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Research Paper

Environmental and economic assessment of biodegradable and compostable alternatives for plastic materials in greenhouses

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ABSTRACT

Plastics and other materials commonly used in horticulture for plant support (e.g. raffia) and soil protection (e.g. mulching film) pose a challenge to achieving a circular economy. These materials contaminate plant residues, hampering their direct reuse due to the need for separation and cleaning. As a result, contaminated plant residues is often landfilled or incinerated. This study investigates the replacement of conventional plastic raffia and mulching film with biodegradable and compostable alternatives. Polypropylene raffia is compared with a biodegradable viscose polymer and compostable jute fibre, while polyethylene mulching film is compared with a biodegradable polylactic acid film. Conventional and novel alternatives are compared economically using Life-Cycle Costing and environmentally using Life-Cycle Assessment. The economic assessment is based on case studies with two horticultural companies in Almeria (south-eastern Spain), while the environmental analysis uses data from the Ecoinvent database. The use of biodegradable and compostable alternatives for raffia and mulching film proved to be 49% more expensive than conventional options. However, when conventional plastic waste is incinerated rather than landfilled, biodegradable and compostable alternatives have a lower carbon footprint. Although biodegradable and compostable options can be more expensive and have higher impacts in certain situations, proper waste management can lead to environmental benefits. With optimisation and incentives, these alternative options support the transition of horticulture to a sustainable circular economy.

1. Introduction

Greenhouse horticulture has long been one of the most effective and widespread techniques for the production of various vegetables. While horticultural products account for 14 % of the value of EU agricultural production, their cultivation occupies only about 1.8 % of the total EU agricultural area (Eurostat, 2016). This is largely due to the fact that greenhouses can achieve 10–15 times higher production capacities than open-field farming (European Commission, 2019). However, the accumulation of plastic waste from agricultural practices, particularly greenhouses, is a growing global concern. As such, several studies have mapped the disposal of agricultural plastic waste at continental (e.g. Briassoulis et al., 2013), national (e.g. Blanco et al., 2018; Zhang et al., 2020) and regional levels (e.g. Batista et al., 2022; Castillo-Díaz et al., 2021).

Plastics for plant support and soil protection are widely used in greenhouses worldwide to improve horticultural productivity (Scarascia-Mugnozza et al., 2011). Plant support or staking systems in greenhouses typically consist of polymeric ropes suspended from wires attached horizontally to the greenhouse structure. These ropes are often called raffia. Raffia is usually made of low-density polyethylene (LDPE) and polypropylene (PP). Another part of the plant support system is the plant staking clips, usually made of LDPE, which attach the plants to the raffia. Regarding soil protection systems, the most relevant are plastic

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mulching films. These are plastic sheets placed on the soil surface to prevent water evaporation, avoid large fluctuations in soil temperature between day and night, and inhibit the proliferation of weeds.

Unfortunately, most plastics used in agriculture persist in the environment for many years due to their non-biodegradable nature (Kyrikou and Briassoulis, 2007). This plastic accumulation contributes to soil degradation, landscape blight and microplastic pollution (Steinmetz et al., 2016; Qi et al., 2020). To address this problem, biodegradable and compostable plastics made from materials such as polylactic acid (PLA), cellulose and starch have been proposed as alternatives. Starch-based biodegradable plastics are proving effective, although they currently cost three to four times more than polyethylene; their advantage is that they degrade into non-toxic compounds (Kasirajan and Ngouajio, 2012). Duque-Acevedo et al. (2020) provided a very comprehensive review of the research that has already been carried out on the use of alternative materials for raffia and mulching film, focusing on the economic, physical and technical feasibility of replacement. The use of such alternative materials for plant support and soil protection may allow greenhouse plastic waste to be composted rather than landfilled.

However, the economic and environmental sustainability of biodegradable and compostable alternatives needs to be rigorously assessed before widespread adoption. Scarascia-Mugnozza et al. (2011) found that the feasibility of using bio-based mulching films depends on its economic cost. Song et al. (2009) found that plastic waste that was designed to be degradable may concentrate toxic materials more effectively than non-degradable plastic waste, due to its higher surface area. Economic and life-cycle assessments are needed to determine if biodegradable and compostable mulching films are truly sustainable options (Steinmetz et al., 2016).

Therefore, holistic assessments, that include environmental impacts and economic costs, are needed to guide the adoption of sustainable alternatives in horticulture. This study presents an integrated economic and environmental analysis of biodegradable and compostable raffia and compostable mulching film in greenhouses and compares them with conventional options. Life-Cycle Cost (LCC) and Life-Cycle Assessment (LCA) methodologies are used to evaluate these options in economic and environmental terms. The models use case study data from two greenhouse companies in south-eastern Spain for the cost analysis and data from the Ecoinvent database for the environmental analysis. Section 2 introduces the context of the case study, Section 3 describes the methodology and data collected, and Section 4 presents the results.

2. Context of the case study

Spain is the largest producer of horticultural products within the EU, accounting for 17.5 % of total production (European Commission, 2021). Within Spain, horticultural land is highly concentrated in the south, particularly in the provinces of Granada and Almeria. The "Campo de Dalias" in the province of Almeria is the largest exponent of greenhouse horticulture in Europe (Mendoza-Fernández et al., 2021). It is therefore an excellent place to conduct case studies on the sustainability opportunities and challenges of intensive greenhouse horticulture.

Before the intensification of horticulture in the 1960 s, Almeria was an underdeveloped region within Spain, ranking as the penultimate province in terms of GDP per capita (INE, 2019). Since then, innovations such as technologically advanced irrigation systems, thermal plastics and soilless crops have allowed the area covered by greenhouses to increase every year, leading to the current very high concentration (Garcia-Caparros et al., 2017). Intensive agriculture has led to the economic development of Almeria, which now ranks in the middle of the Spanish provinces in terms of GDP per capita (INE, 2019). Currently, agriculture and related sectors account for around 40 % of GDP in the province of Almeria (Castro et al., 2019) and employ 74,000 people (Analistas Económicos de Andalucía, 2017). The physical area under plastic in the province of Almeria is 32,827 ha (Junta de Andalucía, 2022), with good climatic conditions allowing more than one production cycle per year (Ministerio de Agricultura, Pesca y Alimentación. Gobierno de España, 2021). This translates into a total production of almost 3.5 million tonnes in the 2021/2022 season, more than a fifth of Spain's annual agricultural production, and a production value at source of almost 2.8 billion euros (Analistas Económicos de Andalucía, 2017; Observatorio de Precios y Mercados, 2022).

The special environmental conditions of the semi-arid coastal region of Almeria have made it one of the world's top 25 biodiversity hotspots (Myers et al., 2000). Favourable natural factors include warm climatic conditions, mild seasons due to the regulating effect of the Mediterranean Sea, and a high number of sunshine hours (between 3200 and 3500 h per year for the Campo de Dalias) (Aznar-Sanchez & Galdeano Gómez, 2011). However, the water scarcity of the area had long made it impossible to take advantage of these environmental conditions for intensive agriculture. Since the 1970 s, however, the use of sophisticated groundwater-fed irrigation systems has allowed these particular environmental conditions to be exploited to form the agro-industrial complex that the region is today (Aznar-Sanchez & Galdeano Gómez, 2011). This has led to an immense loss of biodiversity, as the habitats of numerous plant species have been fragmented or modified (Rodríguez et al., 2018a; Rodríguez et al., 2018b; Rodríguez et al., 2019). Another environmental challenge is the decline in groundwater quantity and quality. This is mainly caused by the overexploitation of aquifers, which lowers the ground water level, and its replacement by intruding marine waters, which increases the salinity of the water (Quintas-Soriano, 2014). This challenge is compounded by the extensive use of nitrogen-based fertilisers, which cause nitrate contamination of groundwater (Srivastav, 2020; Thompson et al., 2007), leading to increasing efforts to reduce such contamination.

One of the economic strengths of intensive horticulture in Almeria is that wealth is relatively well distributed, with 95 % of farms remaining family owned. Sales and coordination are mainly organised through cooperatives, which has further strengthened the role of smaller farms and discouraged takeovers by larger companies. As a result, farms tend to be small, with an average of only five employees. Organisation into small farms and cooperatives has ensured that economic growth has brought social benefits through the equal distribution of income, but other social problems have arisen. The horticulture sector requires both skilled labour to build and maintain highly technical greenhouses and their irrigation systems, and unskilled labour to carry out routine physical tasks (Castro et al., 2019). While both tasks were originally carried out by members of the farm's owning family, since the 1990 s the latter has increasingly been carried out by externally hired workers, often immigrants (García-García et al., 2016). These often non-contractual labour arrangements tend to exclude the hired unskilled workers from the economic and social benefits of the sector by paying them low wages and denying them access to social security systems (Pumares & Jolivet, 2014). Currently, 64 % of socially insured workers are foreigners, more than half of whom are Moroccan (Servicio de Estudios Agroalimentarios de Cajamar, 2021). It is suspected that the foreign share of uninsured workers is even higher, as immigrants often lack the documentation to enter into an official work contract (Boza Martínez & Pérez Medina, 2019). This has led to the economic and social marginalisation of these groups, a major social problem that is likely to worsen with the impending automation of tasks traditionally performed by low-skilled workers (Castro et al., 2019).

Another important challenge in the greenhouse horticulture sector is the generation of large amounts of both organic residues and inorganic waste. The abundance of small farms complicates the issue of waste management, as regulations must take into account the financial and technical constraints of smaller producers (Sayadi-Gmada et al., 2019). The total amount of waste in this sector in Almeria is estimated at around 1.5 million tonnes per year, of which 94 % is organic plant and soil residues and 6 % is mostly plastic structures of the greenhouses and disinfection infrastructure, as well as metal structures (Sayadi-Gmada et al., 2019). While the metal structures are largely recycled due to their intrinsic value, circular systems for recycling most of the plastics are not common. In particular, the plastic plant support and protection systems pose a problem as they are mixed with the organic plant and soil residues, making it difficult to use this waste.

3. Methodology

This section describes the alternatives and scenarios modelled, the functional unit, the system boundaries, the data sources and the main assumptions made.

3.1. Alternatives and scenarios

Two alternatives to conventional raffia are analysed, one biodegradable and one compostable. Conventional raffia is made from polypropylene. The biodegradable raffia alternative is a viscose biopolymer coated with cellulose, while the compostable alternative is made from jute plant fibre. For the plastic mulching film, a fully compostable alternative is compared to the conventional option. The conventional mulching film is made from LDPE, while the biodegradable alternative is mainly made from polylactic acid (PLA).

This means that there are five different alternatives to consider in terms of production, purchase and transport: three for the raffia and two for the mulching film (Fig. 1). However, for separation and waste management, only the difference between conventional and composting scenarios is considered. This means that the two conventional alternatives for the raffia and the mulching film make up the 'conventional separation' scenario, while the biodegradable and compostable alternatives for the raffia together with the compostable alternative for the mulching film make up the 'composting' scenario.

3.2. Functional unit

The functional unit for this study is set as 1 ha of greenhouse area used for the production of long-cycle tomatoes. The tomatoes grown in greenhouses in Almeria in the 2021/2022 season amounted to 716,739 tonnes in an area of 8187 ha, with a yield of 87.55 tonnes ha^{-1} (Observatorio de Precios y Mercados, 2022), which is used as a reference for this study. Therefore, the functional unit area corresponds to a productivity of 87.55 tonnes of tomatoes per year. All the economic costs and environmental impacts presented in this article are based on this functional unit of 1 ha of greenhouse area.

3.3. System boundaries

The system boundaries for the assessment are defined using a cradle-to-grave approach. This includes not only the impact of the production and supply of the new agricultural material, but also its disposal, in particular how it may affect the disposal of the organic residues with which it is mixed. This approach is justified by the fact that the purpose of replacing conventional equipment with biodegradable alternatives is to improve the management of plant residues. Fig. 2 gives an overview of the different steps in the life cycle of raffia and mulching film and how they are assessed for their economic and environmental impacts.

It should be noted that none of the alternatives showed significant differences in their effect on plant growth or application method. Therefore, the "use" block in the diagram above is assumed to be the same for all alternatives, which allows the greenhouse area or the quantity of tomatoes produced to be used interchangeably as a functional unit. During the "use" of the raffia and mulching film, the main organic waste is produced in the form of plant residues. The production of these plant residues is not considered, as it is the same for all alternatives. However, their management as waste affects the waste management of the different alternatives used and is therefore included in the assessment. It has been assumed that the biodegradable and compostable alternatives allow the plant residues to be used "on site", eliminating the need for transport to waste management facilities. However, some farmers may prefer to manage this waste collectively, in which case some waste transport would occur.

3.4. Data sources and assumptions

The economic and technical data were collected from two case studies of two companies operating in the provinces of Almeria and Granada, in south-eastern Spain. Both companies are organised as cooperatives between different individual farmers. They each have a turnover of around €50 million year-1 and have their own research and development greenhouses where the different alternatives were tested. One company tested the different types of raffia, while the other tested different types of mulching film. The fact that two different companies carried out the trials was advantageous as it allowed the waste produced by each to be compared, giving a comprehensive assessment.

Environmental data for carbon footprint were taken from the life-cycle inventory database Ecoinvent version 3 (Wernet et al., 2016). Data for the other environmental impact categories were taken from Ecoinvent version 2 (Frischknecht et al., 2005). The environmental impact categories considered were acidification potential, eutrophication potential, ozone depletion potential, photochemical smog potential and human toxicity potential. All environmental impacts were modelled in the CCaLC2 software developed by the University of Manchester (Azapagic, 2015). CCaLC2 follows the internationally accepted life cycle methodology defined by ISO 14040 and PAS 2050 using the CML-IA methodology (BSI, 2011).

The biodegradable raffia alternative was assumed to be two-thirds viscose and one-third virgin cellulose. The raw material emissions for viscose are based on the 'viscose asia' process, which includes separate processing steps for the pulp mill and viscose fibre production. Globally, this process dominates over the 'viscose austria' process, which combines these two steps into one, thereby reducing emissions (Shen & Patell, 2010; Water Footprint Network, 2017).

Raw material data for all alternatives were taken from the 'at plant' inventory in Ecoinvent. The only exception is jute fibre, which is taken from the 'at farm' inventory. This is because the carbon footprint that Ecoinvent assigns to jute 'at plant' is much higher than that assigned to jute 'at farm' (3.07 kg CO_2-eq/kg jute vs. 0.614 kg CO_2-eq/kg jute). The literature appears to be much more consistent with the 'at farm' value (Singh et al., 2018; Rahman & Bala, 2009), and transport does not appear to account for enough emissions to justify the 'at plant' values.

For energy consumption of extrusion and manufacturing, Benavides

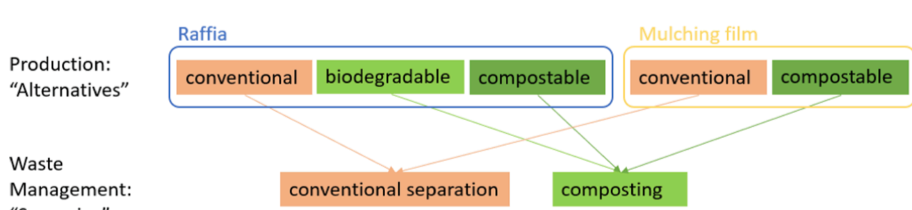

Fig. 1. Production and waste management alternatives and scenarios.

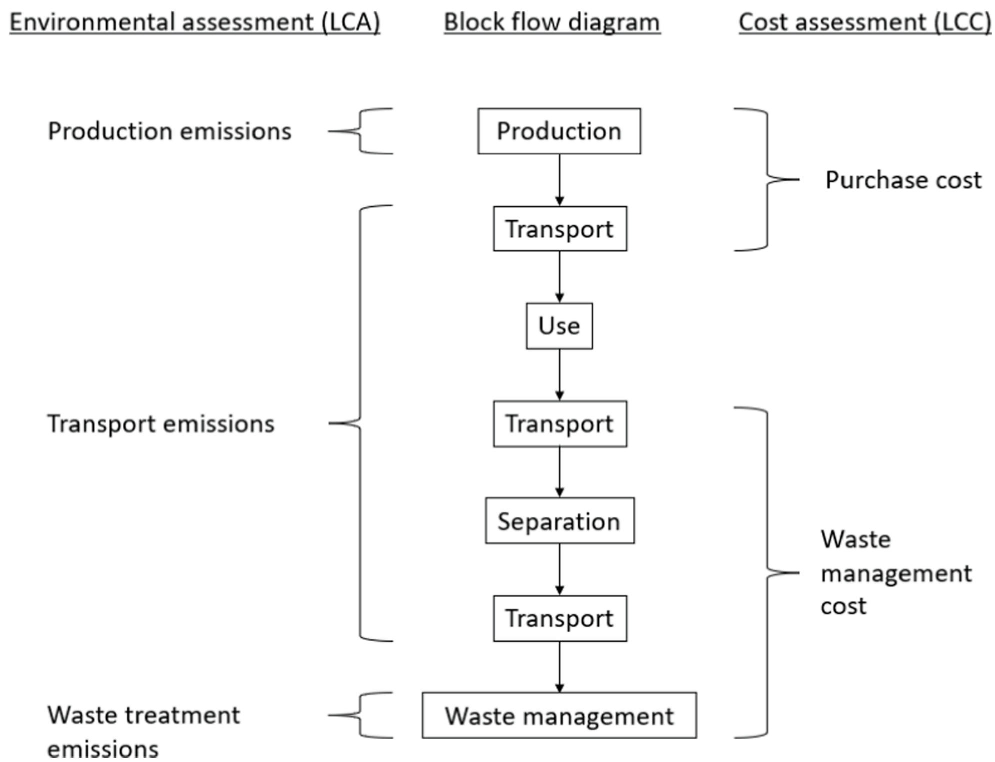

Fig. 2. Block flow diagram for the life cycle of raffia and mulching film.

et al. (2020) assumed that it is the same for all polymers at 2 MJ kg^{-1} (Keolian et al., 2012). This value is assumed for this study as similar data can be found for the polymers not covered by Benavides et al. (2020), such as PP (Funaki et al., 2010; Abeykoon et al., 2021) and viscose (Shen et al., 2010). The energy to process the plastics into twine and mulching film is supplied entirely by electricity and the electricity mix is assumed to be the average EU electricity mix. It is very likely that most of the plastics used are of EU origin or that their production uses an electricity mix with a similar carbon intensity. While both conventional (PP and LDPE) and bio-based polymers (viscose and PLA) require energy-intensive extrusion, there is no such extrusion/processing step for jute. Therefore, there is no energy to consider for 'production'. The energy for processing the jute fibre into twine is assumed to be negligible as it consists only of mechanical energy for the spinning step (Reza & Faisal-E-Alam, 2022).

With Asia accounting for 99.7 % of global jute production (FAOSTAT, 2020), an additional 13,000 km of transoceanic shipping was considered for this alternative. Pre-use transport for each of the alternatives is assumed to be 800 km in a 32-t truck (Shen et al., 2010). This is also considered for the jute alternative as it is likely that commercial functions would require further transport after shipping from Asia to Europe.

It is also assumed that the different alternatives do not differ in their impact during greenhouse use. While the case studies confirm this assumption for the mulching film, the economic impact appears to be different for the raffia because of a different risk of breakage leading to a reduction in tomato production. However, this economic risk is manageable (López-Marín et al., 2022) and its inclusion is beyond the scope of this study. Other studies confirm the similar properties of biodegradable and compostable plastics compared to conventional plastics used in agriculture (e.g. Guerrini et al., 2017; López-Marín et al., 2011).

Waste management of conventional raffia is a major cost driver as the waste is not biodegradable and cannot be composted. Furthermore, composting raffia with plant debris is impractical as raffia complicates the mixing and turning of plant debris and can damage equipment such as grinders. In addition, if raffia is separated from plant residues, it still contains a significant amount of organic matter, making it difficult to recycle.

It is assumed that all farmers deposit conventional waste together with plant residues at an authorised waste processor, who then composts the plant residues and separates the conventional plastic from the compost, which is sent to landfill. This is mostly the case in the olive sector, where 80 % of farmers follow this practice, while the remaining 20 % practice self-management, meaning that they compost and separate themselves (AGAPA, 2015). However, due to the increasing costs of full waste management, quantified below, some farmers currently simply store the waste. However, our economic analysis includes the full costs of waste management. For the biodegradable alternatives, farmers are assumed to self-manage as they no longer have to pay for collection and separation.

While the case study presented did not estimate the cost of collection and separation of used raffia from plant residues by the official collector, a recent study found this cost to be €392 per hectare (Duque-Acevedo et al., 2020), which is the value used in this study. The cost of managing the conventional mulching film was estimated from discussions with experts to be €70 per tonne of mulching film. To this should be added the cost of transport from the farm to the composting facility and from the composting facility to the landfill, as well as the cost of landfill management. It is assumed that all non-biodegradable waste is sent to a sanitary landfill (to an authorised operator) and not to a recycling or incineration plant. Raffia and mulching film are not recycled and it seems unusual for this type of waste to be sent to an incineration plant.

The total transport distance for waste management was assumed to be 15 km in a 7.5-t truck (Torrellas et al., 2012). We estimated that the cost is €75 per trip, regardless of the load volume, and that the truck collects 480 kg of mulching and 72 kg of raffia (Duque-Acevedo et al., 2020) along with plant material once a year. The cost of landfill management for non-hazardous and non-valorisable waste with a density greater than 0.7 t m^{-3} is €30 t^{-1}. Nevertheless, the recently approved Law 7/2022, of 8 April (amended on 24/12/2022), on waste and contaminated soil for a circular economy (Gobierno de España, 2022), adds a tax of €0.45 kg^{-1} for non-recyclable plastic products and a tax of €15 t^{-1} for waste sent to landfill, incineration or co-incineration. The results presented in Table 3 show the economic costs excluding these two taxes and the total economic costs if they were included.

4. Results

This section presents the economic and the environmental results for conventional and biodegradable/compostable raffia and mulching film.

4.1. Economic assessment

The results indicate that 1 ha of greenhouse area required 40,000 m of raffia and 480 kg of mulching film per year. Table 1 shows the cost of purchasing these conventional materials and the cost of purchasing the biodegradable or compostable alternatives. It should be noted that Duque-Acevedo et al. (2020) estimated the purchase cost of conventional raffia to be slightly higher, at €126 ha^{-1}.

Table 1 also shows that the viscose and jute alternatives are respectively €450 and €514 more expensive per hectare than the conventional PP raffia. The PLA mulching film is €1166 more expensive than the conventional LDPE film. As previously described, a major advantage of using biodegradable raffia is that the plant residues can be used for composting or anaerobic digestion as they are not mixed with non-biodegradable waste such as conventional raffia. Disposing of waste with non-biodegradable contaminants is inevitably more expensive than disposing of a fully biodegradable waste mix. Similarly, compostable mulching film requires no special disposal and can be composted on the soil, saving transportation costs and emissions. This has been confirmed by previous research (e.g. Guerrini et al., 2017).

The different waste management costs for conventional and biodegradable or compostable materials are shown in Table 2. It can be seen that the waste management costs for the biodegradable or compostable materials are zero as they do not need to be separated, transported and landfilled.

The total costs for each alternative, taking into account the purchase and waste management costs from Tables 1 and 2, are shown in Table 3. The costs when applying Law 7/2022, which adds two taxes to the waste management costs of the conventional alternative, as mentioned in Section 3.4, are also included. Even with the higher waste management costs, the conventional alternatives still perform better economically than the biodegradable and compostable options, especially for mulching film.

Comparing the cheapest fully biodegradable option with the fully conventional option, the former exceeds the latter in total cost per hectare by €842.4 (i.e. €2575 vs. €1732.6). This is equivalent to a 49 % increase in the cost of raffia and mulching film. Financial support instruments are available to assist Andalusian farmers in such investments into more sustainable farming practices. Considering this and the fact that one hectare of tomato greenhouse area can correspond to an annual turnover of around €160,000 (López-Marín et al., 2022; Gázquez et al., 2015), an investment of €842.4 ha^{-1} seems to be a bearable financial burden for farmers, also taking into account the additional benefits that the biodegradable options can offer, such as marketing a more sustainable product.

Table 2
Waste management costs of the different alternatives.

			Conventional	Biodegradable or compostable
Raffia and plant residues	Separation	€ $(1000\ m)^{-1}$	9.8	0
		€ ha^{-1}	392	0
	Transport	€ ha^{-1}	9.8	0
	Landfill	€ t^{-1}	30	0
		€ ha^{-1}	2.16	0
Mulching film	Separation	€ kg^{-1}	0.07	0
		€ ha^{-1}	33.6	0
	Transport	€ ha^{-1}	65.2	0
	Landfill	€ t^{-1}	30	0
		€ ha^{-1}	14.4	0
Total		€ ha^{-1}	517.2	0

4.2. Environmental assessment

Fig. 3 shows the carbon footprint for each of the alternatives, broken down by life-cycle stage. By far the largest contributor to the carbon footprint is the raw materials. This is surprising for the non-conventional alternatives as they are from renewable sources and their raw material carbon footprint includes the carbon absorbed by the plants as they grow. However, this appears to be largely offset by emissions from planting, growing, harvesting and initial processing. It should be noted that any processing prior to the extrusion step is included in the 'raw materials' bar. Therefore, the biodegradable and compostable alternatives emit more CO^2 than the conventional alternatives for both raffia and mulching film. This surprising fact seems to be partly due to the high methane emissions during the growing and harvesting of the renewable alternative raw materials (Singh et al., 2018; Shen & Patel, 2010). Finally, it should be noted that the mulching film alternatives generally contribute much more to the carbon footprint of the functional unit (1 ha) than the raffia alternatives. This can be explained by the fact that mulching film requires much more material in terms of weight per unit area.

Fig. 4 shows the carbon footprints of the raffia and mulching film alternatives. This figure also includes the potential emissions for a scenario where waste management is changed from landfill to incineration. Of course, there are no emissions associated with waste management for the non-conventional alternatives as they are composted with soil and plant residues. Therefore, there are no additional potential emissions from this new incineration scenario.

Fig. 4 shows that the cellulose coated viscose polymer has by far the largest carbon footprint due to the carbon intensity of its raw materials. As mentioned in Section 3.4, this is largely due to the assumed 'asia viscose' production process which is more carbon intensive. While the 'austria viscose' process is more sustainable, it is largely irrelevant to world supply (Water Footprint Network, 2017). Therefore, if world supply shifts to this more sustainable process, the viscose polymer may become more attractive from a sustainability perspective. Fig. 4 also shows a large transport impact for the jute alternative. This is due to the fact that 99.7 % of the world's jute is produced in Asia and therefore has long transport routes. In addition, the jute alternative requires the largest weight per hectare, as its weight per metre is higher than the other alternatives. Finally, Fig. 4 also shows the potential emissions that

Table 1
Economic costs of purchasing the different alternatives.

	Units for raffia	Raffia Convent.PP	Biodegradable. Viscose + Cellulose	Compost.Jute	Units for mulching film	Mulching film Covent.LDPE	Compost.PLA
Amount	m ha^{-1}	40,000	40,000	40,000	kg ha^{-1}	480	480
Price	€ $(1000\ m)^{-1}$	2.72	13.98	15.56	€ kg^{-1}	1.77	4.2
Price	€ ha^{-1}	108.8	559.2	622.4	€ ha^{-1}	849.6	2016

Table 3
Total costs of the different alternatives.

		Raffia			Mulching film	
		Conventional	Biodegr.	Compost.	Conventional	Compost.
Total cost	€ ha^{-1}	512.8	559.2	622.4	962.8	2016
Total cost, applying Law 7/2022	€ ha^{-1}	546.2	559.2	622.4	1186.4	2016

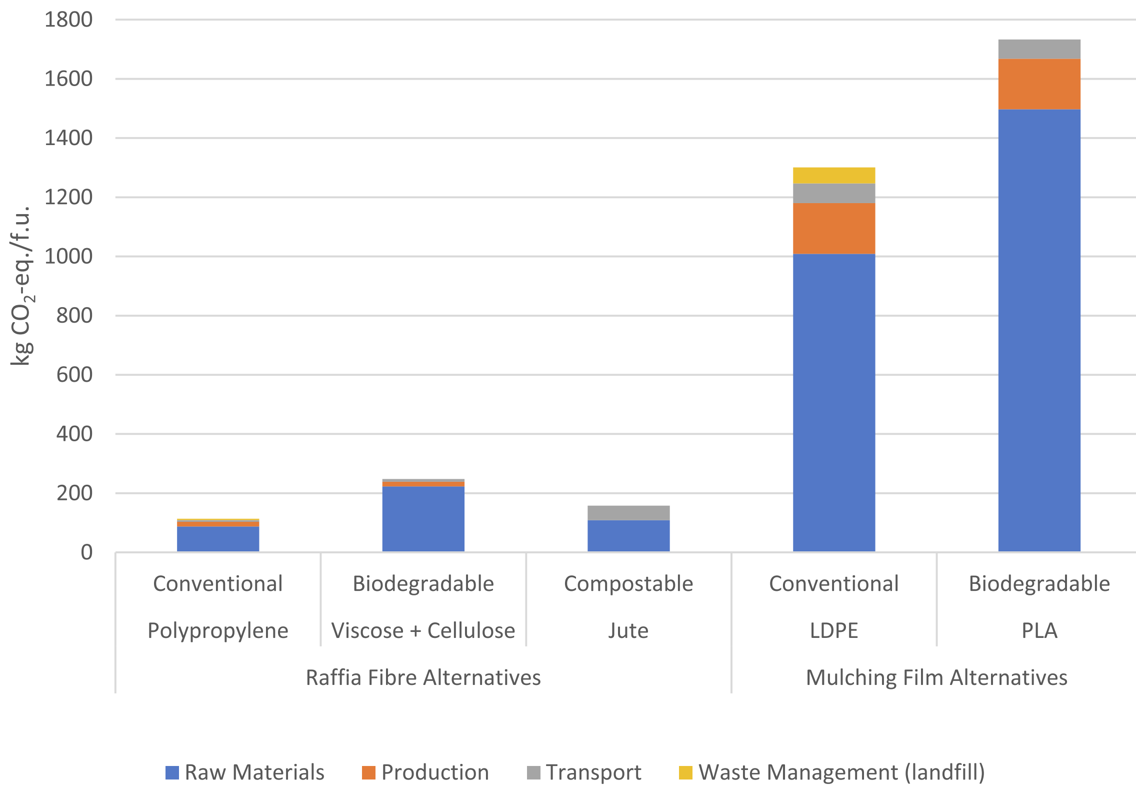

Fig. 3. Carbon footprints of different alternatives.

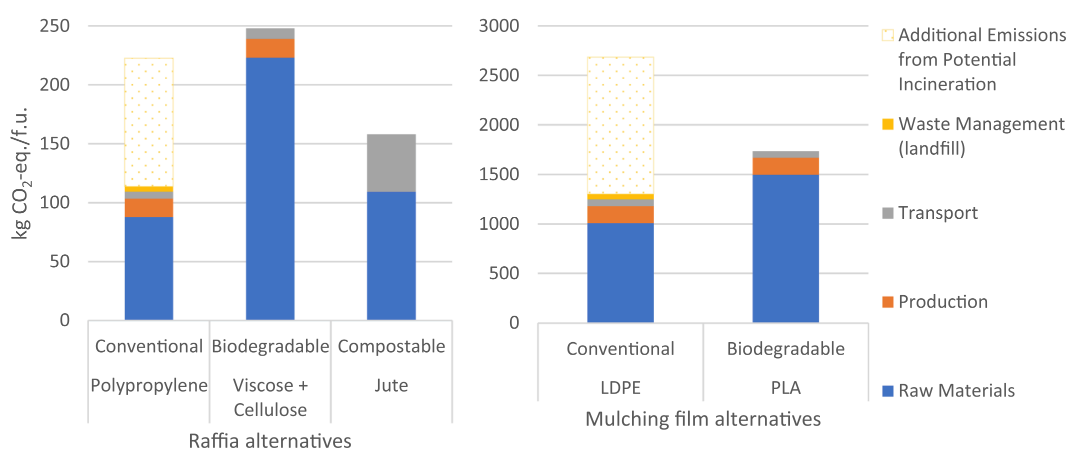

Fig. 4. Carbon footprints of raffia and mulching film alternatives including potential incineration.

would occur if the waste were sent to an incinerator instead of a landfill. This is largely not the case at present, but may be in the future as awareness of plastic pollution grows. When emissions from potential incineration are included, the jute alternative actually ends up having a lower carbon footprint than the conventional alternative.

Regarding the mulching alternatives, while LDPE and PLA film appear to be very similar in terms of transport and processing emissions, PLA appears to be about 50 % more carbon intensive as a raw material (Fig. 4). This makes the conventional alternative less carbon intensive, as the emissions from landfill disposal are not large enough to offset this difference. However, PLA becomes the least carbon intensive alternative when the landfill scenario is replaced by an incineration scenario.

Table 4 shows the impact of each alternative for other environmental impact categories. Here the trends are less clear, but in most cases the

Table 4
Other environmental impacts of the different alternatives.

	Raffia			Mulching film	
	Convent.	Biodegrb.	Comp.	Convent.	Biodegr.
	PP	Viscose + Cellulose	Jute	LDPE	PLA
Acidification (kg SO_2 eq)	0.309	2.49	2.04	4.21	5.86
Eutrophication (kg phosphate eq)	0.095	0.621	1.44	1.02	6.3
Ozone layer depletion (kg R11 eq)	1.38E-6	1.66E-5	1.05E-5	1.50E-5	1.59E-4
Photochemical smog (kg ethene eq)	0.021	0.102	0.033	0.226	0.203
Human toxicity (kg dichlorobenzene eq)	99.9	155	63.5	1265	770

non-conventional alternatives perform worse than the conventional alternative. The only exceptions are the PLA mulching film, which performs better in terms of human toxicity potential and photochemical smog potential, and the jute raffia alternative, which has a slightly lower human toxicity potential than the PP raffia.

The conclusion of this LCA is that although the main objective of using biodegradable and compostable alternatives is to support the transition to more sustainable agriculture, this does not occur when we consider the most commonly used landfill waste management method. However, a shift from landfill to incineration would make jute raffia and PLA mulching film more environmentally attractive than their conventional counterparts.

5. Discussion and conclusions

Materials commonly used in the horticultural sector for plant support (e.g. raffia) and soil protection (e.g. mulching film) pose an issue in the pursuit of a circular economy, as their separation and cleaning can prevent the direct reuse of soil and plant residues. Plastic mulching films can lead to soil degradation and pollution, particularly from microplastics and associated chemical residues (Steinmetz et al., 2016). This article investigated the replacement of plastic raffia and mulching film with biodegradable and compostable alternatives.

Results from the case studies of two greenhouse companies in Almeria showed that replacing raffia and mulching film with biodegradable or compostable alternatives costs €842.4 more per hectare, an increase of 49 %. This is consistent with findings that the higher cost of biodegradable materials is an important barrier to adoption (Kasirajan & Ngouajio, 2012). Results from the LCA concluded that under current landfill waste management, all biodegradable and compostable alternatives have a higher carbon footprint than conventional alternatives. However, when incinerated, jute raffia and PLA mulching film have lower footprints, indicating that proper end-of-life management is critical (Yates & Barlow, 2013). Furthermore, there is a possibility that the waste from the conventional alternatives of raffia and mulching film is not properly managed and instead ends up polluting the environment, including various bodies of water (e.g. groundwater, oceans, rivers). The impact of this type of pollution has not been considered, nor has the likelihood of it occurring. In terms of other environmental impacts, the biodegradable and compostable alternatives do not appear to perform better overall than the conventional alternatives. This is consistent with previous work (e.g. Yates & Barlow, 2013).

Our results show that replacing conventional materials with biodegradable/compostable alternatives may, under certain circumstances, compromise economic and environmental performance. To address this, production processes should be optimised. Several other barriers to adoption include lack of local raw materials, high costs, product unavailability, lack of field trials and farmer reluctance.

Other factors that may hinder the use of biodegradable and compostable raffia and mulching film are related to the production and marketing of the products and the reluctance of farmers to use these products. With regard to the former, the lack of availability of raw materials for the production of raffia and mulching film, particularly in Europe, and their high cost are problematic. These factors reduce the demand for, and therefore the supply of, these products. In addition, few recent studies have investigated the use of these alternative materials in the field. These preliminary studies show that these biodegradable and compostable materials have long degradation or composting times. For farmers, the main challenges to overcome are the higher economic costs and greater breakage and moisture absorption of biodegradable and compostable raffia. In addition, farmers are often unaware of the possibility of using alternative materials and of subsidies that could make their use profitable.

Further research should therefore focus on improving the production and properties of biodegradable materials. Promotion of alternative materials and policy support for economic viability are key to successful market integration. With appropriate optimisations and incentives, biodegradable/compostable raffia and mulching film can support the transition of Spanish horticulture towards circularity and sustainability. In particular, research should look at modifying production processes such as the viscose process to reduce environmental impacts. More field trials are needed to assess the long-term performance, durability and degradability of materials such as PLA under real agricultural conditions. Techno-economic analyses can identify optimisation potential in production. Policy options such as tax incentives, subsidies and public procurement should be explored to improve economic viability. Standards and certification can promote market uptake. Finally, collaboration between industry, government and farmers is essential to develop solutions tailored to Spanish greenhouse horticulture and beyond.

In conclusion, realising the potential sustainability benefits of biodegradable/compostable raffia and mulching film requires a systemic approach that addresses production, policy and practice. With concerted efforts across these dimensions, these alternative materials can play an important role in the transition of greenhouse horticulture towards circularity, enhancing soil health and reducing plastic pollution.

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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