



Environmental and social life cycle assessment of growing media for urban rooftop farming

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Abstract

Purpose New environmental strategies are emerging for cities to become more self-sufficient, such as hydroponic crop production. The implementation of such systems requires materials that usually originate in countries with low labour costs and other legal regulations. To what extent could these strategies be shifting problems across the globe? To answer this question, we performed a comprehensive environmental and social assessment of the various extended soilless systems used to grow vegetables on urban roofs.

Methods Three different growing media constituents were chosen for this study: perlite, peat and coir; which are produced in three countries, Turkey, Germany and the Philippines, respectively, and are imported to Spain. By using a life cycle assessment, we evaluated the environmental performances of the production and transport of these growing media. Additionally, we performed a social life cycle assessment at different levels. First, we used the Social Hotspots Database to analyse the constituents in aggregated sectors. Second, we performed a social assessment at the country and sector levels, and finally, we evaluated primary company data for the social assessment of the constituents through questionnaires given to businesses.

Results and discussion The coir-based growing medium exerted the lowest environmental burden in 5 out of 8 impact categories because it is a by-product from coconut trees. In contrast, perlite obtained the highest environmental impacts, with impacts 44 to 99.9% higher than those of peat and coir, except in the land use. Perlite is a material extracted from open-pit mines that requires high energy consumption and a long road trip. Regarding the social assessment, peat demonstrated the best performance on all the social assessment levels. In contrast, coir showed the worst scores in the Social Hotspots Database and for the impact categories of community infrastructure and human rights, whereas perlite displayed the lowest performance in health and safety. Nevertheless, coir and perlite evidenced much better scores than peat in the impact subcategory of the contribution to economic development.

Conclusions This study contributes to a first comparison of three imported growing media constituents for urban rooftop farming from environmental and social perspectives to choose the most suitable option. Peat appears to be the best alternative from a social perspective. However, from an environmental standpoint, peat represents a growing medium whose availability is aiming to disappear in Germany to preserve peatlands. Therefore, we identify a new market niche for the development of local growing media for future rooftop farming in cities.

Keywords Life cycle assessment · Soilless systems · Open-air farming · Rooftop greenhouses · Green cities · Urban agriculture

1 Introduction

Cities are primordial human settlements of prosperity in our society, generating approximately 80% of the global gross domestic product (GDP) (Floater et al. 2014), and they provide economic and cultural wealth and dynamic territories. Nonetheless, the accumulation of populations, activities and resource demands triggers high pressures

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regarding pollution, resource use, and land/space competition (Legner and Lilja 2010). Organisations, governments and academia have focused their attention on cities as high emitters but also because they offer potentials for multi-purpose and easily replicable solutions for sustainability actions (Grimm et al. 2008; Rosenzweig et al. 2010). Many strategies for redressing the ecological problems associated with urban areas have emerged over the years. These initiatives can be grouped into different topics, such as waste management, energy efficiency, water demand, buildings, and renewable energy (Lamb et al. 2019). One initiative has stood out for its remarkable exploitation potential: the use of urban roofs for different purposes, as roofs can comprise up to 32% of the horizontal surface of build-up areas and are mostly underutilised spaces (Frazer 2005). Roofs can be used for implementing energy production (Madessa 2015; Kyriaki et al. 2017; Bazán et al. 2018), green roofs (Fioretti et al. 2010; El Bachawati et al. 2016; Brudermann and Sangkakool 2017), rooftop farming (Montero et al. 2017; Nadal et al. 2017, 2018a, b), the harvesting of rainwater (Farreny et al. 2011; Angrill et al. 2012, 2016) or a combination of these applications (Benis et al. 2018; Corcelli et al. 2019; Toboso-Chavero et al. 2019, 2021).

To deploy these new systems, not only the environmental, social and economic benefits should be analysed but also the potential drawbacks and externalities¹ of the production of these products to attain a holistic and forward-looking overview of the corresponding strategy (Ramaswami et al. 2016). Materialising these food-energy-water (FEW) systems requires the manufacturing of new materials/products such as photovoltaic panels, rainwater tanks, greenhouses and growing media. Such externalities generated by the production of new materials are usually related to the maelstrom of global trade; thus, the production, and also the supply chain, have become longer and more complex (Pichler et al. 2017). The locations of consumption and production are separated by several miles, and developed countries are mainly favoured by cheap products with high environmental and social impacts (Hoekstra and Wiedmann 2014) while developing countries bear the brunt of these externalities (Riisgaard et al. 2010). The differences in the living and working conditions, the low labour costs or lenient environmental and labour regulations make these developing countries appealing to companies (Hoekstra and Wiedmann 2014).

This globalised delocalisation, i.e. the relocation of production activities from developed to developing countries, which mainly occurs because of lower labour costs in the developing

countries than in the developed countries (Hammami et al. 2008), is also inherent in obtaining the necessary products for the implementation of FEW systems on rooftops. The main elements are extracted and produced overseas, such as the growing media for agriculture, often coir or perlite, which are manufactured in Asian countries, and Turkey, Greece and different African countries (Bennett 2018; U.S. Geological Survey 2019), or the production of photovoltaic panels, mainly dominated by China, which yielded 43% of the global production in 2018 (Solar Power Europe 2019). This separation between the points of production and consumption causes environmental and social impacts that should be screened and included in any new strategy we propose to enhance the sustainability of cities. Notwithstanding, this global delocalisation has also brought prosperity, in some cases, to these countries that have become factories for developed countries (Panagariya 2019). Some of these positive consequences include job creation, GDP increase and improvement of infrastructure (World Trade Organization 2017, 2018).

Intended for calculating environmental impacts of the production of such systems, the life cycle assessment (LCA) (International Organization for Standardization 2006) is the leading and most extensive methodology (European Commission 2003). The environmental burdens of some elements of these systems described herein have been extensively assessed, such as the manufacturing of PV panels in countries such as China, Germany and Spain (Sumper et al. 2011; Gerbinet et al. 2014; Yue et al. 2014; Fu et al. 2015; Hong et al. 2016; Xu et al. 2018; Lamnatou et al. 2019). Nonetheless, few studies have focused their interests only on the growing media used for soilless culture systems (Verhagen and Boon 2008; Warwick HRI 2009; Quantis 2012; Stucki et al. 2019; Vinci and Rapa 2019) because they are usually not assessed stand-alone and without relating them to plant management practices (e.g. fertigation) (Barrett et al. 2016).

Additionally, little attention has been given to the social impacts, either positive or negative, that these complex supply chains have (Traverso et al. 2012a). Social impacts affect the local communities, workers, and society in general in these centres of production. One of the widespread frameworks used to account for social impacts is the social life cycle assessment (S-LCA) (UNEP/SETAC 2009), which is also used and recommended by the European Commission (Mancini et al. 2018). The S-LCA has already been applied in the renewable energies sector (Traverso et al. 2012a; Corona et al. 2017; Takeda et al. 2019), but to our knowledge, it has not yet been applied in the growing media sector. This methodology does not have an ISO standard but has a guideline that was updated in December 2020 (UNEP et al. 2020). The S-LCA still has various limitations due to the complexity of social aspects and because of the lack of data and tools used as sector-specific social indicators or general standardised indicators for social performance

¹ An externality is a consequence of an economic activity that affects other parties and is not reflected in the final cost of a product or service.

(Traverso et al. 2012b; Zamagni et al. 2015; UNEP et al. 2020); only two databases are in operation, the Social Hotspots Database (SHDB) (New Earth 2019) and the PSILCA (Ciroth and Eisfeldt 2016). For a general and first screening of aggregated sectors, these databases are suitable; however, for specific products/sectors, in-depth and specific screenings are recommended.

Therefore, to gain insight into this gap in knowledge regarding suitable growing media for implementation on urban roofs, we targeted our study toward the most extensively used growing media constituents in the sector to analyse their environmental and social impacts. We selected the most commonly used growing media worldwide: perlite, peat and coir (Growing Media Europe 2019). Hence, our research has a twofold goal: to assess the environmental and social impacts, including the positive and negative impacts, of the extraction and production of three constituents to be used in urban rooftop farming (URF), i.e. in open-air farming (OAF) and in rooftop greenhouses (RTG) to grow vegetables. This is the first attempt to dive into the growing media sector suitable for urban rooftops, procuring comprehensive environmental and social life cycle assessment of three different growing media constituents.

1.1 Case study description

Various constituents are used as components of the soilless growing media sector. In this case, three different constituents were chosen. The data used to characterise the growing media were defined based on the literature (Maher et al. 2008; Barrett et al. 2016) and based on their relevancy to this research. Consequently, five different categories were proposed: physical characterisation, including the main features; the market price; the world's leading producers; the total production (current and forecasted); and the applications of each growing medium. Data were retrieved from the literature, mainly from scientific papers, books and different reports.

Perlite is an inorganic growing medium sourced from open-pit mining in different countries, whereas peat (extracted from peatlands) and coir are organic growing media, albeit coir is a by-product from coconut trees (Table 1). In general, the three constituents do not contain enough nutrients for plants; therefore, they need additional fertilisers. They have similar air-filled porosities and high water retentions. Furthermore, peat and coir have lower bulk densities than perlite. Regarding the market prices, the most economical constituent is peat, then, coir, as it is a by-product obtained from coconut husks, while perlite costs twice as much as the other two constituents. The producers of peat are mainly located in Europe. Therefore, the cost of peat transport and the related environmental impacts are presumably lower than those of the other growing media. Coir

is sourced from tropical countries with large crops of coconut trees mainly from Indonesia, the Philippines, India and Sri Lanka. The perlite consumed in Europe usually comes from Greece and Turkey because China, the largest producer of perlite, mainly consumes all its produced perlite internally (U.S. Geological Survey 2019). The highest projected increase by 2050 is assigned to coir and then perlite, the production of which is expected to increase by approximately 700% of its current production (Growing Media Europe 2019). Coir, from coir fibres and the coir pith, is the only growing medium that is used exclusively for horticulture, while peat is also used for producing energy and perlite has more diversified uses. (Table 1)

2 Materials and methods

The system under study involves the growing media used to grow vegetables on rooftops. The growing media are mainly imported from other countries to Spain, which is the top producer of vegetables and fruits in the European Union (EU) (Messe Berlin 2020). We selected the three most extensively used growing media constituents: perlite, peat and coir (Growing Media Europe 2019). The methodology consists of two parts: the environmental LCA (E-LCA) (Sect. 2.1.1) and the social LCA (S-LCA) (Sect. 2.1.2) of these growing media constituents.

2.1 Life cycle assessment

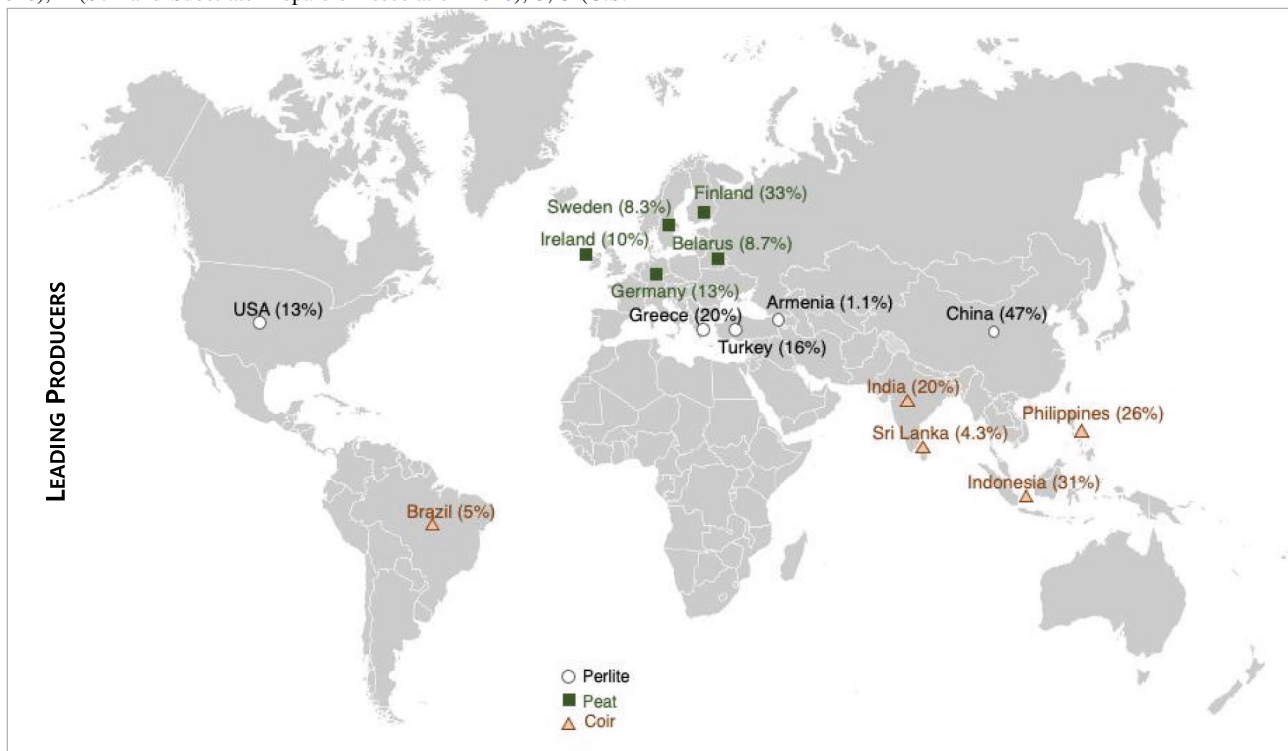
The E-LCA was performed following the ISO 14,040–44 (International Organization for Standardization 2006) and the S-LCA was performed using the established guidelines for S-LCA (UNEP/SETAC 2009). Details are provided for the different sections of the LCA, including the goal and scope, inventory and life cycle impact assessment. The S-LCA was conducted in three steps: (a) a social risk hotspot assessment, (b) country- and sector-specific assessment and (c) a company-specific assessment.

2.1.1 Environmental life cycle assessment (E-LCA)

Goal and scope The goal of this study was to analyse the environmental and social impacts of the extraction, production and transportation of three different growing media constituents imported to Spain that are suitable for URF. The function of these growing media is to serve as the medium with which to grow vegetables, and the functional unit is 1 m³ of a growing medium for URF, so the reference flow is 1 m³ of each growing media. The system boundaries include the extraction and production of the constituents (perlite, peat and coir) and their transportation to Spain from Turkey, Germany and the Philippines, respectively (see system

Table 1 Characterisation of the growing media. *kt*, kilotons. 1 (Grillas et al. 2001; Maher et al. 2008; Papadopoulos et al. 2008; Barrett et al. 2016); 2 (Soil and Substrate Preparers Association 2020); 3, 5 (U.S.

Geological Survey 2020); 4 (Growing Media Europe 2019); "a" only for Europe; "b" Coconut production



CHARACTERISATION	PERLITE	PEAT	COIR
Physical characterisation ¹	Siliceous volcanic glass (inorganic)	Organic substrate of natural origin - vegetal fossilisation	Waste product of the coconut (cocos nucifera) (organic)
Nutrient content	No	Very low	High
Air-filled porosity	High (22-25%)	High (14-22%)	High (12-55%)
Water retention	Low	High	High
Bulk density (g/cm ³)	0.1-0.9	0.05-0.29	0.03-0.1
Market price ²	55-60 €/m ³	30-36 €/m ³	33-38 €/m ³
World's leading producers (2019) ³	China 47% (1,900kt) Greece 20% (800kt) Turkey 16% (650kt) USA 13% (520kt) Armenia 1.1% (45kt) Total 4,100 kt	Finland 33% (10,000 kt) Germany 13% (4,000 kt) Ireland 10% (3,000 kt) Belarus 8.7% (2,600 kt) Sweden 8.3% (2,500 kt) Total 30,000 kt	Indonesia ^b 31% (18,300 kt) Philippines ^b 26% (15,353 kt) India ^b 20% (11,930 kt) Brazil ^b 5% (2,890 kt) Sri Lanka ^b 4.3% (2,513 kt) Total 58,352 kt
Production (current & forecasted) ⁴	2017 1.5 Mm ³ /y 2050 10 Mm ³ /y Increase (%) 667 %	2017 40 Mm ³ /y 2050 80 Mm ³ /y Increase 250 %	2017 5 Mm ³ /y 2050 35 Mm ³ /y Increase 700 %
Applications ⁵	Construction 58 % Horticulture 18 % Fillers 15 % Filters 9 % Others 8 %	Energy ^a 58 % Horticulture ^a 42 %	Horticulture 100 %

boundary diagrams in the supplementary information). The use phase is not included because other elements, such as fertilisers, water and auxiliary equipment, would have to

be included, and the end-of-life phase is also not included. Consequently, we focused the analysis on the stand-alone constituents.

Life cycle inventory (LCI) The life cycle inventory can be seen in the supplementary information (Table 1), which includes the constituents and their transportation based on the functional unit. We used Simapro 9.0 software by PRÉ Consultants, Ecoinvent 3.5 database (Swiss Centre For Life Cycle Inventories 2018) and GaBi ts software 9.1.0.53 by Sphera. We used the cutoff system model, therefore, in the case of the coir, as a by-product enters the system burden-free.

Life cycle impact assessment (LCIA) For the LCIA, we used the ReCiPe 2016 (Huijbregts et al. 2017) midpoints (hierarchical) V1.03. According to previous literature (Boneta et al. 2019; Rufí-Salís et al. 2020), we selected the following impact categories: global warming (GW; kg CO₂ eq), terrestrial acidification (TA; kg SO₂ eq), freshwater eutrophication (FE; kg P eq), marine eutrophication (ME; kg N eq), ecotoxicity (ET; kg 1,4-DCB) (which sums all three impact categories, including marine, terrestrial and freshwater ecotoxicity), land use (LO; m²a crop eq), fossil resource scarcity (FRS; kg oil eq) and water consumption (WC; m³) (Goedkoop et al. 2013). We applied the WAVE+ factor (Water Accounting and Vulnerability Evaluation Model) (Berger et al. 2018) to

the WC impact category at the country level to relate to the potential local impacts of water consumption in the studied countries.

2.1.1.1 Interpretation A sensitivity analysis was performed to evaluate the significant parameters and how they influenced the outcomes. Three different parameters related to energy and transport were used for the sensitivity analysis because these growing media constituents are energy intensive. We proposed an improved scenario using more eco-friendly road (euro 5 to euro 6) and ship transports and more decarbonized energy in the production of perlite, which requires a high amount of heat to expand it. The parameters can be seen in the supplementary information.

2.1.2 Social life cycle assessment (S-LCA)

A first social analysis was performed to obtain a general overview of the growing media and to identify higher social risks using the SHDB. Subsequently, the second and third assessments were conducted to narrow down the social analysis of these growing media in their countries of origin at the sector and company levels.

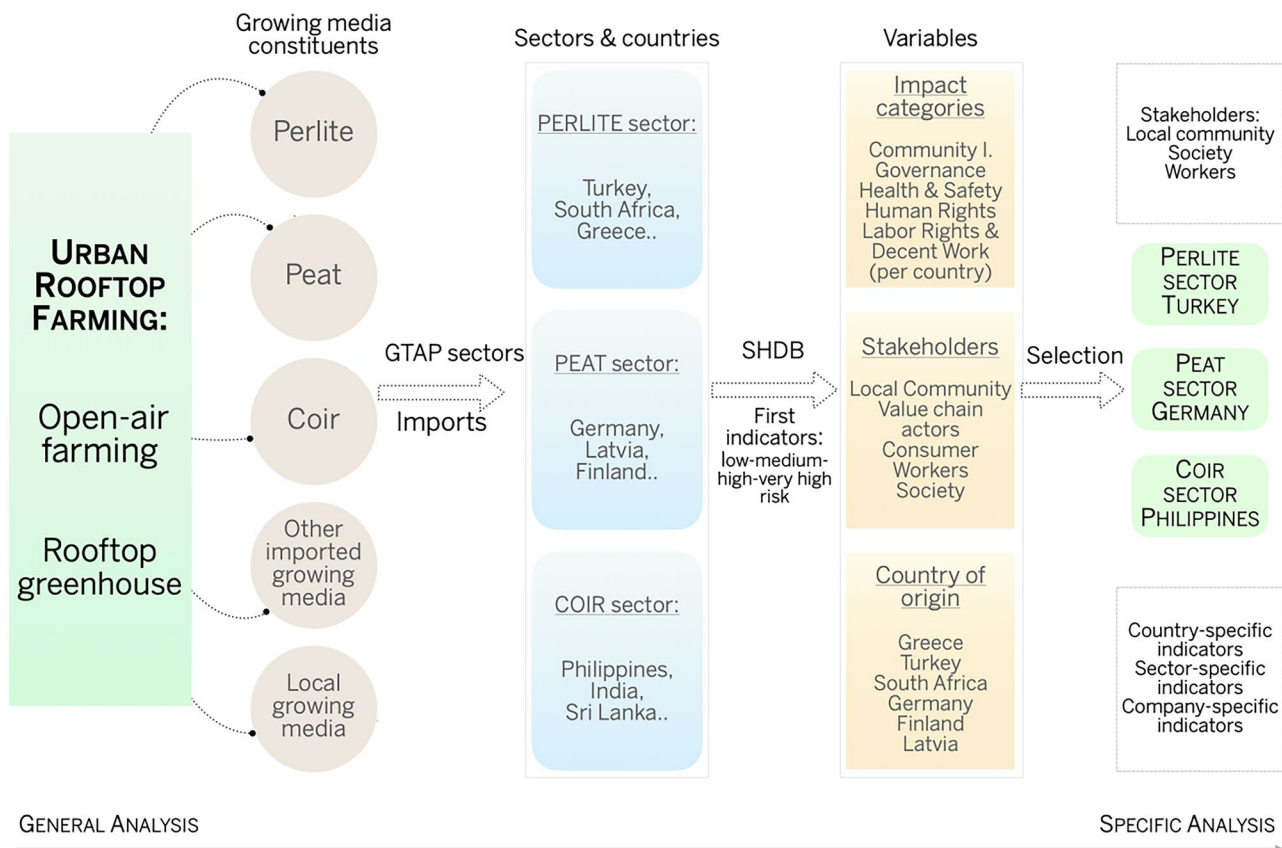


Fig. 1 Workflow used in this study, from a general analysis to a specific analysis. GTAP, Global Trade Analysis Project; SHDB, Social Hotspots Database

Goal and scope The goal of the S-LCA was the same as that in the E-LCA but reduced in scope and focused only on the extraction and production of the three constituents, excluding transportation. We used the same functional unit as that in the E-LCA, i.e. 1 m³ of growing medium for URF. Three different scales were taken into account to comprehensively analyse constituents' production, i.e. country-specific, sector-specific and company-specific indicators, following the UNEP/SETAC S-LCA guidelines (UNEP/SETAC 2009). Figure 1 illustrates the steps taken to obtain the different social indicators at different scales.

Two systems can be implemented on URF: OAF and RTGs. Such systems require different elements to grow vegetables. Among these components, a growing medium is essential for the proper operation of URF, and it is the component with the most volume used. In this context, an array of growing media can be used for vegetable cultivation. These substances have to share features such as lightness, porosity and water retention capacity (Maher et al. 2008; Papadopoulos et al. 2008). In this case study, three constituents were analysed: perlite, peat and coir.

Life cycle inventory (LCI) For this research, we collected two different types of data: general data and site-specific data. General data belong to the potential social risks at the country and sector scales in aggregated sectors applied in the SHDB, and site-specific data relate to social impacts at the country, sector and company scales in the specific sectors of perlite, peat and coir.

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Data from the social hotspots database (SHDB)

Social performance was analysed by means of the SHDB. The SHDB is based on an input–output model, the Global Trade Analysis Project (GTAP), and includes country-specific indicators for 57 aggregated sectors in 140 countries. We used the SHDB 2019 version (New Earth 2019) based on the GTAP global equilibrium model version 9. First, there are five impact categories in the SHDB: community infrastructure, governance, health and safety, human rights, and labour rights and decent work. Second, the stakeholders we chose to examine were local community, value chain actors, consumers, workers and society; third, we determined the country of origin. In our case study, perlite and peat belonged to the aggregated mineral nec (not elsewhere classified) sector, and coir belonged to the plant-based fibre sector of the GTAP model. We retrieved the import data (2018) of these growing media to Spain from official

statistics (DataComex) (The Ministry of Industry Trade and Tourism). We selected the countries that imported the largest percentage of each growing medium (higher than 3%) (see Fig. 3). Hence, the first outcomes came from the SHDB performance in the aggregated mineral and plant-based sectors.

Site-specific data for perlite, peat and coir

We performed more specific analyses because the social assessment with the SHDB was performed for aggregated sectors. Consequently, we collected data in two ways:

- Country- and sector-specific data retrieved from official statistics, institutions and experts, and
- Company-specific data (primary data) obtained through questionnaires

We performed a comprehensive social analysis related to the Sustainable Development Goals (SDGs) and in reasonable time consuming. Therefore, we selected the same impact categories proposed by the SHDB except for governance, and 14 indicators within these impact categories were selected to analyse the social impacts at the country and sector scales considered under the scope of this research (see Table 1). The indicators were chosen following the UNEP/SETAC S-LCA guidelines (Benoît-Norris et al. 2013) and for being the most extended and accessible indicators in the growing media sector. The stakeholders relevant to this project were the local community, society and workers, and the countries selected were Turkey, Germany and the Philippines, which export the largest amount of each growing medium to Spain. Table 2 summarises the different impact categories, subcategories, indicators and stakeholders selected in this research; moreover, the last column indicates our own classification of how these social indicators are related to SDGs.

The company-specific data of the growing media constituents were gathered through a questionnaire. The questionnaire was sent via email to 22 companies of the growing media sector, but only three companies answered it. The questionnaire was divided into a first part including basic information about the company/organisation, then some general questions related to social reports; the last part dealt with more specific questions about three major themes: health and safety, human rights, and labour rights and decent work in the company. The design protocol can be checked in the supplementary information (page 2). (Table 2)

Social life cycle impact assessment (LCIA) This research follows the use of an ordinal scale to analyse the social performance of the three types of growing media by comparing the three options (known as the type I approach). The resulting indicators are scored depending on their relative relevance among the three options (UNEP/SETAC 2009).

Table 2 Summary of the impact categories and subcategories, social indicators, and stakeholders and these related to SDGs, proposed for this research. *NA*, not available

Impact category- Social indicator	Country specific	Sector specific	Stakeholder	Impact subcategory	Sustainable Development Goals
Community Infrastructure					
Drinking water access	x		Local community	Access to material resources	Goal 6: 6.a.1 Amount of water- and sanitation-related official development assistance that is part of a government-coordinated spending plan
Children out of school	x		Local community	NA	Goal 4: 4.1.1 Proportion of children and young people: (a) in grades 2/3; (b) at the end of primary; and (c) at the end of lower secondary achieving at least a minimum proficiency level in (i) reading and (ii) mathematics, by sex
Hospital beds per 1000 population	x		Local community	NA	Goal 3: 3.8.1 Coverage of essential health services (defined as the average coverage of essential services based on tracer interventions that include reproductive, maternal, newborn and child health, infectious diseases, non-communicable diseases and service capacity and access, among the general and the most disadvantaged population)
Employment share (Positive impacts)		x	Society	Contribution to economic development	Goal 10: 10.4.1 Labour share of GDP, comprising wages and social protection transfers
GDP contribution (Positive impacts)		x	Society	Contribution to economic development	
National poverty line (% population)	x		Society	Contribution to economic development	Goal 1: 1.2.1 Proportion of population living below the national poverty line, by sex and age
Human Rights					
Gender inequality	x	x	Worker/Society	Equal opportunities/ Discrimination	Goal 5: 5.5.2 Proportion of women in managerial positions
Health & Safety:					
Fatal injuries		x	Worker	Health & safety	Goal 8: 8.8.1 Frequency rates of fatal and non-fatal occupational injuries, by sex and migrant status
Non-fatal injuries		x	Worker	Health & safety	
Labour Rights & Decent Work					
Child labour	x	x	Worker/Society	Child labour	Goal 8: 8.7.1 Proportion and number of children aged 5–17 years engaged in child labour, by sex and age
Excessive work hours		x	Worker	Hours of work	Goal 8: not specific indicator
Fair salary		x	Worker	Fair salary	Goal 8: 8.5.1 Average hourly earnings of female and male employees, by occupation, age and persons with disabilities

Social Hotspots Database (SHDB)

We used the SHDB to assess generic social hotspots. This method measures the risk hours of the social impact: “risk hours represent the weighted cumulative labour hours where workers in the supply chain may be at risk for each specific social issue” (Takeda et al. 2019). It, therefore, assesses the indicators by assigning a risk level, proposing different classes of risks, from very high to high, medium and low, based on the data distribution, expert judgement and literature. It is based on labour intensity and divides the GTAP data into wage payments by country and sector by the average country and sector wage; this method offers estimates of worker hours for each sector in each country. The data used for the SHDB come from public institutions, country statistics, NGO reports, trade unions and academic papers. The

inventory inputs for the SHDB were the aggregated sector of each growing medium: the mineral nec sector for perlite and peat and the plant-based fibre sector for coir. The countries of perlite production were Turkey, South Africa, Greece, the UK, Germany, Uganda, Brazil and Mozambique; those for peat were Germany, Latvia, the Netherlands, Estonia, Lithuania, Ireland and Finland; and those for coir were the Philippines, India, Mozambique, Tanzania, Madagascar, Kenya, Ecuador and Colombia.

Site-specific assessment

In the case of each site-specific assessment, we scored the indicators in reference to the direct comparison of the alternatives. The indicators were divided into three different scales: the country scale, sector scale and company scale.

Country scale

The outcomes obtained from the country-specific data were presented numerically on a scale from high (most positive) to medium to low (least positive) performance by a comparison among the alternatives, and a colour scale was applied.

Sector scale

For the sector scale, we quantified all the indicators and provided a comparative scale among the options: high, medium or low performance. Additionally, a colour scale was applied.

Company scale

The primary data from companies were assessed following the same method as that used for the sector scale. When possible, a score was given to each indicator (high, medium or low performance), and a colour scale was applied.

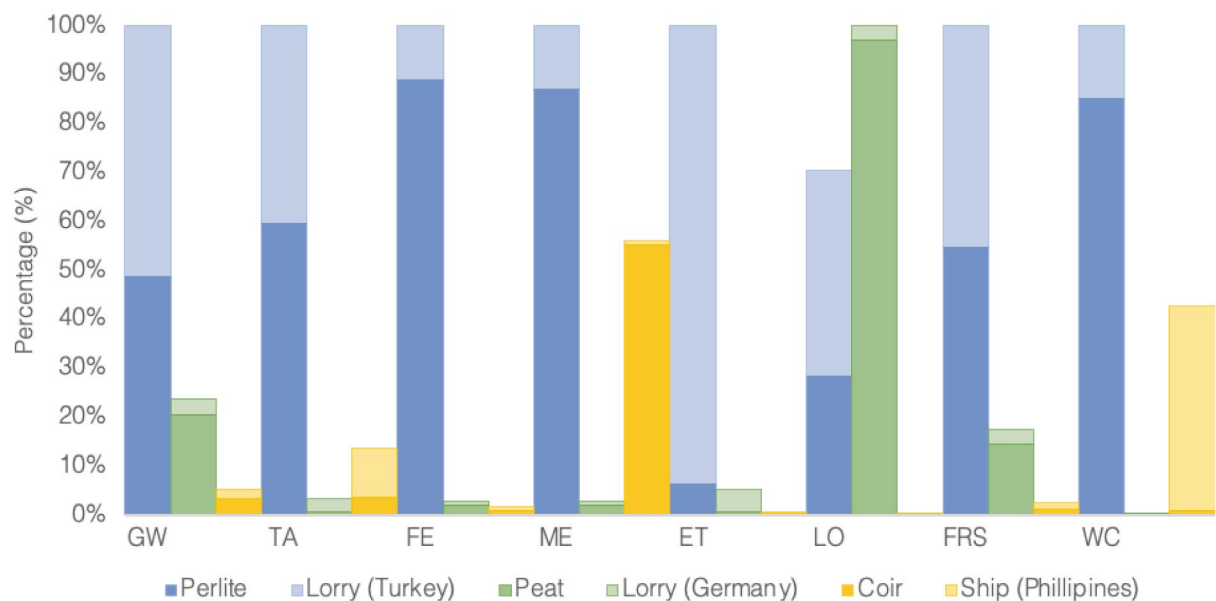
Subsequently, the different outcomes of the different levels were compared (Tables 4 and 5), and the overall performances of the three growing media constituents were determined (Fig. 4).

3 Results and discussion

This section presents the results of the E-LCA (Sect. 3.1) and the S-LCA (Sect. 3.2) and a comprehensive assessment of all the outcomes (Sect. 3.3).

3.1 Environmental life cycle assessment

The environmental assessment is represented by each constituent in its country of origin. The outcomes illustrate that in 7 out of 8 impact categories, perlite, along with its transport from Turkey, had the highest environmental burdens, accounting for 44 to 99.9% higher impacts than those of peat and 65 to 99.7% higher impacts than those of coir (Fig. 2). In particular, perlite had higher impacts in freshwater eutrophication (FE) ($2.4\text{E}-01$ kg P eq) and ecotoxicity (ET) ($5.9\text{E}+03$ kg 1,4-DCB eq) compared to the those of other two constituents (peat and coir). There was only one category where the highest environmental impact



Impact category	GW (kg CO ₂ eq)	TA (kg SO ₂ eq)	FE (kg P eq)	ME (kg N eq)	ET (kg 1,4-DCB)	LO (m ² a crop eq)	FRS (kg oil eq)	WC (m ³)
Perlite	6.2E+02	2.0E+00	2.4E-01	1.7E-02	5.9E+03	2.2E+01	2.4E+02	3.1E+00
Peat	1.5E+02	6.8E-02	6.7E-03	4.5E-04	3.1E+02	3.1E+01	4.2E+01	3.9E-03
Coir	3.2E+01	2.7E-01	9.4E-03	9.4E-03	3.2E+01	1.0E-01	6.0E+00	1.3E+00

Fig. 2 Relative impacts of the extraction and production of 1 m³ of each growing media constituent and its transport. Relative impacts are shown with respect to the highest values in the graph and table with absolute values. The impacts include global warming (GW; kg CO₂ eq), terrestrial acidification (TA; kg SO₂ eq), freshwater eutrophication (FE; kg P eq), marine eutrophication (ME; kg N eq), ecotoxicity (ET; kg 1,4-DCB), land use (LO; m²a crop eq), fossil resource scarcity (FRS; kg oil eq) and water consumption (WC; m³). See all the absolute values in the supplementary information

ication (FE; kg P eq), marine eutrophication (ME; kg N eq), ecotoxicity (ET; kg 1,4-DCB), land use (LO; m²a crop eq), fossil resource scarcity (FRS; kg oil eq) and water consumption (WC; m³). See all the absolute values in the supplementary information

was attributed to peat; this impact was the land use (LO) impact category ($3.1E+01$ m²a crop eq) due to the extraction of peat. On the other hand, coir obtained the highest impact in water consumption before the WAVE + factor was applied; however, after applying this factor, the water consumption of the perlite growing medium rose considerably due to the scarcity of this resource in its country of origin, Turkey. Coir only obtained significant impacts compared to perlite in marine eutrophication (ME) and water consumption (WC) because of its transport by sea, representing 56 and 42%, respectively, of the impacts of perlite.

The extraction and production of perlite dominated the environmental impacts; perlite had the highest contribution in most of the categories (5 out of 8 midpoints), whereas its transport by road caused the highest environmental burden in ecotoxicity (92%) and land use (60%).

Considering these results, the best performance was observed for coir, despite the long route it must take by ship. Because coir is a by-product that is transformed into a product and almost does not have environmental impacts, most of its impact comes from its transportation by ship. Peat also had low environmental burdens except for those of global warming, land occupation and fossil resource scarcity. Consequently, perlite is the least favourable option from an environmental perspective since it implies the extraction of a mineral, the use of new resources, the consumption of energy for expanding the perlite, and a long trip by lorry from Turkey.

We have found two studies which are comparable to our study in terms of system boundaries and assumptions, albeit they use different impact assessment methods than the one we applied (ReCiPe). Quantis (2012) performed an LCA of various substrates and applied the Impact 2002 + method (Jolliet et al. 2003), obtaining similar global warming impacts as we found for the three growing media constituents except for perlite, ours is expanded perlite and the global warming impact is much higher (620 kg CO₂ eq/m³). They ranked from highest to lowest as follows: black peat (150 kg CO₂ eq/m³), perlite (100 kg CO₂ eq/m³), white peat (90 kg CO₂ eq/m³) and coir (70 kg CO₂ eq/m³). Another study by Eymann et al. (2015) assessed peat and coir using the IPCC 2013 method for the global warming

impact, which gave comparable results of 250 kg CO₂ eq/m³ and 41–85 kg CO₂ eq/m³, respectively.

3.1.1 Consistency and completeness analysis

We used the most updated datasets for the modelling of the three growing media constituents. For electricity, water and heating, we used specific processes from each country. For transportation, we used a European dataset for Germany, a “rest of the world” (ROW) dataset for Turkey and a global dataset (GLO) for the Philippines. We did not use any allocation in the case of coir by-product as other studies did (Quantis 2012); therefore, we considered the coir burden-free. Furthermore, as stated in the methods section, we did not model the use phase or end-of-life phase because other materials and processes are necessary in those phases, e.g. fertigation; therefore, we analysed the stand-alone constituents.

3.1.2 Sensitivity analysis

The sensitivity analysis further supported the importance of energy (electricity, heating and fuel) in these growing media. We consider transportation, which relies on distance from the country of origin and the weight/volume of the growing media constituents, in the sensitivity analysis due to the relevance of the results depending on these parameters and how the country of origin where the constituents come from can affect the environmental performance.

The analysis indicated that with changes such as the use of an electricity mix that is less reliant on fossil fuels and more recent vehicles (euro 5 to euro 6) and ships, most of the outcomes improved considerably (Table 3). We found reductions in the impacts from 100 to 0.1%. Perlite would reduce its impact on all midpoints by changing the energy that perlite requires for its manufacturing and by changing the mode of transportation from lorry euro 5 to euro 6. For peat and coir, only changing the transportation mode would decrease their impacts in most of the categories except marine eutrophication and land use for peat and terrestrial acidification and ecotoxicity for coir. (Table 3)

Accordingly, changing the processes that require relevant amounts of energy to other processes based on renewable

Table 3 Sensitivity analysis based on more environmentally friendly alternatives for the energy source of perlite production and the transport of the three constituents. See the absolute values in the supplementary information (Table 4)

Impact category	GW (kg CO ₂ eq)	TA (kg SO ₂ eq)	FE (kg P eq)	ME (kg N eq)	ET (kg 1,4-DCB)	LO (m ² a crop eq)	FRS (kg oil eq)	WC (m ³)
Perlite	-23%	-44%	-27%	-24%	-8%	-14%	-23%	-9%
Peat	-2%	-26%	-9%	1%	-0.1%	3%	-3%	-43%
Coir	-13%	3%	-80%	-72%	21%	-27%	-17%	-100%



Fig. 3 Social risks obtained from the SHDB regarding the aggregated sectors and the imports of the three growing media to Spain. h, hours

energies or cleaner technologies can aid in enhancing the environmental performances of these growing media.

3.2 Social life cycle assessment

3.2.1 Outcomes from the social hotspots database (SHDB)

These outcomes are related to the growing media constituents in the aggregated sector of each country, retrieved from the SHDB (Fig. 3). The figures on the top are the total risk hours per country and their imports to Spain in 2018, and the bottom figures are related to the five social impact categories.

The SHDB offers a general overview of the different aggregated sectors. For the mineral aggregated sector to which perlite belongs, the highest-risk hours fall into two African countries: Uganda (243 h (h)) and Mozambique (294 h), which mainly have risks in community infrastructure and governance, though they represented only 6% and 3% of the total imports to Spain, respectively. The following countries that perform worst are South Africa, Turkey and Brazil. The highest risks among the impact categories in Turkey are health and safety (65 h), human rights (28 h)

and labour rights and decent work (27 h), and this country exports the third part of total perlite imported to Spain.

Regarding peat, Latvia, Lithuania and Estonia exhibited the highest risk, particularly in the health and safety category. The rest of the countries performed properly, meaning that the risk hours ranged only from 22 to 53 h. Germany is the country that performed best, with only 22 h, and its highest score was in health and safety. Moreover, the import of peat to Spain was predominantly concentrated in this country (42%).

In general, concerning the coir-based growing media, all of the countries had very high numbers of risk hours, from Ecuador, with 198 risk hours, to the highest, India, with 319 h; in India, governance, human rights, and labour rights and decent work had the highest scores. The Philippines is the third best-performing among these countries and exports the most coir to Spain, comprising 28% of the total exports. In general, the Philippines has high risks in all the impact categories.

Taking into consideration these outcomes, the best scores were obtained for peat in Germany, followed by perlite in Turkey, and the highest risk was assigned for coir in the Philippines.

3.2.2 Social assessment at the sector and country scales

The following assessment was focused on the specific sectors of perlite, peat and coir from the countries that export the most of each growing medium to Spain (Table 4). These outcomes provide specific data about the types of growing media in three different countries that are relevant importers in this sector. Peat from Germany depicts the best

performance because 8 out of 14 indicators (57%) performed more positively than the other two options. In contrast, coir obtained the worst performance, with 7 out of 14 indicators (50%) displaying the lowest values, and perlite had most of the intermediate values (50%) among the three options. (Table 4)

In three out of four impact categories, i.e. community infrastructure, human rights, and labour rights and decent

Table 4 Social assessment of the three constituents at the country and sector levels. The sources of the data can be checked in the supplementary information (Table 5). Gender inequality is sourced from the

Classification of Social Institutions and Gender Index (SIGI category (very low, low, medium, high, very high) (OECD 2020)

Stakeholder-Impact category (Impact subcategory)- Social indicator	Perlite (Turkey)		Peat (Germany)		Coir (Philippines)	
	country specific	sector specific	country specific	sector specific	country specific	sector specific
LOCAL COMMUNITY						
Community Infrastructure						
Drinking water access	99%		100%		91%	
Children out of school	5.12%		0.53%		3.25%	
Hospital beds per 1000 population	2.81		8		1	
SOCIETY						
Community Infrastructure (Contribution to Economic Development)						
Employment share (Positive impacts)		6.06%				24.3%
		0.05%		0.0066%		0.53%
GDP contribution (Positive impacts)		1%		0.0021%		0.35%
						8.80%
National poverty line (% population)	13.50%		10.40%		21.60%	
Human Rights						
Gender inequality	25% (low)		18% (low)		53% (very high)	
Child labour	5.90%		4.10%		18.90%	
WORKER						
Health & Safety						
Fatal injuries (number)		33		1		15
Incidence rate:Occupational Injuries per 1,000 Employed Persons		4.41		1.33		0.11
Non-fatal injuries (number)		2806		797		1862
Incidence rate:Occupational Injuries per 1,000 Employed Persons		350		20.2		13
Human Rights						
Gender inequality (woman representation in labor force)		4.60%		NA		14%
Labour Rights & Decent Work						
Child labour		0.002%		0%		2.80%
Excessive work hours		+10%		0%		-22%
Fair salary		331 €/month		2696 €/month		114 €/month
		+16%		-22%		-53%

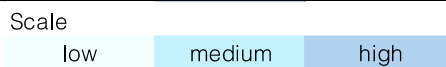


Table 5 Social assessment at company scale of the three constituents. The complete questionnaire and answers can be checked in the supplementary information (Table 6)

Stakeholder-impact category- Social indicator	Perilite (Turkey) company specific	Peat (Germany) company specific	Coir (Philippines) company specific
LOCAL COMMUNITY & SOCIETY			
Community Infrastructure			
Ongoing social or community development infrastructures in local communities	No	Yes. The promotion of nature conservation, restoration and protection. The promotion of science, research and of education	Provide local jobs - Paint schools and temples - Provide student bursaries
Percentage (%) local workers vs migrants	100% local	20% migrants- 80 % locals	100% local
WORKER Health & Safety			
Does your company have a code of conduct that addresses worker rights, health and safety?	Yes	Yes. All the workers' rights of our staff are fulfilled through rigorous compliance of the law and pertinent legal provisions of the countries where our peat extraction centers and substrates manufacturing are located. Strict compliance with the SA-8000 Certification	Yes. Follow ILO Rules: ISO 9000 Production
Measure of noise, dust and hazardous material exposures in the company and their surroundings	Yes, not available	Yes. This is internal information that cannot be provided	No
Statistics in fatal and non-fatal injuries	No	Yes. This is internal information that cannot be provided	Not available
Statistics in total staff hours worked per week (included overtime)	No	Yes. This is internal information that cannot be provided	40 h/week
Human Rights			
<i>Gender inequality</i>			
% women in the workforce	30 % women	33% women	70% women
% women in management positions	25% women-75% men	100% men	50 % women-50% men
Labour Rights & Decent Work			
Child labour	No relevant	No relevant	No relevant
Excessive work hours	9-18h	Our organisation complies with the national legal provisions regarding working hours.	Equal to country sector specific
Fair salary	Legal minimum wage published by government. It is overall higher than other sectors	This is internal information that cannot be provided. In any case it complies the minimum inter-professional wage	Equal to country sector specific wage
Policies regarding non-discrimination and equal opportunity in employment	Yes	Our organisation fulfils the law to guarantee equal treatment and opportunities between women and men in employment and occupation	Yes
Policies regarding freedom for workers to form or join trade unions	Yes	Our organisation complies with the law of freedom association	Yes
Scale			
	low	medium	high

work, peat in Germany had the best achievement indicators, followed by perlite in Turkey and coir in the Philippines. These achievements mainly occurred due to the better working conditions and better infrastructure in a highly developed country such as Germany. In contrast, in the subcategory of the contribution to economic development, perlite showed the best behaviour, followed by coir and then peat. The reason for this result is that the perlite sector and the coir sector (coconut production) in the studied countries are more prominent, creating more jobs and contributing more to the corresponding GDP than the peat sector, which is a small, family sector with fewer than 20 permanent workers in the companies that is shrinking in recent years due to the Climate Action Plan 2050 proposed by the German government to preserve peatlands (Federal Ministry for Environment Nature Conservation and Nuclear Safety 2016). By the same token, in the health and safety category, the best performance is observed for coir, then for peat, and the worst performance is observed for perlite. The cause of this result is the high incidence of fatal and non-fatal injuries in mining, which is the mode of production of perlite, an inorganic mineral coming from open-pit mines. Perlite mining is usually associated with a range of respiratory problems (Sampatakakis et al. 2013; Maxim et al. 2016). Nevertheless, in most countries, perlite is classified as a “nuisance dust” (Maxim et al. 2016).

Concerning the analysis of various stakeholders, the rankings for the local community and society follow the general trend, i.e. peat, perlite then coir, due to better conditions in Germany and Turkey than in the Philippines. Nevertheless, for the worker group, the worst performance is assigned to perlite in Turkey because of the worst values of the fatal and non-fatal injuries and excessive working hours indicators, whereas coir exhibits the best scores in general in this group but the worst values for the child labour and fair salary indicators.

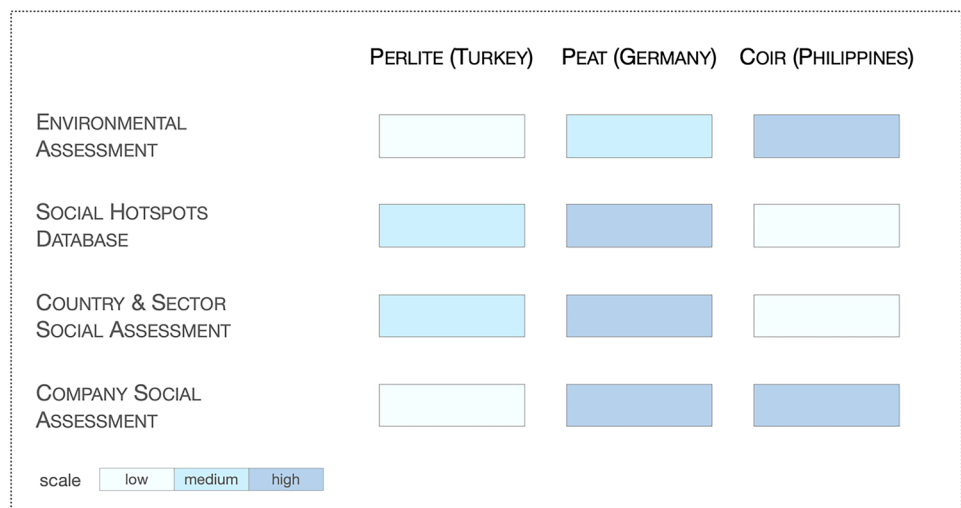
3.2.3 Social assessment at the company scale

The following assessment at the company level was retrieved from the questionnaire sent to 22 companies. After a long period, we received answers from three companies in each sector and country (Table 5). In general, the peat and coir companies shared slightly more information than did the perlite company. Regarding community infrastructure, both companies (peat and coir) have ongoing social or community developments, such as the promotion of nature, research and education or the provision of different projects in schools. In all three companies, most workers are locals (perlite: 100% local; peat: 80% local and 20% migrants; coir: 100% local).

In the same context, the peat and coir companies follow different certifications: the Social Accountability 8000 (SA8000) certification, which involves recognised standards of decent work, and the ISO 9000 production, which is related to quality management systems; however, the perlite company answered positively about the code of conduct in the company but did not mention any specifics. All the companies agreed that they control parameters such as noise, dust and fatal and non-fatal injuries, but none of them provided any data related to these statistics.

Regarding gender inequality, the coir company received the best score because 50% of employees in management positions are women; however, the company was unbalanced in the workforce because 70% of workforce employees are women. In contrast, in the peat company, the majority of employees in management positions are men, and of the total labour force, only 33% are women. Concerning child labour, all of the companies concurred that it is not an issue in this sector. Regarding fair salary and excessive work hours, the companies claimed these were internal information or that they follow national sector-specific rules. However, the perlite company that mentioned that

Fig. 4 Summary of the three growing media constituents and their performances in each assessment type



the salary in this sector is higher than that in other sectors, which coincides with the fair salary indicator at the sector scale retrieved from official sources (Table 4). However, all of the companies failed to provide any specific figures. With respect to policies related to non-discrimination and freedom to join trade unions, the companies asserted that they follow the standards and laws related to their countries, but no specific data were provided.

These outcomes demonstrate some main issues: (a) companies in this sector lack knowledge about the social life cycle assessment; (b) it is very complex to obtain social data from companies; 22 companies were contacted and, after much effort, we obtained 3 responses; and (c) companies do not share or do not have sufficient social data, and the data they do share are usually very unspecific. (Table 5)

3.3 Overall performance for the analysed growing media constituents. Which growing media are most suitable for urban rooftop farming?

Different outcomes emerged among the different assessments (Fig. 4). Comparatively, the peat growing medium obtained the highest performance in all the social assessments. This is due to its excellent performance in the SHDB and the impact categories of the local community, human rights and labour rights. Most of its positive performance is related to peat being sourced from a European Union (EU) country, Germany, because of the deployment of human, labour and social security rights and the remarkable work conditions in this country. On the other hand, the peat industry is a small-scale sector that is decreasing in size due to the restrictive peat extraction regulation of the German government that aims to preserve peatlands and cease extraction in the future (Federal Ministry for Environment Nature Conservation and Nuclear Safety 2016).

Coir obtained the best environmental outcome since it is a by-product resulting from coconut husks transformed into a value-added product, despite the long journey from the Philippines. The coconut sector in tropical countries such as India, Sri Lanka and the Philippines is quite extended, and a variety of products are extracted from coconut trees, such as coconut oil; coconut fibres, for example, for ropes and mats; beverages; and medicines (Maher et al. 2008). Therefore, indicators such as GDP contribution or employment share are very positive in this sector. Conversely, this growing medium has low performance in the SHDB, being the constituent with the highest risk hours in all the impact categories. In the same way, coir has low scores in community infrastructure, in human rights related to gender equality and child labour—approximately 19% in the country and 2.8% in the coconut sector—and in labour rights and decent work.

Perlite is the least environmentally friendly of the three growing media constituents under study, mainly because

it is a mineral extracted from mines that requires energy, water and many other processes to be produced and due to its road transportation from Turkey; for example, this could be reduced if perlite comes from Greece, one of the main exporters. Furthermore, the perlite company limited their answers mainly to yes/no and did not provide sufficient details about the social data of the company. Despite these results, this growing medium is affordable, and many conventional greenhouses in Almeria (Spain), where the highest concentration of greenhouses in the world exists, use this growing medium due to its easy management and competitive price (Urrestarazu 2013). Additionally, Spain is one of the leading global producers of vegetables and fruits, producing 12.9 and 14.4 million tons (2018), respectively (Messe Berlin 2020). This growing medium showed acceptable performance in the SHDB and in country- and sector-specific assessments, such as community infrastructure and contribution to economic development. Nonetheless, in fatal and non-fatal injuries, perlite scored distinctly worse than the other growing media.

According to the outcomes, some issues should be highlighted as follows.

- Peat is, according to this study, ideal for use on rooftops in Spain because its social assessment is positive at all scales; however, peat fails in the environmental aspect due to the aim of preserving peatlands and the reduction in their exploitation. A reasonable solution might be the combination of local by-products such as cork granulates or sawdust with peat. In this line, the peat company proposed a combination of peat, coir, perlite and other constituents, and the coir company suggested a terracotta tile waste mixed with coir. Consequently, we identify a plausible new market of local growing media that tailor best in the area where they are applied. The transformation and reuse of waste or by-products could be the solution for future URF (Stucki et al. 2019; Manríquez-Altamirano et al. 2020, 2021; Parada et al. 2021).
- Coir is suitable for local and short-distance countries but not for long-distance countries, such as those in Europe. Coir is a good example of transforming waste into a value-added product. However, all the social impacts of coir related to community infrastructure and human and labour rights should be enhanced for better social performance.
- Perlite has major environmental burdens that should be reduced, but because of its low cost, it is widespread in Spanish greenhouses (Urrestarazu 2013). Some social indicators of perlite should be improved, such as reducing fatal and non-fatal injuries and controlling noise and dust, for better management of all these aspects. Another solution for this growing medium would be to reutilise it as many

times as possible to increase its lifespan, as some studies advocate that this can decrease its environmental footprint (Diara et al. 2012; Acuña et al. 2013).

Future URF should not repeat the same errors made in conventional food supply chains, such as externalising the social and environmental costs of delocalised production. Therefore, the growing medium is a key product that must be selected to minimise environmental, social and economic impacts. Proposing local products, and, when possible, growing media from waste/by-products, can improve this selection. As shown in this study, new products, such as perlite, have high environmental and social burdens and long distances from their points of production in countries with lenient labour regulations that rocket these impacts. Accordingly, we display the first attempt to conduct comprehensive assessments of three commercial growing media constituents that will aid in selecting the most feasible growing medium option, in this case for Spain; however, this could be used for other European countries.

4 Conclusions

4.1 Outcomes from the environmental and social life cycle assessment

We contributed comprehensive assessments of three growing medium constituents used to grow vegetables in future scenarios in cities where land availability is scarce and there will be a need for soilless systems. We analysed the most extensively used growing media, perlite from Turkey, peat from Germany and coir from the Philippines, to be used in urban roofs to cultivate vegetables by performing an environmental and social life cycle assessment.

The environmental assessment highlighted perlite as the most harmful option compared to peat and coir. Due to the extraction of new material from open-pit mines and the quantity of energy needed for all the manufacturing processes, the highest values in freshwater eutrophication ($2.4\text{E}-01$ kg P eq) and ecotoxicity ($5.9\text{E}+03$ kg 1,4-DCB eq) were obtained for perlite compared with the rest of the growing media. Transport by road from Turkey to Spain also contributed considerably to the environmental impacts of perlite, mainly in ecotoxicity (92%; $5.49\text{E}+03$ kg 1,4-DCB eq) and land use (60%; $1.29\text{E}+01$ m²a crop eq). In contrast, the most environmentally friendly option was coir, despite its long transport route from the Philippines to Spain.

Regarding the social assessment, owing to its origin in an EU country, peat was the most socially friendly growing medium in the three assessments performed due to its more favourable indicators in impact categories such as community infrastructure, human rights, and labour rights and

decent work compared to the other two alternatives. Subsequently, coir displayed better scores than perlite in general but obtained the worst values of the three alternatives in the SHDB, in the community infrastructure impact category and for social indicators such as gender inequality, child labour and fair salary. Perlite obtained the worst performance in the general assessment; however, it had positive impacts in the GDP contribution and fair salary indicators.

4.2 Limitations and methodological challenges

From a methodological standpoint, it was very complex to obtain data for the indicators/impact categories used for the social assessment of not-very-mainstream products, and companies were reluctant to share this information. Therefore, much effort had to be made in this regard. In the same context, social data are not centralised in any institution, and countries sometimes use different indicators with the same purpose; thus, it is necessary to harmonise social indicators and prioritise which social indicators to use. To progress in social assessments and make the assessments more dynamic to perform, we recommend further research aiming to (a) prioritise social indicators, as S-LCA presents multiple indicators; we advocate for centralising efforts in the most common and widespread indicators, such as gender inequality, labour rights, and health and safety, or SDGs indicators; (b) increase the data availability of disaggregated sectors in databases such as the SHDB and PSILCA targeting to easily perform social assessments; and (c) promote among companies the control of social data to generate open-source databases to be used for researchers and organisations. In addition, this research was performed using the first S-LCA guidelines (2009) by the UNEP/SETAC Life Cycle Initiative. Last December (2020), a new guideline was launched, which means that many efforts are already being made, for example reinforcing and clarifying, with a range of examples, the methodological developments in S-LCAs or linking the S-LCA impact subcategories with SDGs due to the fact that fourteen of the seventeen goals concern social impacts and have many connections with the S-LCA framework.

Obtaining the social data for these growing media in the studied countries was a constraint for this study. On the one hand, few social data, even those related to health and safety and labour rights, are recorded by companies or for specific products, and these data are usually aggregated in general sectors such as agriculture and mining. On the other hand, businesses are reluctant to respond to surveys and share information; hence, new mechanisms must be developed to foster advancements in this field, such as a kind of certification for sharing social data, another type of compensation, or increasing pressure on companies from consumers and institutions to demand transparency in value chains. Ultimately,

the social assessment of products is equally relevant as environmental assessment but less developed and harmonised. Consequently, this study aids in progress in this sense in the soilless systems sector, a key industry in feeding cities on an environmentally and socially sustainable path, by identifying a market niche to develop new growing medium mixtures for URF with the objective of seeking growing media from local wastes/by-products that are easy to manage and socially and environmentally sustainable.

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Declarations

Conflict of interest The authors declare no competing interests.

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