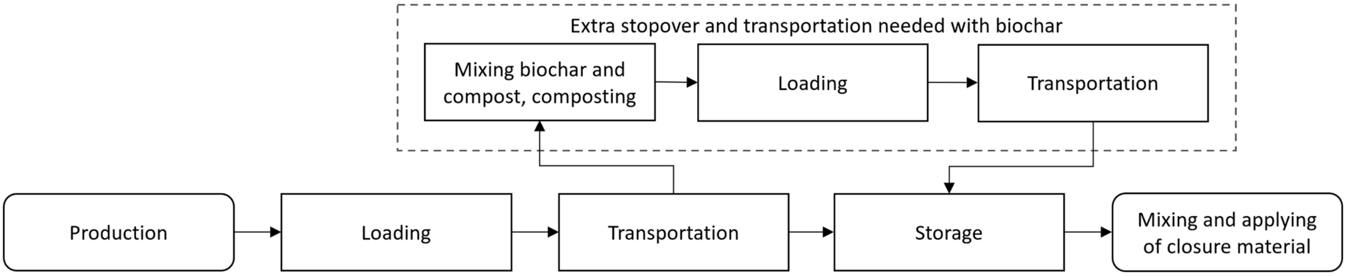

Fig. 2. System boundaries of growing media scenarios from production of the material for the mining site as a ready-made and applied growing media.

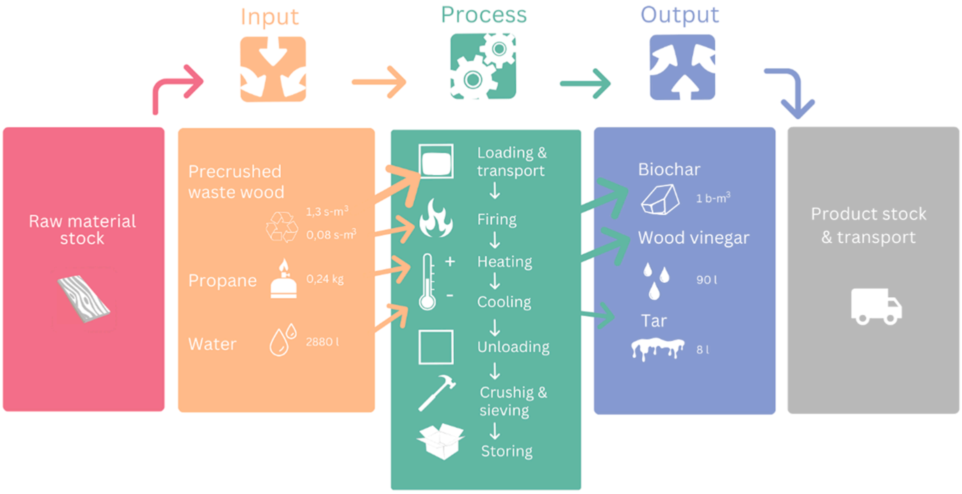

Fig. 3. Pyrolysis process of biochar.

Production started from waste wood storage (not shown in Fig 3). Initially, waste wood was pre-shredded to reduce the particle size suitable for pyrolysis (<30 cm). After new round of storing, the coarse wood pieces from shredding were then pyrolyzed in a mobile retort to produce biochar. Tar and wood vinegar were formed as by-products. After pyrolysis, the biochar was shredded to attain a particle size suitable for further application (<3 cm), and the material was stored once more. Biochar can facilitate organic matter decomposition, accelerating compost maturity (Xiao et al., 2017). Fine-textured biochar was therefore delivered to a water treatment plant (Fig 2) where biochar and wastewater sludge were mixed to enhance the compost product's properties. It was assumed that a shortened composting time would compensate the costs of the slightly longer worktime for mixing the materials. After composting, the mixture was delivered to the mining area and finally mixed with till to form a closure material used as growing media.

The pyrolysis unit used was a mobile retort manufactured by Soil-Care Oy (Table 1). The retort (AMACEE 1700) is designed for small-scale biochar production (≤ 850 m^3 a^{-1}) and is transportable by truck. It is considered a suitable machine for biochar production in sparsely populated areas, where waste wood supplies can be small and sparsely distributed. The biochar production cycle with the retort typically lasts

Table 1

Specifications and hourly costs of the machines used in the scenarios (pwh = productive working hours, owh = operating working hours).*Insurance, administration, and risk and profit of shredder, pyrolyzer, wheel loader, or excavator is included in process costs (15 % of cost of processing of recycled wood or pyrolization). **Not used with retort loading in pyrolysis, which was analyzed based on time consumption per production cycle (1.25 h). For more details, see Appendix A.

	Shredder	Pyrolyzer	Wheel loader	Exca-vator	76t truck	Dumb truck	48t semi
Specifications	[a,c,g]	[i]	[b,e,f,h]	[b,e,f]	[g]	[g]	[g]
Purchase price, €	1250000	80000	270000	273000	355000	175000	130000
Acqusition cost, €	5000	500					
Disposal cost, €	5000	600					
Annual depreciation	115000 €	27500 €	20%	20%	20%	20%	20%
Salvage value, €	100000	15000	79,633	57252	57822	34876	41309
Lifetime	24725 h	12600 h	12000 h	14000 h	657842 km	657842 km	302732 km
Lifetime, years	10	6	6	7	7	7	8
Operating time, h $year^{-1}$	4075	2720	2000	2000	4320	4320	2160
Utilization rate	0.58	0.75	0.65	0.65			
Productive time, h	2344	2040	1300	1300			
Productivity, m^3 pwh^{-1}	45	0.42	200**	100			
Fuel consumption, l h^{-1}	68	some wood/	10	12			
Fuel consumption, l/100 km	gas				66	50	45
Fuel price, €/l	0.94		0.94	0.94	1.46	1.46	1.46
Fixed cost, €/pwh or owh	(€/pwh)				(€/owh)		
Depreciation, €	49.05	13.48	24.41	23.71	9.27	4.35	5.13
Interests, €	14.40	2.39	6.39	5.93	2.07	1.09	1.28
Insurance, admin & other, €	*	*	*	*	3.99	3.54	2.70
Risk & profit margin, €	*	*	*	*	3.66	3.03	2.59
Variable cost, € / pwh or km	(€/pwh)				(€/km)		
Fuel cost, €	63.45	0.52	9.40	11.28	0.96	0.73	0.66
Repair/service, €	50.00	4.00	1.54	4.62	0.30	0.30	0.16
Wheels & tyres, €			2.51		0.10	0.05	0.03
Lubricant cost, €			1.41	1.69	0.04	0.04	0.02
Employee costs, € / pwh	38.11	48.57	42.03	42.03	42.03	42.03	42.03
Total cost, €/h	215.01	68.96	87.68	89.25	61.03	54.03	53.73
Additional cost, €/km					1.41	1.12	0.87

Sources (based on): [a]Ikäheimo & Asikainen (1999), [b]Pflueger (2005), [c]Rinne (2010), [d]Laitila et al. (2013), [e]MMurto (2015), [f]Klanfar et al. (2016), [g]Laitila et al. (2016), [h]Manzone (2017), [i]Manufacturer estimate.

12 h with pyrolysis temperatures of 550–600 °C. Production capacity per cycle is 5 m^3 of biochar with 6.5 solid m^3 of wood as an input (Fig 3). By-products are tar and wood vinegar. The retort consumes 0.4 solid m^3 of wood for fuel in addition to input wood and 1.2 kg of propane for ignition in the production cycle. Worktime consumption is 16 h per cycle, including wheel loader driving. The retort's economic life is eight years. Retort was assumed to be used at full capacity (850 m^3 a^{-1}). Inputs needed in production and outputs of by-products relative to production of a cubic meter of biochar is shown in Fig 3. All the production costs of biochar were allocated to biochar, none to by-products. However, by-products were acknowledged as a possible side stream of revenues, and in LCA up to 89 % of the emissions from the pyrolysis process were allocated to biochar and the rest to the by-products according to their economic allocation rules (See Section 2.4). If the emissions of the pyrolysis process had been allocated 100 % to biochar, it would have increased the emissions of biochar production in Fig 7 by 13 % and thus the emissions of the growth media containing biochar (BC—COM-TILL) by 2 % in Fig 8. The retort has been introduced recently, and little published information is available. In the waste wood pyrolysis environment, the retort's technological readiness was approximated as level 6–7 according to the European Union classification (Giacomella, 2021). The machine's specifications are professional estimates from the retort's manufacturer.

2.3. Life cycle costing (LCC)

Costs were first analyzed individually for different growing media components (biochar, compost, ash, till, and peat). The total cost of four closure scenarios was then estimated based on component mixtures. The hypothetical cost (or compensation) of the environmental effect of the growing media components for mine closure was further acknowledged according to their CO_2-equivalent (CO_2eq) emissions estimated in LCA (see Section 2.4). Similar approach for estimating the effect of carbon price on mining industry has been formerly used by e.g. Ulrich et al. (2022). Costs were assessed on the € m^{-3} basis of the produced component or applied growing media in various mining closure scenarios. The cost assessment was conducted using a reference period (2021) that can be updated based on current economic conditions. Prices were adjusted for inflation based on the national consumer price index of the study region (StatFin, 2022c), which was considered to reflect price changes well in the labor-intensive biochar production. Time series which were partly dated to 2021 were used as such without adjustment. MS Excel (Microsoft 365 Apps for enterprise) was used in analyses.

Deterministic life cycle costing (LCC) principles were used to assess the costs of the goods and their production when applicable (Woodward, 1997; Matthews et al., 2014), i.e., in biochar production costing, earthworks, and loading and transportation processes. In LCC, value for money is optimized in the ownership of physical assets by considering all the cost factors related to the asset during its operational life (Woodward, 1997), e.g., acquisition, installation, operation, maintenance and servicing, and disposal cost. These were derived per time unit during the assets' lifespan. Unlike LCA, there are no complete general standards for LCC (Giacomella, 2021). The cost of each scenario was calculated from the modelled resource need in the system (Fig 2) and their unit cost, and then these costs were allocated to the output of the system. The resources, including their estimated time consumption and costs, are described in the following sections, along with the sources and methods used to obtain this data.

The evaluated system in LCC required shredding, pyrolysis, loading, transportation, and earthworks machines (Table 1, Appendix A). The parameters Ahmed et al. (2016) propose for biochar cost estimation were acknowledged in LCC. A medium-sized wheel loader was used to load the goods, and an excavator to apply the growing media on the mining site. A large shredder was used for waste wood shredding and post-shredding of biochar from pyrolysis. Road transportation was done with truck-trailer; a dump truck was used to transport growing media within the mining site, and the shredder was relocated with a semi-trailer. Table 2 shows transportation distances and cargo specifications. The specifications and cost factors of vehicles and machinery is described in Table 1, and more details of determining them in Appendix A.

The depreciation of shredder and pyrolysis retort was calculated with the straight-line depreciation method (Eq. (1)) (Miyata, 1980). The annual depreciation percentage (declining balance method (Miyata, 1980)) was used for transportation vehicles, loaders, and excavators (Eq. (2)). The average value of the annual investment (AVI) (Miyata, 1980) during the asset's lifespan was used to estimate the depreciating assets' interests (Eq. (3)). AVI is calculated using the values at the start of the year; we deduct half a year's depreciation from both the initial investment cost and the salvage value, ensuring that the results represent the annual mean values of the machines.

$$D = (P - S)/N \tag{1}$$

D = annual depreciation, S = salvage value, N = economic life, P = initial investment cost of equipment

$$Di = Pi * R \tag{2}$$

Di = Depreciation charge in year i, Pi value of the asset at the beginning of year i, R = depreciation rate

$$AVI = (P - S)(N + 1)/(2N) + S \tag{3}$$

AVI = average value of annual investment over its entire economic life, P = Initial investment cost, S = Salvage value, N = Economic life in years

Table 1 shows insurance, administration, and other transportation vehicle costs. In shredding, insurance and other expenses were €0.05 m^{-3} in solid wood shredded. Insurance and other costs in pyrolysis process were €2300 $year^{-1}$ (€2.71 m^{-3} of produced biochar). In both processes, 15 % was added to all costs to represent administration, risk, and profit.

Storage included fixed annual costs from facility and interests from stored materials, depending on storage lead times. The fixed cost was €1000 $year^{-1}$ per storage area in shredding (two separate areas), €1000 $year^{-1}$ in pyrolysis, and €4000 $year^{-1}$ on the mining site. Lead times were 82.58 days at both storages in shredding, 16.8 days in pyrolysis, and 5 days in the mining area. In pyrolysis, sheltering of biochar also consumed 5 min of worktime per productive day, accounted for as storage cost.

An interest rate of 5 % per annum was assumed for facilities, machinery, equipment, and material storage and included in average

Table 2
Densities of transported materials and cargo capacities based on total cargo and volume weight and truck frame payload, and one-way distance of the transportation of materials to the application area. In parentheses is weight-based moisture content of biochar during delivery, which varied according to delivery stage. *Waste wood density is expressed in 20 % moisture content, with porosity of 60 %.

Material	Density, kg m^{-3}	Cargo capacity, m^3	Distance, km	Reference for density
Waste wood	197	157	0	Hakkila (1979)*
Biochar (5 %)	252	157	200	Gray et al. (2014), Dias júnior et al. (2016), Wang et al. (2020)
Compost	800	63	100	Pesola (2022 professional estimate), Malińska et al. (2013)
Compost-biochar (62.5 %)	762	66	100	Moisture of biochar: Gray et al. (2014)
Ash	800	63	130	Tiainen (2014)
Till	1692	30	15	Ronkainen (2012)
Peat	250	157	25	Kesäniemi (2009)

annual costs. Unit cost for goods was estimated directly, and interests were factored in Risk was accounted for as a risk and profit factor in the cost of goods. All goods were assumed to escalate in line with inflation. A discount rate of 0 % was applied, as the short and uniform timescale across scenarios made discounting negligible.

Market prices were utilized for the products that were not assessed by the principles of LCC, i.e. composted wastewater sludge, ash, peat, and till, and all the other inputs like waste wood used for biochar feedstock, as well as for the tradable by-products of biochar: tar and wood vinegar. Prices were obtained in the first hand from the company operators involved in designing the concept case or derived from publicly available pricelists as a second option. The prices used did not include loading (separately estimated) or value-added tax. Table 3 and Appendix B show all the materials, and their estimated costs and sources used to determine the costs.

The cost (or compensation) of the CO_2eq emissions or sequestration was determined according to the value of the European Union Emission Allowances (EUA) in the EU Emissions Trading System (European Commission, 2015). The price was determined as an average of the local EUA auctions in 2021 (Energiavirasto 2022). Cost of carbon emissions was then added to total cost of the scenario or subtracted in the case of the scenario being a carbon sink. Similar approach has been used by e.g. Ulrich et al. (2022) and Fawzy et al. (2022).

Cost estimates as well as the further development are subjected to uncertainty. To estimate the effect of varying costs, a sensitivity analysis was performed for the economic analysis's key cost contributors (Table 3). Variables considered unrobust were analyzed with higher variation. Ash was valued at zero in the base calculation. However, ash may need purification from heavy metals in broad application, and in sensitivity analyses, an alternative price of €10 m^{-3} was used for ash. The base value for waste wood was zero, but €30 m^{-3} was used as an alternative to the approximate commercial value of alternatively applicable roundwood. Other adjustment factors were a factor of three (cost of emission allowances), 2pp change (interest rate), 25 % change (compost price, employee cost, peat price, and till price), and 50 % change (fuel price, wood vinegar price, retort productivity)

2.4. *Life cycle assessment (LCA)*

Methodologically, the work followed the ISO 14,040 and ISO 14,044 standards (ISO, 2006a, 2006b). The emission assessments did not consider capital goods, e.g., emissions from the facility's or other infrastructure's manufacture/construction (vehicles, road maintenance, etc.). LCA consists of four phases: the definition of the goal and scope, the inventory analysis, the life cycle impact assessment and life cycle interpretation phase as presenting the results (Section 3).

The assessed climate impact category (Global Warming Potential (GWP100)), based on IPCC (2013), includes carbon dioxide (CO_2), methane (CH_4), and dinitrogen monoxide (N_2O) emissions. The results of the life cycle inventory were characterized using factors for fossil $CO_2 = 1$, $CH_4 = 29.8$, and $N_2O = 273$ and presented as carbon dioxide equivalents, kg CO_2 eq. (Munoz and Schmidt, 2016). For the assessment of climate impacts, the Environmental Footprint 3.1. method (Bassi et al. 2023) and the Simapro calculation system were used.

Considering the biogenic carbon sequestration and storage during the agriculture phase, the EF guide (European Commission, 2021a) indicates that credits from "temporary carbon storage" are excluded, and biogenic carbon emitted later than 100 years after its uptake is considered permanent carbon storage. Both carbon emissions and removals are instructed to be reported separately (ISO 14,067; European Commission, 2021a) due to uncertainties in meeting the definition of permanent carbon stock. In this study, the emissions and storage of permanent carbon stock were therefore reported separately but also analyzed together as removals extracted from emissions if carbon met the definition of long-term carbon.

Table 3
Market-based prices used in analysis. In addition to base values, alternative high or low values along with the adjustment factor are shown for the parameters used in sensitivity analysis. Detailed explanations for prices used are given in Appendix B.

Parameter	Low	Base	High	Factor	References
Ash, € m^{-3}		**0**	10	+10 €	Obtained from industry in cooperation in the study
Compost price, € m^{-3}	6	**8**	10	±25%	Obtained from industry in cooperation in the study
Crude Oil, € l^{-1}	0.47	**0.94**	1.41	±50%	StatFin 2022b
Diesel, € l^{-1}	0.73	**1.46**	2.19	±50%	StatFin 2022b
Electricity, € kWh^{-1}		**0.0877**			StatFin 2022b
Emissions, € CO2e t^{-1}	17.52	**52.56**	157.68	x 3	Energiavirasto 2022
Employee cost, € h^{-1}	20.49	**27.32**	34.15	±25%	Official Statistics of Finland 2016, StatFin 2022
Interest, %	3	**5**	7	±2pp	Assumed
Wood vinegar, € l^{-1}	0.15	**0.30**	0.45	±50%	Derived from Elliot 1986, Ringer et al. 2006, StatFin 2022b
Peat, € m^{-3}	9	**12**	15	±25%	Derived from Laakso 2015, StatFin 2022b
Propane, € kg^{-1}		**2.50**			Derived from public pricelists
Retort lifetime, years	6	**8**	10	±2 years	Obtained from industry in cooperation in the study
Retort productivity, m^3 $year^{-1}$	425	**850**	1275	±50%	Obtained from industry in cooperation in the study
Tar, € l^{-1}	1.50	**3.00**	4.50	±50%	Derived from public pricelists
Till price, € m^{-3}	5.63	**7.50**	9.38	±25%	Obtained from industry in cooperation in the study
Water, € m^{-3}		**5.12**			VEETI 2022
Wood, € m^{-3}		**0**	30	+30 €	Obtained from industry in cooperation in the study

2.4.1. *Allocation methods*

If a process or facility delivers several goods or services (co-products, residual, or waste stream), it is "multifunctional", where all inputs and emissions linked to the process are partitioned between the product of interest and the other co-products in a principled manner. EF method (EC 2021) recommends ISO allocation hierarchy which prioritizes subdivision or system expansion, followed by physical allocation and then economic allocation. Economic allocation is commonly used when co-products have very different physical relationships or end use in the market (Kyttä et al. 2022). Therefore, this study applied economic allocation rules for different feedstocks and end-products in proportion to their relative market price. According to economic allocation rules, certain raw materials used for growing media were classified as waste with no market value and, therefore, had zero emissions. For example, ash has no market price at the energy production plant gate. Emissions from ash production are seen as part of the energy production facility's emission calculation and were therefore not considered in input acquisition emissions for growing medium material. Recycled waste wood used in biochar manufacturing has no economic value (market price) at the eco station before entering the pyrolysis process and is considered a waste stream.

Compost has an economic value (market price) at the wastewater treatment plant gate, as it is exported to growing medium production. It is therefore considered a co-product (not residual or waste) of water cleaning as a service. However, as the economic value (income share) for cleaned water through collected waste fees leaves the compost product's income share itself marginally small and computationally insignificant, no significant emissions are allocated for compost. In addition, sewage sludge composting is part of conventional wastewater treatment which is the downstream end of many different product value chains (EoL). Till was sourced from the closest available deposit and is seen as a product with a price on the market.

The pyrolysis process's total emissions are allocated to three final products (biochar, tar, wood vinegar) based on an economic value ratio of 0.89 for biochar. In the pyrolysis, no electricity or district heat is produced for the grid, so there is no emission allocation for energy production.

2.4.2. *Emission factors*

The assessment is conducted to use most representative emissions data available, e.g. specific Finland's national level data applied from literature but in other cases mainly following IPCC (2006), IPCC (2019) and Ecoinvent data. The applied emission factor references are presented in Table 4.

As for the raw materials with market value and emissions to be allocated (see more in section for allocation methods), the Ecoinvent emission factor for the sand "Sand, at mine/CH U" was applied for till in mining area, as no specific emission factor for till was found. Peat emissions from extraction and decomposition are based on an expert estimate (Frans Silvenius, Luke) applied from a study by Pohjola (2014). Further details in Appendix C.

Emissions from producing biochar start from the pre-treatment of wood (shredding and sieving of wood) before the pyrolysis process conducted next to the eco station. Waste wood pyrolysis also generates direct CO_2 emissions. However, they are seen as biogenic, as they come from renewable biomass and have a characterization factor of 0 (zero-emissions) due to a short rotation time. The amount of methane contained in the gas is also estimated to be non-existent.

The IPCC (2019) default N_2O coefficients for organic amendments were applied in the estimates of direct and indirect gaseous N_2O emissions of growing media applied in soil and are evaluated based on the total amount of nitrogen in the growing medium.

In this study, the emissions and storage of permanent carbon stock in soil were reported separately but also analyzed together as removals extracted from the emissions. Biochar applied in the growing media remains in the soil in a centennial timescale (over 100 years)— much longer than wood-bound carbon released into the atmosphere when wood decays. More specifically, during pyrolysis, wood chemical composition changes in a form that is resistant to microbiological decomposition. The biochar, including carbon, which remains unburned, becomes long-term carbon storage. No actual carbon sequestration occurs during pyrolysis, but when biochar will be applied to soil, it forms long term unburned carbon. In our case, the carbon content of biochar was 87 % of which 80 % is considered long term carbon according to maximum estimate by IPCC (2019). This is because the carbon stability may vary, but in northern cold environment slow decomposition rate is expected. More precisely, because a kilo of C binds 3.667 kg of CO_2 (mass ratio of C to CO_2 is 44.01/12.01), a kilo of C in biochar binds 2.93 kg of CO_2 eq (87 %). Furthermore, one kg of biochar in dry basis binds 2.55 kg of CO_2 eq and in 5 % moisture content 2.68 kg of CO_2 eq. This is the same amount than assessed in the case study by Fawzy et al. (2022) where assessed amount of C removal embodied per kg of biochar was 2.68 kg CO2eq (dry basis) but however with a bit different biochar properties (85 % C, 1.7 % moisture content).

In addition to biochar, approximately 5 % of the total carbon in the form of compost was considered to meet the definition of permanent carbon storage. Estimate was made by an expert in Natural Resources Institute Finland (Jouni Sorvali) using the Yasso model. This estimate

Table 4
LCA emission factors and their sources.

Life cycle stage	Input/Process phase	Emission factor	Source
Raw material acquisition			
Ash	Ash acquisition	–	according to economic allocation key
Compost	Compost acquisition	–	according to economic allocation key
Till	Till acquisition	Sand, at mine/CH U	Ecoinvent 3 database
Waste wood	Waste wood acquisition	–	according to economic allocation key
Peat	Extraction and decomposition		an expert estimate (Frans Silvenius, Luke) applied from a study by Pohjola (2014)*
Pyrolyses process	Pre-treatment of wood (shredding and sieving of wood)	Wood chipping, industrial residual wood, stationary electric chipper {RER}| processing | Cut-off, U *	Ecoinvent 3 database
	Loading wood into the cage with a wheel loader	Fuel consumption	LIPASTO (2017)
		Fuel production and distribution	Ecoinvent 3
	The shredding and sieving of the wood	Average Finnish electricity emission factor	modelled by experts in Luke*
	Kindling wood	for pine wood chips, "Bundle, energy wood, measured as dry mass {SE}| Softwood forestry, pine, sustainable forest management | Cut-off" for spruce chips "Bundle, energy wood, measured as dry mass {SE}| Softwood forestry, spruce, sustainable forest management | Cut-off.	Ecoinvent 3 database
	support gas (propane production and combustion)	Propane, burned in building machine {GLO}| market for	Ecoinvent 3 database
	transportation (propane production and combustion)	semi-trailers (total mass 40t and load capacity 25t)	LIPASTO (2017)
		Fuel production and distribution	Ecoinvent 3
Transportation of growing media to the mining area **	Compost and ash	a full trailer, 100 % load (total weight 76 t, load capacity 51 t, EURO VI)	LIPASTO (2017)
	For lighter biomasses (biochar and growing peat)	a full trailer, 80 % load (total weight 76 t, load capacity 51 t, EURO VI)	LIPASTO (2017)

(*continued on next page*)

Table 4 (*continued*)

Life cycle stage	Input/Process phase	Emission factor	Source
	The return load is empty in all cases	a full trailer, empty load (total weight 76 t, load capacity 51 t, EURO VI)	LIPASTO (2017)
		Diesel, low-sulfur {Europe without Switzerland}| market for | Cut-off	Ecoinvent 3 (Wernet et al., 2016)
Mixing and loading	A medium-sized wheel loader	Fuel consumption	LIPASTO (2017)
		Diesel, low-sulfur {Europe without Switzerland}| market for | Cut-off	Ecoinvent 3
Spreading	A medium-sized excavator preformed spreading.	Emission factor per litre for tractor fuel consumption	LIPASTO (2017)
		Diesel, low-sulfur {Europe without Switzerland}| market for | Cut-off	Ecoinvent 3
Use in the mining area	Direct N2O emissions	0.006 kg N2O—N/ kg N	IPCC 2019, coefficients for organic amendments in wet climates
	Indirect N2O emissions from ammonia that evaporates from the N contained in the growing media	0.021 kg N2O—N/ kg N deposited	IPCC 2019, coefficients for organic amendments, animal manures N in crop residues and mineralized N from soil organic matter decomposition
	Indirect N_2O emissions from leaching of N contained in the growing media	0.011 kg N_2O—N/kg of N leaching	IPCC 2019, coefficients for organic amendments, animal manures N in crop residues and mineralized N from soil organic matter decomposition
Carbon sequestration	Biochar	2.93 kg CO2eq/ kg C (tot) in biochar (80 % of total C in biochar)	IPCC (2019)
	Compost	1.83 kg CO2eq/ kg C in (5 % of total C in compost)	estimated by experts in Luke

[*] Ecoinvent, country-specific, electricity emission process, modified with the statistical data of Finnish Energy (ET) Electricity Statistics on the structure of Finnish electricity production in 2020. Construction and maintenance of the transmission network have not been taken into account.

[**] The emissions from the transportation of the compost-biochar mixture are granulated according to the transported volume from the wastewater treatment plant onward (20 % biochar, 80 % compost).

was based on the carbon decomposition rate in field conditions calculated from the compost's carbon content (22 %) and chemical quality (Heikkinen et al., 2021).

3. Results

3.1. Cost of biochar production and unit costs of the different growing media components

Biochar production consisted of two processes: a) pre-shredding; and b) waste wood pyrolysis. The cost of pre-shredding of waste wood a) was €8.23 m^{-3} per solid matter of waste wood crushed. The production of one cubic meter of biochar requires 1.3 m^{3} of crushed waste wood solid matter. The cost of raw material for pyrolysis was therefore €10.70 m^{-3} of biochar produced. The cost of pyrolysis b) was €192.72 m^{-3}, and the total cost, including raw material, was €204 m^{-3}, equating to the price of break-even production from the factory gate. More detailed cost structure of pyrolysis production is represented in appendices D.

Final costs of the biochar component delivered to the mining site were €217.37 m^{-3}, including transportation costs of €13.18 m^{-3} from the production facilities to the mining site via the wastewater facility. Transportation was long, and an extra stopover was needed.

Pyrolysis by-products may lower the break-even price. The value of wood vinegar and tar were estimated to be €27 and €24 respectively per produced cubic meter of biochar. The break-even price for biochar production was €153 m^{-3} when the value of by-products was deducted from production costs. Carbon sequestration was considered to take place in application of biochar enhanced growing media, and it was acknowledged later in the scenario analyses.

The costs of components other than biochar (compost, ash, till, and peat) delivered to the site were €9–16 m^{-3} (Fig. 4). Ash was the most affordable component. The material itself was free; the costs were solely for loading and transportation. Till and peat cost €10.54 m^{-3} and €13.39 m^{-3} respectively. Short transportation meant costs were mainly associated with the value of the material. Transportation cost €3.04 m^{-3} for till and €1.39 m^{-3} for peat. Compost was the second most expensive component, costing €15.72 m^{-3}, nearly half of which was transportation (€7.72 m^{-3}). The transportation distance was long, and volumetric cargo capacity was quite low.

3.2. Costs of mining closure scenarios

Initially, the scenario costs are represented without any compensation or costs from by-products or emission allowances. When only

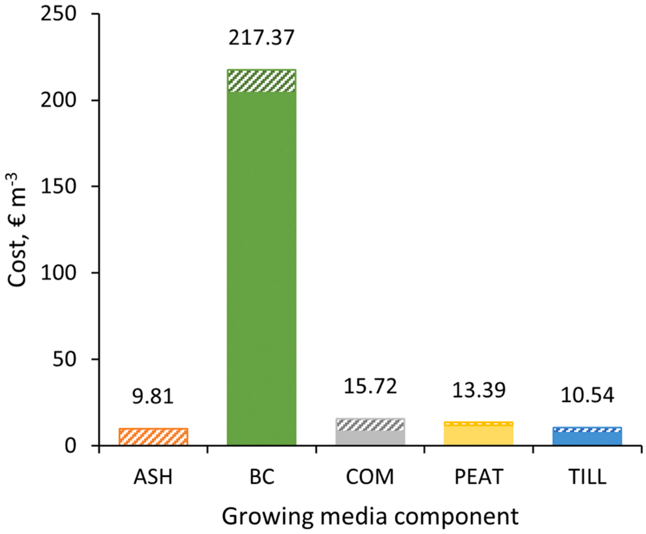

Fig. 4. Costs of growing media components delivered to the mining area (mixing or application of material or emission costs not included). Solid color in a bar represents production costs; hatched pattern, transportation or loading costs. Ash had no production costs, so the column has only hatched pattern (BC = biochar, COM = compost).

material, production, transportation, and application costs are included, the cost of growing media in different scenarios, from highest to lowest, were: ii) BC—COM-TILL, €36.32 m^{-3}, i) COM-TILL, €16.14 m^{-3}, iii) ASH—COM-TILL, €16.12 m^{-3}, iv) PEAT-TILL, €14.97 m^{-3}.

A 10 % share of biochar in the BC—COM-TILL scenario caused 60 % of the scenario's costs (Fig. 5). Evidently, the amount of biochar in the growing media had a high impact on costs: for example, substituting half of biochar (5 percentage points) with till decreased the total costs of BC—COM-TILL to €25.97 m^{-3}.

Furthermore, sellable by-products (tar and wood vinegar) were valued at €51 m^{-3} of produced biochar, i.e., €5.10 m^{-3} of ready-made growing media in the BC—COM-TILL scenario. Taking compensation from by-products into account, the cost of the BC—COM-TILL scenario (10 % of biochar by volume) decreased to €31.22 m^{-3}.

The BC—COM-TILL scenario acts as a carbon sink because biochar results in a long-term carbon stock. Biochar containing growing media sequestered 49.7 kg CO2eq m^{-3}, worth €2.61 m^{-3}. Considering compensation from both emission allowances and by-products, the total closure cost in the BC—COM-TILL scenario was €28.60 m^{-3} of growing media used. Acknowledging all costs and compensations (Fig. 5), the scenarios from highest to lowest were ii) BC—COM-TILL, €28.60 m^{-3}, iv) PEAT-TILL, €18.90 m^{-3}, i) COM-TILL, €16.78 m^{-3}, and iii) ASH—COM-TILL, €16.76 m^{-3}.

When costs from emission allowances were not acknowledged, PEAT-TILL was the most affordable scenario, at €14.97 m^{-3}. However, emission allowances increased the PEAT-TILL scenario's costs most, €3.92 m^{-3}. Acknowledging the increase, the cost was higher than in the ASH—COM-TILL and COM-TILL scenarios.

Transportation costs were €2.2–5.9 m^{-3} (12–32 % of total costs) and were highest in the BC—COM-TILL scenario. Compost was typically a high cause of transportation costs in the scenarios it was included (Fig. 5).

3.3. Sensitivity analysis

Cost sensitivity in the different scenarios was tested for the key cost contributors (Fig. 6). By-products and emission allowances were included in costs. The results were most sensitive for the mobile retort productivity in the BC—COM-TILL scenario. Increasing productivity decreased costs by €5.27 m^{-3}; in contrast, decreasing productivity increased costs by €15.68 m^{-3} (see Table 3 for the rate of increase/ decrease). Retort lifetime had only a small effect on costs.

All scenarios were sensitive to changes in the price of emissions, but especially those of BC—COM-TILL and PEAT-TILL. With the highest price for emission allowances €157.68 CO2eq t^{-1}, PEAT-TILL was the most expensive scenario, €26.75 m^{-3}, €3.36 m^{-3} more expensive than BC—COM-TILL with the same emission allowances price. The impact of labor costs, wood price, and by-product value was also modest, whereas the rest of the variables had only a minor impact on closure material costs.

3.4. Climate impacts of different growing media components

Emissions of individual growing media components per m^3 vary greatly (Fig. 7). Peat had the highest emissions (142.4 kg CO_2eq m^{-3}) due to significant production emissions (harvesting and digging of peat). Biochar had the second-highest emissions (35.6 kg CO_2eq m^{-3}), mainly due to significant production emissions from pyrolysis (highest impact from the ignition stage, including acquisition of kindling (energy) wood and acquisition and combustion of propane as support gas). For till excavation and transportation, the total emission was 5.2 kg CO_2eq m^{-3}. For ASH and COM, production emissions were considered zero due to economic allocation rules. Both ASH and COM had the lowest total emissions as the only source of emissions emerged from transportation with zero production emissions.

For ASH, transportation emissions were responsible for the total climate impact (4.7 kg CO_2eq m^{-3}) but were highest due to the quite long distance (130 km) combined with a high biomass weight of 0.8 t m^{-3}. For

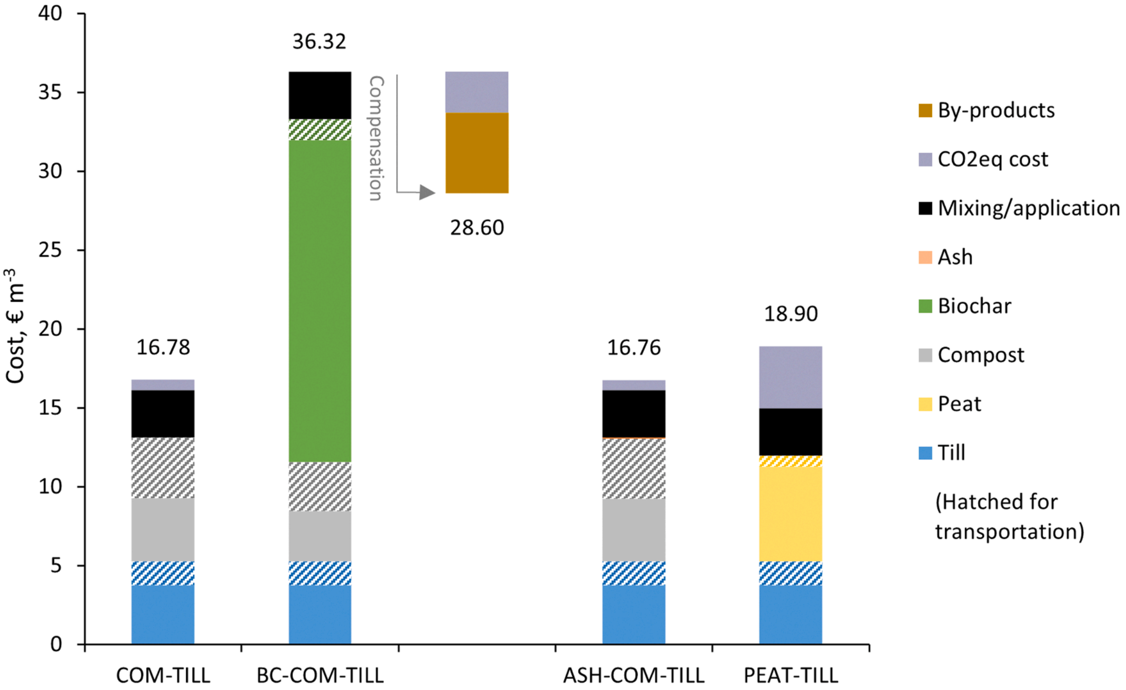

Fig. 5. Costs of four growing media mine closure scenarios, broken down into production of materials (till, peat, compost, biochar, ash), transportation (hatched pattern), and mixing/application costs at the mining closure site. Estimated CO_2 emission allowance costs or compensations (co2eq cost), and revenues from biochar by-products (wood vinegar, tar), are also included. Costs from emission allowances are added to the total, while compensations and revenues are shown in a separate bar, reducing the net cost. This figure compares the cost-effectiveness of each scenario.

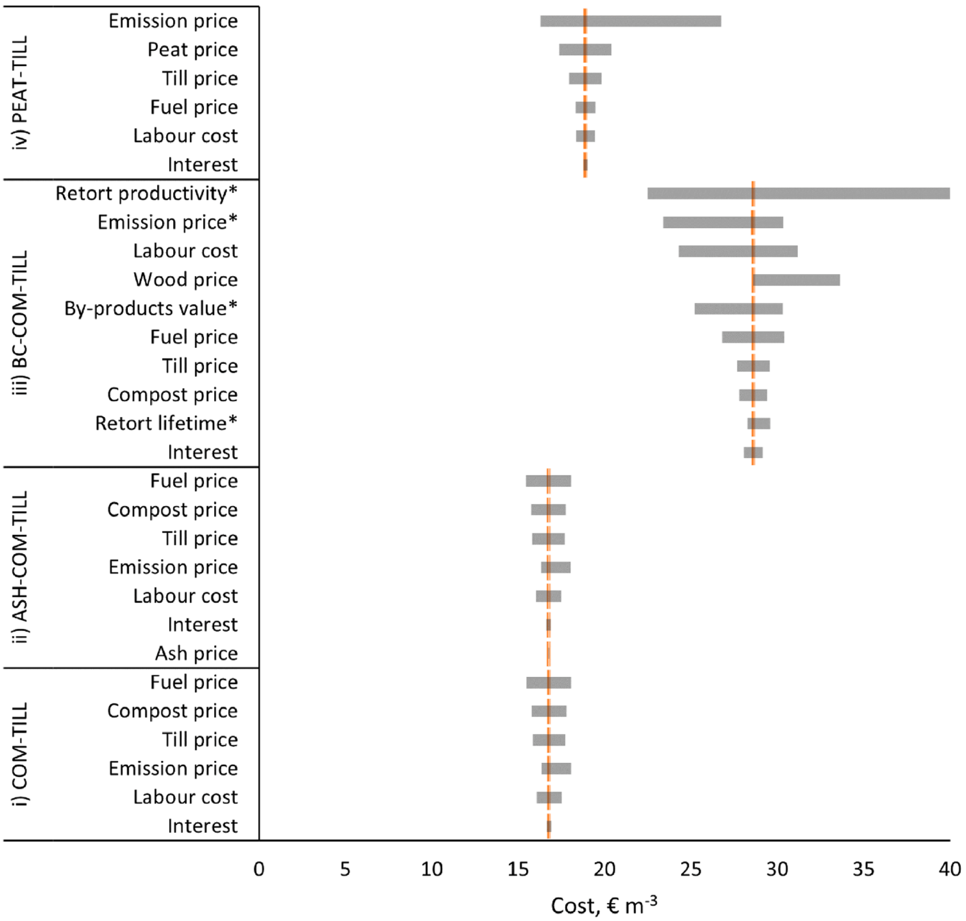

Fig. 6. Sensitivity analysis of costs of mining closure with different growing media. Table 3 shows the values used in the analysis. Fuel includes diesel and crude oil. By-products include tar and wood vinegar. Rows marked with an asterisk (*) refer to an inverse effect, that higher value decreases costs, which is typical for productivity but not for production factor prices.

COM, transportation emissions were responsible for the total climate impact (3.6 kg CO_2eq m^{-3}) and were second highest due to a slightly shorter distance (100 km) but combined with a high biomass weight of 0.8 t m^{-3} (Fig. 7). Despite the longest distance (300 km) for BC transportation, emissions were only third highest because of biochar's light biomass weight (0.25 t m^{-3}), and one-third-of the distance (100 km) was assumed to be transported with compost (only 20 % of these emissions to BC). TILL transportation emissions were second lowest due to the shortest distance to the mining area (15 km), despite the greatest weight. Peat transportation emissions were almost insignificant due to the short distance (25 km) to the mining area and the component's light biomass weight, 0.25 t m^{-3}.

3.5. Climate impacts of mining closure scenarios

The climate emissions of four different growing media scenarios are shown in Fig. 8. The significantly highest emissions result from the PEAT-TILL (74.7 kg CO_2eq m^{-3}) closure scenario due to the high emissions associated with peat decomposition (Fig. 8). However, growing media scenario emissions, including circular material, varied little: the scenario including biochar (BC—COM-TILL) was only slightly higher (18.1 kg CO_2eq m^{-3}) than COM-TILL (16.6 kg CO_2eq m^{-3}) and ASH-COM-TILL (16.6 kg CO_2eq m^{-3}). The share of biochar in the BC-COM-TILL scenario was 10 % of the total volume, and emissions associated with biochar production (mainly pyrolysis) therefore had only a minor impact on the mixture's total emissions. It is noteworthy that N_2O emissions made a major contribution to emissions in all COM-containing scenarios. The estimation of N_2O emissions is based on the compost's total nitrogen content.

When long-term carbon storage was considered in calculations (Fig. 8), BC—COM-TILL scenario emissions became a carbon sink, with a total value of −65.8 kg CO_2eq m^{-3} (carbon storage −83.9 kg CO_2eq m^{-3}). Carbon added in the form of compost decomposes relatively fast and contributes mostly to short- or medium-term carbon storage. The amount of permanent carbon in the compost was estimated to be 5 % of the total carbon content, and the carbon storage potential was therefore −4.4 kg CO_2eq m^{-3} for both COM-TILL and ASH-COM-TILL scenarios, decreasing their emissions and resulting in a total carbon footprint of 12.2 kg CO_2eq m^{-3} for both. The ash's carbon content is so low that its carbon storage potential is considered insignificant. The carbon contained in peat, meanwhile, is considered to completely decompose into CO_2 and is counted as fossil emissions in peat's carbon footprint.

4. Discussion

This case study investigated the economic and environmental viability of various value chains for circular-bioeconomy-based growing media in mine closure from a total life-cycle perspective. It revealed that while incorporating wood waste biochar to compost-till growing media increases mine closure costs, it also transforms the system into a carbon sink with negative CO_2-equivalent emissions.

In addition to traditional till and peat, growing media mixtures contained organic side streams derived from local bioeconomy actors. While the new growing media components, compost and ash, were available for free, biochar production was expected to be rather costly. Including biochar in the growth media was justified in a recent

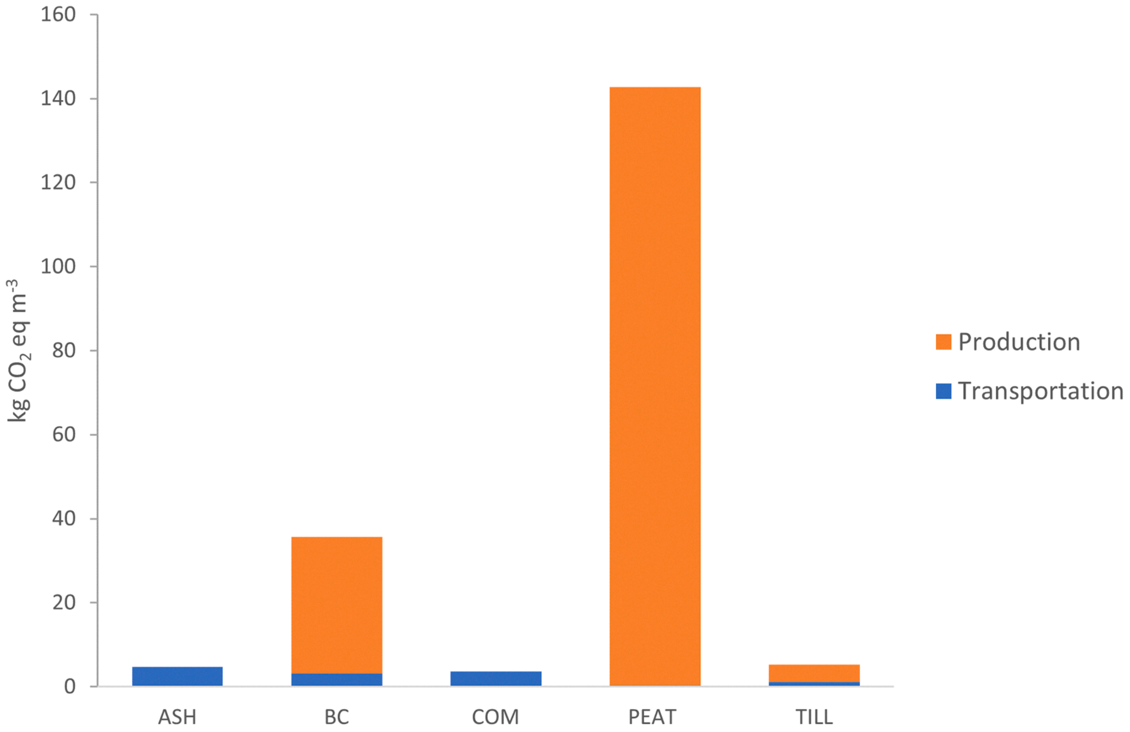

Fig. 7. Emissions of components used in different growth media. The orange bar represents production emissions; blue represents emissions of transportation to the mine. Emissions do not include use of components in the mining area.

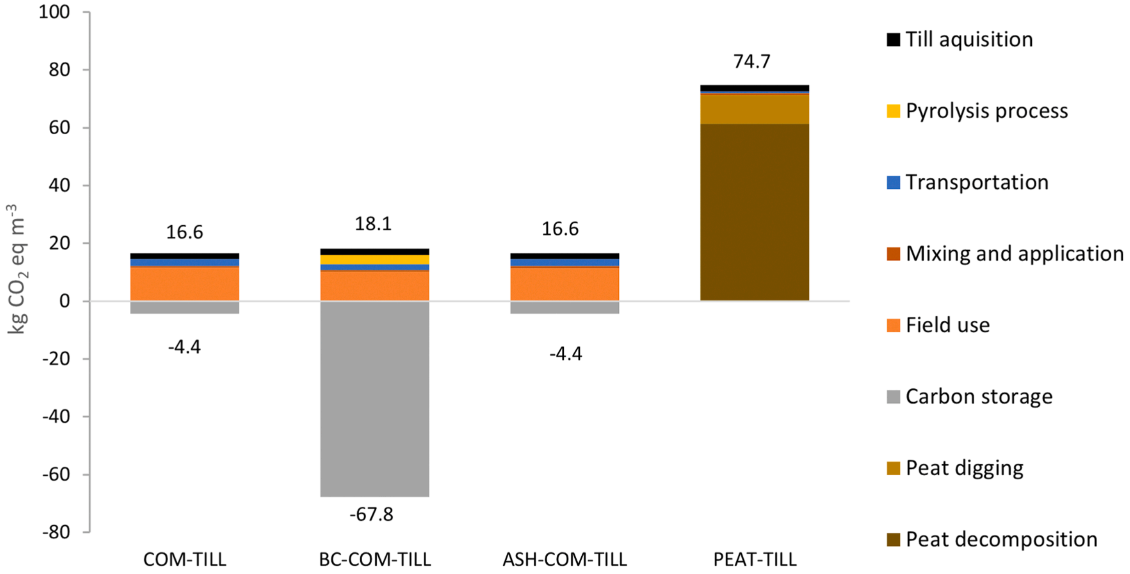

Fig. 8. Climate emissions of growth media scenarios for mining closure. The carbon storage potential of biochar and compost are shown as a negative impact with gray bars.

publication by Hagner et al. (2021), which indicated that the application of wood-based biochar in growth media increased vegetation survival and aboveground biomass by 71−250 % in the Rautuvaara mine closure 170 km from the Kevitsa mine. Well-performing growing media was therefore considered to give additional benefits by improving plant growth in harsh climate conditions in northern mine closures. From the climatic perspective, replacement of peat with other organic circular bioeconomy side stream materials was foreseen as beneficial, while life-cycle effects on the cost of growing media options were unknown.

4.1. Biochar production costs and environmental impacts

Total production prices for biochar varies from €200 t^{-1} to over €1000 t^{-1}, depending on location, methods, and production scale (Shabangu et al., 2014; Kim et al., 2015; Hakala et al., 2020; Keske et al., 2020; Nematian et al., 2021). In our study, biochar production costs using mobile retort were €851 t^{-1} (€204 m^{-3}) without compensation from by-products and carbon credits. Biochar costs in our study case were therefore at the upper end of the range and close to the baseline analyses of Keske et al. (2020) and Nematian et al. (2021), who analyzed mobile retort biochar production in Labrador, Canada, at €881 t^{-1} ($1004 t^{-1}, 2020 exchange rate, \$1.14 per euro) and California, USA, at €1307 t^{-1} (\$1542 t^{-1}, 2021 exchange rate, \$1.18 per euro) respectively.

We identified labor as a major biochar production cost factor. Moreover, pyrolysis equipment and water consumption during biochar production were equal to or higher than the total cost of the alternative materials (ash, compost, peat). Technical and operational rationalization and automation can improve pyrolysis, as shown in the study by Kim et al. (2015). The authors analyzed biochar production from forest or mill residues, which were like the waste wood we used. The estimated production costs were €388 t^{-1} (considering 21 % inflation and the 2021 exchange rate, \$391 t^{-1} in 2011 US dollars), 46 % of our study's costs. The main reason for the difference was the mobile retort's productivity in Kim et al. (2015) being 56 % higher than in our study. In our sensitivity analysis, a 50 % increase in retort productivity reduced costs by 26 % to €631 t^{-1}. However, this alone does not solve the current challenge of the high cost of producing quite large amounts of biochar for a mine closure using a relatively small mobile pyrolysis unit.

Shabangu et al. (2014) and Hakala et al. (2020) analyzed large-scale industrial systems, resulting in costs well below one-third-of the mobile retort costs in our study. Hakala et al. (2020) theoretically evaluated large-scale industrial pyrolysis, either as a stand-alone process or integrated into a pulp mill. Plants' annual capacity reached 95,000 tonnes (about 400,000 m^3), up to 500 times the capacity of the mobile retort in our study. Average costs were €367 t^{-1} for the stand-alone plant and €257 t^{-1} for the integrated plant. Most of the costs were due to raw materials (€222–253 t^{-1}). In Hakala et al. (2020), the use of surplus pyrolysis energy for heating or electricity compensated a large part of the production costs, which were only €24–86 t^{-1}, including compensation but excluding transportation and raw material costs. This sum is a small fraction compared to our study's corresponding costs, demonstrating the benefits of integration and economies of scale. Although surplus energy can also be utilized with smaller production units, economic gains may remain lower.

Our pilot concept's initial assumption was that the mobile retort could be efficient for producing biochar close to the raw material supply and end use, reducing the need for feedstock transportation (Vochozka et al., 2016; Nematian et al., 2021). We expected that in sparsely populated areas such as Northern Finland, where most mines operate over long distances, a mobile solution might be particularly efficient. In reality, the options for rational location sites were limited. Waste wood needs to be pre-processed and sorted at recycling centers, but it is more expensive to transport feedstock waste wood from the recycling center for pyrolysis than it is to transport the produced biochar. These factors in our concept limited the retort's rational location. The ideal location for the retort would be at a large recycling center close to a wastewater treatment plant that can provide an abundant supply of feedstock and compost. As demonstrated by the benefits of economies of scale and integration by Shabangu et al. (2014) and Hakala et al. (2020), the pyrolysis unit at such a site could therefore essentially be a fixed installation.

Considering production phase of individual growing media components from the LCA perspective, biochar's climate impact was significantly greater than that of other materials (ash and compost) or till. This is mainly due to further processing needs (pyrolysis) of circular waste material (waste wood) causing both extra emissions and costs. Instead, ash, compost, till, and peat lack further processing needs. More specifically, the major impacts during pyrolysis emerged from the ignition stage, which included acquisition of energy wood for lighting, as well as support gas (Appendix C in detail). On the other hand, emissions were also avoided in this case by using waste wood instead of energy wood, the latter of which is considered to generate emissions during its production phase. Biogenic CO_2 emissions from burning wood are significant, but they are not included in the climate impact calculations.

Adding biochar to sewage sludge during the early phase of composting has been identified as a highly effective method for reducing greenhouse gas emissions (Yin et al., 2021). Even though this idea falls outside the system boundaries of our study, incorporating biochar into composting could provide additional insights. It may affect emissions of composting or permanence of compost incorporated biochar in growing media, but it was not acknowledged in this study.

4.2. *Costs and emissions of ash, compost, peat, and till*

When the growth media materials were considered separately, the LCA and LCC results were parallel. In other words, for some aspects, lower environmental impacts coincide with lower costs. For example, fly ash, compost, and till as separate materials had significantly lower climate impacts and costs, while biochar material had significantly higher emissions and highest costs, partly because climate impacts are assessed for growth material products using economic allocation rules. Ash was not assumed to have an economic value (market price) because it is regarded as a residual material without an upstream burden emission allocation. In other words, emissions related to ash production up to the energy plant gate were allocated to other energy production. Compost had a market value, but the income share of the compost product itself for the wastewater treatment plant was marginally small and computationally insignificant, and no significant emissions were allocated. Till also had a quite low market value and the emission coefficient (applying Ecoinvent coefficient for sand), leading to no significant climate impacts next to low transportation impacts due to the short transportation distance to the mining area. It should be noted that biochar's emissions and costs were high because waste wood as a circular waste material needed further processing before pyrolysis. Ash and compost required no further processing.

Peat was a contradictory material in LCA and LCC. Significant emissions were caused by peat harvesting and digging. Peat had the highest emissions as a separate material but also when incorporated and applied in growth media. Peat extraction is known to rapidly remove carbon from the peatland carbon store and result in substantial carbon losses from the extraction site (Pohjola, 2014). Though the climate impact of peat extraction is high, the costs and market price for growing peat is low because of its low value as a natural resource (MML 2024: value of peat extraction site, €2000 ha^{-1} vs. till extraction site, €14,000 ha^{-1}) and relatively low labor needed in extraction (StatFin, 2024). Poor environmental effects mean peat extraction encounters tightening legislation (International Energy Association, 2023), concerning mainly energy use. Also, the EU Biodiversity and Soil Strategies seek to protect peatlands —vital carbon sinks that store twice as much carbon as all the world's forests (Global Peatlands Initiative, 2022). Increasing regulations can decrease peat supply, which in turn increase costs according to the microeconomic theory (Shapiro et al. 2022). Peat energy use reduction may also decrease synergies for peat growing media extraction, but in lack of more precise information, it is a thing that should be found out in further research.

When examining hotspots, transportation emissions and costs were not perfectly interrelated, as fuel consumption accounted for only 25 % of total transportation costs but usually 100 % of total transportation emissions. For example, biochar transportation costs are highest due to the intermediate stop (or loading compost with biochar), requiring extra labor and vehicle time consumption, but biochar transportation emissions are lowest because of low fuel consumption. Shortening transportation distances therefore reduces fuel consumption and emissions more effectively than costs. The results have been analyzed with fossil fuels.

The highest emissions for all circular waste material containing growing media scenarios emerged from N_2O emissions formed from the total nitrogen amount of the growing media when spread on the soil. For this assessment, the study applied the same N_2O emission coefficients for organic fertilizers (IPCC 2019) based on manure studies in agricultural soil. N_2O emission coefficients for growing media materials used in mining sites should be studied in detail to provide a more precise estimate of their climate impacts.

4.3. Costs and environmental impacts of growing media scenarios

When examining different growing media scenarios applied in the mining area, growth media emissions containing biochar were only slightly higher than those of the others because of the mix's relatively small share of biochar. When the long-term carbon storage potential of the materials was considered alongside their emissions, growth media including biochar was the most environmentally beneficial alternative. Although the carbon sequestration potential may vary depending on the biochar quality and prevailing environmental conditions, the biochar stability in cold northern climate is expected to be high. In general, the circular-bioeconomy-based recycled material (ash, biochar, compost) containing growing media scenarios had significantly lower emissions than the scenario containing peat.

In addition to benefits as a carbon sink, biochar is shown to improve seed germination, seedling survival, and plant growth in harsh conditions (Juno, 2019; Hagner et al., 2021) and reduce N_2O, CH_4 (Van Zwieten et al., 2009; Karhu et al., 2011; Liu Z et al., 2017), and CO_2 emissions (Spokas and Reicosky, 2009). However, the LCC of these benefits is challenging for non-harvest plants. Many authors have used the LCA method to assess biochar's environmental impacts in different applications, but the assessments typically do not include effects on plant growth, a comprehensive evaluation of which requires expensive long-term experiments. Differences in the contexts and characteristics of studies do not allow a direct comparison of results, limiting the scope of LCA studies (Carvalho et al., 2022). Appendix E further discusses our case study's limitations.

LCC showed that fly ash and sewage sludge compost, mixed with till, were economically viable materials for use in the growth media used for mine closure. However, the economics of applying 10 % waste wood biochar to the growth media are questionable, as it (BC—COM-TILL) increased costs by 51–71 % compared to the other scenarios (ASH—COM-TILL, COM-TILL, PEAT-TILL). However, the addition of 10 % biochar to till and compost containing growing media improved plant growth significantly on northern mine sites (Hagner et al., 2021). Lower biochar doses (1–3 %) have also been shown to increase plant growth in various environments, but the effects depend on biochar type, dose, soil type, climate conditions, and plant species (Premalatha et al., 2023). A study on sufficient biochar application doses in northern mine closures is needed to achieve well-established vegetation with low environmental impact and tolerable costs.

The methods used to assess costs and sensitivity across various scenarios offer valuable insights but are limited by simplifications, limited number of parameters and rigid boundaries that could be improved. The sensitivity analysis identifies labor cost as a key factor driving mining closure costs, with a notably wide range of impact. However, the labor cost and boundaries assumed reflect conditions typical of a developed economy, likely with higher wage levels. Broadening the analysis to include additional growing media, diverse regions, or wider parameter ranges could significantly change the results. For instance, labor costs in developing countries could be much lower. Yet, a detailed examination across significantly different regions would require further investigation to account for complex interactions between cost factors.

4.4. Practical implications and future studies

The interrelations between costs (LCC), emissions (LCA), and the practical performance of growing media for use in mining areas in northern latitude countries allow the following summary. The addition of biochar to growing media outperforms the traditional solution based on till and peat. The recent review by Shi et al. (2022) conclude that biochar induced changes in the soil of heavy metal contaminated mine tailings, such as increased soil porosity, water holding capacity, and abundance of microbial communities have salutary effect on enhanced phytostabilization. Similarly, Hagner et al. (2021) showed in Rautuvaara mine tailings in northern Finland that the application of wood-based biochar in growth media increased aboveground biomass of grasses by 71–250 %.

The positive plant growth effects associated with biochar use were not included in LCA calculations, nor was the monetary value estimated. The present study indicated that biochar-based growing media was the most expensive, but also the most beneficial, solution from the environmental perspective. Regarding the latter, the carbon storage potential of biochar generates a significant climate impact reduction for growth material when applied in soil. However, regarding the economic impact, compensation revenues derived from carbon storage were insufficient to compensate pyrolysis production expenses. Which of the angles considered here is most decisive for mine closure solution, is beyond the present study's scope. In present analysis though, when carbon price exceeds €130 CO_2 t^{-1}, biochar scenario becomes the most affordable one (when revenues from by-products is also acknowledged).

Although no specific European regulations mandate the adoption of circular bioeconomy practices in mine closure, several policy frameworks and guidelines support their integration into mining operations. These include the Circular Economy Action Plan (European Commission, 2020), which emphasizes waste reduction, the Bioeconomy Strategy (European Commission, 2018), which highlights the role of bio-based solutions, and Guidelines for Mine Closure Activities (European Commission, 2021b), which encourage best practices for mine rehabilitation. Collectively, these initiatives align with circular economy principles, promoting sustainability in the mining sector. However, Osei et al. (2023) argued that the mining industry faces challenges in adopting recycling and regeneration strategies as part of the circular economy for many reasons, including a lack of value chain alliances to facilitate greater availability of suitable alternative materials, money, or government support. The findings of this case study could encourage the mining industry to genuinely meet environmental sustainability requirements —avoiding "greenwashing"—while continuing to supply the critical minerals needed for the green transition. The study also provided valuable quantified data for regulators to support decision making. We also acknowledged the limited resource of waste wood in sensitivity analysis of biochar production costs. Expanding the feedstock to include energy wood harvested from the forests can significantly enhance the availability and scalability of the concept, with only a modest increase in biochar production costs. This enables continued production even when circular bioeconomy resources are limited. Zilberman et al. (2023) also suggested focusing on bioregions with active forest management to maximize the net value of biochar systems.

Among several circular economy approaches, biochar production is a good example of pushing the economy toward a carbon-neutral balance (Hu et al., 2021). We showed that growing media containing circular bioeconomy materials could act as a carbon sink in mine closure, as the carbon in biochar was expected to remain in the soil for >100 years. It was also shown that a value set for carbon sequestration substantially decreases biochar-containing growing media costs. Carbon sinks have value, e.g., through decreasing the need to buy allowances in trading in the form of the European Union Emission Allowances (EUA) (European Commission, 2015b). The value of these allowances reached €53 CO2eq t^{-1} in 2021 and has recently been rising (Energiavirasto, 2022). Also Fawzy et al. (2022) noted that carbon compensation significantly impacts biochar costs, while Ruett et al. (2024) found that higher biochar content in growing media reduces the carbon footprint but initially increases expenses. However, with sufficient carbon compensation, a high biochar mix becomes the most cost-effective option. For example, a 15 % biochar blend in tomato cultivation acts as a carbon sink. Moreover, as carbon emission prices climb, traditional peat-based growing media become less affordable compared to biochar alternatives (Ruett et al. 2024). In addition, technological development may substantially decrease biochar costs, e.g., through improvements in process productivity and its integration with other industrial processes and utilizing economies of scale.

Above all, incorporating biochar into growing media can improve soil's physical and chemical properties (Ajayi and Horn, 2016) and, most importantly, promote vegetation growth (Ennis et al., 2012; Mohan et al., 2018; Hagner et al., 2021), which is among key objectives of mine site rehabilitation. Fast and effective rehabilitation, combined with the use of circular bioeconomy-based materials in covering structures may further enhance the social acceptability of mining activities. Additionally, healthy and thriving vegetation boosts carbon sequestration over time, providing long-term environmental benefits.

5. Conclusions

The study highlighted that circular-bioeconomy-based mine closure solutions generate lower emissions compared to peat, traditionally used as a growing media material. By replacing peat use with composted sewage sludge CO_2eq emissions lowered by 84 %. From the climate emissions perspective, the growing media containing biochar and compost became a carbon sink. However, biochar induced climate benefit was realized with c.a. 10 € additional price per m^3 compared to the other growing medias. In other words, the application of wood waste biochar increased the costs of growing media by 51–71 %. However, based on a sensitivity analysis, the price difference between traditional till and peat containing cover and biochar-based solutions evens out if both emission prices and pyrolysis retort productivity increase. Ultimately, the preferred choice depends on the value placed on the benefits of biochar for carbon sequestration and ecosystem restoration. According to previous research, the benefits of biochar observed in this study can be enhanced by accelerating restoration and thriving vegetation, further increasing carbon sequestration and the social acceptance of biochar-enriched growing media. The key finding of this study is that while a well-executed biochar-based mine closure solution is more expensive, it reduces climate emissions. This makes circular bioeconomy-based cover solutions a valuable area for further research across different mining sites.

CRediT authorship contribution statement

Karri Uotila: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Karetta Vikki:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marja Uusitalo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Kimmo Rasa:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Ilkka Leinonen:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Marleena Hagner:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Marleena Hagner reports financial support was provided by European Regional Development Fund. Marleena Hagner reports financial support was provided by Hannukainen Mining Oy. Marleena Hagner reports financial support was provided by Boliden Kevitsa Mining Oy. Marleena Hagner reports financial support was provided by Neve Oy. Marleena Hagner reports financial support was provided by Napapiirin kuljetus Oy. Marleena Hagner reports financial support was provided by Municipality of Kittila. Marleena Hagner reports financial support was provided by Municipality of Sodankyla. Co-financiers (all the rest listed financiers) of European Regional Development Fund were consulted in the study for the created concept as well as technical experts in the production and logistics processes. The final decisions regarding the parameters and the shaping of the concept were always made by the authors. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.clcb.2025.100173.

Data availability

Data will be made available on request.

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