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

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:

Cascone S., Ingrao C., Valenti F., Porto S.M.C. (2020). Energy and environmental assessment of plastic granule production from recycled greenhouse covering films in a circular economy perspective. JOURNAL OF ENVIRONMENTAL MANAGEMENT, 254, 1-11 [10.1016/j.jenvman.2019.109796].

Availability:

This version is available at: https://hdl.handle.net/11585/935084 since: 2023-07-17

Published:

DOI: http://doi.org/10.1016/j.jenvman.2019.109796

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(Article begins on next page)

Elsevier Editorial System(tm) for Journal of

Environmental Management

Manuscript Draft

Manuscript Number:

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

Article Type: Research Article

Keywords: greenhouse cultivation; agricultural plastic waste; LCA; secondary raw material; LDPE-granules.

Corresponding Author: Dr. Francesca Valenti, Ph.D.

Corresponding Author's Institution: University of Catania

First Author: Stefano Cascone

Order of Authors: Stefano Cascone; Carlo Ingrao; Francesca Valenti, Ph.D.; Simona M.C. Porto

Abstract: Plastic films can be considered as a high-value auxiliary material in agriculture with multiple important uses to fulfil, including greenhouse coverage. 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 increase in the demand for these films to be treated as wastes after usage posed relevant environmental challenges as related to consumption of Non-Renewable Primary Energy (NRPE) resources and emission of Greenhouse Gases (GHGs). Environmental analysis is needed to find and follow cleaner paths for the management and treatment of this 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 the agricultural plastic waste (APW) collection and recycling of Low-Density Polyethylene (LDPE) granules. The results showed that electricity consumption for the whole process is the most NRPE resource demanding and the most GHG emitting input item, and APW cleaning is the most water demanding phase within the system. Potential improvements could be achieved through a change in the energy source, by shifting from fossil to renewable. 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	Energy and environmental assessment of plastic granule production from recycled greenhouse
2	covering films in a circular economy perspective
3	
4	Stefano Cascone <sup>a</sup> , Carlo Ingrao <sup>b</sup> , Francesca Valenti <sup>c</sup> <sup>*</sup> , Simona M.C. Porto <sup>c</sup>
5	<sup>a</sup> Department of Civil Engineering and Architecture, University of Catania, Via Santa Sofia 64,
6	95123, Catania, Italy
7	<sup>b</sup> Faculty of Engineering and Architecture, Kore University of Enna, Cittadella Universitaria -
8	94100 Enna, Italy
9	<sup>c</sup> Department of Agriculture, Food and Environment (Di3A), University of Catania, Via S. Sofia,
10	100 - 95123 Catania, Italy
11	
12	* Corresponding author: Francesca Valenti, email: francesca.valenti@unict.it
13	



### Dipartimento di Agricoltura, Alimentazione e Ambiente

Catania, August 01, 2019

Editor-in- Chief

Journal of Environmental Management

Dear Editor,

here I enclose the manuscript of the paper "Energy and environmental assessment of plastic granule production from recycled greenhouse covering films" authored by Stefano Cascone, Carlo Ingrao, Francesca Valenti, and Simona M.C. Porto for your consideration to publish it in Journal of Environmental Management.

Please know that I am the corresponding author of the paper and so the person to whom address any kind of information related to this paper's submission process.

All authors have seen and approved the manuscript and have contributed significantly for the paper.

The manuscript is about 6600 words and contains 8 figures and 8 tables.

Di3A

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We hope you will find the paper to be suitable for Your magnificent Journal and you will subsequently send it out for review, so that we will be provided constructive review comments enabling improvement of the paper.

Sincerely

Ph.D. Eng. Francesca Valenti (Corresponding Author) Department of Agriculture, Food and Environment University of Catania via S. Sofia 100, 95123 Catania, Italy, e-mail address: francesca.valenti@unict.it mob. +39 3348066812

Via S. Sofia, 100 95123 Catania (Italy) Tel. 0957147111 Fax 0957147605 P.IVA n.02772010878

- Single-issue LCA was applied to recycled greenhouse covering films
- The functional unit was chosen to be 1 ton of produced LDPE-granules
- Primary and secondary data were inventoried
- Environmental criticalities were highlighted
- Sensitivity analyses were carried out to identify potential improvements

#### 1 Energy and environmental assessment of plastic granule production from recycled

#### 2 greenhouse covering films in a circular economy perspective

- 3
- 4 Abstract

5 Plastic films can be considered as a high-value auxiliary material in agriculture with multiple 6 important uses to fulfil, including greenhouse coverage. Such an application enables several 7 benefits and, therefore, it is going through an important upsurge, especially in regions where 8 protected crop cultivation is highly widespread. However, the increase in the demand for these films 9 to be treated as wastes after usage posed relevant environmental challenges as related to 10 consumption of Non-Renewable Primary Energy (NRPE) resources and emission of Greenhouse 11 Gases (GHGs). Environmental analysis is needed to find and follow cleaner paths for the 12 management and treatment of this Agricultural Plastic Waste (APW), especially in the light of the 13 gap currently existing in the specialised literature.

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Keywords: greenhouse cultivation; agricultural plastic waste; LCA; secondary raw material;
LDPE-granules

29

### 30 1 Introduction

31 Plastic films are utilised in greenhouse cultivation system as covering materials, in the form of 32 transparent sheets for under-tarp moisture collection or as black sheets for crops mulching 33 (Granadosa et al., 2012). With regard to covering materials in greenhouse cultivation system, usage 34 of plastic films has been increasing since the middle of the twentieth century due to several benefits such as: increase in crop yield; earlier harvest; reduced consumption of both herbicides and 35 36 pesticides; frost protection; and water conservation (CPCB, 2016). By analysing official statistical 37 data (Istat, 2018), a large amount of plastic films was found as being utilised in the Mediterranean 38 countries where protected crops are widely cultivated (Scarascia-Mugnozza et al., 2012). In detail, 39 the consumption of plastic films as greenhouse and low tunnel covering material is about 72,000 40 and 75,000 tons per year, respectively (Plastics Europe, 2016). Because of direct exposure to both 41 solar radiation and wind, greenhouse plastic coverings are replaced every 6 to 45 months (Barnes et 42 al., 2009; Scarascia-Mugnozza et al., 2012; Nanna et al., 2018). At the end of their useful life, these 43 covers are taken off and treated as waste in two different ways: one is about disposing them of in 44 landfills, often equipped with energy recovery systems; while the other regards recycling them into 45 secondary raw materials for a wide range of applications, including rubbish bags and boxes, so contributing to reduction of the environmental impact overall associated with the film life cycle 46 47 (Montero et al., 2014; Aryan et al., 2019). Unfortunately, to-date, around 50% of plastic wastes 48 generated by agricultural activities is treated in landfills, so emphasising upon the urgent need to 49 find and follow alternative, more sustainable routes (Briassoulis et al., 2013).

50 In Italy, each year, more than 350,000 t of agricultural plastic materials are utilised with a 51 consequent post-consumption material flow of about 200,000 t (Picuno et al., 2012). With regard to

protected cultivation areas, more than 2 million hectares are covered by greenhouses (Istat, 2018),
i.e. approximately 21% of the whole cultivated surface.

54 In this context, given the relevance of plastic film amount to be collected and recycled, evaluations 55 would be desirable to check upon energy-efficiency and sustainability related issues of raw materials obtained from recycled greenhouse covering films: Life Cycle Assessment (LCA) could 56 57 be one valid tool for such a purpose. As a matter of fact, it has been used by authors like 58 Horodytska et al. (2018), to identify and pursue the best environmentally performing waste 59 treatments among a set of alternatives. In details, the authors reviewed previously published LCAs 60 on waste management. While several LCA studies were carried out in different counties to assess 61 the municipal solid waste management, only few LCAs were focused upon flexible plastic film 62 waste management. According to the authors, this can be attributed - even only in part - to a lower 63 degree of sorting and recycling technologies development as compared with rigid plastics and the 64 modelling of e.g. shredding, washing, and drying operations is required to better understand and 65 improve the plastic films recycling processes. Gu et al. (2017) presented a detailed LCA 66 investigation on plastic from various sources, such as agricultural wastes, by analysing a recycling 67 company in China. The results demonstrated that the extrusion process was the primary process in 68 determining the overall impacts of recycled plastic production, while the introduction of fillers and 69 additives contributed the most significant part in the environmental impacts associated with 70 recycled composite production. Finally, Hottle et al. (2017) explored the impacts associated with 71 the production and disposal of biopolymers compared to fossil-based plastics by means of LCA. 72 The authors found that recycling resulted 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 the production or recycling process of flexible film used for agricultural purposes. Moreover, another gap stays in the fact that, though mechanical recycling of agricultural post-consumer films is highly recommended because of the high amount of homogenous, single polymer waste available 3 (Martínez-Lera et al., 2013), to the authors' knowledge, no research studies have been conducted
thus far to assess the environmental impact deriving from such recycling process.

80 This research was designed to contribute filling those two gaps, with the final objectives of 81 stimulating creation of cleaner paths for plastic waste disposal, as well as of enriching the current 82 specialised literature with findings obtained and lessons learned.

83 It reports upon a combined evaluation of environmental issues, like consumption of water and
84 energy, and resultant emissions of Greenhouse Gases (GHGs), arising from manufacturing plastic
85 granules by utilising Agricultural Plastic Waste (APW) as a zero-burden material input.

A Sicilian firm operating in the sector was positively involved in giving all technical support to this author team as needed for development of the 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 14040-44:2006 (ISO, 2006a, ISO, 2006b) and applied to a Sicilian firm, representative of the agricultural plastic waste (APW) collection and recycling.

92 Apart from the above-reported introduction, the study was conducted through the framework93 depicted in Fig.1.



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2

#### Fig.1. Study content framework

97 2.1 Study area

Materials and methods

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).

Within Sicily, Ragusa is the province with the largest protected cultivation area (Arcidiacono and Porto, 2010), which covers about 470,000 ha and is nearly 68% of the protected cultivation of the whole region (Istat, 2018). In particular, that 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 increase in supply chains being implemented for manufacturing and distribution of plastic covering films, especially in those parts of Sicily (e.g., the province of Ragusa) where protected crop production was documented to be significant. However, to meet the necessary demand for those films to be treated as waste after usage, those chains are increasingly expanding to incorporate industrial plants for sustainable treatment of those films at the end of their service life, so reducing harmful consequences to the environment and to the health of humans. As the result of 110 this, several firms have been founded over last thirty years or so, to deal with recycling of post-use 111 covering films, so to convert them into value-added material commodities in line with the principle 112 of circular economy. One of those firms was involved to technical support this study development: its geographical position within the province of Ragusa was depicted in Figure 2. It collects and 113 114 recycles Agricultural Plastic Waste (APW) to obtain Low-Density Polyethylene (LDPE) granules, 115 which find application as a secondary raw material in a wide range of sectors. These recycled 116 granules are generally characterised by quality rates that are highly comparable to the virgin 117 counterparts and, therefore, are suitable for manufacturing of printed materials, pipes and 118 bituminous membranes, and new films (Aryan et al., 2019).

119

120

#### Table 1. Cultivated and greenhouse surfaces in Italy.

Italian regions	Cultivated surface (TCS)	Green	nhouse e (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	5,891.0	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	1,665.4	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	4,541.0	0.8%
Tuscany	846,496.7	69,648.7	8.2%
Umbria	354,323.1	5,562.0	1.6%
Valle d'Aosta	34,393.4	130.0	0.4%
Veneto	551,923.1	169,525.7	30.7%
Total	10142,334.2	2164,696.6	21.3%

121

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

124

126 2.2 Description of the analysed industrial process

127 The production process of the considered firm starts with supply of APWs, which is entirely 128 collected from the surrounding areas and stored before being processed (Figure 3). APW is initially 129 subjected to grinding and to a first phase of pre-washing and spinning. After these phases, all 130 macroscopic impurities are eliminated through decantation in a water tank. The post-use water is 131 treated in an adjacent plant and stored in tanks before being pumped back to the LDPE-granule 132 production process, so it continuously feeds the recycling process.

133 The sludge resulting from the wastewater treatment is decanted and extracted from the bottom of 134 the tanks for the dehydration process on drying beds. Next, the APW goes through a subsequence of 135 processes to eliminate all the impurities and humidity within the material by washing, drying, and milling. During the final step of the entire transformation chain, material (in small pieces) is melted,
extruded and stored in silos before marketing and distribution.

138

139 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 14040-44:2006 (ISO, 2006a, ISO, 2006b) and organised in the standard phases, i.e. Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Life Cycle Interpretation. The development of each of these phases was discussed in the sections below.

145

#### 146 2.3.1 Goal and scope definition

The study was developed by following the LCA standard framework and the LCIA phase was focused upon single issues, such as water consumption, primary-energy sources exploitation, and GHG emissions. In fact, based upon the inventory analysis, they 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 as they are worldwide known as key indicators for the assessment of energy and environmental performance.

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

As regards the system boundaries (see Figure 3), they were defined to include: 1) APW acquisition, pre-treatment and transformation into the reference finished-product (1t recycled-LDPE); 2) preparation and acquisition of auxiliaries, oils, and energy; 3) the treatments of all waste materials 8 as generated by the recycling process; and 4) the annexed plant for treatment and recirculation ofthe APW-cleaning water.

164 Those boundaries were designed based upon information provided by the supporting firm to clearly highlight the material and energy flows throughout the investigated chain, which enabled 165 166 connecting the up-stream processes to the down-stream ones. Furthermore, as emerges from Figure 167 3, all transports for input material supply and for delivery of the wastes generated by the process to treatment were considered in the assessment. Only the recycled-LDPE distribution was excluded 168 169 because it was considered as pertaining to the utilisation phase and, therefore, the downstream 170 border of the system was set at the firm exit gate. All transport flows considered were detailed in 171 the following section, together with the related diesel consumptions and Ecoinvent modules used 172 for the system assessment based upon information provided by the firm.



Figure 3. Boundaries of the system investigated.

### 175 2.3.2 Life cycle inventory (LCI)

This is the key phase of any LCA 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., 2018).

In this context, since it comes to investigation of a system being highly interconnected with the local territory, the LCI was centred upon collection of site-specific data (primary data), regarding typologies and amounts of both inputs and outputs. A specific questionnaire was developed to be filled in through interviews with technicians and to gather firm-management related information, like main structural and economic features; production system; the product obtained (i.e., the recycled granule), and the wastes to be treated (Valenti et al., 2016).

186 The questionnaire was organised into five different parts: i) a general section containing questions 187 aimed at getting information about the input materials, such as water and covering plastic films (the 188 amount of product to be processed); ii) the second section, 'electricity consumption', for acquiring 189 information on the type of process and its electricity consumption, the techniques and the 190 machinery utilised; iii) the third section aimed to acquire data related to the production process, i.e. 191 the type and amount of the obtained products and which kind of auxiliary materials were adopted 192 during the process; iv) the waste disposal section was aimed to collect information about typologies 193 and quantities of by-products and wastes obtained during the production and which kind of disposal 194 processes was adopted; v) the last section, 'supplying section', contained information related to the 195 logistics phases, before, during and after process production. In detail, in this section of the 196 questionnaire, information about distances in kilometres were required to detail as much as possible 197 the logistics phase with regard the transport flows, which often in Sicily region represent a key 198 factor for managing sustainable processes.

199 Primary data were combined with background ones extrapolated from the database of200 acknowledged scientific value and relevance, like Ecoinvent v.3 as available in SimaPro 8.1. This

• •

201 database was used because it is recognised worldwide as accommodating most of the background 202 materials and processes often used in LCAs (Frischknecht and Rebitzer, 2005), which contributes 203 making it suitable for the modelling of industrial systems like the one investigated in this study. 204 Data collection regarded a 3-year campaign between 2015 and 2017 and information used for the 205 LCI were reported in Table 2 and Table 3. In detail, Table 2 shows that data related on LDPE 206 granules production differ only about 5% during the three years analysed, confirming the 207 standardisation of the process. Therefore, the LCA developed in this study is representative of the 208 production process of LDPE granules from recycled greenhouse covering films.

209

Table 2. Data collected at the LDPE granules production site from 3-year campaign and the annual average
 base. All data reported are referred to the annual production.

Outputs					
14					
Items	2015	2016	2017	UM	
	Products				
LDPE granules	11445	11536	12359	ton	
Wa	aste stream	5			
Inert	5923	6213	6988	ton	
Exhausted mineral oil	3778	4000	4889	kg	
Steel	11000	21800	24290	kg	
	Inputs				
Itoma		UМ			
nems	2015	2016	2017	UM	
Material an	d energy co	mmodities			
Underground water without					
treatment (production and	43051	51617	45528	ton	
distribution)					
Aluminium sulphate	24600	29760	20860	kg	
Mineral oil	3778	4000	4889	kg	
Steel	11000	21800	24290	kg	
Diesel*	34500	37000	35000	1	
Electricity	1.115E7	1.094E7	1.011E7	kWh	
Melt filter band	15000	18000	24000	m	

\*All emissions related to Diesel combustion were extrapolated from Ecoinvent and referred to the Diesel consumption volume

### Table 3. Transport flows related to the system investigated, calculated from average values.

Transport	Raw material	Waste	Flow	Diesel consumption	- Ecoinvent module
	Kuw material	TT ubie	(kgkm)	( <b>kg</b> )	
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
ТЗ	Mineral oil	-	39.38	4.29	Transport, freight, lorry 7.5-16 metric ton, EURO5 {RoW}  transport,
15	-	Exhausted oil	132.82	14.48	freight, lorry 7.5-16 metric ton, EURO5   Alloc Def, S
T4	Steel wire	-	2.75	0.30	Transport, freight, lorry 16-32 metric ton, EURO5 {RoW}  transport,
	-	Iron waste	4.893	0.53	- freight, lorry 16-32 metric ton, EUROS   Alloc Def, S

217 For the assessment, the collected data were averaged to obtain a yearly LDPE-granule production of 218 about 11780 tons and an electricity consumption of about 1.11E7 kWh, i.e. approximately 950 kWh 219 are required to produce 1 ton of LDPE-granules. In Table 3, forward and reverse transport flows 220 were detailed and the chosen Ecoinvent modules were reported. All the data recorded and averaged 221 (Table 2 and Table 3) were then elaborated to be referred to the system FU, namely 1 ton of 222 recycled LDPE, and reported in Table 4.

223

Outputs	1	
Items	Average U.M/ton <sub>LDPE</sub>	UM
Products		
LDPE granules	1.000	ton
Waste stream	ns	
Inert	0.521	ton
Exhausted mineral oil	0.358	kg
Steel	1.615	kg
Inputs		
Items	Average U.M/ton <sub>LDPE</sub>	UM
Material and energy commodities		
Underground water without treatmen (production and distribution)	t 3.882	ton
Aluminium sulphate	2.128	kg
Mineral oil	0.358	kg
Steel	1.615	kg
Diesel	3.014	1
Electricity	942.275	kWh
	1.613	m
Melt filter band		
Melt filter band Total of transports (as sum of	f values in Tables	3)
Melt filter band <i>Total of transports (as sum of</i> Raw material supply	f values in Table3 7.364	() kgkn

224 d LDPE

226 Considering the uncertainty and variability in LCA studies, it is important to determine both the 227 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 uncertainties, 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.

232

### 233 2.3.3 Life cycle impact assessment (LCIA)

Within the LCIA step, two approaches of characterisation, i.e. mid-point and end-point, can take place along the pathway of an impact indicator. According to De Benedetto and Klemes (2010), LCIA phase was carried out by aggregating the output flows, previously quantified in the LCI phase, in a limited set of Impact Categories (ICs), by adopting a mid-point approach. Then, the study was extended to the damage assessment as part of the end-point approach, and the ICs were grouped into Damage Categories (DCs) which are the environmental compartments that suffer the damage caused by the LDPE granule production during its life cycle.

To this aim, the authors accessed and used the classification/characterisation framework provided by three single-issue impact assessments i.e., CF, CED, WF, available in Simapro 8.1, to evaluate the created inventory dataset (Table 4).

244

#### 245 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 weighted 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). The weighting 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<sub>2</sub> equivalent (CO<sub>2eo</sub>) (Wiedmann and Minx, 2008, Maalouf et al., 2018).

252	In this study, among the mid-point approaches the IPCC 2013 GWP 100a method (IPCC, 2013) was
253	used, which was developed by the Intergovernmental Panel on Climate Change and it contains the
254	climate change factors of IPCC with a timeframe of 100 years.
255	According to eq. (1) by Maalouf et al. (2018):
256	$CF_i = \sum_j GWP_j * e_j \tag{1}$
257	where:
258	• $e_j$ is the emission (in mass unit) of the j-th GHG associated with the given process;
259	• $GWP_j$ is the Global Warming Potential of the j-th GHG for a 100-year temporal horizon
260	(GWP100), which is required for any CF assessment.

Table 5 reports the GWP100 of the GHGs that were considered by the authors as the most representative of the investigated system and extrapolated by Simapro 8.1.

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264

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

GHG	Formula	GWP <sub>100</sub> [gCO <sub>2eq</sub> /gGHG]
Carbon dioxide	CO <sub>2</sub>	1
Methane	$CH_4$	28
Nitrous oxide	$N_2O$	265

265

At the end-point approach, the computed impacts were transformed into damages 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, for quantification of environmental damages that the emissions of the most significant GHGs generate upon the DCs, i.e. Climate Change (CC), Human Health (HH) and Ecosystem Quality (EQ).

### 271 2.3.3.2 Cumulative Energy Demand (CED)

The CED is an impact indicator that expresses the energy utilisation 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 based upon the 'Cumulative Energy 275 276 Demand'method described in the Ecoinvent database. The aim of the method is both to calculate the 277 direct and indirect energy used throughout the life cycle of the LDPE-granules and differentiate 278 among renewable and non-renewable energy sources (Huijbregts et al., 2006). Therefore, this 279 method allows the evaluation of environmental effects related to both the emissions and energy 280 consumption (Girgenti et al., 2013). In detail, the method includes the direct and indirect uses of 281 energy and it is organised in eight different impact categories. Normalisation or weighting data are 282 not included in the method. In this study, the CED was calculated by including both non-renewable 283 (from fossil fuels, nuclear, and non-renewable biomass) and renewable (from wind, solar, 284 geothermal, and water) energy sources, associated to each input considered in the LDPE granules 285 production process.

286

#### 287 2.3.3.3 Water Footprint (WF)

288 Among the methods involved in LCA-based water footprint, the Water Footprint Assessment 289 (WFA) was adopted, according to Pfister et al. (2009). This method is centred upon computation of 290 the Water Stress Index (WSI), which calculates the water impact on the consumption-to-availability 291 perspective of freshwater deprivation, corresponding to the 'blue water' in the WFA methodology. 292 The Water Stress Index was used as a general screening indicator or characterisation factor for the 293 freshwater consumption at the mid-point approach for all three areas of protection: Resources, 294 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 295 296 Spriensma, 2001) were computed. In detail, Eco-indicator-99 was used for estimating the 17

environmental damages as the consequence of water consumption upon DCs, i.e. Resources (Re),
Human Health (HH) and Ecosystem Quality (EQ).

299

#### **300 3 Results and discussion**

301 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 to 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 Figure 4.



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307 308

## Figure 4. Emitted GHGs, with aggregated and disaggregated values

Two different results can be gathered from Figure 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 were grouped in the '*Others*' category since they contribute with less than 5% to the GHG emissions: 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.

316 From Figure 4 there is evidence that the most contributing phases are: the production and 317 distribution of electricity required for the process working and the transports (Table 3). Electricity, 318 in particular, is the largest contributor for each of GHG emissions, with percentage values (up to the 319 total ones) equal to: 88.02% (CO<sub>2</sub>); 91.90% (N<sub>2</sub>O); and 94.63% (CH<sub>4</sub>). Contribution from the 320 transport section is far lower and ranges from 2.74% in the case of CH<sub>4</sub> to 7.34% as per CO<sub>2</sub>-321 emission.

322 Mid-point results demonstrate that CF is equal to 655.46 kgCO<sub>2</sub>, which, based upon results shown 323 in Table 6, is due for the major percentage (91.18%) to CO<sub>2</sub>. As anticipated in the methodological-324 approach discussion, the study was extended to incorporate the damages assessment phase as part of 325 the end-point approach, so considering the environmental damage that each emitted GHG 326 considered causes to CC, HH and EQ. The end-point categories affected by the three GHGs were 327 reported in Table 6.

328

329

	Mid-point analysis*	En	ndpoint ana	lysis
CHC	Characterisation	Damages assessment		sment
GHG	<b>GWP</b> <sub>100</sub>	CC	HH**	EQ**
	kgCO <sub>2</sub> eq	kgCO2 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

Table 6. Mid-noint and end-point ment

\* IPCC 2013

\*\* values are referred to kg of emitted substance (ReCiPe Endpoint (E/E)

- 330
- 331 3.2 Cumulative Energy Demand assessment
- 332 The CED was found 12.015 GJ per kg of recycled-LDPE granules, with electricity contributing
- 333 88.72%, as evident from Figure 5. In addition, from this figure emerges that the electricity utilised
- 334 in the recycling process is 76.17% of fossil origins.



338

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

339 As shown in Table 7, gas natural, crude oil, and hard coal represent 77.3% of the overall amount of 340 fossil primary-energy resources, and so can be considered as the most consumed ones within the 341 process.

342 Electricity is the most impacting item, with the aforementioned energy resources exhibiting 343 comparable values in the range 90-98% as of Table 7, except for crude oil, with a far lower 344 contribution rate being around 54%. This should be attributed to the transport issue showing – as 345 expected - its greatest contribution (26.3%) in crude oil rather than in the other ones.

346

347 Table 7. Inventory and CED values for each of the most contributing fossil primary energy resources, with 348 details on the contributions given by electricity, transports, all of the other processes, materials and phases

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Primary Energy Resources	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.

The same was found for '*Others*', as they contribute a total of 20% to the CED associated with crude oil, which is far higher than that shown in the case of 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.

- 356
- 357 3.3 Water footprint assessment

At the mid-point approach, the WSI resulted equal to 4.15 m<sup>3</sup>, and 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 weigh the three DCs and identify the most affected one, because 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.

370

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

Damage categories	Damages assessment		Water	Electricity	Transport	Others
(DCs)	UM	Amount		[%	<b>[</b> ]	
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

#### **374 4 Interpretation and improvements**

375 The study highlighted that the electricity required by the process for 1 ton of recycled-LDPE 376 production (942.75 kWh) is the largest contributor to both the CF and CED, so emphasising upon 377 the importance to search for potential improvements. In agreement with the firm technicians, it was 378 understood that no solutions are viable at the plant level by improving the technical quality and 379 energy efficiency of machineries used in the production process. Therefore, electricity consumption 380 is with no doubt the major energy and environmental issue of the whole system. Nonetheless, the 381 energy/environmental burden associated with the electricity consumption may be reduced through a 382 change in the energy source, by shifting it from fossil to renewable. A valid solution could be to 383 install a wind power plant to cover the whole energy demand. In this regard, a first sensitivity 384 analysis conducted for the purpose highlighted significant reductions for all the three indicators that 385 have been addressed in this study, with CED and GWP<sub>100</sub> showing the greatest reduction of about 386 56% and 85%, respectively, as they are clearly most affected by electricity use (Figure 6). It should 387 be observed that this is just a preliminary evaluation that must be checked in terms of technical and 388 economic feasibility.



393 394 Figure 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. 

By contrast, no solutions were found to be viable for reduction of the water consumption demandedby the process in the cleaning steps.

399 Finally, to validate the energy and environmental sound of the recycled-LDPE granule, another 400 sensitivity analysis was conducted with the virgin counterpart of the LDPE granule, on the same 401 base of FU and system boundaries. In addition, a comparable quality level was assumed between 402 the two differently produced LDPE granules. It was found that, for all indicators considered in the 403 study, i.e. CF, CED and WF, production of LDPE from APW is far more sustainable than the virgin 404 counterpart (Figure 7), mainly because the recycled-LDPE granules is produced from a zero-burden 405 resource, like the AWP utilised, rather than crude oil as happens for the virgin equivalent. In detail, the considered indicators decreased of about 85% (CED), 69% (GWP<sub>100</sub>) and 32% (WSI). Such a 406 407 result contributes validating processes like this as viable for production of comparable-quality 408 secondary raw materials for application in the market.



#### 413 **5** Conclusion

The 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 environmentalperformance are the following:

- The CF was equal to 655.46 kgCO<sub>2</sub>, showing that CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O are the most significant GHGs emitted, since they represent the 94.87%, and electricity was the largest contributor for each of these GHGs.
- The CED was found 12.015 GJ per kg of recycled LDPE granules, with electricity
   contributing 88.72% 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<sup>3</sup>, with significant contributions coming from the cleaning steps of the
   process as operational water, and from the consumption of electricity as virtual water.

428 Other important lessons were learned through the two sensitivity analyses that were incorporated in 429 this study. The first showed that the energy and environmental impacts associated with the 430 electricity consumption could be reduced through the installation of a wind power plant, resulting in 431 significant reductions in all the three indicators addressed. While, the second allowed to understand that, despite the huge consumption of energy and water and the resultant GHG emissions 432 433 characterising the recycling process, the production of recycled-LDPE resulted as far more 434 sustainable than the virgin counterpart, mainly because it is produced from a zero-burden resource 435 rather than crude oil as happens for the virgin equivalent.

Such 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 26

transport. For example, using polyethylene granules for construction applications, such as for the drainage layer in green roofs, is an innovative way of using this material, transforming it from an unfinished product into a finished product. The polyethylene granule as drainage material could be a cost-effective solution compared to those used for green roofs, from an environmental, economic and social point of view.

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.

449

#### 450 Acknowledgements

This research was carried out within the research project: UPB: 5A722192127 (Piano per la ricerca 2016-2018 – 'Contributo della meccanica agraria e delle costruzioni rurali per il miglioramento della sostenibilità delle produzioni agricole, zootecniche e agro-industriali') which was financially supported by University of Catania. This research was partially funded by 'the Notice 5/2016 for financing the Ph.D. regional grant in Sicily' as part of the Operational Program of European Social Funding 2014–2020 (PO FSE 2014–2020).

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