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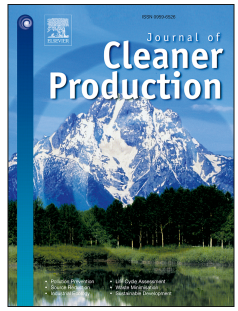

Peat production for horticultural use in the Latvian context: Sustainability assessment through LCA modeling

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Abstract **– Peat is used in various fields, from energy sources to fertilizer substrates. Peat bogs account for 3% of the earth's surface and represent a significant natural environment and carbon sink. Latvia is one of the European countries with the highest percentage of them and peat extraction plays an important role in the national economic market. Thus, the peat sector must be sustainably managed to regulate exploitation. In this context, this study's objective is to evaluate the overall environmental impact of the peat product chain. The tool used is a Life Cycle Assessment analysis (LCA), using a database made with primary data from a Latvian peat company and secondary data from a life cycle inventory database (*Ecoinvent v3.7.1*). The functional unit chosen is *1 m^3 of peat substrate made for professional and non-professional horticultural use*, a reference that consistently compares other standard substrates, namely coir pith and rock wool. The system boundaries include all the procedures from peat extraction to the product's end-of-life. Results of the study expressed with an ecological score (i.e., Pt) show that the stage that produces the most significant impact is that of the distribution of the final product for *Human health* (2.3 mPt), *Climate change* (1.39 mPt), and *Resources* (1.48 mPt) indicators and it is related to use of the diesel fuel. While for the *Ecosystem quality* indicator is peat extraction (1.59 mPt) and it is connected to the peat bogs opening. From the comparison with other alternative substrates for horticultural use, it has been concluded that coir pith has the highest impact (48.51 mPt), followed by rock wool (10.6 mPt) and peat (6.79 mPt).**

Keywords **– LCA, GHG emissions, circular economy, sustainability, peat, horticultural industry.**

Nomenclature

LCA	Life Cycle Assessment	-
LCI	Life Cycle Inventory	-
Mt	Million tonnes	-
Pt	Eco point	-
tkm	tons per kilometers	-

Peat production for horticultural use in the Latvian context: sustainability assessment through LCA modeling

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Highlights

✓ The sustainable assessment of peat extraction for horticultural use in the Latvian context.

[1]

✓ Cradle-to-grave Life Cycle Assessment (LCA) of peat substrate compared with two other standard coir pith and rock wool.

[2]

[3]

✓ Results show that the life cycle stages with the highest impact on the **peat substrate** are the **distribution of the final product** and **peat extraction**.

✓ **Compared** with the alternative substrates, **coir pith** has the **highest impact**, followed by rock wool and peat.

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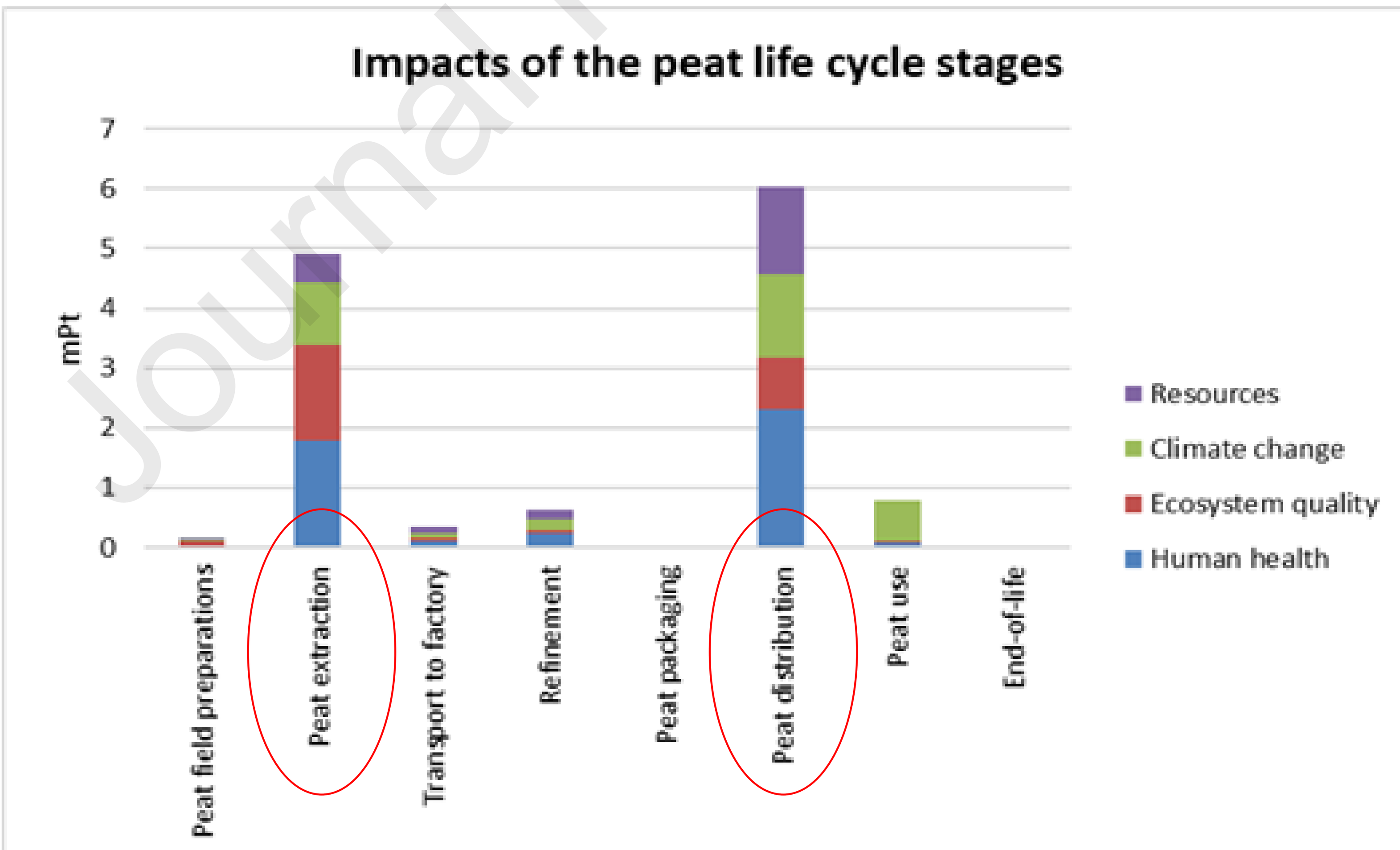
[2] Farmexporters. Coir pith. https://farmexporters.blogspot.com/p/coir-pith.html
[3] Burea-uinsurance. Mineral wool as a substrate for growing plants – hydroponics. https://burea-uinsurance.com/en/mineral-wool-as-a-substrate-for-growing-plants-hydroponics/

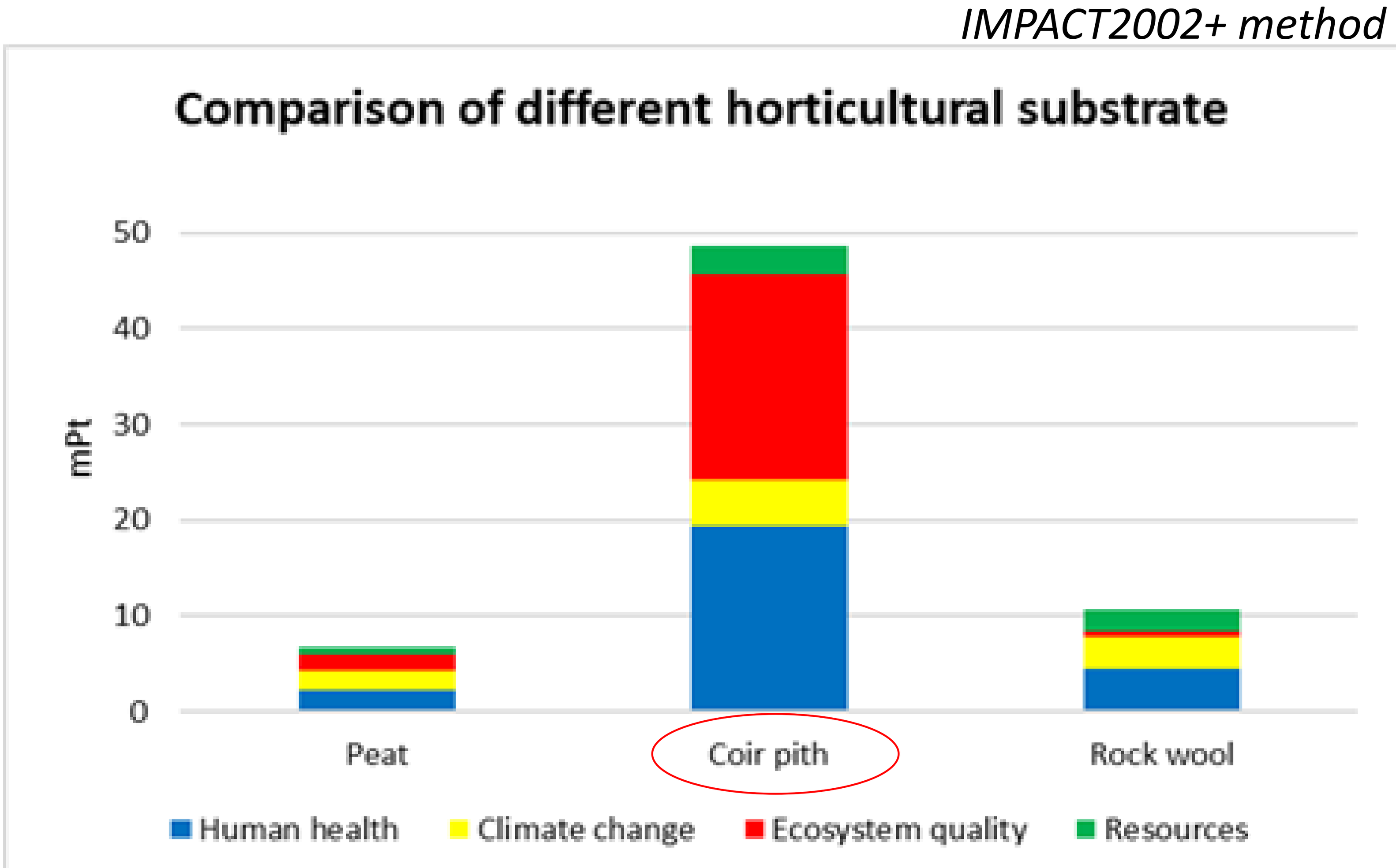
Introduction

- Latvia is one of the European states with the highest percentage of relative cover of peat soil;
- Peat is a significant income for Latvia's economy, and is also a **natural carbon sink,** which has to be managed sustainably;
- The analysis tool used for the sustainable assessment is the **Life Cycle Assessment (LCA)**.

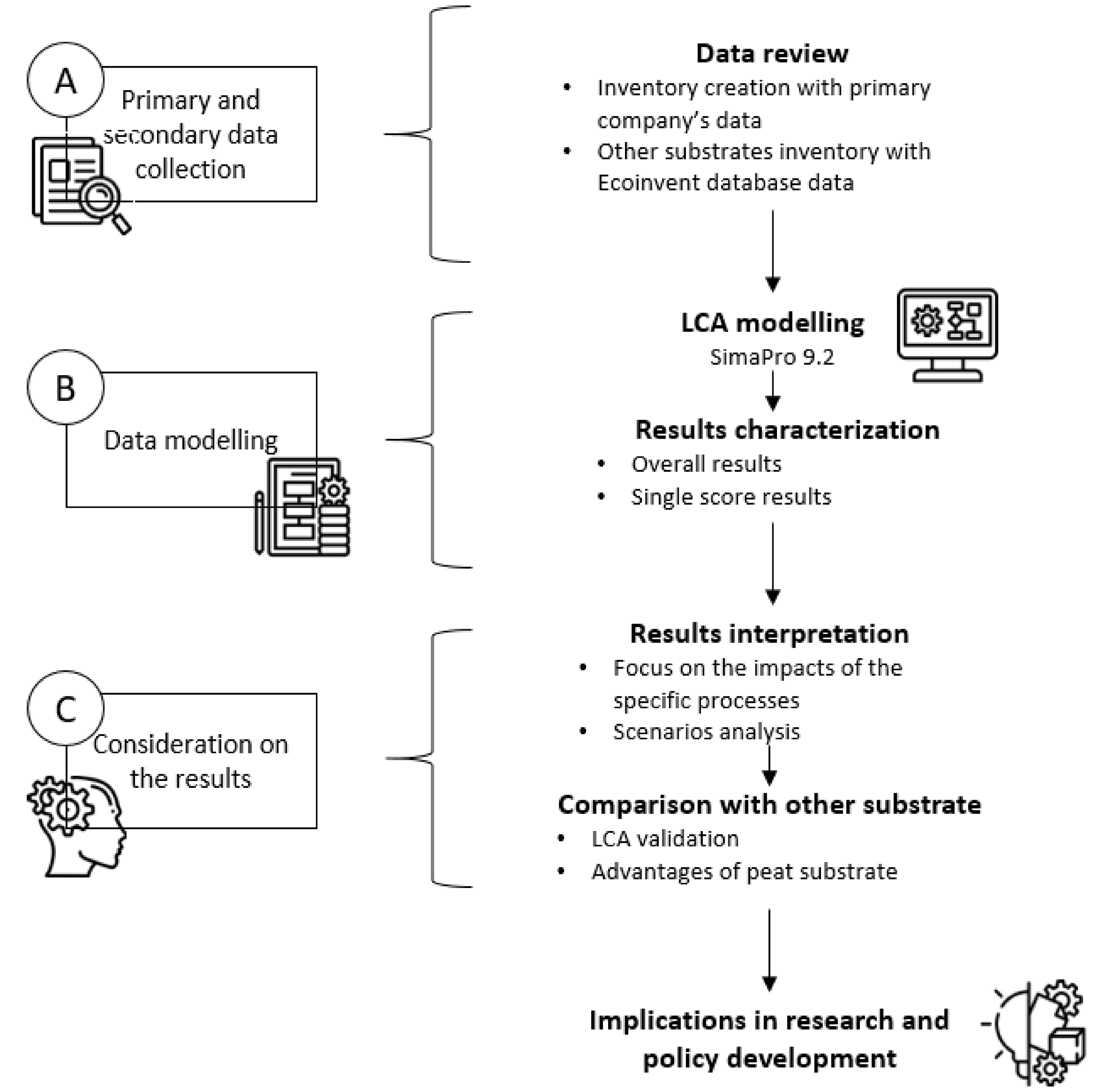
Results



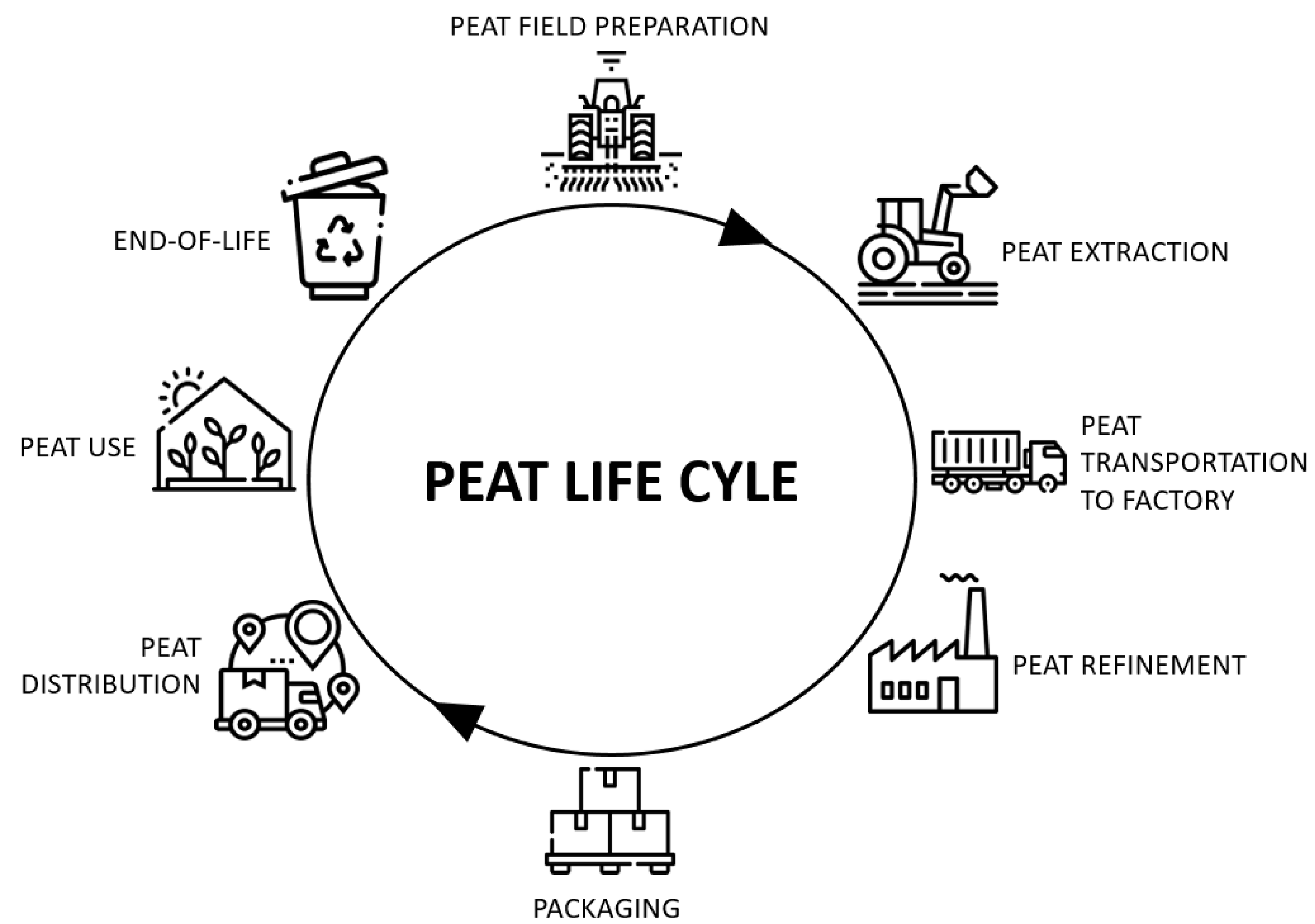
IMPACT2002+ method



Methodology



The life cycle of peat:



Peat production for horticultural use in the Latvian context: sustainability assessment through LCA modeling

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1. INTRODUCTION

Peatlands represent one of the most significant soil carbon, carbon dioxide, and atmospheric methane reserve with approximately 100 million tonnes (Mt), the equivalent of 372 Mt CO_2 yr^{-1} [1]. In addition to that, peat is classified as *slowly renewable biomass*, having a natural production rate of 1 mm per year [2], and it is classified as a *solid fossil* by the Intergovernmental Panel on Climate Change (IPCC) with greenhouse gas (GHG) emissions comparable to that of fossil fuels. Therefore, a wide range of applications uses peat, from energy sources to fertilizer substrate [3], [4], [5], [6]. Specifically, the use of peat for agriculture and horticulture is in connection with its properties like the degree of decomposition, ash content, pH, the presence of carbonates, the density of solid phase, bulk density, and porosity [7]. Furthermore, peat has a low content of heavy metal, which limits the leachate problem over time [8].

Peat bogs account for 3% of the earth's surface [9] and are in temperate zones. They represent an essential step for the natural water cycle [10], for the microclimate and the hydrogeological regime of the surrounding environment, and above all, a large deposit of natural carbon [11], [12]. These peculiarities are due to several factors: moderate climate characterized by heavy precipitation followed by evaporation, particular soil conformations (i.e., slightly undulated relief, clayey, poorly permeable deposit in relief depressions), and hydrological regime. These three conditions lead to the formation of peatlands in two ways: land paludification or filling-in in shallow water. In this context, the vegetation begins to grow in an environment of humid depression. Once it deteriorates, it starts to create a layer of peat that is the basis for new crops of marsh plants, thus forming the stratified peat bog over time [11].

Latvia is one of the European states with the highest percentage of relative cover of peat and peat-topped soils (0-30 cm) [13]. Peatlands in Latvia are not equally distributed in the national territory. In addition, their age and prerequisites for development are different depending on the region. According to Fig. 1, the significant peatbogs are in Eastern Latvia Lowland, Coastal Lowland, Middle Latvia Lowland, and North Vidzeme Lowland [11]. Nowadays, the total area of Latvia covered by peat bogs is equivalent to around 10% of the national territory [11]. Since some of them have developed in woody areas or are dried up for agricultural or extractive use, they are an essential resource within the Latvian territory that must be sustainably managed to regulate yearly exploitation. The actual situation of Latvian peat deposits is 1.7 billion tons of material contained, of which 145,7 Mt were harvested at the beginning of 2019 [14]. The export of this peat (92%) [15], or peat-based product, brought revenues of 185 million euros and 12 million euros in taxes paid [14]. 95% of the extracted peat goes for horticultural purposes (i.e., food plant growing and gardening).

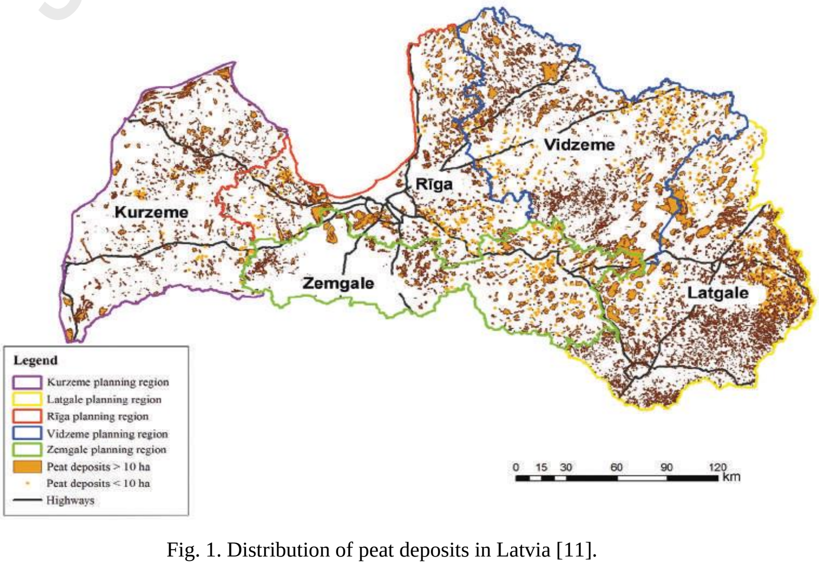


Fig. 1. Distribution of peat deposits in Latvia [11].

The main problem to face is related to the previously described unsolved and controversial situation. In 2017 the total volume of peat extraction in the whole European Union (EU) was ~47 000 million, of which 55% was energy, 37% growing media, and 8% other [15]. Moreover, despite the evidence on how peatlands are pivotal to climate change, the remediation or sustainable management strategies must cope with the status of peatland use - for example, in Germany, almost 10% of agricultural land is still made on drained peatlands [16]. Implementing sustainable management or recovery strategies of peatlands must still face the important European market mostly focused on peat-based growing media produced in horticulture, including home gardening. In fact, the volume of peat in the sector of horticulture is about 16 million m^3 per year [17]. However, replacing peat is difficult because alternatives developed by the industry are either expensive or have limited availability. Peat is still widely used as a growing and fertilizer substrate in the horticultural sector due to its suitable physical, chemical, and microbiological properties (e.g., low PH value and nutrient content, free of plant pathogens, along with high water retention capacity [18]). Of the total growing media in horticulture in the EU, 86% is made from peat [19]. In the EU, the total actual volume of growing media (including home gardening) is around 35 million m^3 per year [17, 18]. Nevertheless, several studies focus on the environmental concerns over the rapid depletion of peat, with the need to find recycled peat alternatives within the horticultural field [20] grouped into four main raw material types: coir, wood fiber, bark, and green compost. Such sustainable alternatives, from by-products from industrial, forestry, or agricultural waste streams like coco-peat, fly-ash, tea waste, paper pulp, pine bark, green waste compost, and spent mushroom substrate and recycled rock-wool have shown overall agronomical feasibility [21]. At the same time, this transition is still controversial. Indeed, as an alternative for growing media, the potential residues are not always suitable raw materials for reasons such as unmatched phyto-hygienic and nutritional aspects or even economic viability and social concerns toward the transition considering key aspect as employment and ethical standards. Thus, since 1980 there is still a question if the use of peat in horticulture is sustainable [22]. Several European countries reacted by imposing a ban on the use of peat like the UK government which banned amateur gardeners by 2024 but still facing an increase of around 9% in 2020 of peat for plant's growing media [23], probably due to the socio-economic effects on the whole supply chain. These aspects are linked to three main reasons [24]: 1) the growing media alternatives are not considering a holistic approach based on environmental, economic, social, and performance evaluations; 2) there is no uniformity and consistent quantitative characterization of these alternatives making difficult the comparison and interpretation; 3) few studies evaluate the macroeconomic aspect on growing media manufacture on being sufficient to meet demand considering the legislative constraints and dynamic nature of the demand/supply for organic material resources [23].

In this context, this research's main objective is to investigate and understand the optimal ways to exploit and manage peat fields, considering the transition towards alternative growing media materials in the market. In relation to this, a comprehensive Life Cycle Assessment (LCA) for the peat extraction procedure, and the entire related industrial supply chain, is necessary to support all the actors involved in selecting a tailored strategy for the sustainable use of peatlands. Furthermore, this research aims to provide a picture of the environmental effects of alternative growing media substrates that must be fit for purpose. Coir pith and rock wool were identified after a survey for the Latvian scenario as main competitors to peat and therefore selected for the comparison.

2. METHODOLOGY

2.1. Characteristics of the three horticultural substrates

The horticultural media are all such products that are found in the professional or hobby market, both created by the growing media industry or by a single user (privately developed mix). This definition includes a substrate for all types of plant cultivation, normally in containers, but also raw fertilized planting media (e.g., for trees and bushes) and casing soil for mushroom cultures. Besides peat substrate, coir pith and rock wool are two of the most common use horticultural substrate, both from the market and literature [25].

2.1.1. Peat substrate

The data relating to the peat-based horticultural substrate have been obtained directly from one of the largest Latvian peat processing companies. The peat substrate production plant is in the Jelgava region. The company prepares the product by purifying the raw peat and mixing it with other chemical components to improve its chemical-physical properties and the final packaging. About 85% of finished products are exported, and the remaining 15% are sold in Latvia. The chemical composition of pure peat is shown below in Table 1.

TABLE 1. CHEMICAL COMPOSITION OF PEAT SUBSTRATE [26]

Chemical composition of peat					
P (g/kg)	K (g/kg)	Ca (g/kg)	Mg (g/kg)	S (g/kg)	N_{TOTAL} (%)
0.19	0.1	1.13	0.94	1.97	0.72

Table 2 lists the overall average values for the added chemical components of the peat substrate used in the study.

TABLE 2. FERTILIZER AGENTS OF PEAT SUBSTRATE

Fertilizer agents in the peat substrate (for 1 m^3)					
Dolomite (kg)	Clay (kg)	Perlite (kg)	Limestone (kg)	Nitrogen (kg)	Other chemicals (kg)
0.017	0.53	0.017	1.75	0.066	0.66

2.1.2. Coir pith substrate

Coir is defined as the fibers that make up the thin layer of the peel of the coconut fruit. This material can be used for different purposes, from ropes to mat production. It shows a light brown color, consisting mainly of lignin and cellulose particles between 0.2 and 2.0 mm in size [27]. From the industrial processes of its processing remains a "coir dust" that is dried and compressed into bricks that can be used for preparing soilless growing media for containerized crop production [28]. The main countries producing coir pith are in the tropical belt of Asia, America, and Asia [28], with India and Sri Lanka leading among those that work it the most [25]. Table 3 gives the chemical composition of coir pith.

TABLE 3. CHEMICAL COMPOSITION OF COIR PITH SUBSTRATE [26]

Chemical composition of coir pith					
P (g/kg)	K (g/kg)	Ca (g/kg)	Mg (g/kg)	S (g/kg)	N_{TOTAL} (%)
1.05	8.5	1.95	1.08	0.68	0.8

2.1.3. Rock wool substrate

Rock wool is a lightweight hydroponic substrate made of fine fibers obtained from spinning basaltic rock at high temperatures (1600 °C) and then formed into a range of cubes, blocks, growing slabs, and granular products [29]. This raw product finds its main application as insulating building materials, but since the end of the 70s, its possible use in the horticultural field has been studied. In this context, rock wool works only as a water-absorbent substrate where plants can grow and propagate [29], [30] and, therefore, has no specific nutritional properties.

2.2. Life Cycle Assessment

This study was framed within the implementation of LCA methodology as a quantitative yet standardized approach to assessing a particular system's environmental impacts from a cradle-to-grave perspective. The reference ISO 14044:2006 Standards [31], [32] were used as guidelines for the study. Accordingly, four main steps were used within the LCA model creation: (1) the goal and scope definition phase, (2) the inventory analysis phase, (3) the impact assessment phase (4) the interpretation phase. The scope refers to the subject and the study's aim, setting a specific system boundary and defining a certain level of detail. The accuracy and depth of an LCA study can vary significantly depending on the goal. The second phase, the Life Cycle Inventory (LCI), is focused on the data collection necessary to characterize each stage of the chosen system. In phase three, the collected inventory data are translated in terms of environmental impacts to understand better the environmental performances of a studied product's system. In the last stage, i.e., conclusions, the results obtained during the previous steps are compared and discussed, guaranteeing a perfect match of the goal and scope definition.

In summary, an LCA is a method for understanding, evaluating, and estimating the potential environmental impact associated with a material, product, service, or process throughout its entire life cycle, from the extraction of the raw material to its transport and various use and its destination [33].

Fig. 2 presents the main steps followed for implementing the proposed LCA research study. As reported by the scheme, the analysis is divided into three main parts: (a) data collection, to gather datasets from both company and literature for implementing the inventory of the LCA; (b) LCA modeling for the assessment of the environmental impacts using *SimaPro 9.2* software; (c) analysis of the results with a comparison with other two types of horticultural substrates.

SimaPro 9.2 software developed by Pré Consultants [34] and *Ecoinvent 3.7.1* [35] supported the data processing for creating the LCA model and evaluating the overall environmental impact using the IMPACT 2002+ method [36]. IMPACT 2002+ method was selected because it is an end-point environmental impact type having climate change as the final standing alone end-point impact category. *SimaPro* software was selected as one of the most consistent software commercially available, useful for its graphic interface, uncertainty analysis, and results point of view [37].

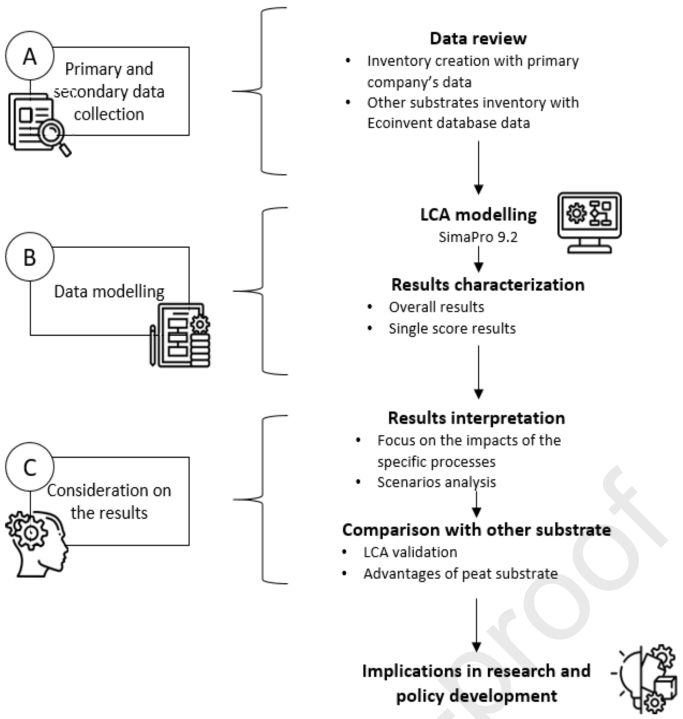


Fig. 2. Methodological research approach including the LCA perspective.

2.3. *Goal and scope definition*

This study aims to quantify the environmental impacts of a horticultural peat-based substrate and compare it with two other available substrates for horticulture: coir pith and rock wool. More specifically, the following main aspects were investigated:

- Definition of the environmental profile through the peat substrate's "cradle-to-grave" LCA approach including transport to customers or retailers, identifying the critical points of the process (i.e., the most significant contributions to impacts) and the key parameters (i.e., those that have a more substantial influence on the environmental footprint) of the system studied.
- Comparison of the environmental impacts evaluated during the life cycle of the three different substrates described in Chapter 2.1.
- Identify the study's critical parameters to estimate their total environmental impacts and understand where optimization strategies are possible.

According to ISO Standards 14044, allocations have been avoided by extending the system boundaries.

2.4. *Functional unit*

The functional unit (FU) is a representative quantity to compare all growth substrates with a similar area of use. For this study, the FU is: "*1 m^3 peat substrate for professional and non-professional horticultural use"*. This is consistent also with finding from literature [38], [39], [40].

2.5. *General description and system boundaries*

The system's boundaries identify the steps, processes, and flows considered in the LCA. They should include: i) all activities relevant to the objectives of the study and its FU; ii) all processes and flows that contribute significantly to potential environmental impacts. The following subchapters describe in detail the boundaries of the system as well as the geographical and temporal ones.

2.5.1. Baseline scenario

The baseline scenario includes all the steps for a cradle-to-grave life cycle analysis. Specifically, it has all the activities for collecting, refining, and distributing peat and those concerning the use and end-of-life phase. Fig. 3 reports a graphic description of the relative inputs and outputs loads. The *peat field preparation* contains all the operations needed to prepare the peat bogs before harvesting can begin. They include the construction of access roads, drainage of the peat bog, land use, cleaning from vegetation, drying of the soil, and leveling. Special vacuum tractors are used in the peat extraction stage depending on the type of peat to be collected (i.e., fine or raw peat). In these phases are also included the gaseous emissions related to the peat bog opening thanks to a specific model for the Latvian context [11]. The *transport-to-the-factory* describes the logistics for the raw substrate collected to the plant and the materials used in the refinement and packaging. The *refinement* includes the operations for particle size separation and adding fertilizer ingredients, while the *packaging* implicates the preparation of the product into plastic bags. The *peat distribution* is based on primary data directly collected from the company, including sea and roadway transportation. The *peat use* refers to the Growing Media Environmental Footprint Guideline V1.0 [39] because unable to use specifically collected data. In particular, for this stage, it is expected that the environmental impact of the growing media is related to the oxidation of the entire carbon content of its peat-based constituent into CO_2. Moreover, the whole emissions count also includes the degradation of the fertilizer additives added to the horticultural substrate following the emissions of the IPCC 2006 Guideline [41]. The *end-of-life* for peat also follows the Growing Media Footprint Guideline V1.0 [39]. Once the peat is used, it is considered naturally degraded on the site of use. For this reason, direct emissions are not considered at this stage because the use phase already includes them.

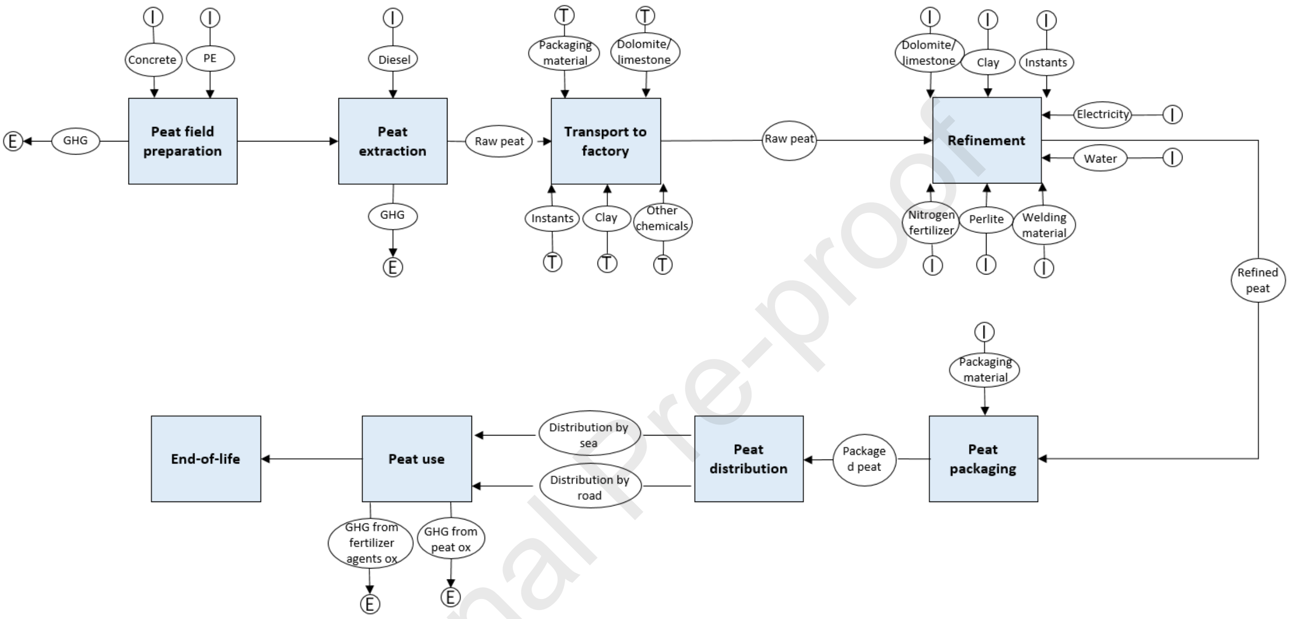


Fig. 3. Boundaries of the studied system. Blue boxes are related to the main steps of the process. *Notes: I: inputs; E: emissions; T: transports.*

In addition, for each of the sub-systems, the following parameters were considered:

- *Resource supply* (water, energy, fertilizer agents, and materials) is directly related to the product's extraction, processing, and transport.
- *Waste management*, including different scenarios depending on the waste products obtained during the various phases. *Ecoinvent 3.7.1* database is the inventory for the waste scenarios. The choice depends on the type of waste and the country in which it is produced and disposed.

2.5.2. Comparison 1

The baseline scenario is explicitly referring to the extracted peat substrate. *Comparison 1* refers to comparing the baseline scenario with the scenario producing horticultural substrate based on coir pith (i.e., *scenario 1*). In this case, the data for the coir pith were taken from the *Ecoinvent 3.7.1* database. The exact quantities of fertilizer used for the peat were added to the scenario using coir pith to make a fair comparison. The use stage assumes the same destiny for the fertilizer components described in the Growing Media Environmental Footprint Guideline V1.0 [39]. For the end-of-life scenario of coir pith, a composting process from the *Ecoinvent 3.7.1* database is assumed.

2.5.3. Comparison 2

Comparison 2 is made between the baseline scenario for the peat horticultural substrate and the horticultural substrate based on rock wool (i.e., *scenario 2*). In this case, the data for the rock wool production were gathered from *Ecoinvent 3.7.1.* database. For an accurate comparison, the exact quantities of fertilizer used for the peat were added, and they have the same emissions in the use stage. For the end-of-life scenario, it is assumed that the substrate is treated using a sanitary landfill [29] with a process presented on *Ecoinvent 3.7.1* database.

2.5.4. Geographic and temporal boundaries

To remain consistent with the selected FU and the system's boundaries, this LCA is representative of Latvian peat production for the 2020-time period. The collection, refinement, and distribution included in the study are modeled on this assumption.

2.6. *Environmental impact assessment*

IMPACT2002+ [36] method was selected for the analysis. It has been chosen because it includes different midpoint indicators grouped into four categories of damage that make the results more usable and interpretable for a non-technical public. It also makes immediately clear which environmental issues are associated with the process. The four damage categories are described below.

- *Human health*: as substances with toxic effects (carcinogens and non-carcinogens) and respiratory effects, which produce ionizing radiation and contribute to ozone depletion.
- *Ecosystem quality*: as impacts on aquatic and terrestrial toxicity, aquatic acidification and eutrophication, terrestrial acidification and nitrification, and land occupation.
- *Climate change*: as the potential effect from greenhouse gas (GHG) calculated in kilograms of carbon dioxide equivalent (kg CO_2 eq.).
- *Resources*: as non-renewable energy resources and extracting minerals and other natural resources. Peat is considered a non-renewable resource, according to [2].

Finally, it should also be noted that:

- The categories described do not cover all environmental impacts related to human activity, such as noise, sound, odors, and electromagnetic fields are not considered in this study.
- The results of the LCIA give potential, not actual, impacts. They represent a relative value that does not predict the final effect or risks to the receiving environment or define a degree and margins of safety [42].

2.7. *Life cycle inventory*

The quality of an LCA depends on the quality of the data used. For this reason, this study pays particular attention to the research and implementation of the most realistic and representative information possible.

Information regarding peat's primary data (i.e., extraction, production, processing, and distribution) was collected directly by a Latvian peat company during its industrial activities in 2020. Instead, for the LCI data describing background processes (e.g., electricity), the *Ecoinvent 3.7.1* database was used. Table 4 shows the life cycle inventory data in a more specific way. These values are then normalized to the functional unit, considering the total volume of peat (m^3) produced by the Latvian peat company in 2020.

TABLE 4. LIFE CYCLE INVENTORY FOR THE PEAT EXTRACTION, REFINEMENT, AND USE

Peat field preparation					
	Category	**Material/component**	**Quantity**	**Unit**	**Data source**
Inputs	Raw materials	Concrete for road	2.42 x 10^7	m^3	Primary data
		PE for pipes	5 000	m	Primary data
	Natural resource	Land use	1 042	ha	Primary data
Outputs	Waste and emissions	CO_2	95.7	kg CO_2/m^2y	[42]
		CH_4	0.2	kg CH_4/m^2y	[42]
		Dissolved Organic Carbon (DOC)	11.7	kg DOC/m^2y	[42]
Peat extraction					
	Category	**Material/component**	**Quantity**	**Unit**	**Data source**
Inputs	Process	Diesel for tractors (for all operations)	921 540	l/y	Primary data
		Oil for tractors	12 800	l/y	Primary data
Outputs	Waste and emissions	Raw peat	864 347	m^3	Primary data
		CO_2	4 200	kg CO_2/m^2y	[11]
		Dissolved Organic Carbon (DOC)	11.7	kg DOC/m^2y	[11]
Refinement					
	Category	**Material/component**	**Quantity**	**Unit**	**Data source**
Inputs	Raw materials	Dolomite	15	ton/y	Primary data
		Instants	57 685	l	Primary data
		Clay	458 000	kg	Primary data
		Perlite	15	ton/y	Primary data
		Limestone	1 510	ton/y	Primary data
		Nitrogen fertilizer	57	ton/y	Primary data
		Welding electrodes	500	kg	Primary data
		Welding wire	400	kg	Primary data
		Others	3.5	ton/y	Primary data
	Natural resource	Tap water	1 900	m^3/y	Primary data
		Electricity (including all operations)	1 112 936	kWh/y	Primary data
		Diesel	205 691	l/y	Primary data
Outputs	Waste and emissions	Wood waste	385	ton/y	Primary data, all recycled
Peat packaging					
	Category	**Material/component**	**Quantity**	**Unit**	**Data source**
Inputs	Raw materials	Pallet	4 105 630	kg	Primary data, all recycled
		Plastic bag	514 953	kg	Primary data
Outputs	Waste and emissions	Wood	34.29	ton/y	Primary data

		Paper	11.95	ton/y	Primary data
		Plastics	9.98	ton/y	Primary data
Peat use (values already for 1 m^3 of peat)					
	Category	**Material/component**	**Quantity**	**Unit**	**Data source**
Outputs	Waste and emissions	CO_2 (peat oxidation)	88	kg	[41]
		CO_2 (lime and dolomite oxidation)	0.78	kg	[41]
		NH_3	0.007	kg	[41]
		NO_3	0.02	kg	[41]
		N_2O	0.039	kg	[41]

Impacts related to the *end-of-life* phase are not considered as suggested by the Growing Media Europe Footprint guideline V1.0. The substrate's complete oxidation occurs in the use phase. The study includes data on the transport of intermediate products at the different plant treatment units. Table 5 shows a detailed summary of all of them. It is assumed a carrier on the road with a freight lorry 16-32 metric ton, euro5, from *Ecoinvent 3.7.1* database and transport on the sea by container ship. These values refer to the FU.

TABLE 5. LIFE CYCLE INVENTORY FOR THE TRANSPORT TO THE FACTORY

	Category	**Material/component**	**Quantity**	**Unit**	**Data source**
Transport to factory	Raw materials	Peat from the extraction site	6	t·km	Primary data
		Packaging	1.833	kg·km	Primary data
		Dolomite/limestone	1.683	kg·km	Primary data
		Instants (sea route)	1.06×10^{-4}	kg·km	Primary data
		Instants (road route)	4.76×10^{-6}	kg·km	Primary data
		Clay	0.228	t·km	Primary data
		Chemicals additives	0.144	t·km	Primary data

Finally, regarding the *peat distribution* of the final product, the company's commercial data were used. The scenarios depend on a European market situation and then a global one. Thus, depending on the identified trade routes, the transportation scenarios are modeled considering either freight lorry 6-32 metric ton, euro5, and sea containers separately or in sequence. Also, in this case, the data for transportation characteristics are already present on *Ecoinvent 3.7.1* database.

2.8. Assessment of inventory data quality

The integrity of the results and conclusions of an LCA depends on the quality of the data in the inventory. Therefore, they must represent the study's objectives [43], [44].

As stated in the ISO standards 14044, the criterion relating to the quality of the data must ensure at least its validity (i.e., representative in terms of age, geographical origin, and technological efficiency). Summarizing:

- The period declared in the functional unit (i.e., 2020).
- The geographical context of the system considered (i.e., Latvia).
- The technological characteristics concern the operations of peat bog preparations, extraction, processing, transport, and distribution of peat.

3. RESULTS

3.1. Environmental profile of the peat substrate over its end-of-life scenario

This section describes the environmental profile of the entire end-of-life scenario of peat substrate. As outlined in Fig. 3., the results obtained with the IMPACT2002+ method were used to identify the processes and parameters that contribute most to the potential environmental impacts of the system considered (i.e., so-called hot spots in the system's life cycle). Fig. 4 shows the results of the impact indicators.

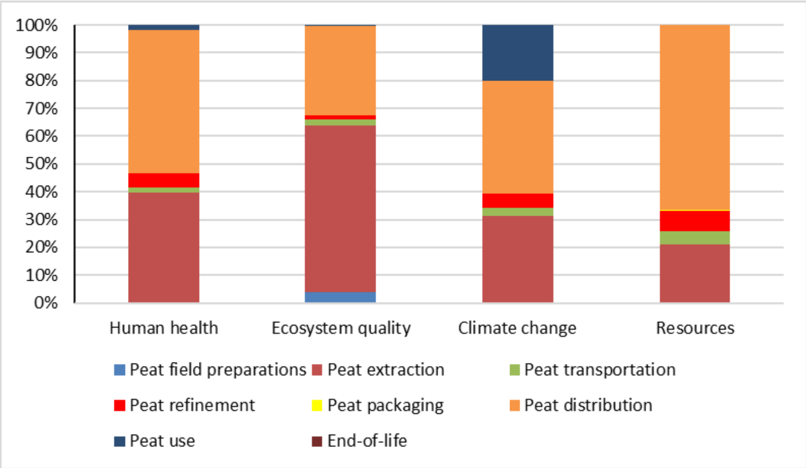


Fig. 4. Environmental profile of the peat substrate

It can be noted that for the indicators of *Human health*, *Climate change*, and *Resources*, the product's distribution gives the highest percentage of impact; this is in line with the literature result [42] and is mainly related to the use of diesel fuel during the extraction stage and transportation. Also, the freight lorry used (i.e., euro 5) does not represent the market's most advanced engine technology level (i.e., euro 6), in turn increasing the impact. Looking at the *Ecosystem quality*, it could be noticed that the most impactful process is peat extraction which comes from the land use for the peatbogs opening. At the same time, peat use is strongly related to the impact of *Climate change* because the horticultural substrate and its fertilizing components release greenhouse gases during their oxidation. The other stages, such as the finishing phase and preparation of the field for extraction, take much smaller percentages. At the same time, the rest concerning the packaging and transport of the materials to the refining plant are negligible (see also Fig. 5). The results are reported in mPt, which stands for milliEcopoint, where 1 Pt is representative of one-thousandth of the yearly environmental load of one average European inhabitant [45].

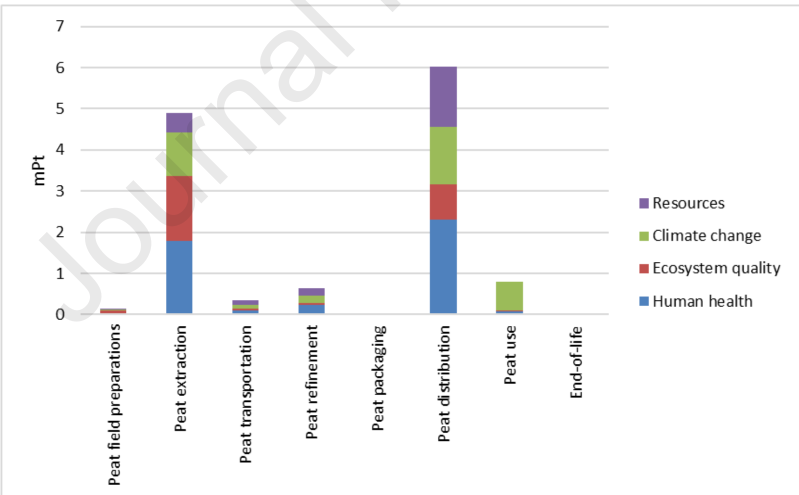


Fig. 5. Impacts of the peat horticultural growing media life's stages.

The phase that impacts most is the distribution stage on *Human health* (2.3 mPt), *Resources* (1.48 mPt), and *Climate change* (1.39 mPt). It is followed by peat extraction for the *Ecosystem quality* (1.59 mPt). To a lesser extent, there are peat use and refining, which show similar burdens. Other impacts present a negligible contribution. In Table 6, they have a contribution of less than 0.5%. On the contrary, grey-colored cells represent the highest percentage of impact.

TABLE 6. RELATIVE CONTRIBUTION OF THE LIFE CYCLE PHASES FOR THE PEAT SUBSTRATE

	Peat field preparation	**Peat extraction**	**Transport to factory**	**Refinement**	**Peat packaging**	**Peat distribution**	**Peat use**	**End-of-life**
Human health	0.10%	39.44%	2.08%	5.16%	0.006%	51.35%	1.86%	0.00%
Ecosystem quality	3.82%	60.09%	1.95%	1.80%	0.0022%	32.04%	0.30%	0.00%
Climate change	0.37%	30.90%	2.87%	5.19%	0.006%	40.46%	20.21%	0.00%
Resources	0.17%	20.75%	4.74%	7.62%	0.018%	66.69%	0.00003%	0.00%

These results confirm what Fig. 4 shows. The peat distribution and extraction represent the most impactful unit processes.

3.2. Detailed results for the peat substrate

The following chapters focus on an in-depth analysis of each life cycle stage with a higher percentage of influence.

3.2.1. System analysis for the peat distribution phase

According to Fig. 6, the distribution phase has the highest impact. Based on the data provided by the company, 74% of the volume of peat marketed is transported by road, while the remaining 26% follows a route by sea. Therefore, it is clear that road transport represents an essential percentage of impact.

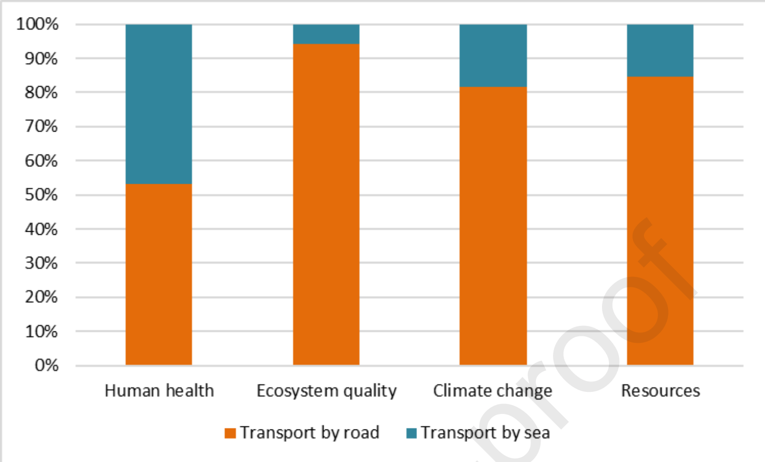
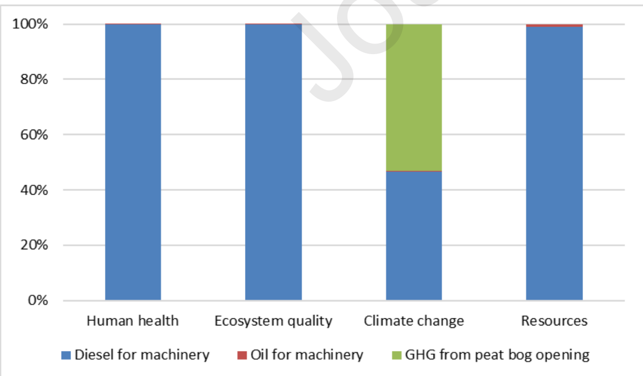


Fig. 6. Detailed results for the peat distribution

Road transport is the one that provides the most significant contributions, to the *Ecosystem quality*, *Climate change*, and *Resource* impact categories. Although, similar results are obtained instead for *Human health*. This result is relevant because it shows that despite the significantly different commercial volumes, the percentages are almost the same, indicating a greater incidence of transport by sea.

3.2.2. System analysis for the peat extraction phase

Peat extraction is the second most impactful stage, particularly for the *Ecosystem quality* indicator, as shown in Fig. 4. It is, therefore, interesting to focus on the significant contributions to the impact of this phase. See Fig. 7.



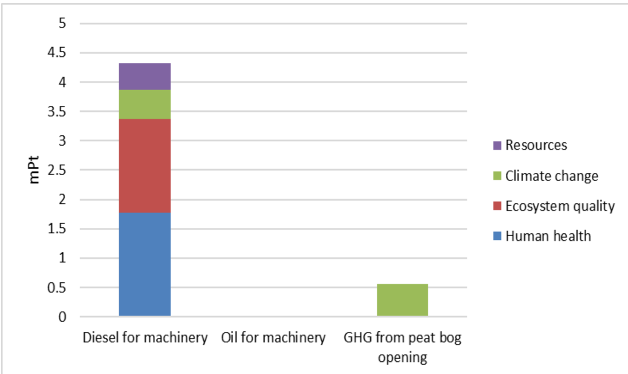


Fig. 7. Results from the peat extraction phase

The consumption of diesel usage in peat extraction machinery accounts for almost the total contributions for each impact category. Thus, it represents the most significant absolute impact. Only *Climate change* at the opening of the peat bog and the related GHG emissions significantly influence the overall effect.

3.2.3. System analysis for the refinement phase

Analyzing the peat refining stage can help understand the contribution to the impacts in the phase of the peat factory. Fig. 8 reports the results.

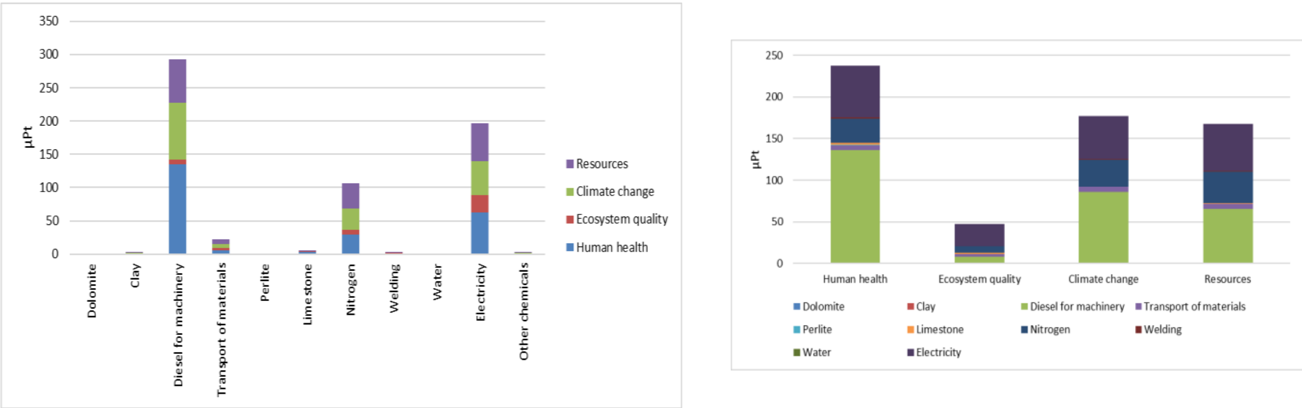


Fig. 8. Results from the refinement phase

From Fig. 8, it is possible to see how the most impactful material is the diesel used for the trucks at the factory, followed by the electricity necessary to keep the plant in operation. While about the fertilizer ingredients added to the peat to improve its properties, the most impactful is nitrogen. The most sensitive impact category is *Human health*, followed by *Climate change* and *Resources*, which have similar values, while *Ecosystem quality* is the one with the most negligible impact. This is because they are the indicators most subject to the impacts due to the gaseous emissions produced by the combustion of diesel engines [46]. It suggests how a possible implementation of electric vehicles can significantly help decrease the environmental load.

3.3. *Comparison with alternative scenarios in the market*

Two comparisons were analyzed in which the peat horticultural substrate is compared with two other widely used products, such as coir pith and rock wool, described in paragraphs 2.3.2. Fig. 9a shows the results regarding the environmental profile described with an ecological score (i.e., mPt), while Fig. 9b shows the global warming impact.

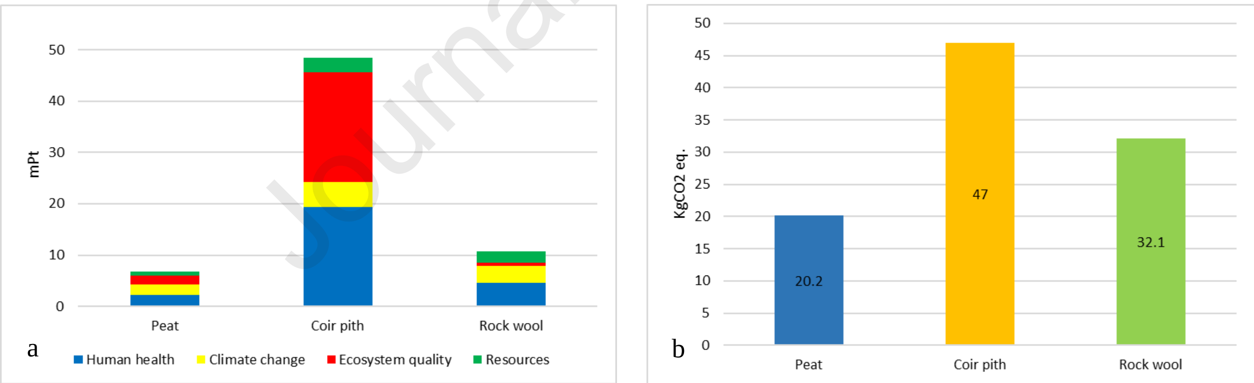


Fig. 9. (a) Comparison with the different horticultural substrates; (b) Comparison of global warming impact category

It was assumed that all the substrates had the same fertilizer ingredients for the modeling. Also, the distribution phases for all three substrates were not considered because the specific distributions for coir pith and rock wool were unknown. As a result, the substrate that obtains the highest value and impact is the coir pith with a 48.51 mPt. The rock wool-based substrate with a value of 10.6 mPt and the peat with 6.79 mPt follow it. Also, the global warming result (Fig. 9b) confirmed that coir pith is the substrate with the most significant impact. However, this study's results disagree with another research that compares the different horticultural substrates in the literature [25]. Given this, we focused on conducting an analysis only for the coir pith's environmental impacts and the data on the *Ecoinvent 3.7.1.* database. It shows that the high result comes from the ample use of fertilizer (i.e., urea and P_2O_5) in the coconut crops. Furthermore, since coir pith is a product obtained through the reuse of coconut peel, the scenario that considers an impact avoided given by the disposal of this quantity was also evaluated. The result led to improvements from an environmental point of view (-0.871 mPt in general, and -1.82 KgCO2 eq. for *Global warming*). However, the values are quite low and do not change the previous result much. Thus, coir pith is the substrate with the most significant impact on the *Global warming* indicator, followed by rock wool and peat. In addition, other considerations can be made regarding the different system boundaries and inventories considered in the information taken as a reference for the comparison. Moreover, not always was possible to gather information due to confidentially aspects.

4. STUDY LIMITATIONS

GHG emissions represent the most critical parameter for the modeling of peat extraction because, as mentioned in the introduction, peatlands represent an actual example of a carbon sink. However, in this research, reference was made only to emissions from one year of extraction, but emissions continue dynamically throughout the life cycle of the peat bog [42], [47], [48]. Therefore, it would be helpful to carry out a dynamic LCA for the entire life of the peat bog and not for a year, assuming a time horizon of 100 years. The impact of climate change uses factors that characterize the global warming potential (i.e., GHG in CO_2 eq.) that are adapted to the temporal flow of emissions that is not constant. Thus, a large share of total created emissions is cut, not considering the long-term ones, or also to estimate a dynamic climate change impact using the DynCO2 [49] tool.

The data relative to the other two substrates used for the comparison in *Scenario 1* and *Scenario 2* is hypothetical scenarios derived from processes already included in the *Ecoinvent* inventory. The use of primary data gathered from manufacturers and directly implemented in the model would provide more consistent results.

Since the peat bogs as natural environments have their biodiversity [50], [51], [52] would be necessary also to include the opinion of experts in the ecology field that can allow modeling of the LCA study more precisely.

It would also be interesting to consider the different agricultural products obtained with the three substrates in the use phase because, as shown in the literature [25], the efficiencies vary depending on the plants. This factor is related to specific properties of hygroscopic and nutrient distribution mechanics that must be considered.

Further research could then focus on the results of different software for the LCA calculation. *SimaPro* software carried out the analysis for this study, but there are other LCA tools such as *Gabi*, *Umberto®*, and *openLCA*. These LCA tools have different characterization factors and subcompartments that can lead to different LCA results. This discrepancy occurs mainly in indicators such as ozone formation and ecotoxicity freshwater categories for the cradle-to-gate scenarios [53]. In this way, it would be interesting to create a range of results for the indicators sensitive to the software variation.

These limitations do not question the main conclusions and results obtained regarding the purpose and objective of this research but may help implement future studies.

5. CONCLUSIONS

This study aims to perform and estimate the potential environmental impacts of peat's life cycle produced in a Latvian context and then compare it with two other horticultural substrates, the coir pith, and the rock wool. The environmental profile of peat has three dominant processes: distribution, extraction, and to a lesser extent, refinement and use phase. More precisely:

- Distribution to end customers represents the most significant contribution in almost all four indicators (contributions between 30% and 70%), particularly *Human health*, *Climate change*, and *Resources*.
- Peat extraction accounts for 61% of the *Ecosystem quality* indicator.
- Less critical than these two previously mentioned is the use phase which represents a value of around 20% in the indicators of *Climate change*.

These results can help the company that has worked in synergy for the data collection for the study and the Latvian peat sector to focus on the underlined parameters. The distribution logistics, especially the option to transfer part of the transportation from road to rail, would help minimize the impacts. It would also be advisable to develop methods that could reduce peat extraction time and shorten site development periods as much as possible with higher or equal yields. The results show that restoration (reforestation and sustainable site development) could improve the score for the Ecosystem quality category.

For the comparison between the three different substrates, the following conclusions can be drawn:

- Coir pith is the substrate with the highest impact in all indicators.
- Between rock wool and peat, it is the first to have more significant impacts on three indicators *Human health*, *Climate change*, and *Resources*. In contrast, the second has the highest value only in *Ecosystem quality*.

Therefore, this research can be a good starting point for more in-depth studies in the peat sector. In particular, focusing on a peat sectorial analysis of the product use and end-of-life stages meantime including a more in-depth cradle-to-grave LCA by analyzing all the true-life steps engaging more customers and retailers could create a more consistent environmental footprint assessment. Moreover, including the economic feasibility analyses through a Life Cycle Cost Assessment (LCCA) and social aspect within a Social Life Cycle Assessment (SLCA) could provide a consistent approach for the overall Life Cycle Sustainability Assessment (LCSA) with a different view of the production of peat substrate.

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From: *Peat production for horticultural use in the Latvian context: sustainability assessment through LCA modeling*

Highlights:

- Sustainable management of the peat extraction for the Latvian context
- Cradle-to-grave life cycle assessment of peat substrate for horticultural use
- Comparison with coir pith and rock wool substrates
- Highest impact from the distribution of the final product and the peat extraction
- Coir pith has the highest impact, followed by rock wool and peat

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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