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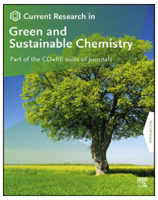

Evaluating and managing the sustainability performance of investments in green and sustainable chemistry: Development and application of an approach to assess bio-based and biodegradable plastics

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ABSTRACT

The state of the world urgently calls for a transition toward production and consumption partners that can support a carbon-neutral, circular and sustainable economy. Green and sustainable chemicals, especially, biodegradable and bio-based plastics, are key components of this transition. However, significant financial investments are required for the implementation of green and sustainable chemistry principles and the broader promotion of sustainability. In this regard, the financial sector needs sound approaches to assess the sustainability of investments. With this paper, we show an approach to assess the environmental performance of investments through key performance indicators calculated based on life cycle assessment. The approach is applied for the assessment of a fictitious investment aimed at financing bio-based and biodegradable plastic mulch films. The performance is assessed by comparing changes induced by the investment, compared with what would have happened without the investment (i.e., using fossil-based plastic mulch films). The application of the approach shows that the investment could be in general favourable from an environmental point of view, in particular for the promotion of a more circular and low-carbon economy. The approach could be easily adapted to reflect the specificities of a wide range of investments. However, it should be noted that other environmental, economic, and social aspects may need to be integrated to depict the sustainability performance of investments in a more comprehensive manner.

1. Introduction

In response to the increase in human population and affluence, global consumption of natural resources such as fossil fuels, metals, and minerals is projected to double in the next forty years [1]. The exploitation of natural resources is strictly associated with environmental degradation and climate change, which pose a threat to all ecosystems. A comprehensive framework is required to support a transformational change towards a sustainable future by minimizing environmental burdens on the planet and creating a healthier place for people and businesses. The three pillars of sustainable development, i.e., environmental protection, economic growth, and social equity, provide a solution-oriented framework for assessing the sustainability of products, organisations, and regions, based on scientific evidence and stakeholders' participation. The framework can ultimately assist decision-making processes aimed at designing and financing more sustainable projects and activities [2].

Societal progress in the three dimensions of sustainability can be pursued by adopting sustainable production and consumption practices, which significantly rely on the sound implementation of circular economy (CE) strategies [3]. CE strategies can help companies make better use of natural resources, and decrease the amount of waste generated, optimizing the economic, social, technical, and environmental costs and benefits across the life cycle of products and materials [4]. This is also reflected in the recent European Green Deal (EGD) [5], a concerted policy strategy in the EU for decoupling sustainable growth from resource depletion and achieving a climate-neutral, resource-efficient, and competitive economy, while also ensuring a just and inclusive transition.

The transition towards sustainability requires long-term planning, as

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well as the capability to channel financial resources towards sustainable long-term plans. However, a short-term economic growth perspective often prevails among investors. The EGD aims to ensure the long-term competitiveness of the EU economy while preserving social well-being and environmental quality. In this respect, is becoming more and more apparent the need of acting on the financial market to divert investments from unsustainable activities towards more sustainable ones [6].

The chemical industry plays a fundamental role in driving global economic and social development [7] although this also comes with environmental and safety concerns. To this aim, chemicals and processes should be designed to satisfy functional, safety and sustainability requirements from a life cycle perspective [8]. In line with CE principles, green chemistry (GC) offers an approach for the design of chemical products and processes aimed at maximizing resource efficiency and minimizing hazardous effects throughout the products' life cycle [9]. In chemical engineering, this can be, for example, achieved by redesigning processes to reduce the dependency on non-renewable resources and avoid the use of hazardous substances [10]. Since the integration of environmental and safety aspects in chemical systems is not sufficient to address societal challenges and promote a transition towards sustainability; recently, the concept of 'green and sustainable chemistry' (GSC) was adopted [11,12] stating that economic, social, political and technological factors must also be considered.

All of this makes the chemical industry a key sector for the sustainability transition and the smart allocation of the necessary financial resources. Within the chemical sector, plastic is nowadays regarded as one of the most crucial topics because of its widespread use and severe environmental impacts generated throughout its life cycle [13]. Nevertheless, plastics are one of the main policy areas of the new Circular Economy Action Plan (CEAP) which functions as one of the main building blocks of the EGD [14]. Hence, the search for sustainable production, consumption and end-of-life (EoL) practices opens a window of opportunities for the plastic sector to adopt GC approaches.

Bioplastics (i.e., plastics that are biodegradable and/or bio-based), and in particular biodegradable and bio-based (BB) plastics, are becoming a key component of the CE because of their potential to "close the loop" via the utilization of regrowing feedstock and their biodegradation [15,16]. Furthermore, by replacing fossil-based plastics, they can contribute to progress towards a low-carbon economy. Bioplastics offer wide application areas in many sectors such as packaging, agriculture, coating, textiles, construction and automotive [17], and, as a consequence of increased demand, they could become economically competitive with their fossil-based counterparts [18]. The focus of this study is on an agricultural application for BB plastics, namely films used for mulching. Opposing agronomical advantages, mulch films raise a debate about environmental impacts concerning, especially their EoL stage. Accordingly, the application of GSC principles to the production of BB mulch films is of great importance [16].

Significant financial investments are required for the implementation of GSC principles, and the broader promotion of sustainability. The search for alternative means of production targeting environmental conservation led to the development of the green finance (GF) concept, aiming at diverting financial stocks and flows to support the achievement of the environment- and climate-related sustainable development goals [19]. To more broadly cover environmental, social and governance (ESG) issues and risks, the sustainable finance (SF) concept has gained more attention [20]. In particular, the EU Taxonomy [21] aims to set technical screening criteria for the classification and prioritisation of sustainable activities with respect to six environmental objectives [i.e., (1) climate change mitigation, (2) climate change adaptation, (3) sustainable use and protection of water and marine resources, (4) transition to a circular economy, (5) pollution prevention and control, and (6) protection and restoration of biodiversity and ecosystems]. The taxonomy states that an environmentally sustainable activity must contribute to the substantial improvement of at least one environmental objective without harming significantly the others, i.e., the so-called do no significant harm (DNSH) principle.

The financial sector needs sound metrics and tools to assess the degree of sustainability of new SF investments. Such metrics and tools are paramount to orient private investments (as well as public financial resources) towards those companies truly involved in green and sustainable activities [22]. In this context, life cycle assessment (LCA) stands out as an important analytical tool for providing a scientific background for the design of engineering solutions for sustainability, especially with respect to the assessment of environmental impacts [23]. Likewise [24,25], mentioned LCA as a practical framework to assess the sustainability impacts of CE strategies. The outputs of the LCA methodology allow for defining *ad-hoc* management techniques, such as key performance indicators (KPIs), to enable efficient and effective business monitoring [22,26]. Considering the impact assessment methods, as outlined by Ref. [27]; LCA-based assessments can provide a coherent framework[1] to use in sustainable finance for defining a comprehensive set of impact categories and indicators. Furthermore, the LCA framework also opens up to the consideration of economic and social aspects in Life Cycle Sustainability Assessment studies [33], which is however beyond the scope of this study.

An analysis of key approaches and metrics to guide the assessment of sustainable investments has been already provided [34]. This paper aims to complement the previous study [34] by:

i. Presenting an approach that uses LCA-based KPIs for assessing the environmental sustainability of investments;
ii. Applying the approach to an illustrative case study referring to BB plastics (i.e., BB mulch films vs. their conventional fossil-based counterpart).
iii. Providing guidance for further development of the approach and its broader application to different cases of interest for GSC.

The following sections are organized as follows: Section 2 outlines the basic principles and KPIs for assessing the sustainability of investments in GSC; Section 3 describes the case study and provides modelling assumptions and data sources, along with results and discussion; Section 4 presents strengths of the approach, challenges and future lines of research; and finally, Section 5 provides concluding remarks.

2. Materials and methods

This section is dedicated to defining an approach to assess the sustainability of investments in GSC by describing: (a) basic principles; (b) LCA-based KPIs used for quantifying the environmental performance; (c) complementary aspects not conventionally addressed through LCA.

2.1. Principles

Several approaches and KPIs exist to evaluate and disclose the Environmental, Social and Governance (ESG) performance of organisations and support SF investments [34]. While the mainstream focus is at the organisation level, the approach developed in this paper aims at adopting a life cycle perspective in the assessment of the environmental performance of investments made in physically tangible GSC projects [22]. The approach presented and applied here (see Fig. 1) builds on the EU Taxonomy [21], and on the work of [22].

According to the ongoing work of the EU Taxonomy, criteria can be set based on different approaches such as (i) impact-based approach; (ii) performance in relation to the environmental target; (iii) best-in-class performance; (iv) relative improvement; (v) practice-based; (vi)

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[1] Please also see Biodiversity Footprint [28], Green financing framework [29], EU Green Bond Standard [30], Water sustainability assessment framework [31], and SDG Finance Taxonomy [32] for some examples of other comparable frameworks.

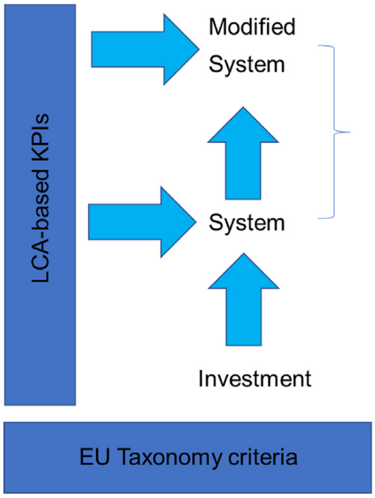


Fig. 1. Schematic representation of the approach developed in this study.

process-based; (vii) nature of the activity [6].

The presented approach quantifies the environmental performance of investments through KPIs defined and calculated based on LCA [35,36], and complemented by additional sustainability considerations. The integration of LCA-based KPIs in sustainable finance allows a holistic consideration of environmental mechanisms [37] and reinforces consistency and correspondence with the Taxonomy Regulation, which explicitly states the necessity to develop technical screening criteria throughout life cycle considerations (Art. 19).

The key concept of the approach is that an investment results in tangible changes at the system level. The KPIs considered in our approach allow for taking a picture of an analysed system before and after the investment. The performance of an investment is assessed by comparing changes induced by the investment, compared with what would have happened without the investment (i.e., the counterfactual). In this sense, the ratio between the difference, Δ ("delta") and a benchmark can give a measure of the improvement or worsening of the environmental sustainability performance [22].

For investments aimed at directly modifying existing conditions, the calculation of Δ is a straightforward process (being equal to the difference of impacts between new and existing conditions). However, a counterfactual analysis is necessary to estimate substituted activity(-ies) for investments aimed at deploying *ex-novo* projects [38].

An investment is considered to support the transition towards a more sustainable economy if at least one KPI is improved without compromising the others, i.e., if the DNSH principle of the EU Taxonomy is respected. If trade-offs occur between KPIs, so that the improvement of an indicator comes at the expense of at least another one, the investment cannot be considered supportive, unless measures are taken to modify the environmental performance of the investment. Thus, apart from supporting environmental protection, this requirement can also stimulate innovations in the direction of sustainability. The approach can also be coupled with positive change thresholds, compatible with the EU Taxonomy [22,39].

Finally, a comprehensive sustainability assessment should address all environmental, economic and social aspects of relevance for an investment category. As an operational assumption, the LCA-based KPIs used in this application have been complemented by qualitative considerations, as described later (Section 2.3).

2.2. LCA-based environmental KPIs

Several metrics can be used to quantify the environmental performance of products and services throughout their life cycles [39–42], with the Environmental Footprint (EF) seeking for LCA harmonisation in the EU [39]. These can be used to define LCA-based KPIs at the level of life cycle inventory (pressures) and life cycle impact assessment (LCIA). The latter can be differentiated into problem-oriented (midpoint) and damage-oriented (endpoint) impact indicators [43], depending on the extent of the cause-impact pathway modelling, which can target different areas of protection. The number of indicators decreases, and the uncertainty increases, while moving from pressures towards midpoints and, then, endpoints [44].

The broader the metrics considered, the more comprehensive and accurate could be the description of the consequences associated with an investment. However, this also increases the complexity of interpreting the overall results, especially in presence of trade-offs. For example, the last Recommendation of the Commission on EF [45] considers 16 categories addressing impacts on human health, ecosystem quality and natural resources.

A practical compromise between the coverage of an extensive set of environmental issues and the ease of quantifying and interpreting results was sought in the present application [22,46]. Selected KPIs are reported in Table 1, also showing how they refer to the six macro-objectives introduced in the EU Taxonomy [6].

Adhering to the LCA methodology for the quantification of KPIs means adopting a system-thinking perspective. This implies the consideration of direct pressures and impacts associated with an investment project (e.g., emissions associated with the combustion of fossil fuels for transportation), as well as system-level contributions (e.g., emissions associated with the production and distribution of fossil fuels). It follows that, preliminarily to the calculation of KPIs, it is needed to define:

i. The system boundaries (SB) of the system are affected by the investment, in terms of time horizon, value chain stages, processes and aspects covered in the assessment, modifications induced by the investment;
ii. The functional unit (FU) of the system, i.e., the calculation basis to which KPIs must be referred (e.g., 1 m^2 of mulched soil in a given period of time).

Given the counterfactual nature of the approach, only the parts of the system that change as a consequence of the investment are sufficient to be included in the assessment. For each part, it is necessary to compile elementary flows (i.e., emissions and consumption of resources) and all additional information that allows the quantification of the KPIs.

2.2.1. Circular economy

The first set of indicators aims to support the transition to a circular economy, i.e., an economy where wastes are recycled into resources, either through technological or natural ecosystem feedback mechanisms, so that the stock of resources is preserved [25].

A variety of circular economy indicators exist [47], including absolute and relative metrics of different levels of complexity as well as qualitative indicators. Parameters addressing circular design, resource efficiency and waste recovery aspects can already be found in financial applications [48]. In order to promote an absolute reduction in primary resource consumption and non-recyclable waste generation [49], this environmental area was dissected into simple KPIs, each one addressing specific circularity aspects:

- CE1. Depletion of fossil fuels [MJ].
- CE2. Depletion of non-renewable primary materials expressed as mass (CE2(a)) [kg] or abiotic depletion potential (CE2(b)) [kg Sb_{eq}].
- CE3. Production of non-recyclable waste [kg].
- CE4. Water scarcity footprint [$m^3{}_{eq}$].

Abiotic depletion potential is used as an alternative indicator for CE2 to take the scarcity of materials into account [39].

Such KPIs can be calculated through mass and energy balances involving the quantification of the following elementary flows for the

Table 1
Key Performance Indicators[a] considered in this study.

Area	KPI (unit)	Methodological references
Circular economy (including water resources)	CE1. Depletion of fossil fuels and non-regenerative biomass (MJ)	Calculation of consumption of fossil fuels and non-regenerative biomass (CE1), consumption of primary minerals, expressed as mass (CE2(a)) or abiotic depletion potential (CE2(b)), and production of non-recyclable waste (CE3), based on a life cycle approach aligned to EF [39].
	CE2. Depletion of primary minerals (kg/kg $Sb_{eq.}$)	
	CE3. Production of non-recyclable waste (kg)	
	CE4. Water scarcity footprint ($m^3_{eq.}$)	Calculation of the overall water consumed from a life cycle perspective, corrected for its scarcity according to the AWARE model, as described in EF [39]
Climate change mitigation	CC1. Net emission of GHGs (kg $CO_{2,\ eq}$)	Calculation of life cycle GHG emissions to and removals from the atmosphere, and characterisation of their overall Global Warming Potential over 100 years (GWP100) based on the IPCC model, as described in EF [39].
Environment (Pollution, biodiversity and ecosystems)	ENV1. Emission of particulate matter (disease incidence)	Calculation of life cycle emissions of pollutants of concern (e.g., PM2.5, NMVOCs, NOx, SOx, NH_3) and characterisation of the impacts associated with emission of particulate matter (UNEP (2016a) model), photochemical ozone formation (LOTOS-EUROS model), acidification (Accumulated Exceedance model), freshwater eutrophication (EUTREND model), as described in EF [39].
	ENV2. Photochemical ozone formation (kg $NMVOC_{eq}$)	
	ENV3. Acidification (mol H^+_{eq})	
	ENV4. Freshwater eutrophication (kg P_{eq})	
	ENV5. Direct land use for anthropic activities (m^2a)	Calculation (sum and/or subtraction) from the life cycle inventory [39] of (a) direct land use (green areas excluded) associated with the investment, (b) difference between direct deforestation (positive value) and direct reforestation and afforestation (negative values).
	ENV6. Direct deforestation balance (m^2)	

[a] KPIs used in this paper were defined with reference to primary environmental areas partly addressing the 6 environmental objectives of the EU Taxonomy. Because of the interconnected nature of cause-effect mechanisms, these KPIs can have an influence on more than one area.

analysed system: (a) consumption of fossil fuels, as well as non-regenerative biomass; (b) use of primary and secondary metals and non-metallic minerals; (c) generation of recyclable and non-recyclable waste.

The approach does not consider the weighting and aggregation of different indicators, since this can entail subjectivity and might mask possible trade-offs. This methodological choice means that green investments addressing this area must promote an improvement for all KPIs.

2.2.2. *Climate change*

The science around climate change distinguishes between 'climate change mitigation' and 'climate change adaptation' [50] which respectively refer to reducing anthropic sources and enhancing sinks of greenhouse gases (GHGs), and system-level adjustments to manage risks and opportunities associated with climatic change.

The only KPI selected for climate change mitigation was the 'net emission of GHGs' (CC1), measured as kg $CO_{2,\ eq.}$, and calculated based on the Global Warming Potential over 100 years, based on the IPCC model [39].

2.2.3. *Environment (pollution, biodiversity and ecosystems)*

Other areas of environmental concern are 'pollution prevention and control' and 'protection and restoration of biodiversity and ecosystems'. These are addressed by a broad set of indicators and methods (see, for example, [39,51].

The first set of KPIs was selected to consider effects associated with the emission of key pollutants such as $PM_{2.5}$, NMVOCs, NO_x, SO_x, NH_3. These include:

- ENV1. 'Emission of particulate matter (PM)' [disease incidence].
- ENV2. 'Photochemical ozone formation' [kg $NMVOC_{eq.}$].
- ENV3. 'Acidification' [mol $H+_{eq.}$].
- ENV4. 'Freshwater eutrophication' [kg $P_{eq.}$].

Such indicators also address impacts on biodiversity and ecosystem quality. In fact, biodiversity and ecosystems are affected by factors such as changes in land (and sea) use, unsustainable exploitation of resources, climate change, emission of pollutants, and invasive alien species [52].

In particular, dramatic loss of biodiversity and ecosystem services can result from deforestation activities and land uses for anthropic activities [53,54]. The need of protecting natural areas and primary forests is also highlighted, among others, in the Biodiversity Strategy of the [52]. To reflect this, the following parameters were considered separately for this area:

- ENV5. Direct land use for anthropic activities (m^2a), measuring the extension of land directly occupied for anthropic activities related to the investment project and not covered by green areas (e.g., urban areas, industrial activities).
- ENV6. Net deforestation balance (m^2), measuring the difference between the area directly deforested to sustain the investment (positive value) and the area reforested or afforested (negative value).

These parameters represent a first approximation to the treatment of biodiversity and ecosystems. Future developments may explore the use of biodiversity equivalence factors between different types of land use [51], as well as the consideration of indirect land use changes (for which there is however an inherent level of uncertainty [55]. Furthermore, other relevant aspects (e.g., pesticide emissions, soil quality) ought to be integrated to evaluate impacts on biodiversity (loss/abundance) and ecosystem services in a systemic way [39,51,56].

2.3. *Complementary sustainability considerations*

The life cycle approach presented in section 2.2 introduces KPIs based on LCA to evaluate the environmental performance of investments. However, economic and social aspects should also be considered along with environmental burdens to assess the sustainability of investments. This could also rely on life cycle approaches [33,57], although they are less mature for the social and economic dimensions of sustainability. Several initiatives, including third-party-verified ESG rating schemes and certifications, provide guidance for measuring how corporate social responsibility (CSR) principles and ESG factors are addressed by organisations [34].

To streamline this application of the approach, the focus is kept on the quantification of the environmental performance of investments. It is inherently considered that investments are economically profitable, which could be assessed through indicators such as Return on Investment (ROI). With respect to social and governance factors, it is implicitly considered in compliance with minimum safeguard criteria referred to in the EU Taxonomy Regulation [21] and requires alignment with the OECD Guidelines for Multinational Enterprises [58] and the UN Guiding Principles on Business and Human Rights [59].

Furthermore, despite "environmental relevance" being a distinctive element of ISO 14044 [36], LCA might not be sufficiently mature for (quantitatively) addressing relevant issues for bio-based products such as biodegradability concerns that lead to the diffusion of plastics in the environment, referred to as white pollution. Such issues are generally addressed through a more qualitative product-oriented discussion, i. e, they should be considered from policy, regulation and technology aspects [60].

The use of quantitative and qualitative indicators can provide complementary insights, especially for social factors [61,62]. Based on the practical and theoretical knowledge of the key stakeholders, qualitative indicators could provide a better understanding of the strengths and weaknesses (e.g., hotspots and trade-offs) of green investments [63].

3. Application of the approach to a case study

Environmental consequences associated with a fictitious investment aimed to shift from fossil-based (FB) mulch films to BB mulch films [16] are assessed through the approach described in Section 2.

3.1. Description of the case study

BB mulch films addressed in this study are a blend of bio-based and fossil-based biodegradable polymers (ecoinvent v3.7.1). Compared to conventional FB films, typically made of polyethylene (PE) and realising micro- and macro-plastics after their application, BB films can be left *in situ* since they can fully biodegrade [60].

A streamlined LCA model was built to calculate KPIs for BB mulch film and conventional FB film. The functional unit (i.e., the calculation basis) of the analysis is 1 ha (ha) of mulched soil. The model covers all relevant life cycle stages of the mulching process, as shown in Fig. 2. Raw material production, raw material transportation, processing and conversion into mulch film, distribution and application of film on the agricultural area are considered for both BB and FB mulch films. However, removal of film, transportation and End-of-Life (EoL) treatment stages are considered only for the FB mulch film. Three EoL scenarios for FB mulch films are considered, being incineration, landfill, and recycling.

Modelling assumptions and data sources used for the calculation of KPIs are reported in Table 2. Inventory data was gathered from the ecoinvent database (v3.7.1) [64] and processed with the LCA software SimaPro (v. 9.2.0.1). Where necessary, life cycle impacts were calculated through the Environmental Footprint 3.0 method (v. 1.01). This was the case for the following KPIs: CE1 (Resource use, fossils); CE2(b) (Resource use, minerals and metals); CE4 (Water use); CC1 (Climate change mitigation); ENV1 (Particulate matter); ENV2 (Photochemical ozone formation); ENV3 (Acidification); ENV4 (Eutrophication, freshwater). Other KPIs were instead calculated based on the analysis of life cycle inventory data: CE2(a) (Resource use, minerals and metals); CE3 (non-recyclable waste), ENV5 (direct land use for anthropic activities); ENV6 (direct deforestation balance).

3.2. Results

The LCA-based KPI scores obtained for the different scenarios described in Section 3 are presented in Table 3. The use of BB mulch film is compared to three EoL scenarios for FB mulch films: landfill, incineration, and recycling. To allow for better visualisation of the results, KPI scores have been normalised with respect to the highest value obtained (for each KPI) and shown in Fig. 3.

3.3. Discussion

From the analysis of results it can be observed that, with the exception of ENV5 and ENV6, the environmental performance of the BB mulch film is superior to that of the FB mulch film, for any other KPI and scenario considered in this application. The BB mulch films appear as a better alternative especially when FB mulch films are disposed of in a landfill or incinerated (worst cases). In particular, the use of BB mulch film can significantly avoid the production of non-recyclable waste (CE3) and allow for saving resources (CE1, CE2, CE4), while at the same time promoting a reduction of GHG emissions (CC1) and other polluting

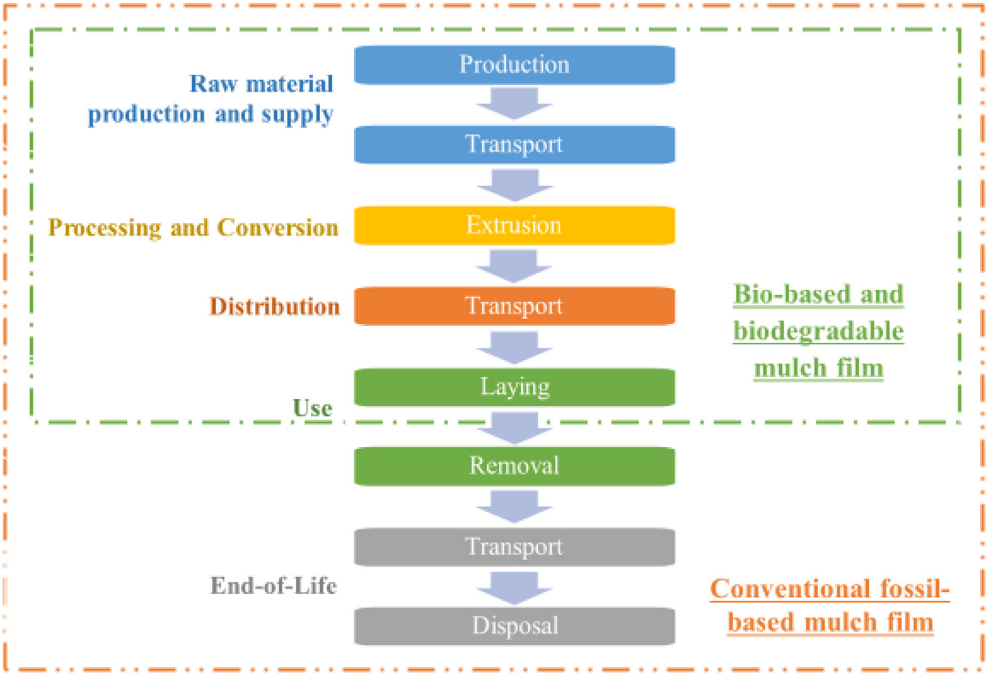


Fig. 2. Life cycle stages and system boundaries considered for BB and FB mulch films.

Table 2
Assumptions and life cycle inventory (LCI) datasets used for modelling.

Stage	FB mulch film (conventional fossil-based mulch film)	BB mulch film (bio-based and biodegradable mulch film)
Raw material production and supply		
Production	Polyethylene (PE) is used for the production of FB mulch film. LCI dataset: Polyethylene, low density, granulate {RER}| production | Cut-off, S (ecoinvent v3.7.1). 0.00145 kg of non-recyclable waste is estimated for the production of 1 kg of polymer granulate.	A polyester-complexed starch biopolymer is used for the production of BB mulch film. LCI dataset: Polyester-complexed starch biopolymer {RER}| production | Cut-off, S (ecoinvent v3.7.1). 0.0119 kg of non-recyclable waste is estimated for the production of 1 kg of granulate of biopolymer.
Transport	A distance of 100 km is estimated for raw materials transported to the production facility. LCI dataset: Transport, freight, lorry >32 metric ton, EURO6 {RER}| Cut-off, S (ecoinvent v3.7.1)	A distance of 100 km is estimated for raw materials transported to the production facility. LCI dataset: Transport, freight, lorry >32 metric ton, EURO6 {RER}| Cut-off, S (ecoinvent v3.7.1)
Processing and conversion	100% conversion yield is assumed [60]. LCI dataset: Extrusion, plastic film {RER}| Cut-off, S (ecoinvent v3.7.1). 0.0241 kg of non-recyclable waste is estimated for the extrusion of 1 kg of polymer granulate.	The same process and conversion yield are assumed for BB mulch films [60].
Distribution	A distance of 500 km is estimated from the production facility to the application area. LCI dataset: Transport, freight, lorry >32 metric ton, EURO6 {RER}| Cut-off, S (ecoinvent v3.7.1)	A distance of 500 km is estimated from the production facility to the application area. LCI dataset: Transport, freight, lorry >32 metric ton, EURO6 {RER}| Cut-off, S (ecoinvent v3.7.1)
Use[a]	288 kg of FB mulch film is needed to cover 1 ha of area [60]. Diesel consumption of 20 + 20 L/ha is assumed for laying and removal of mulch film.	96 kg of BB mulch film is needed to cover 1 ha of area [60]. Diesel consumption of 20 L/ha is assumed for laying the mulch film.
Laying	LCI dataset: Diesel, burned in agricultural machinery {GLO}| Cut-off, S (ecoinvent v3.7.1)	LCI dataset: Diesel, burned in agricultural machinery {GLO}| Cut-off, S (ecoinvent v3.7.1)
Removal	LCI dataset: Diesel, burned in agricultural machinery {GLO}| Cut-off, S (ecoinvent v3.7.1)	not applicable
EoL		Complete biodegradation considered, not affecting soil quality
Transport	A distance of 50 km is assumed from the application area to the EoL facility. LCI dataset: Transport, freight, lorry >32 metric ton, EURO6 {RER}| Cut-off, S (ecoinvent v3.7.1)	not applicable
Landfill	LCI dataset: Waste polyethylene {RoW}| treatment of waste polyethylene, sanitary landfill | Cut-off, S (ecoinvent v3.7.1). Mulch film waste is estimated as fully landfilled.	not applicable
Incineration	LCI dataset: Waste polyethylene {RoW}| treatment of waste polyethylene, municipal incineration | Cut-off, S (ecoinvent v3.7.1). Mulch film waste is estimated as fully incinerated.	not applicable
Recycling	LCI dataset: Polyethylene, high density, granulate, recycled {Europe without Switzerland}| Cut-off, S (ecoinvent v3.7.1)[b]. 0.07067 kg of non-recyclable waste (0.0585 kg of plastic waste) is estimated during the recycling of 1 kg of plastic.	not applicable

[a] The thickness of mulch films is representative of Italy, in Europe the thickness of PE film is generally lower.

[b] High-density PE was used instead of low-density PE because of the lack of inventory data.

emissions (ENV1, ENV2, ENV3).

To provide a clearer understanding of the most influential life cycle stages and processes on environmental performance, a contribution analysis for each scenario was also performed (however, not shown here). In general, the largest contributions to the KPIs are associated with the supply and processing of materials for the scenario involving the use of the FB mulch film and disposal into landfills. When incineration is the EoL treatment, CC1 increases considerably and the EoL stage becomes the largest contributor to this KPI. A shift to BB mulch film is generally beneficial, as described in the previous section, mainly associated with lower needs in terms of the film (96 kg of BB mulch film vs. 288 kg of FB mulch film) and processes associated with their production. Similarly, recycling can allow improving the performance of the FB mulch film by saving raw materials. The potential recycling of FB mulch film can partly help reduce the gap with the BB mulch film. However, in interpreting the relatively better performance of the recycled FB mulch films it should be considered that the estimation considered a very high rate of recycling efficiency (about 94%), no downgrading of quality, and the use of high-density PE process instead of low-density PE (due to the lack of inventory data).

Delta scores have been calculated by comparing the BB mulch film with different EoL scenarios for FB films, as reported in Table 4. Compared to the scenarios involving the use of FB mulch film followed by landfilling or incineration, the use of the BB mulch film would allow for a drastic reduction of non-recyclable waste production (CE3 decreases by 97%), water use (CE4 decreases by 89%), and GHG emissions (CC1 decreases by 71–85%).

Improvements are significant also in other KPIs. Depletion of fossil fuels (CE1) decreases by 76%, while the depletion of primary minerals decreased by 60–64% when measured as mass (CE2(a)), and by 47% when measured as abiotic depletion potential (CE2(b)). It must be observed, that CE2(a) sums all elementary flows of the life cycle inventory addressing metals and other mineral ores (e.g., construction materials) independently from their availability. Differently from CE2(a), CE2(b) takes the scarcity of such elementary flows into account, generally addressing metals. Although using different units, both CE2(a) and CE2(b) refer to mass flows. The different order of magnitude between CE2(a) and CE2(b), with CE2(a) being five orders larger than CE2(b), depends on the presence of a large amount of non-metallic materials (e.g., gravel, gangue, calcite) in the life cycle inventory, possibly associated with infrastructure. Moreover, the calculation of CE2(a) and CE2(b) is particularly affected by the economic allocation currently adopted in background data for mining processes (which is being revised in the database considered for this application). In particular, this scenario almost achieves the same performance as the BB mulch film for CE2(b). Finally, regarding the production of non-recyclable waste (CE3), the shift to BB mulch films allows for drastically reducing waste flows. However, it is worth mentioning that the evaluation of this CE3 is not straightforward with current tools since scores are significantly affected by how datasets are defined and allocation procedures (as per materials). Furthermore, in the case of waste flows it is necessary to check individually datasets and related processes to make an estimation of the associated waste flows.

The impact associated with the emission of particulate matter (ENV1) is halved, and other emissions causing photochemical ozone formation (ENV2), acidification (ENV3) and eutrophication (ENV4) are also reduced significantly (ENV2 by 67–68%, ENV3 by 47–48%, ENV4 by 60%). Some trade-offs are instead observable for ENV5 and ENV6. The nature of the biomass feedstock used for the BB mulch film requires a larger amount of land (see ENV5 when the use phase is excluded). However, this increased demand for land can be considered negligible, compared to the 1-ha land occupied during the use phase (see ENV5

Table 3
Absolute scores of the KPI for the evaluated scenarios*.

KPI	Unit	BB	FB, landfill	FB, incineration	FB, recycling
CE1. Depletion of fossil fuels and non-regenerative biomass	MJ	**6.07E+03**	**2.57E+04**	**2.57E+04**	8.15E+03
CE2(a). Depletion of primary minerals – mass based	kg	**1.68E+02**	**4.61E+02**	4.22E+02	2.78E+02
CE2(b). Depletion of primary minerals – abiotic depletion potential	kg Sb_{eq}	**3.52E-03**	6.61E-03	**6.62E-03**	3.87E-03
CE3. Production of non-recyclable waste	kg	**3.46E+00**	**2.96E+02**	**2.96E+02**	2.74E+01
CE4. Water use	$m^3_{eq.}$	**1.07E+02**	**9.35E+02**	9.33E+02	3.23E+02
CC1. Climate change	kg CO_{2eq}	**2.72E+02**	9.53E+02	**1.78E+03**	5.33E+02
ENV1. Particulate matter	disease inc.	**1.40E-05**	**2.85E-05**	2.84E-05	1.95E-05
ENV2. Photochemical ozone formation	kg $NMVOC_{eq}$	**1.51E+00**	4.64E+00	**4.74E+00**	2.65E+00
ENV3. Acidification	mol $H+_{eq}$	**2.26E+00**	4.26E+00	**4.35E+00**	2.84E+00
ENV4. Eutrophication, freshwater	kg P_{eq}	**1.00E-01**	2.50E-01	**2.51E-01**	1.91E-01
ENV5. Direct land use for anthropic activities, use phase included(/excluded)	m^2a (m^2a)	1.00E+04 **(3.07E+01)**	1.00E+04 (1.56E+01)	1.00E+04 **(1.45E+01)**	1.00E+04 (1.83E+01)
ENV6. Direct deforestation balance (% of land use)	m^2 (%)	**7.89E-02** **(0.31%)**	**6.31E-02** (0.16%)	7.65E-02 **(0.15%)**	7.84E-02 (0.18%)

** The lowest values obtained for each KPI are shown in bold and green, the greatest values in bold and red.*

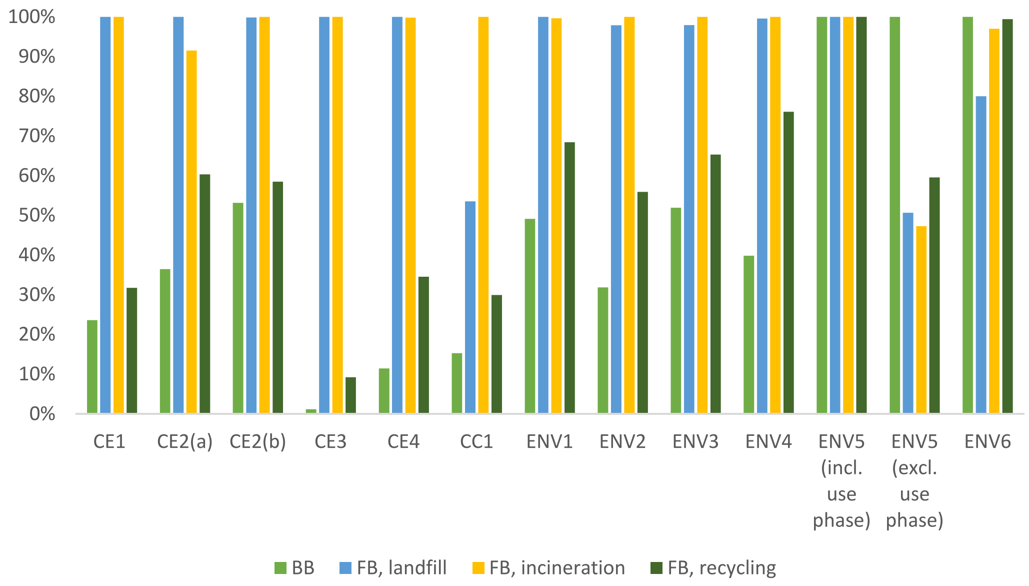


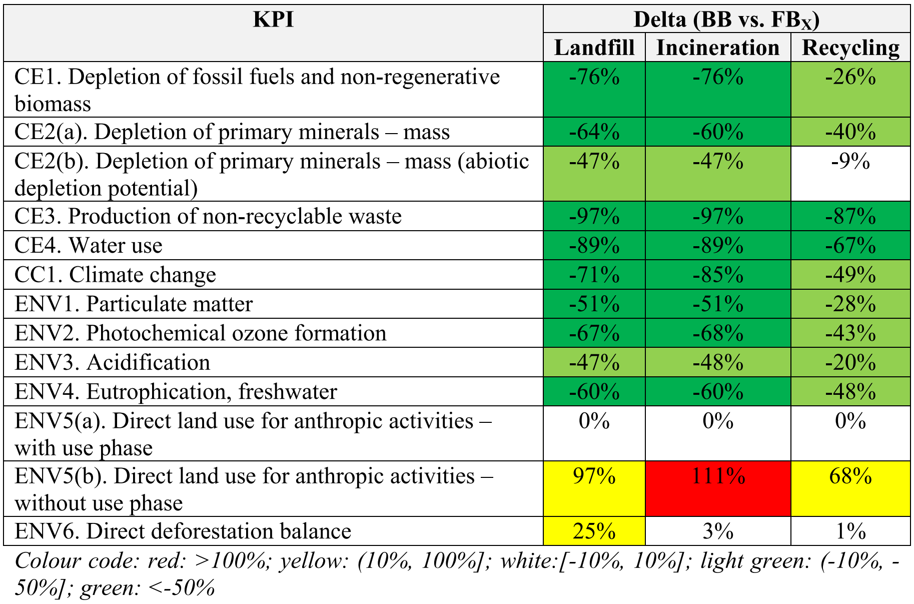
Fig. 3. Relative scores of the KPI for the evaluated scenarios.

when the use phase is included). Similarly, the BB mulch film has the maximum score for ENV6, although all scenarios yielded similar positive scores, meaning that all scenarios to a certain extent cause deforestation. However, also, in this case, the degree of deforestation can be considered negligible, if compared with the land need during the use phase, and possibly associated with background processes in the life cycle inventory rather than with primary processes and data.

KPIs selected for this case studies focus on a limited number of (relevant) environmental issues. In particular, only direct land use changes were considered in this application. However, also indirect land use change (iLUC) may be important for bio-based materials. iLUC comprises the cascading changes in land use outside a biomass production area that are nonetheless induced by the newly established bioeconomy activity (i.e., the biomass production for mulch film in this case). For example, crops previously produced in the biomass production area are being produced elsewhere to meet demand, resulting in

Table 4

Delta scores comparing the BB mulch film with different EoL scenarios for FB films.



KPI	Delta (BB vs. FB_X)		
	Landfill	Incineration	Recycling
CE1. Depletion of fossil fuels and non-regenerative biomass	-76%	-76%	-26%
CE2(a). Depletion of primary minerals – mass	-64%	-60%	-40%
CE2(b). Depletion of primary minerals – mass (abiotic depletion potential)	-47%	-47%	-9%
CE3. Production of non-recyclable waste	-97%	-97%	-87%
CE4. Water use	-89%	-89%	-67%
CC1. Climate change	-71%	-85%	-49%
ENV1. Particulate matter	-51%	-51%	-28%
ENV2. Photochemical ozone formation	-67%	-68%	-43%
ENV3. Acidification	-47%	-48%	-20%
ENV4. Eutrophication, freshwater	-60%	-60%	-48%
ENV5(a). Direct land use for anthropic activities – with use phase	0%	0%	0%
ENV5(b). Direct land use for anthropic activities – without use phase	97%	111%	68%
ENV6. Direct deforestation balance	25%	3%	1%

Colour code: red: >100%; yellow: (10%, 100%]; white:[-10%, 10%]; light green: (-10%, -50%]; green: <-50%

additional land being converted to agricultural land. Neither conventional LCI databases nor the LCA framework offers a standardised way to satisfactorily handle this problem yet. However, different evaluation models for assessing iLUC in LCA have started to emerge [65].

4. Strengths, challenges and future work

The approach proposed here can be useful for a wide range of investments involving different types of applications, due to its systemic nature and the possibility of adapting it by selecting relevant indicators. Investors, and industrial stakeholders that are transitioning their *modus operandi* from a linear economic model to a circular one, are the main target audience of the approach. For financial applications, the approach provides a ground to identify the performance of novel products and services against their conventional counterparts, which can support the green funding of environmentally and inherently socially conscious business models. For example [37], affirms that LCA-based metrics can be integrated into green bonds to evaluate the sustainability performance of renewable energy systems and finance them. From a broader perspective, the presented approach could also support policy-makers in comprehensively evaluating whether and how large and small investment flows are contributing to protecting and/or improving key environmental areas, as recently defined by the EU Taxonomy.

Despite its potential strengths, the approach comes with some challenges and potential limitations inherently related to optimizing rigorousness and/or applicability of LCA with respect to, e.g., comprehensiveness and complexity of life cycle data and their modelling, coverage of a manageable number of relevant indicators and dealing with trade-offs.

A more comprehensive life cycle sustainability assessment should be envisaged in future that seeks the integration of environmental, economic and social metrics [33,57]. However, it should be also observed that the broader the KPI considered, the more comprehensive the description of the impacts of a product but also its complexity in obtaining and interpreting results (e.g., because of trade-offs). Materiality assessment can have a key role to identify the key issues to consider for a certain application [66]. Qualitative indicators could be also developed jointly with stakeholders to boost communication, societal engagement and participation [61]. Qualitative indicators, for example, can provide knowledge about how different actors perceive green investments and how to prioritise financial resources for the "right" product based on the identification of critical issues and the analysis of results and trade-offs [67]. However, it should be noted that combining qualitative and quantitative approaches can be challenging [61] as they would most likely complicate the evaluation process.

With respect to the management of trade-offs, alternative ways to handle them could include the possibility of defining margins of tolerance for each delta, the aggregation of KPIs through normalisation and weighting procedures [35,36], or the use of scoring system approaches [68]. However, elements of subjectivity are implicitly acknowledged in such cases. These issues become particularly sensitive in light of the EU Taxonomy principle that an environmentally sustainable activity must contribute to the substantial improvement of at least one environmental objective (e.g., climate change mitigation) without harming significantly the others (e.g., pollution prevention and control).

Furthermore, third-party verification, documentation and reporting are required to improve the reliability, comparability, and verifiability of inventory data, assumptions, and results [69,70] as well as the consistency of the adopted LCA approach. Without these elements described above, results can only be considered indicative.

5. Conclusions

This study provides a test bench for an approach developed to assess the environmental performance of investments in green and sustainable (GSC) chemistry through the use of LCA-based KPIs. The approach was applied to the analysis of a fictitious investment aimed to introduce a product, i.e., mulch film, made of bio-based and biodegradable plastics. The results show that investments promoting the use of bio-based mulch films, compared to their fossil-based conventional alternatives, could be in general favourable from an environmental point of view, in particular for supporting the transition towards a more circular and low-carbon economy. The approach offers a potentially useful tool to comprehensively evaluate the performance of bio-based alternatives, as well as other products/services, and attract sustainable finance investors. However, further developments are needed to overcome some methodological drawbacks, in particular relating to the need of expanding the scope to a more holistic sustainability assessment addressing relevant environmental, economic and social issues.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

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