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Research article

Energy and environmental assessment of plastic granule production from recycled greenhouse covering films in a circular economy perspective

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ABSTRACT

Plastic films can be considered as a high-value auxiliary material in agriculture with multiple important uses to fulfil, including covering films in greenhouse cultivation system. Such an application enables several benefits and, therefore, it is going through an important upsurge, especially in regions where protected crop cultivation is highly widespread. However, the increased demand for these covering films arouses concerns for their post-use treatment with regard to both the consumption of Non-Renewable Primary Energy (NRPE) resources and the emission of Greenhouse Gases (GHGs). Therefore, environmental analysis is needed to find and follow cleaner paths for the management and treatment of this kind of Agricultural Plastic Waste (APW), especially in the light of the gap currently existing in the specialised literature.

In this context, this paper reports upon findings from a combined Life Cycle Assessment (LCA) of single environmental issues (i.e., energy and water consumption, and GHG emissions) applied to a Sicilian firm, representative of APW collection and recycling to obtain Low-Density Polyethylene (LDPE) granules.

The results showed that electricity consumption for the whole recycling process is the most NRPE resource demanding and the most GHG emitting input item. Moreover, the washing phase of disused covering films is the highest water demanding within the recycling process. Potential improvements could be achieved by shifting from fossil energy source to renewable one. The installation of a wind power plant would lead to around 56% and 85% reduction in NRPE resource exploitation and GHG emission, respectively. Finally, despite the huge consumption of water and NRPE resources and the resulting GHG emissions, the production of recycled-LDPE granules is far more sustainable than the virgin counterpart.

1. Introduction

Plastic films are used in greenhouse cultivation system as covering materials, in the form of transparent sheets for under-tarp moisture collection or as black sheets for crop mulching (Granadosa et al., 2012). With regard to covering materials in greenhouse cultivation system, usage of plastic films has been increasing steadily since the middle of the twentieth century due to several benefits for agricultural activities such as increased crop yield, earlier harvest, decrease in consumption of both herbicides and pesticides, frost crop protection, and water conservation (CPCB, 2016).

By analysing official statistical data (ISTAT, 2018), a large amount of plastic films is utilised in the Mediterranean countries where protected crops are widely cultivated (Scarascia-Mugnozza et al., 2012). In detail, consumption of plastic films for covering tunnels in A-shaped greenhouses and tunnel-greenhouses is equal to of 72,000 and 75,000 tons per year on average, respectively (Plastics Europe, 2016). Because of direct exposure to both solar radiation and wind, covering films are replaced every 6–45 months (Barnes et al., 2009; Scarascia-Mugnozza et al., 2012; Nanna et al., 2018). At the end of their useful life, these films are taken off and treated as waste by disposing of them in landfills, which are often equipped with energy recovery systems, or by recycling them into secondary raw materials for a wide range of applications, including rubbish bags and boxes. This second option would contribute to the reduction in the environmental impact associated with the life cycle of these films (Montero et al., 2014; Aryan et al., 2019). Unfortunately, by now, around 50% of plastic wastes generated by agricultural activities is treated in landfills, so emphasising upon the urgent need to find and follow alternative and more sustainable routes (Briassoulis et al., 2013).

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Acronym list

APW	Agricultural Plastic Waste
CC	Climate Change
CED	Cumulative Energy Demand
CF	Carbon Footprint
DC	Damage Category
EQ	Ecosystem Quality
FU	Functional Unit
GHG	GreenHouse Gas
GWP	Global Warming Potential
GWP100	100-year GWP
HH	Human Health
IC	Impact Category
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low Density Polyethylene
NRPE	Non-Renewable Primary Energy
PER	Primary Energy Resource
TCS	Total Cultivated Surface
UM	Unit of Measure
WF	Water Footprint
WFA	Water Footprint Assessment
WSI	Water Stress Index

In Italy, each year, more than 350,000 t of plastic materials are used in agricultural activities with a consequent post-use material flow of about 200,000 t (Picuno et al., 2012). In addition, more than 2 million hectares are used for greenhouse cultivation system (ISTAT, 2018), i.e. approximately 21% of the whole cultivated surface in Italy. In this context, given the relevant amount of covering films to be collected and recycled, evaluations on sustainability issues of raw materials obtained from their recycling process are needed: Life Cycle Assessment (LCA) could be a valid tool for this purpose (Aljerf, 2016). LCA was used by authors like Horodytska et al. (2018) to identify and pursue the best environmentally performing waste treatments among a set of alternatives, by means of a critical review of previously published LCAs. Through their study, the authors highlighted that several LCAs dealt with municipal solid waste management, but only a few of them focussed upon the management of flexible plastic films. According to the authors, this can be attributed - even only in part - to a lower degree of development in sorting and recycling technologies for flexible plastic films compared with rigid ones. In this context, the in-depth knowledge of all steps for recycling these films was recommended by the authors for creation of a model that is consistent with the real system. In another study, Gu et al. (2017) carried out a detailed LCA investigation on plastic production from various sources, such as agricultural wastes, by analysing a recycling company in China. Results demonstrated that the extrusion process was determinant in the overall impacts due to the production of recycled plastics, while the introduction of fillers and additives contributed to the most significant part in the environmental impacts associated with the production of recycled composed materials.

Finally, Hottle et al. (2017) explored the impacts associated with the production and disposal of biopolymers compared to fossil-based plastics by means of LCA and have found that the recycling results in significant life cycle impact reductions.

Although the topic of plastic waste management and recycling is an important environmental issue at the global level, the review conducted highlighted a gap in the literature of LCAs on both the production and the end-life treatment of flexible films used for agricultural applications. Though mechanical recycling of agricultural post-consumer films is recommended because of the high availability of homogenous single-polymer waste (Martínez-Lera et al., 2013), to the authors' knowledge, no research studies have been conducted to assess the environmental impact deriving from such recycling processes.

This research was designed to contribute filling these gaps, with the final objective of stimulating creation of cleaner paths for plastic waste management and treatment. This can be considered a novelty of this study that, according to the authors, strengthens its positive contribution to the enrichment of the scientific literature currently available in the field.

The study reports upon a combined evaluation of environmental issues associated with the manufacture of plastic granules from Agricultural Plastic Waste (APW) as a zero-burden material input. The study was specifically focussed upon issues like the consumption of water and energy, and resultant emissions of Greenhouse Gases (GHGs), because they were considered as highly representative of the most significant environmental burdens associated with the process investigated. Furthermore, the studied system meets the requirements of sustainable circular economy aimed at minimising both waste and excessive resources-usage, by turning material commodities at the end of their service lives into zero-burden resources to feed the manufacturing of new commodities (Venkata Mohan et al., 2016; Ingrao et al., 2018a).

A Sicilian firm operating in the recycling sector was positively involved in providing technical support for the development of this study. The latter addresses energy and environmental issues related to the reuse of plastic covering films for producing recycled granules as a secondary raw material. To this end, a Life Cycle Assessment (LCA) approach was adopted according to the specific International Standards 14,040–44:2006 (ISO, 2006a; ISO, 2006b) and applied to a Sicilian firm, representative of the agricultural plastic waste (APW) collection and recycling.

Apart from the above-reported introduction, the study was conducted through the framework depicted in Fig. 1.

2. Materials and methods

2.1. Study area

Sicily is the Italian region with the highest percentage (76.1%) of greenhouse surface (GHS) among the Total Cultivated Surface (TCS), followed by Campania e Lazio (Table 1).

Greenhouse cultivation system characterises the agricultural activities of the Southern-Est part of the Sicily (Arcidiacono and Porto, 2012), and Ragusa is the province with the highest concentration of tunnels, greenhouses of both A-shaped and tunnel type (Arcidiacono and Porto, 2010), with a covered surface of about 470,000 ha, nearly 68% of the protected cultivation in the whole region (ISTAT, 2018). In particular, this area is invested as follows: 58.7%, for tomatoes; 33.6%, for other vegetables; and the remaining 6.7%, for flowers and ornamental plants. This has led to increase the supply chains being implemented for manufacturing and distribution of plastic covering films, with huge amounts produced every year, especially in Ragusa. However, in order to meet the necessary demand for plastic films to be treated as waste after usage, the aforementioned chains are increasingly expanding to incorporate industrial plants for sustainable treatment of plastic films at the end of their service lives, so reducing harmful consequences to the environment and human health (Song et al., 2009). Several firms have been founded over the last thirty years to deal with recycling of post-use covering films with the final aim of converting them into value-added material commodities, in line with the modern principles of circular economy. One of these firms was involved to technically support the development of this study: its geographical position within the province

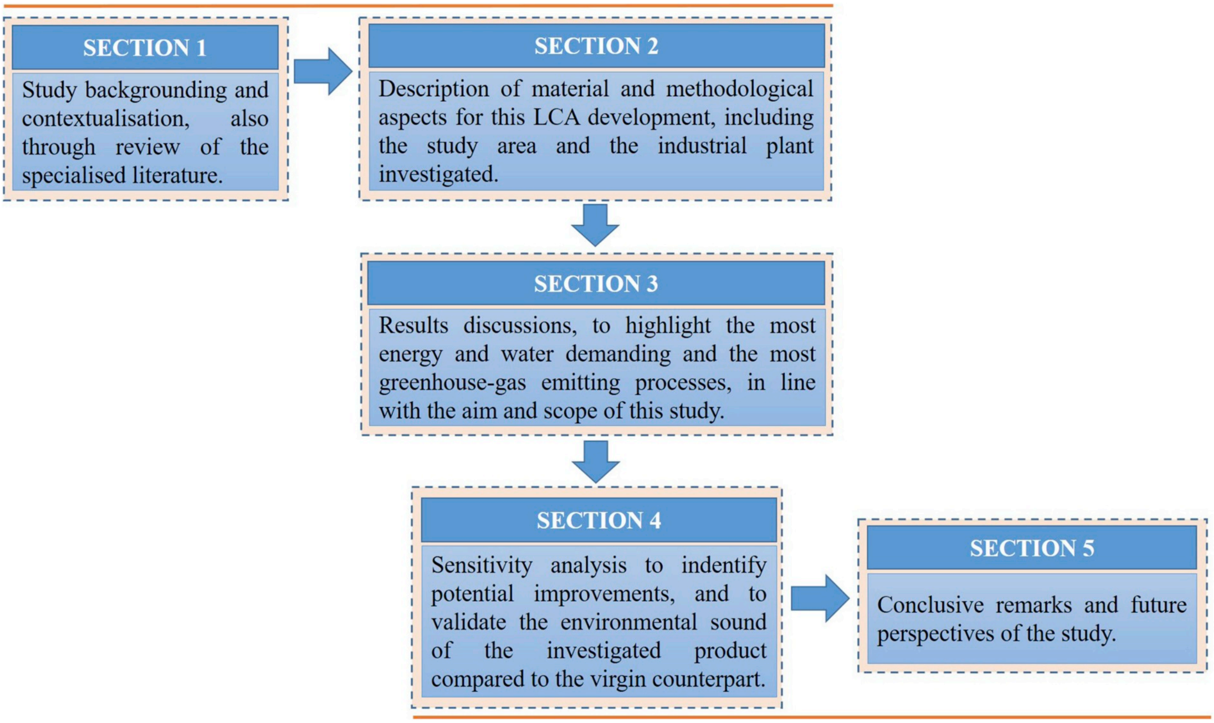


Fig. 1. Study content framework.

Table 1
Cultivated and greenhouse surfaces in Italy.

Italian regions	Cultivated surface (TCS)	Greenhouse surface (GHS)	
	[ha]	[ha]	[GHS/TCS]
Abruzzo	481,043.2	22,588.5	4.7%
Apulia	855,847.2	125,094.5	14.6%
Basilicata	471,100.2	45,793.0	9.7%
Calabria	507,203.0	55,737.0	11.0%
Campania	479,295.2	355,096.0	74.1%
Emilia-Romagna	783,905.2	49,697.4	6.3%
Friuli-Venezia Giulia	94,425.7	5891.0	6.2%
Lazio	666,610.3	312,409.0	46.9%
Liguria	58,921.2	58,336.0	99.0%
Lombardy	498,982.2	72,525.0	14.5%
Marche	366,105.0	13,492.9	3.7%
Molise	148,728.0	1665.4	1.1%
Piedmont	505,085.5	45,426.0	9.0%
Sardinia	994,106.2	64,779.5	6.5%
Sicily	902,429.3	686,758.0	76.1%
Trentino Alto Adige	541,410.6	4541.0	0.8%
Tuscany	846,496.7	69,648.7	8.2%
Umbria	354,323.1	5562.0	1.6%
Valle d'Aosta	34,393.4	130.0	0.4%
Veneto	551,923.1	169,525.7	30.7%
Total	1,0142,334.2	2,164,696.6	21.3%

of Ragusa was depicted in Fig. 2. It collects and recycles APW to obtain Low-Density Polyethylene (LDPE) granules, which find application as a secondary raw material in a wide range of sectors. These granules are generally characterised by quality rates that are comparable to the virgin counterparts and, therefore, are suitable to manufacture printed materials, pipes and bituminous membranes, and new films (Aryan et al., 2019).

2.2. *Description of the analysed industrial process*

The production process of the considered firm starts with the supply of APW, which is entirely collected from the surrounding areas and stored before being processed (Fig. 3). APW is initially subjected to grinding and to a first phase of pre-washing and spinning (Briassoulis et al., 2013). Thereafter, all macroscopic impurities are removed by decantation in a water tank. This post-use water is treated in an adjacent plant and stored in tanks before being pumped back to the LDPE-granule production process, so it feeds the recycling process continuously (Naviroj et al., 2019).

The sludge resulting from the wastewater treatment is decanted and extracted from the bottom of the tanks to be dehydrated on drying beds. Next, the APW goes through a subsequence of processes to eliminate all impurities and humidity by washing, drying, and milling. During the final step of the production process, material (in small pieces) is melted, extruded and stored in silos before marketing and distribution.

2.3. *Assessment of energy and environmental issues*

To estimate energy and environmental impacts of the production process of recycled LDPE granules above-described, an LCA approach was developed according to the specific International Standards 14,040–44:2006 (ISO, 2006a; ISO, 2006b) and organised as follows:1) Goal and Scope Definition; 2) Life Cycle Inventory (LCI); 3) Life Cycle Impact Assessment (LCIA); and 4) Life Cycle Interpretation. Each phase was discussed in the sections below, which give to the reader a well-known standardised framework to reproduce this research.

2.3.1. *Goal and scope definition*

This study is about inventorying and assessing from an energy and environmental perspective the production of plastic granules from recycled APW. For this purpose, the LCA framework was carried out and the LCIA phase was focalised upon single issues, such as water consumption, primary-energy sources exploitation, and GHG emissions. In fact, based on the inventory analysis, these issues were found to be both highly representative of the analysed process and a priority in the EU agricultural policy for their impact reduction (Caffrey and Veal, 2013; Cerutti et al., 2015; EC, 2013). To this end, Carbon Footprint (CF), Cumulative Energy Demand (CED) and Water Footprint (WF) were applied because they are worldwide known as key indicators for the assessment of energy and environmental performance.

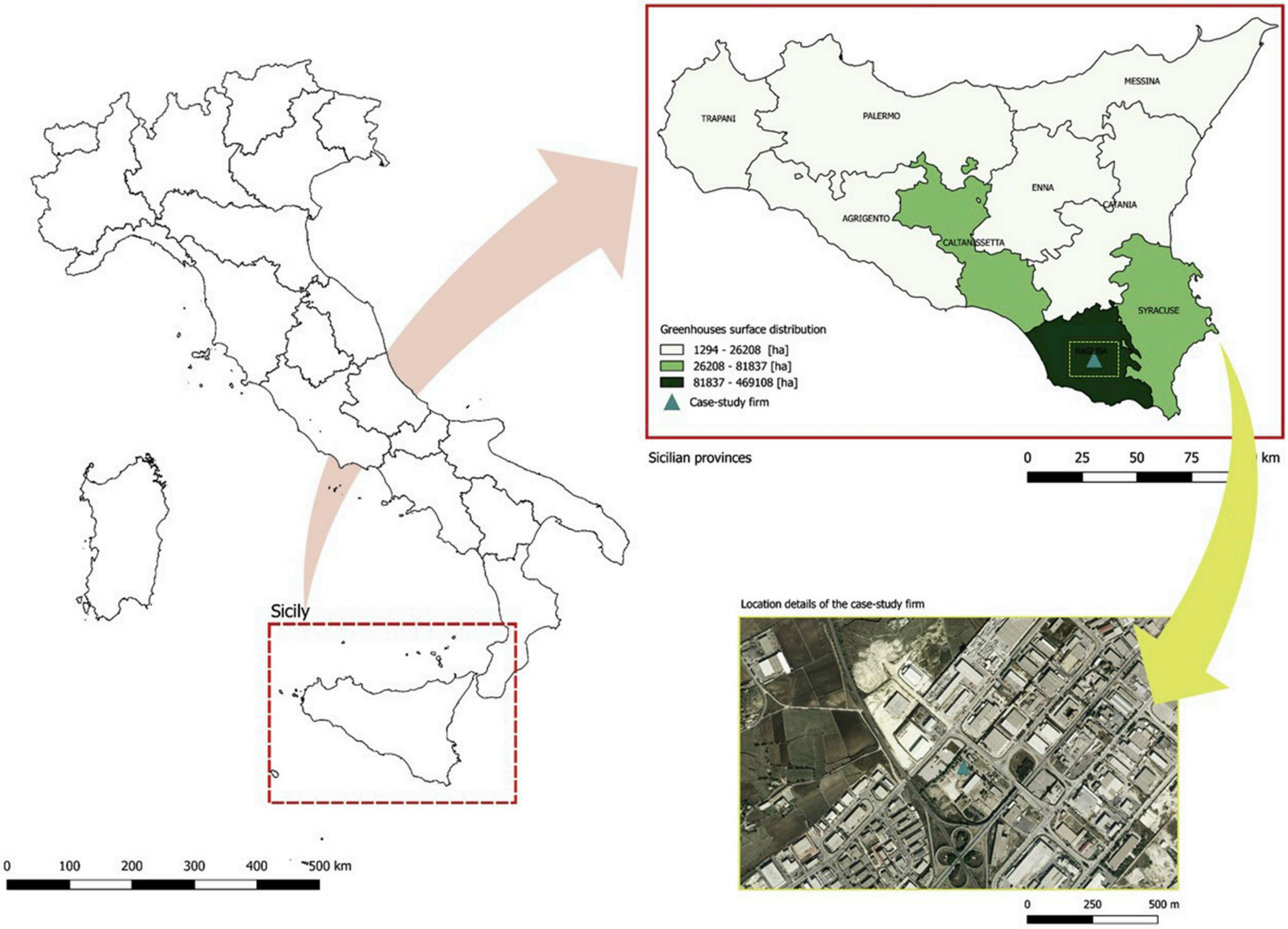


Fig. 2. Geographic position of the study area and the firm considered in the case study.

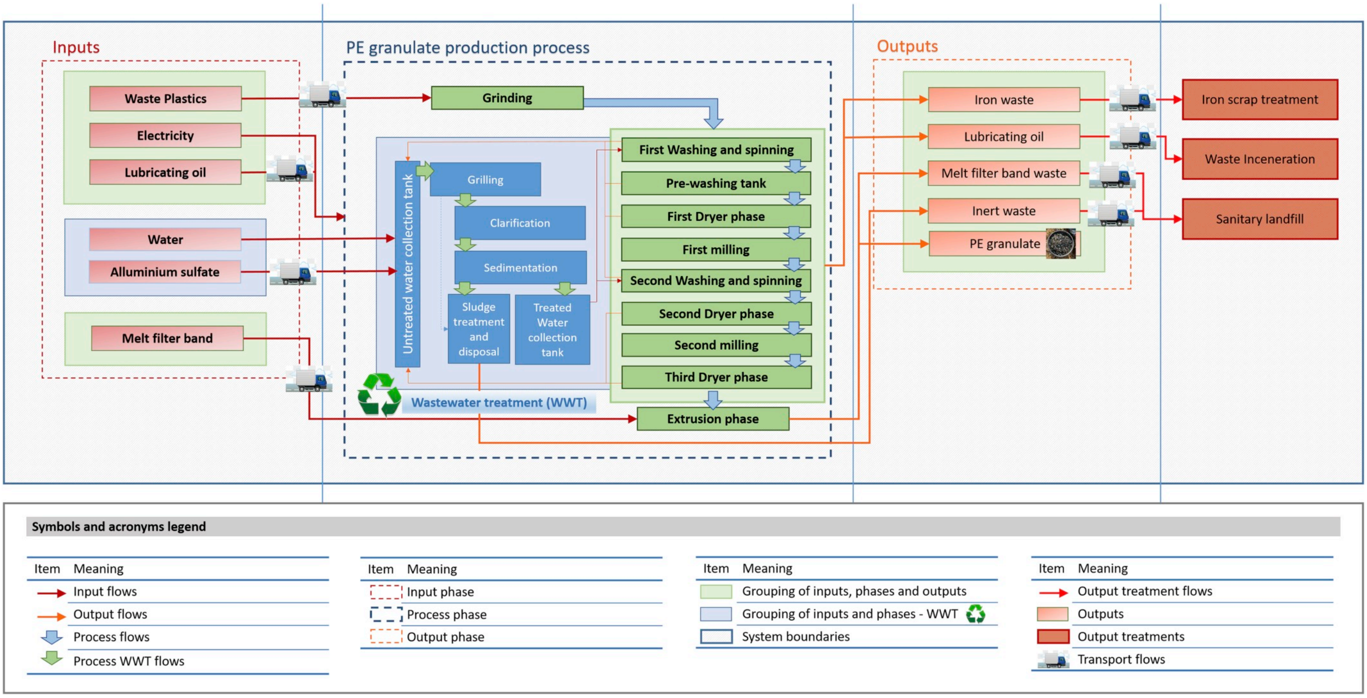


Fig. 3. Boundaries of the system investigated.

As part of this phase development, the Functional Unit (FU) and the system boundaries were defined by following the International Standards (ISO, 2006a; ISO, 2006b) to best represent the investigated process, consistent with the aim of the study. The FU represents the unit of product and provides a reference linking inputs to outputs and to resulting impacts and damages (Arzoumanidis et al., 2013): in this case study, 1 ton of produced LDPE-granules was chosen as FU.

Concerning the system boundaries (see Fig. 3), they were defined to include: 1) APW acquisition, pre-treatment and transformation into the reference finished-product (1 ton recycled-LDPE); 2) preparation and acquisition of auxiliaries, oils, and energy; 3) the treatments of all waste materials as generated by the recycling process; and 4) the annexed plant for treatment and recirculation of the APW-cleaning water.

These boundaries were designed based upon information provided by the supporting firm to clearly highlight the material and energy flows throughout the investigated chain which enable connecting the up-stream processes to the down-stream ones. Furthermore, as emerges from Fig. 3, all transports were considered in the assessment for both supplying input materials and delivering wastes generated by the process to the treatment plants. The transport phase for the distribution of the produced recycled-LDPE granule was excluded by the system boundaries because it was considered as pertaining to several other processes regarding the utilisation of the recycled-LDPE granule. Therefore, the downstream border of the system was set at the firm exit-gate. All transport flows included in the LCA were detailed in the following section, together with the related diesel consumptions and the Ecoinvent modules used for the system assessment using information provided by the firm (Whitaker and Heath, 2009).

2.3.2. Life cycle inventory (LCI)

This is the key phase of LCA elaborations, since it deals with compilation, qualification and quantification of all input and output streams, as needed for the goal achievement. The inputs considered are the resources, materials, fuels, and energies, while the outputs are the material emissions in air, water and soil, as well as the exploitation of natural and primary-energy resources (Ingrao et al., 2018b).

The system investigated is highly interconnected with the local territory: for this reason, the LCI was centred upon collection of site-specific data (primary data), regarding typologies and amounts of inputs and outputs. A specific questionnaire was developed to be filled in through interviews with firm technicians, in order to gather management information on main structural and economic features, stages of the production process, features of the obtained product (i.e., the recycled granule), and amount and type of the wastes to be treated (Valenti et al., 2016).

The questionnaire was organised into the following parts: i) a general section containing questions aimed at getting information about the input materials, such as water and covering plastic films (the amount of product to be processed); ii) the second section was created to gather information on the electricity consumption associated with the whole process investigated, considering the different technologies and machineries utilised in each step; iii) the third section, regarding the whole process operation, was aimed at collecting the data on the auxiliary materials and fuels utilised, as well as on both main features and amounts of the obtained products; iv) the waste disposal section was used to collect information about typologies and amounts of wastes produced during the production process, and related disposal treatment adopted; while, v) the last section, labelled as '*supply section*', was conceived to collect information related to the logistics phases, before, during and after the production process. In detail, in this section of the questionnaire, information about distances in kilometres were required to detail as much as possible the logistics phase related to the transport flows, which often in Sicily region represent a key factor for the sustainability of production systems.

Primary data were combined with secondary ones extrapolated from databases of acknowledged scientific value and relevance, Ecoinvent v.3 as available in SimaPro 8.1. This database was used because it is recognised worldwide as accommodating most of the background materials and processes often used in LCAs (Frischknecht and Rebitzer, 2005). Furthermore, this database contributes making it suitable for the modelling of industrial systems like the one investigated in this study.

Data collection regarded a 3-year campaign between 2015 and 2017 and information used for the LCI were reported in Table 2 and Table 3. In detail, Table 2 shows that data related to LDPE granules production differ only about 5% during the three years analysed, confirming the standardisation of the process. Therefore, the LCA developed in this study is representative of the production process of LDPE granules from recycled covering films used in greenhouse cultivation system.

For the assessment, the collected data were averaged to obtain a yearly LDPE-granule production of about 11,780 tons and an electricity consumption of about 1.11E7 kWh, i.e. approximately 950 kWh are required to produce 1 ton of LDPE-granules. In Table 3, forward and reverse transport flows were detailed and the chosen Ecoinvent modules were reported. All the data recorded and averaged (Tables 2 and 3) were then elaborated to be referred to the system FU, namely 1 ton of recycled LDPE, and reported in Table 4.

Considering the uncertainty and variability in LCA studies, it is important to determine both the validity of the collected data (Cerutti et al., 2015) and the reliability and robustness of the results (Notarnicola et al., 2017). As reported by Huijbregts (1998), the different types of uncertainties can be distinguished in: parameter uncertainty, model uncertainty and uncertainty linked with choices.

The robustness of data and modelling of this study should be considered very high since the analysis is based on real acquired data, during a 3-years campaign.

2.3.3. Life cycle impact assessment (LCIA)

Both the mid-point and the end-point approach were used for the development of the LCIA phase. As part of the former one, according to De Benedetto and Klemes (2010), output inventories were aggregated into a limited set of Impact Categories (ICs) by using characterisation factors for the given single-issue assessed. Then, the study was extended to the damage assessment as part of the end-point approach, and the ICs were linked to Damage Categories (DCs), representing the environmental compartments that suffer the damage caused by the system investigated, namely the LDPE-granule production. To this end, the authors used the classification/characterisation and the weighing

Table 2
Data collected at the LDPE-granule production site from 3-year campaign and the annual average base. All data reported are referred to the annual production, and are associated the related Unit of Measure (UM).

Items	Amount			UM
	2015	2016	2017	
	Outputs			
	Products			
LDPE granules	11,445	11,536	12,359	ton
	Waste streams			
Inert	5923	6213	6988	ton
Exhausted mineral oil	3778	4000	4889	kg
Steel	11,000	21,800	24,290	kg
	Inputs			
	Material and energy commodities			
Underground water without treatment (production and distribution)	43,051	51,617	45,528	ton
Aluminium sulphate	24,600	29,760	20,860	kg
Mineral oil	3778	4000	4889	kg
Steel	11,000	21,800	24,290	kg
Diesel[a]	34,500	37,000	35,000	l
Electricity	1.115E7	1.094E7	1.011E7	kWh
Melt filter band	15,000	18,000	24,000	m

[a] Diesel is for material handling within the firm yard. All emissions related to its combustion were extrapolated from Ecoinvent and referred to the diesel consumption volume.

Table 3
Transport flows related to the system investigated for both material supply and waste delivery. The values reported are on an average base.

Transport	Raw material	Waste	Flow	Diesel consumption	Ecoinvent module
			[kgkm]	[kg]	
T1	Aluminium sulphate	–	219.39	23.91	Transport, freight, lorry 3.5–7.5 metric ton, EURO5 {RoW}| transport, freight, lorry 3.5–7.5 metric ton, EURO5 | Alloc Def, S
T2	Plastic waste	–	8.649E4	9.43E3	Transport, freight, lorry 3.5–7.5 metric ton, EURO4 {RoW}| transport, freight, lorry 3.5–7.5 metric ton, EURO4 | Alloc Def, S
T3	Mineral oil	–	39.38	4.29	Transport, freight, lorry 7.5–16 metric ton, EURO5 {RoW}| transport, freight, lorry 7.5–16 metric ton, EURO5 | Alloc Def, S
	–	Exhausted oil	132.82	14.48	
T4	Steel wire	–	2.75	0.30	Transport, freight, lorry 16–32 metric ton, EURO5 {RoW}| transport, freight, lorry 16–32 metric ton, EURO5 | Alloc Def, S
	–	Iron waste	4.893	0.53	

Table 4
Average data from Tables 2 and 3 as referred to the system FU, namely 1 ton recycled LDPE.

Items	Average	*UM*
	U.M/ton$_{LDPE}$	
Outputs		
Products		
LDPE granules	1.000	ton
Waste streams		
Inert	0.521	ton
Exhausted mineral oil	0.358	kg
Steel	1.615	kg
Inputs		
Material and energy commodities		
Underground water without treatment (production and distribution)	3.882	ton
Aluminium sulphate	2.128	kg
Mineral oil	0.358	kg
Steel	1.615	kg
Diesel	3.014	l
Electricity	942.275	kWh
Melt filter band	1.613	m
Total of transports (as sum of values in Table 3)		
Raw material supply	7.364	Kgkm
Waste to treatment	0.012	Kgkm

framework provided by the three single-issue impact assessment methods considered (i.e. CF, CED, and WF) within Simapro 8.1 (Table 4).

2.3.3.1. Carbon Footprint (CF). The CF is one of the most popular 'impact category indicators', for the climate change category. The emissions of different greenhouse gases are weighed based on their Global Warming Potential (GWP) relative to carbon dioxide (e.g., one kg of methane has a much greater GWP than one kg of carbon dioxide) (Hoekstra, 2016). The weighing is technically called 'characterisation' of the inventory results, and the GWPs of different greenhouse gases are the characterisation factors. The resultant CF is expressed in terms of CO_2 equivalent (CO_{2eq}) (Wiedmann and Minx, 2008; Maalouf et al., 2018).

In this study, among the mid-point approaches the 'IPCC 2013 GWP 100a' method (IPCC, 2013) was used, which was developed by the Intergovernmental Panel on Climate Change (IPCC) and it contains the climate change factors of IPCC with a timeframe of 100 years.

Following Maalouf et al. (2018), the following equation was elaborated and applied:

$$CF_i = \sum_j GWP_j * e_j \qquad (1)$$

where:

- e_j is the emission (in mass unit) of the j-th GHG associated with the given process;
- GWP_j is the GWP of the j-th GHG for a 100-year temporal horizon (GWP_{100}), which is required for any CF assessment.

Table 5 reports the GWP_{100} of the GHGs that were considered by the authors as the most representative of the investigated system and were extrapolated by Simapro 8.1.

At the end-point approach, the computed impacts were transformed into damages by using conversion factors based upon the classification scheme provided by '*ReCiPe Endpoint*' (Goedkoop et al., 2013) in the Egalitarian perspective (E/E) for the CF. ReCiPe method was used, in particular, to quantify the environmental damages due to the emissions of the most significant GHGs -upon the DCs, i.e. Climate Change (CC), Human Health (HH) and Ecosystem Quality (EQ).

2.3.3.2. Cumulative Energy Demand (CED). The CED is an impact indicator that expresses the energy consumption throughout the life cycle of a product or a service (Hischier et al., 2010); so, it can be considered as an indicator of environmental impacts with regard to the energy resource depletion (Gürzenich et al., 1999).

According to Wiesen and Wirges (2017), CED was calculated following the 'Cumulative Energy Demand' method described in the Ecoinvent database. The aim of the method is both to calculate the direct and indirect energy used throughout the life cycle of the LDPE-granules and to differentiate among renewable and non-renewable energy sources (Huijbregts et al., 2006). Therefore, this method allows the evaluation of environmental effects related to the emissions and energy consumption (Girgenti et al., 2013). In detail, the method includes the direct and indirect uses of energy and it is organised in eight different impact categories. As a well-consolidated practice, normalisation and weighting were not applied, because they are not considered by the method itself. In this study, the CED was calculated by including both non-renewable (from fossil fuels, nuclear, and non-renewable biomass) and renewable (from wind, solar, geothermal, and water) energy sources, associated with each input considered in the LDPE granules production process.

2.3.3.3. Water footprint (WF). Among the methods involved in LCA-based water footprint, the Water Footprint Assessment (WFA) was adopted, according to Pfister et al. (2009). This method is centred upon computation of the Water Stress Index (WSI) that calculates the water

Table 5
Global Warming Potential of relevant GHGs. Conversion factors from IPCC (2013).

GHG	Nomenclature	GWP_{100} [gCO_{2eq}/gGHG]
Carbon dioxide	CO_2	1
Methane	CH_4	28
Nitrous oxide	N_2O	265

impact on the consumption-to-availability perspective of freshwater deprivation, corresponding to the 'blue water' in the WFA methodology (Pfister et al., 2009). The WSI was used as a general screening indicator or characterisation factor for the freshwater consumption at the mid-point approach for all three areas of protection: resources, ecosystems and human health. Then, at the end-point approach, the damages using conversion factors based upon the classification scheme provided by Eco-indicator 99 (Goedkoop and Spriensma, 2001) were computed. In detail, Eco-indicator-99 was used for estimating the environmental damages as the consequence of water consumption upon DCs, i.e. Resources (Re), Human Health (HH) and Ecosystem Quality (EQ) (Singh et al., 2018).

3. Results and discussion

3.1. Carbon Footprint assessment

The assessment showed that CO_2, CH_4 and N_2O are the most significant GHGs since they represent the 94.87% of the CF associated with the system investigated. In particular, CO_2 is characterised by the highest GWP_{100}, as shown in Table 6, and it is the most emitted GHG, as reported in Fig. 4.

Two different results can be gathered from Fig. 4: one per emitted GHG by taking into account the considered phases (horizontal sum); and the other one per each considered phase by taking into account the three selected gases (vertical sum). Furthermore, the following materials, fuels and activities, contributing with less than 5% to the GHG emissions, were grouped in the '*Others*' category: production of diesel (and emissions from its combustion), tap water, aluminium sulphate, lubricating oil; manufacturing of steel wire and of filtering material; as well as treatment of inert waste, waste mineral oil, and steel waste pre-treatment.

Fig. 4 shows that the most contributing phases are the production and distribution of electricity required for the process working and transports (Table 3). Electricity, in particular, is the largest contributor for each of GHG emissions, with percentage values (up to the total ones) equal to 88.02% (CO_2), 91.90% (N_2O), and 94.63% (CH_4). Contribution from the transport section is far lower and ranges from 2.74% for CH_4 to 7.34% for CO_2-emission.

Mid-point results demonstrated that CF is equal to 655.46 $kgCO_2$ and, based upon results shown in Table 6, it is due for the major percentage (91.18%) to CO_2. As anticipated in the methodological approach, the study was extended to incorporate the damages assessment phase as part of the end-point approach, considering the environmental damage that each emitted GHG causes to CC, HH and EQ. The end-point categories affected by the three GHGs were reported in Table 6.

3.2. Cumulative Energy Demand assessment

The CED was found 12.015 GJ per kg of recycled-LDPE granules, with electricity contributing 88.72%, as evident from Fig. 5. In addition, from this figure emerges that the electricity utilised in the recycling process is 76.17% of fossil origins.

Table 6
Mid-point and end-point results per each GHG emitted considered in the assessment.

GHG	Mid-point analysis[a]	End-point analysis		
	Characterisation	Damages assessment		
	GWP_{100}	**CC**	**HH[b]**	**EQ[b]**
	$kgCO_2$ eq	**$kgCO_2$ eq**	**DALY**	**species.yr**
CO_2	597.63	597.63	2.10E-03	1.12E-05
CH_4	47.97	47.97	4.57E-05	2.43E-07
N_2O	5.97	5.97	1.21E-05	6.44E-08

[a] IPCC 2013.

[b] Values are referred to kg of emitted substance (ReCiPe Endpoint - E/E).

As shown in Table 7, gas natural, crude oil, and hard coal represent 77.3% of the overall amount of fossil primary-energy resources, and so they can be considered as the most consumed ones within the process.

Electricity is the most impacting item, with the aforementioned energy resources exhibiting comparable values in the range 90–98% (Table 7), except for crude oil, characterised by a far lower contribution rate being around 54%. This should be attributed to the transport issue, showing its greatest contribution (26.3%) in crude oil rather than in the other ones.

Similar results were found for '*Others*', as they contribute a total of 20% to the CED associated with crude oil, which is far higher than the other energy resources (1.2–5.6%). This should be attributed to materials, processes, and phases grouped in this category consuming, overall, more crude oil than gas natural or hard coal or other minor energy resources, as considered by the CED assessment method used in this study.

3.3. Water footprint assessment

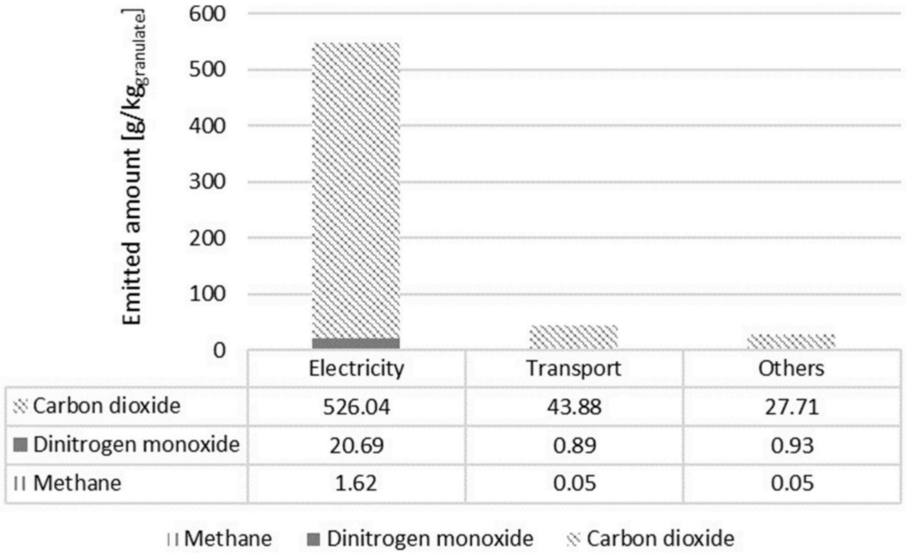
At the mid-point approach, the WSI resulted equal to 4.15 m^3, and it was significantly due to the cleaning steps as operational water and to the consumption of electricity as virtual water. With regard to the damage assessment step, Table 8 shows the DCs affected by the overall consumption of water. In detail, '*water*', '*electricity*', '*transportation*' and '*others*' columns refer to water consumption due to the recycling-process and water consumption embodied in the electricity consumed as well as in the transports and in all the other materials, processes, grouped under the '*Others*'.

As for the CF assessment, it was not possible to weight the three DCs and identify the most affected one, because for each of them is assigned a specific damage indicator, which is established by Eco-Indicator 99. However, from Table 8, it is possible to assert that for each DCs the most damaging issue is the consumption of operational water, with contribution around 65%, followed by electricity with a 25.15% average contribution.

4. Interpretation and improvements

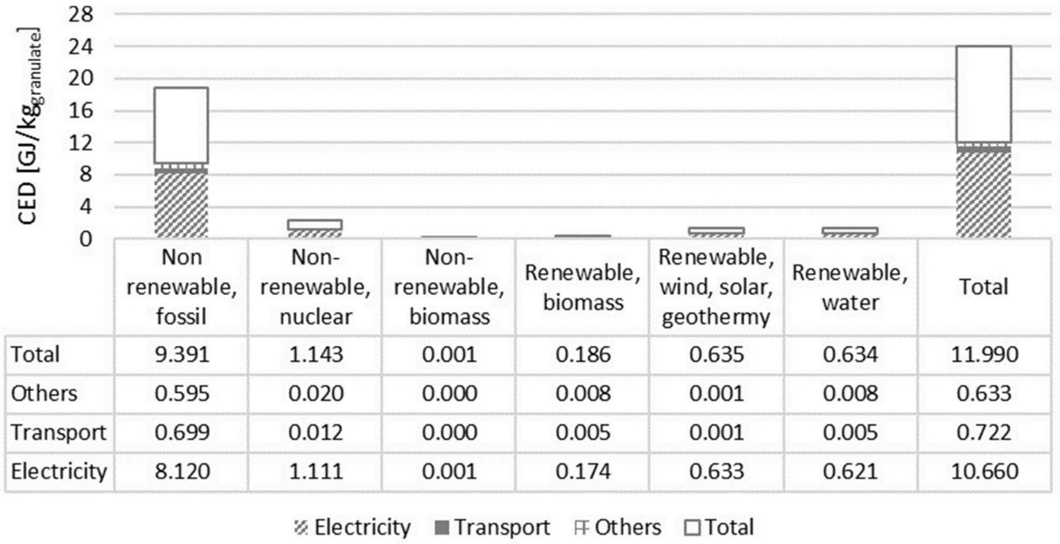
The study highlighted that the electricity required by the process for 1 ton of recycled-LDPE production (942.75 kWh) is the largest contributor to both the CF and CED, so emphasising upon the importance to search for potential improvements. In agreement with the firm technicians, it was assumed that no solutions are viable at the plant level by improving the technical quality and energy efficiency of machineries used in the production process. Therefore, electricity consumption is the major energy and environmental issue of the whole system. Nonetheless, the energy/environmental burden associated with the electricity consumption may be reduced through a change in the energy source, by shifting it from fossil to renewable. A valid solution could be to install a wind power plant to cover the whole energy demand. In this regard, a first sensitivity analysis highlighted significant reductions for all the three indicators that have been addressed in this study, with CED and GWP_{100} showing the greatest reduction of about 56% and 85%, respectively, as they are most affected by electricity use (Fig. 6). It should be observed that this is a preliminary evaluation that should be checked in terms of technical and economic feasibility.

Whereas, no solutions were found to be viable for reduction of in the water consumption demanded by the process infor the cleaning steps. Finally, in order to validate the energy and environmental sound of the recycled-LDPE granule, another sensitivity analysis was conducted by comparing the virgin and recycled LDPE granule, on the same base of FU and system boundaries. In addition, a comparable quality level was assumed between the two differently produced LDPE granules. It was found that, for all indicators considered in the study, i.e. CF, CED and



	Electricity	Transport	Others
▨ Carbon dioxide	526.04	43.88	27.71
■ Dinitrogen monoxide	20.69	0.89	0.93
‖ Methane	1.62	0.05	0.05

Fig. 4. Emitted GHGs, with aggregated and disaggregated values.



	Non renewable, fossil	Non-renewable, nuclear	Non-renewable, biomass	Renewable, biomass	Renewable, wind, solar, geothermy	Renewable, water	Total
Total	9.391	1.143	0.001	0.186	0.635	0.634	11.990
Others	0.595	0.020	0.000	0.008	0.001	0.008	0.633
Transport	0.699	0.012	0.000	0.005	0.001	0.005	0.722
Electricity	8.120	1.111	0.001	0.174	0.633	0.621	10.660

Fig. 5. Primary-energy resources considered for CED estimation, with aggregated and disaggregated values.

Table 7
Inventory and CED values for each of the most contributing fossil Primary Energy Resources (PERs), with details on the contributions given by electricity, transports, all of the other processes, materials and phases.

PER	Inventory		CED	Electricity	Transport	Others
	Amount	UM	GJ	[%]		
Gas, natural	95.6	kg	5.41	97.9	0.9	1.2
Oil, crude	49.6	kg	2.27	53.7	26.3	20.0
Coal, hard	81.5	kg	1.56	93.9	3.0	3.1
Others (*)	66.6	kg	0.15	90.1	4.3	5.6

*These are the resources that contribute far less than the others and are represented by coal brown, peat and gas mine. ‘Others’ represent 1.60% of the total primary energy resources.

WF, production of LDPE from APW is far more sustainable than the virgin counterpart (Fig. 7), mainly because the recycled-LDPE granules is produced from a zero-burden resource, like the AWP utilised, rather than crude oil, as happens for the virgin equivalent. In detail, the indicators decreased of about 85% (CED), 69% (GWP$_{100}$) and 32% (WSI). This result contributes to validate recycling processes as viable solution to produce comparable-quality secondary raw materials for application in the market.

5. Conclusions and future perspectives

This study attained the proposed goal of evaluating the environmental impacts generated from the recycling of plastic films used for greenhouse cultivation system. To this end, a Life Cycle Assessment (LCA) approach was adopted and applied to an Italian firm located in Sicily, representative of the agricultural plastic waste (APW) collection and recycling.

The main conclusions related to the key indicators for the assessment of energy and environmental performance are the following:

- The CF was equal to 655.46 kgCO$_2$, showing that CO$_2$, CH$_4$ and N$_2$O are the most significant GHGs emitted, since they represent the 94.87%, and electricity was the largest contributor for each of these GHGs.

Table 8
Results from the WF-related damages assessment (endpoint approach), with percentages for the most contributing items within the system investigated.

Damage categories (DCs)	Damages assessment		Water	Electricity	Transport	Others
	UM	Amount	[%]			
Resources	MJ surplus	1.24E+01	69.29	21.07	2.07	7.57
Ecosystem Quality	PAF*m2yr	3.69E+00	61.97	29.05	1.95	7.03
Human Health	DALY	4.45E-06	65.32	25.33	2.03	7.31

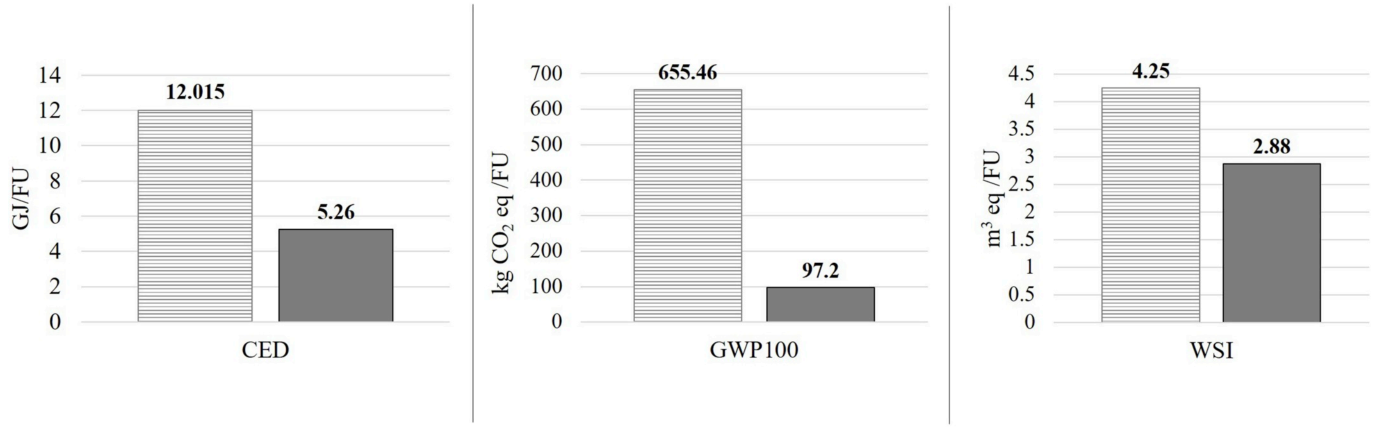


Fig. 6. Comparison based upon application of the wind power-based solution. The horizontal lines-column is referred to results from the first study, while the grey column reports results from the improved study.

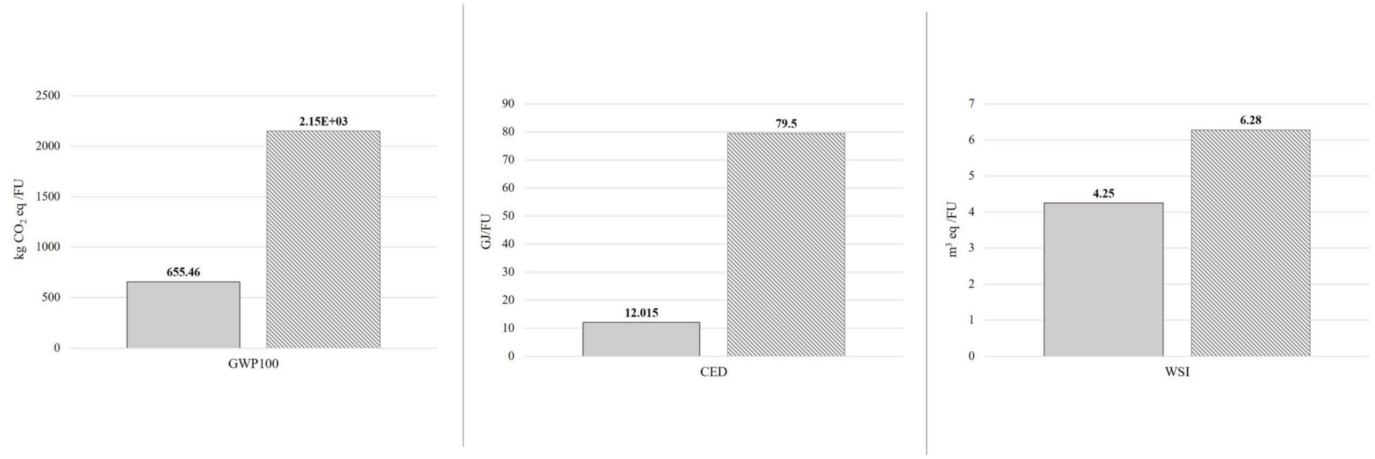


Fig. 7. Comparison between the recycled-LDPE (light grey column) and the virgin counterpart (diagonal lines-column).

- The CED was found 12.015 GJ per kg of recycled LDPE granules, with electricity contributing 88.72% and produced from fossil origins for 76.17%. Gas natural, crude oil, and hard coal represented 77.3% of the fossil primary-energy resources.
- The WSI was 4.15 m^3, with significant contributions coming from the cleaning steps of the process as operational water, and from the consumption of electricity as virtual water.

Other important results were achieved through two sensitivity analyses that were incorporated in this study. The first showed that the energy and environmental impacts associated with the electricity consumption could be reduced through the installation of a wind power plant, resulting in significant reductions in all the three indicators addressed. While, the second made it possible to understand that, despite the huge consumption of energy and water and the resultant GHG emissions characterising the recycling process, the production of recycled-LDPE resulted as far more sustainable than the virgin counterpart.

Recycled granules can be considered as intermediate products for the manufacture of bags, pipes, and other products for several applications. Such transformations generally take place in industries outside Sicily, resulting in potentially high environmental impacts, mainly related to transport. These impacts could be reduced, for example, using polyethylene granules for innovative construction applications, such as the drainage layer in green roofs, thus transforming it from an unfinished product into a finished product. The polyethylene granule as drainage material could be a cost-effective solution from an environmental, economic and social point of view, compared to those used for commercial green roofs (Cascone, 2019).

Furthermore, by considering the widespread diffusion of the eco-industrial technology, hydroponics, polyethylene granules could be used as an alternative substrate. In detail, this could contribute to reduce the use of inert substrates made of natural non-renewable materials and improve the environmental sustainability of the soilless crops production process in a circular economy perspective.

Finally, nowadays half of the plastic collected for recycling is exported to be treated in countries outside the EU, but some of these countries, such as China, has started to ban on plastic waste imports: therefore, it is extremely important to find adequate solutions for sustainable management of agricultural plastic waste. In Italy, the policy and management disposal of plastic films is unable to constructively deal with the related problems (Picuno et al., 2011). In this regard, results from this study could help local administrators, which play a crucial role for the plastics disposal management system, for putting forward adequate corrective actions to accomplish the European Commission Directives, with the aim of contributing transforming Europe into a more circular and resource efficient economy. In this context, the use of a new generation of bio-polymers for covering films, e.g., recycled-LDPE, represents an alternative and sustainable solution of agricultural plastic use concerns, feeding the transitions towards sustainable models of circular economy.

Contributions of authors

Dr. Stefano Cascone conceived and designed the research, collected the data from the firm managers and worked on introducing and presenting the topic addressed; Dr. Carlo Ingrao and Dr. Francesca Valenti co-worked to both LCA development and result analyses, interpretation and improvement; Prof. Simona M.C. Porto coordinated the author team, defined the structure of the paper and revised it.

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