Life Cycle Impact Assessment of Carrot Cultivation and Processing: An Italian Case Study for a Small Family Company in the Marche Region

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Abstract

Carrot environmental impact assessment was conducted using the Life Cycle Assessment (LCA) method (ISO 14040:2006; 14044:2006) and following Product Category Rules (PCR) on arable crops. SimaPro® has been used for impact assessment calculation. Goal and scope: the goal was to assess the impact of 1 kg of carrots for different packaging solutions. Life Cycle Inventory (LCI): was carried out with primary data provided by the farmers and by the processing company through interviews and consultation of official documents. Life Cycle Impact Assessment (LCIA): was carried out using CML_IA characterization model. Interpretation: results obtained were interpreted highlighting the phases of greatest impact through a contribution analysis, and the impact variability due to data uncertainties through an uncertainty analysis. The potential impact for the Global Warming (GW) category varies between $1.2 \times 10^{-1}$and 2.1×10^{-1} kg CO_2 eq, for Acidification (AC) between 7.04×10^{-4} and 1.06×10^{-3} kg SO_2 eq, for Ozone Depletion (OP) between 2.89×10^{-5} and 5.25×10^{-5} kg C_2H_4 eq, for Eutrophication (EP) between 2.19×10^{-4} and 3.05×10^{-4} kg PO_4^{3-}. The greatest impacts were recorded for products with smaller sizes (0.5 kg trays). For larger formats the most impactful phase is field cultivation while for the smaller ones is packaging. As far as transport is concerned, the greatest impact is on the product coming from Mesola and not from Sicily, this is due to greater loading efficiency of transportation from Sicily.

Keywords: LCA, Horticulture, Vegetables, Environmental sustainability, Comparative assessment.

1 Introduction

Sustainability in the food sector is considered increasingly important. The reasons are different: from the marketing point of view because consumers are increasingly careful to choose products with low environmental impact but above all because according to different studies the food and beverage sector is one of the most impactful (Tukker, 2006). In fact, food and drink cause about 20-30% of the environmental impact of private consumption and represent more than 50% regarding the impact for the eutrophication indicator. Many authors have demonstrated that the sector requires a consistent amount of water and energy (Beccali et al., 2009, Frankowska et al., 2019) and the production is often organized in complex processes and subprocesses with different impacts. Vegetables have an important role in human diet and have been subjected to impact assessment over the years (Beccali et al., 2009, Ilari and Duca, 2018, Frankowska et al., 2019a, Frankowska et al., 2019b) but only recently several studies were conducted about horticultural products that are considered potentially more impactful than other agricultural products (Wainwright et al., 2014). From FAOSTAT data the world carrot and turnip production in 2017 was over 42 million of tons. China is the first producer with 47% of total production. Italy is only at the 14^{th} place with 553000 tons produced. Considering only the European level Italy is the 6^{th} producer after UK, Ukraine, Poland, Germany and France. Considering the yield, Italy is at a medium level with 36 t/ha (FAOSTAT, 2017). This paper focuses on carrot analyzing the environmental impact from field production to industry gate. Goal of the study is to evaluate the environmental impact of 1 kilogram of carrots at the industrial gate and in different packaging forms. The main reason is to calculate the level of environmental sustainability of the functional unit. Another goal is to identify and propose possible mitigations to the manufacturing process with significant environmental impact.

2 Materials and Methods

LCA analysis was conducted following the reference standards (ISO, 2006a, ISO, 2006b)) and PCR on arable crops (EPD International, 2016).

2.1 Scope definition

The definition of the scope involves the deepening of the following issues:

- Description of the production system to be analyzed
  The first step is crop cultivation that takes place in fields located in 4 different Italian regions (Lazio, Abruzzo, Emilia-Romagna and Sicily). The total yearly surface cultivated is 33 ha with a yield of 80 t/ha. The cultivation is performed in continuous cropping system. Although this practice should be avoided the cultivation systems in Italy concerning the carrot are very intensive. This is due to the added value of the product compared to other crops and to the reduced size of the fields that hinder the organization of crop rotations.

Next step is transport to industry that is performed with a truck from the company excepted for the raw product from Sicily. In table 1 is reported the raw LCI table for transportation.

Table 1 LCI table for transportation (raw data referred to single trip with empty return)

	Distance (km)	Consumption diesel (kg/km)	Consumption urea (kg/km)	Gross capacity (kg)	Payload (kg)
Emilia-Romagna	300	0.28	0.015	13500	12695
Lazio	250	0.28	0.015	13500	12695
Abruzzo	150	0.28	0.015	13500	12695
Sicily	1000	0.28	0.015	25000	24650

The following step is the industry processing. The first elaboration is a cold storage not exceeding 6 days in winter and 24 hours in summer. Second elaboration is washing to remove soil and plant residues. It is performed with three machines. First, an immersion tank removes ground, precipitated on the bottom, and leaves floating on the top. In the second machine carrots pass through a washing and brushing system that removes all the remaining ground. The third machine is also a sorter that removes all the broken carrots and small pieces. A further elaboration is a manual selection of the material washed based on the dimension of single pieces; the smaller are intended for smaller size packaging, the bigger for up to 10 kg packaging size. A last elaboration is the packaging. The company produces 8 different formats: small bags of 0.5 and 1.0 kg; trays of 0.5 (2 types) and 1.0 kg; bags of 5.0 and 10.0 kg; chest of 10.0 kg.

- Production system functions
  The function of the system is to produce carrots in different packaging.
- Functional Unit (FU)
  Following PCR the FU has been set on 1 kg of carrots not considering the packaging mass.
- System boundaries
  The system boundaries have been set from cradle to industry gate. The analysis stops at industry gate.
- Allocation procedures
  For the study was used an allocation on mass basis for what concerning the residues produced in washing phase and for the different packaging solutions.
- Impact categories and calculation methods.
  The calculation method selected for this study is the CML_IA. The impact categories considered according to PCR are: Greenhouse gases emissions (GWP 100yr kg CO_2 eq), emission of acidifying substances (AC kg SO_2 eq), gas emissions active on ozone (POCP kg C_2H_4 eq), emissions of eutrophic substances (EP kg PO_4^{3-} eq). other indices considered are byproducts produced,

land use, human toxicity (HTP kg 1-4 DB eq), freshwater ecotoxicity (FTP kg 1-4 DB eq), use of water (kg H_2O/FU).

- Data quality requirements
  Data collected are primary and representative of the specific case study. The reference year is 2017. From the technological point of view the system under analysis has an average technology. All the data regarding field production, transportation and industry processing are primary data excepted water consumption that has been calculated as an average consumption from secondary data.
- Assumptions and limitations
  The main limitation of this study regards the estimation of water consumption. The water used in the washing process comes from artesian aquifers for which it is difficult to assess the actual quantity extracted. In addition to this the water is often reused making it recirculate between one machine and another without an actual measurement system.

2.2 Inventory

The inventory table is calculated by dividing the inventory value of each material and operation by the total final production considering the transformation efficiency. In table 2a, 2b and 3 are reported the results of LCI analysis for all the considered processes.

Table 2a LCI table referred to 1 kg of fresh processed product (cultivation input, emissions and primary output)

Input/output	amount/U	unit		Emission to soil	amount/U	unit
Land use (arable)	1.53x10^{-5}	ha		Pendimethalin	1.19x10^{-5}	kg
Soil plowing	1.38x10^{-3}	l	diesel	Chlorantraniliprol	4.56x10^{-8}	kg
Convexing	3.07x10^{-4}	l	diesel	Azoxystrobin	2.61x10^{-6}	kg
Sowing	1.84x10^{-4}	l	diesel	Copper	9.58x10^{-6}	kg
Seeds	9.20x10^{-5}	kg		Difenoconazole	1.30x10^{-6}	kg
Fertilization	9.20x10^{-4}	l	diesel	Azoxystrobin	2.61x10^{-6}	kg
Pesticide	5.37x10^{-4}	l	diesel	Lambda	1.30x10^{-7}	kg
Weeding	2.30x10^{-4}	l	diesel	Copper	9.58x10^{-6}	kg
Irrigation	6.14x10^{-3}	l	diesel	**Emission to water**		
Harvesting	9.20x10^{-4}	l	diesel	Nitrates	2.83x10^{-4}	kg
Bins handling	4.60x10^{-4}	l	diesel	Phosphorus total	9.11x10^{-6}	kg
Water (irrigation)	3.83	l		Phosphorus	2.81x10^{-7}	kg
Emission to air				Phosphorus river	7.02x10^{-7}	kg
NH3	7.25x10^{-5}	kg		Phosphorus river	8.13x10^{-6}	kg
N2O (direct)	1.01x10^{-5}	kg		Pendimethalin	6.98x10^{-7}	kg
NO (direct)	6.42x10^{-6}	kg		Chlorantraniliprol	2.68x10^{-9}	kg
N2O (indirect)	5.20x10^{-6}	kg		Azoxystrobin	1.53x10^{-7}	kg
N2O (residues)	1.27x10^{-7}	kg		Copper	5.64x10^{-7}	kg
N2O (leaves)	2.84x10^{-5}	kg		Difenoconazole	7.67x10^{-8}	kg
Pendimethalin	1.40x10^{-6}	kg		Azoxystrobin	1.53x10^{-7}	kg
Chlorantraniliprol	5.37x10^{-9}	kg		Lambda	7.67x10^{-9}	kg
Azoxystrobin	3.07x10^{-7}	kg		Copper	5.64x10^{-7}	kg
Copper	1.13x10^{-6}	kg		**Primary output**		
Difenoconazole	1.53x10^{-7}	kg		Carrots	1.0	kg
Azoxystrobin	3.07x10^{-7}	kg		Carrots (losses)	1.63x10^{-3}	kg
Lambda	1.53x10^{-8}	kg		Vegetal residues	1.53x10^{-1}	kg
Copper	1.13x10^{-6}	kg				

Table 2b LCI table referred to 1 kg of fresh processed product (transportation and industry processing)

Input	amount/U	unit	Transport to plant			
Fertilizers			Destination	distance		
Dap eurochem®	1.53x10^{-3}	kg	300	km	320.71	kgkm
Agromaster®	2.30x10^{-3}	kg	250	km	267.26	kgkm
Entec perfect®	2.30x10^{-3}	kg	150	km	160.35	kgkm
N total	9.43x10^{-4}	kg	1000	km	1069.0	kgkm
P total	1.42x10^{-3}	kg	Bin HDPE		6.91x10^{-3}	kg
K total	6.21x10^{-4}	kg	Bigbag (Sicily)		3.53x10^{-5}	kg
Pesticides			Input	amount/U	unit	
Water (pesticides)	7.36x10^{-2}	l	Storage			
Stomp aqua®	3.07x10^{-5}	l	input	average		
Altacor®	1.53x10^{-6}	kg	Electricity	8.02x10^{-3}	kWh	
Ortiva®	1.22x10^{-5}	l	input	average		
Ossiclor 35WG®	3.22x10^{-5}	kg	Pre-washing	8.61x10^{-5}	kWh	
Score 25 EC®	6.13x10^{-6}	l	Washer/brusher	1.18x10^{-4}	kWh	
Ortiva®	1.22x10^{-5}	l	Sorter	1.08x10^{-4}	kWh	
Karate zeon®	1.53x10^{-6}	l	Water pumping	1.62x10^{-4}	kWh	
Ossiclor 35WG®	3.22x10^{-5}	kg	Water	2.32x10^{+1}	l	
			output			
			Residues (feed)	2.32x10^{-2}	kg	
			Herb and stones	2.79x10^{-3}	kg	
			Ground	3.83x10^{-2}	kg	
			Processing			
			Input	average		
			Conveyors	1.10x10^{-4}	kWh	
			output			
			Residues (feed)	4.63x10^{-3}	kg	

Table 3 LCI table for packaging referred to FU for each format

	Tray 1 kg	Tray 0.5 kg type 2	Tray 0.5 kg type 1	Bag 5 kg	Bag 10 kg	Bag 1 kg	Small bag 0.5 kg	Box 10 kg
LDPE tray[1]	$1.6x10^{-2}$	$2.0x10^{-2}$						
Printed paper[1]	$5.1x10^{-4}$	$1.0x10^{-3}$	$1.0x10^{-3}$	$1.0x10^{-4}$	$5.0x10^{-5}$	$5.0x10^{-4}$	$1.0x10^{-3}$	$6.1x10^{-5}$
packaging	$1.0x10^{-3}$	$2.0x10^{-3}$	$2.0x10^{-3}$	$3.1x10^{-3}$	$3.8x10^{-3}$	$3.5x10^{-3}$	$3.0x10^{-3}$	$2.6x10^{-3}$
Polystyrene[1]			$8.0x10^{-3}$					
Electricity[2]	$1.3x10^{-3}$	$2.6x10^{-3}$	$2.6x10^{-3}$			$8.0x10^{-4}$	$1.6x10^{-3}$	

[1] u.m. kg/FU, [2] u.m. kWh/FU

3 Results

In table 4 is reported the impact for 8 different types of packaging and for 11 impact categories.

Table 4 Total impact for 1 kg of carrots in different packaging formats

Category	Unit	Tray 1 kg	Tray 0.5 kg type 2	Tray 0.5 kg type 1	Bag 5 kg	Bag 10 kg	Bag 1 kg	Small bag 0.5 kg	Box 10 kg
ADP	kgSb eq	5.49x 10^{-7}	5.60x 10^{-7}	5.41x 10^{-7}	5.10x 10^{-7}	5.11x 10^{-7}	5.21x 10^{-7}	5.27x 10^{-7}	5.17x 10^{-7}
ADP (fossi	MJ eq	2.54	2.97	2.05	6.13x 10^{-1}	6.61x 10^{-1}	1.09	1.26	1.05
GWP 100yr	$kgCO_2$ eq	1.88x 10^{-1}	2.06x 10^{-1}	1.79x 10^{-1}	1.16x 10^{-1}	1.18x 10^{-1}	1.35x 10^{-1}	1.42x 10^{-1}	1.32x 10^{-1}
ODP	kgCFC-11 eq	8.16x 10^{-9}	8.86x 10^{-9}	7.36x 10^{-9}	5.02x 10^{-9}	5.04x 10^{-9}	5.79x 10^{-9}	6.17x 10^{-10}	5.70x 10^{-9}
HTP	kg1,4-DB eq	2.63x 10^{-2}	2.94x 10^{-2}	2.39x 10^{-2}	1.49x 10^{-2}	1.50x 10^{-2}	1.80x 10^{-2}	1.96x 10^{-2}	1.71x 10^{-2}
FEP.	kg1,4-DB eq	4.27x 10^{-2}	4.54x 10^{-2}	4.04x 10^{-2}	3.17x 10^{-2}	3.18x 10^{-2}	3.45x 10^{-2}	3.60x 10^{-2}	3.41x 10^{-2}
MEP	kg1,4-DB eq	6.55x 10^{+1}	7.64x 10^{+1}	5.88x 10^{+1}	2.84x 10^{+1}	2.86x 10^{+1}	3.95x 10^{+1}	4.64x 10^{+1}	3.56x 10^{+1}
TEP	kg1,4-DB eq	1.71x 10^{-4}	1.87x 10^{-4}	1.56x 10^{-4}	1.06x 10^{-4}	1.06x 10^{-4}	1.23x 10^{-4}	1.32x 10	1.20x 10^{-4}
POCP	kgC_2H_4 eq	4.78x 10^{-5}	5.26x 10^{-5}	4.66x 10^{-5}	2.89x 10^{-5}	2.92x 10^{-5}	3.49x 10^{-5}	3.79x 10^{-5}	3.36x 10^{-5}
AP	$kgSO_2$ eq	9.88x 10^{-4}	1.06x 10^{-3}	9.40x 10^{-4}	7.12x 10^{-4}	7.18x 10^{-4}	7.85x 10^{-4}	8.17x 10^{-4}	7.66x 10^{-4}
EP	$kgPO_4^{3-}$ eq	2.86x 10^{-4}	3.03x 10^{-4}	2.70x 10^{-4}	2.17x 10^{-4}	2.17x 10^{-4}	2.35x 10^{-4}	2.44x 10^{-4}	2.31x 10^{-4}

From result analysis smaller format shows the greatest impacts. This is due to the larger use of packaging material, in relation to the same quantity of product. For larger format products the impact per FU is lower because of the less use of primary packaging.
Considering all the impact categories on a contribution analysis for the different products the major contributor is the open field production, the second contributor is the packaging phase. Transportation accounts for a limited impact, significant only for GWP, POCP, AP, EP. The other processing phases (temporary cool storage, washing and sorting) contribute for less than 1% for almost all the categories. As an example, contribution analysis for the two most impactful products is reported in figure 1.

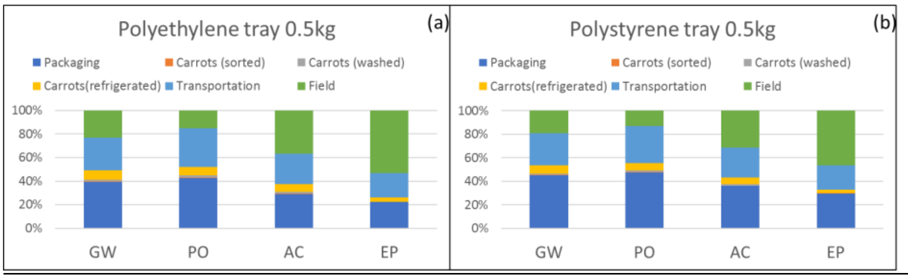

Fig. 1 GWP, POCP, AP, EP for Polyethylene tray 0.5 kg(a) and Polystyrene tray 0.5 kg (b).

The comparison reported in figure 1 is interesting because considering two alternative products. In fact, industry customers require different formats depending on final purchasers (1kg formats for large-scale retail trade, 10 kg for small markets) the 0.5 kg formats are completely alternative, and the two solutions depend only on marketing choices. Polyethylene tray carrots are from 3 to 31% less impactful. This difference is all due to the different packaging solution. In order to assess the impact variability due to the data uncertainties, a Montecarlo analysis was conducted for open field and industry phases. For open field the variability results between 5 and 23% and the only data uncertainties regard emission from fertilizers (IPCC emission factors).
For industry phase the impact variability is lower and ranges between 7 and 11%. In this case the variability is mainly due to energy (from country mix) and background processes of LCA database (included in SimaPro software).

4 Conclusions

Considering scientific literature the results of the present study are comparable or slightly lower if compared with other specific study like (Raghu, 2014).
The difference between this case study and the one cited lie in the transport phase which has much more significant incidence because carrots are transported from Sicily up to Finland. The other phases including cultivation and processing are essentially similar in the two studies. From the contribution analysis it was possible to observe which are the main causes for the absolute impact. The cultivation phase has the greatest impact, followed by packaging and transport. In cultivation there are in fact a long series of direct emissions derived both from the various field operations, but above all also from the use of fertilizers and plant protection products. In transport, the direct emissions due to fuel combustion are equally important, while the packaging assumes a considerable importance for the use of high amounts plastic material compared to the product mass. The impacts related to the refrigeration of the carrots, to the washing and to the calibration together presented a rather limited impact compared to the other phases.

Acknowledgements The activity presented in the paper has been conducted inside a bachelor's degree research program. The authors are grateful to the company C.I.L.P.O. DI VECCHIARELLI MARIO & C. S.N.C. that provided the necessary data for the analysis.

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