Research Article

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Cradle-to-grave carbon footprint of dried organic pasta: assessment and potential mitigation measures

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Abstract

BACKGROUND: In several Environmental Product Declarations, the business-to-business carbon footprint (CF_{CDC}) of durum wheat semolina dried pasta ranged from 0.57 to 1.72 kg carbon dioxide equivalent (CO_{2e}) kg^{-1}. In this work, the business-to-consumer carbon footprint (CF_{CG}) of 1 kg of dry decorticated organic durum wheat semolina pasta, as packed in 0.5 kg polypropylene bags by a South Italian medium-sized pasta factory in the years 2016 and 2017, was assessed in compliance with the Publicly Available Specification 2050 standard method.

RESULTS: Whereas CF_{CDC} was mostly conditioned by the greenhouse gases emitted throughout durum wheat cultivation (0.67 *vs* 1.12 kg CO_{2e} kg^{-1}), CF_{CG} was mainly dependent on the use and post-consume phases (0.68 *vs* 1.81 kg CO_{2e} kg^{-1}). CF_{CG} was more or less affected by the pasta types and packing formats used, since it varied from +0.3 to +14.8% with respect to the minimum score estimated (1.74 kg CO_{2e} kg^{-1}), which corresponded to long goods packed in 3 kg bags for catering service. Once the main hotspots had been identified, CF_{CG} was stepwise reduced by resorting to a series of mitigation actions.

CONCLUSION: Use of more eco-sustainable cooking practices, organic durum wheat kernels resulting from less impacting cultivation techniques, and renewable resources to generate the thermal and electric energy needs reduced CF_{CG} by about 58% with respect to the above reference case. Finally, by shifting from road to rail freight transport and shortening the supply logistics of dry pasta and grains, a further 5% reduction in CF_{CG} was achieved.

Supporting information may be found in the online version of this article.

Keywords: business-to-consumer carbon footprint; cooking phase; decorticated organic durum wheat; dry organic pasta; paperboard boxes, polypropylene or polyethylene bags; sensitivity analysis

LIST OF SYMBOLS

1PEoL	primary packaging end of life
2-3PEoL	secondary and tertiary packaging end of life
AG_{DM}	above ground residues (kg ha^{-1})
AT	articulated truck
BC	byproduct credit
BG_{DM}	below ground residues (kg ha^{-1})
CA	cartons (kg)
CAL	carton labels (kg)
CALW	carton label waste (kg)
CAW	carton waste (kg)
CDW	cleaned durum wheat (kg)
CE	cooking energy needs
CF_{CDC}	cradle-to-distribution center carbon footprint of a functional unit including the CO_{2e} credits due to the feed use of processing byproducts (kg CO_{2e} kg^{-1})
$CF_{CDC'}$	cradle-to-distribution center carbon footprint of a functional unit excluding the CO_{2e} credits due to the feed use of processing byproducts (kg CO_{2e} kg^{-1})
CF_{CG}	cradle-to-grave carbon footprint of a functional unit as defined by Eqn (1) (kg CO_{2e} kg^{-1})
CF_{CGR}	reference value for the cradle-to-grave carbon footprint of a functional unit (kg CO_{2e} kg^{-1})
CHP	combined heat and power system
COD	chemical oxygen demand
CP	consumer phase
D	pasta dough (kg)
DC	distribution center
DDWK	decorticated durum wheat kernels (kg)
DKPC	pre-cleaning dockage (kg)
DKC	cleaning dockage (kg)
DIW	water used to prepare the dough (kg)
DP	dried pasta (kg)
DPB	dried pasta in primary packs (kg)
DPC	dried pasta in secondary packs (kg)
DPP	dried pasta in tertiary packs (kg)
DPW	dried pasta wastes (kg)
DW	durum wheat (kg)

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DWLS	local supply of durum wheat (km)
DWS	DW semolina (kg)
DWSD	DW supply distance (km)
E_e	electric energy
EF_1	N_2O-N emissions per N fertilizer mass (kg N_2O-N kg^{-1} N)
EF_4	N_2O-N emissions per unit mass of NH_3 and N oxides emitted, both expressed in N mass (kg N_2O-N kg^{-1} NH_3-N + NO_x-N emitted)
EF_5	N_2O-N emissions per unit mass of N leached off (kg N_2O-N kg^{-1} N leaching off)
EF_i	emission factor for the generic ith activity (kg CO_{2e} kg^{-1}, kg CO_{2e} kWh^{-1} or kg CO_{2e} Mg^{-1} km^{-1})
EoL	end of life
EPD	Environmental Product Declaration
EPMC	Euro pallet managing center
ESCP	eco-sustainable cooking procedure
E_T	thermal energy
ETBG	thermal energy from biogas
EV	water evaporated during dough extrusion (kg)
F_{CR}	specific N content of crop residues (kg N ha^{-1} yr^{-1})
FDF	first decortication fraction (kg)
FP	field phase
$Frac_{GASF}$	NH_3 and NO_x emissions per unit N fertilizer mass (kg NH_3-N + NO_x-N kg^{-1} N)
$Frac_{LEACH}$	N leaching off per unit N fertilizer mass (kg N kg^{-1} N)
F_{SN}	specific N content of organic fertilizer (kg N ha^{-1} yr^{-1})
GHG	greenhouse gas
GB	grinding bran particles (kg)
GWP	global warming potential
HERS	high extraction rate semolina (kg)
HRT	heavy rigid truck
ISS	impurities, stones and straw (kg)
KW	pasta dough discarded during kneading (kg)
LCA	life cycle assessment
LP	long extruded pasta
MAL	multiple axle lorry
MI	milling phase
m_i	slope of the relative variation of CF_{CG} ($\Delta CF_{CG}/CF_{CGR}$) as referred to the relative variation of each independent parameter X_i ($\Delta X_i/X_{iR}$), as defined by Eqn (2) (dimensionless)
MLBF	milling light branny fraction (kg)
ORCS	organic rotation cropping system
PAS	Publicly Available Specification
PB	paperboard box (kg)
PCDW	pre-cleaned DW (kg)
PCF	product carbon footprint
PE	polyethylene
PEE	photovoltaic electric energy
PEF	product environmental footprint
PM	packaging manufacture
PP	polypropylene
PPB	PP bag or paperboard box (kg)
PPDD	palletized pasta delivery distance (km)
PPP	pasta production and packaging
PPTM	palletized pasta transport modality
PPW	PP bag or paperboard box wastes (kg)
PRD	regional distribution of pasta
PRM	packaging raw material
PRT	pasta rail transport
PS	pasta scraps (kg)
PST	pasta shipping transport
PV	water evaporated during pasta drying (kg)
PWM	processing waste management
Q_e	specific electric energy consumption (kWh Mg^{-1})
Q_T	specific thermal energy consumption (kWh Mg^{-1})
R_{BG-BIO}	below ground/above ground biomass ratio (dimensionless)
RC	reference case
RWDWS	recombined whole durum wheat semolina (kg)
RT	light–medium rigid truck
SDF	second decortication fraction (kg)
SC	carton scotch tape (kg)
SCW	carton scotch tape waste (kg)
SP	short-cut extruded pasta
TR	transportation
TRfp	transport of final product
TRpaw	transport of packaging and auxiliary materials and wastes
TS	table salt (kg)
TW	tempering water (kg)
WCC	waste collection center
WCDW	wet cleaned durum wheat (kg)
WDP	wet extruded product (kg)
WDWS	whole durum wheat semolina (kg)
WE	water evaporated (kg)
WEP	wet extruded pasta (kg)
WFP	wheat feed pellets (kg)
WP	wooden pallet (kg)
WPF	wooden pallet wrap film (kg)
WPFW	wooden pallet wrap film waste (kg)
WPL	wooden pallet label (kg)
WPLW	wooden pallet label waste (kg)
WPR	cooking water/pasta ratio (L kg^{-1})
WPW	wooden pallet waste (kg)
X_i	generic ith independent variable
X_{iR}	reference value for any generic ith variable X_i
ΔCF_{CG}	relative variation of CF_{CG} with respect to the reference value (= $CF_{CG} - CF_{CGR}$) (kg CO_{2e} kg^{-1})
ΔX_i	relative variation of each independent parameter X_i with respect to the corresponding reference value X_{iR}
Ψ_i	entity of the ith activity (kg, J or Mg km)

INTRODUCTION

Pasta is a staple food of traditional Italian cuisine, popular worldwide owing to its convenience, versatility, sensory and nutritional value. Its consumption is recommended by Mediterranean dietary guidelines and it is perceived as one of the 'healthy options'. It is mainly composed of carbohydrates (70% w/w) and proteins (11.5% w/w) and is considered to be a slowly digestible starchy food.[1] About 14.3 million metric tons of pasta is produced annually worldwide, with 22.7 and 14.0% of the total being produced in Italy and the USA respectively.[2] The per capita consumption of pasta is maximum in Italy (about 23.5 kg yr^{-1}), followed by Tunisia (16 kg yr^{-1}) and Venezuela (12 kg yr^{-1}).[3]

The application of life cycle assessment (LCA) methodologies to basic cereals, as well as their main derived products, was recently reviewed by Renzulli *et al.*[4] In the case of dry durum wheat semolina pasta, its environmental impact has been assessed by several LCA studies, the great majority of which involving a cradle-to-retail approach,[5–7] and just a few a cradle-to-grave one.[8–10]

The agricultural phase was generally the primary hotspot owing to the environmental impacts (i.e. climate change, eutrophication, acidification, stratospheric ozone depletion potential, etc.) associated with production and use of fertilizers and pesticides, as well as fuel use. The organic cultivation of wheat avoids using pesticides and fertilizers of fossil origin and thus lessens the impact of the field phase, even if this can be counterbalanced by lower crop yields that result in both greater specific energy consumption for fieldwork and land use. By planning a four-year crop rotation, where durum wheat cultivation foregoes legume or fodder cultivation, it was possible to reduce not only the environmental impact but also the production costs and deoxynivalenol risk.[11]

In addition, several Environmental Product Declarations (EPDs)[12–20] have been published and revised so far. As shown in the electronic supplement (Table S1), the estimated cradle-to-distribution center (business-to-business) carbon footprint (CF_{CDC}) of dried durum wheat semolina pasta exhibited quite a large range of variation from 0.57 to 1.7 kg carbon dioxide equivalent (CO_{2e}) kg^{-1}. The field phase contributed from 40 to 82% of CF_{CDC} and thus resulted to be the main hotspot. However, when the use and post-consumption waste disposal phases are accounted for, the contribution of pasta consumption seemed to be highly relevant in terms of energy consumption and associated impacts.[8,11]

The use of water associated with food and drink production and consumption is currently a critical issue related to both the scarcity of drinking water and resulting pollution. In particular, the fact that Italy had one of the largest water footprints of the world was associated with the consumption of two typical Italian foods (pasta and pizza margherita).[21] Actually, pasta cooking for an average time of 10 min involves the consumption of about 10 L of water and 2.3 kWh of energy per 1 kg of dried pasta.[17,22] Thus, depending on the use of a gas or electric hob, further greenhouse gas (GHG) emissions in the range of 0.6[13] to 3.1[18] kg CO_{2e} kg^{-1} respectively are to be accounted for. Therefore such a phase might be the most impacting one of the overall life cycle of dried pasta.

Beyond the impact category of climate change, other impact categories such as acidification, eutrophication, ozone layer depletion, eco-toxicity and abiotic depletion were accounted for in such studies,[4] but rarely normalized. In particular, the normalized results revealed that the most affected impact categories were land use and fossil fuel, followed by respiratory inorganics and climate change.[8]

Even if all the functional units selected in the aforementioned studies were mass-based and, in the great majority of cases, comprised 1 kg of dry pasta differently packed, such carbon quantification exercises did not enable the environmental impact of dry pasta to be directly compared, mainly because of the great number of assumptions made and the different operating variables and yield factors used.

Although the Directorate-General for Environment of the European Commission is developing a unified methodology to estimate the environmental footprint of products (including carbon), based on life cycle analysis (LCA), with the ultimate goal of classifying them through appropriate reference values (benchmark), the current product environmental footprint (PEF) method has been largely criticized by several stakeholders, namely academia,[23–25] industry,[26,27] policy-makers[28] and consumer associations.[29] In particular, the assessment of 14 different impact categories embedded in such a method appeared to be quite a useless and expansive exercise with no value added owing to the huge amount of reliable data needed, the excessive number of decisions that are to be made, the necessity of running LCAs for every single product in the portfolio and, what is more, the difficulty of communicating the results to environmentally unconscious consumers, especially for the 99% EU food and drink enterprises.[23] Thus, since numerous independent studies have shown that climate change is the impact category with the lowest uncertainty level, the mere assessment of the product carbon footprint (PCF) was recommended as the most direct and economical method to allow small- and medium-sized enterprises to improve their sustainability via a simple and stepwise virtuous approach.[23]

To calculate the PCF, it is crucial to rely on appropriate and transparent emission factors. Unfortunately, the numerous EPDs published so far do not report the characterization factors used. This is unquestionably a critical aspect, the rule of the scientific method requiring the impact category indicators to be recalculated by any researcher. Only the Bilan Carbone®[30] and Australian Wine Carbon Calculator[31] procedures rely on specific guidebooks, where the default values of the essential emission factors are listed. In this way, not only is the calculation of GHG emissions for a specific food or beverage transparent, but also easy to compare.

Based upon the data shown in the electronic supplement (Table S1), the environmental performance of dried organic pasta using semolinas obtained from decorticated organic durum wheat kernels has not been addressed so far. Nowadays, there is a great interest to expand the consumption of 'whole grain' cereal flours, their nutritional value being recognized as a fundamental element of a healthy diet.[32] However, their use is limited by a few negative sensory elements such as appearance (dark color), texture (rough, heavy) and some off-flavors (rancid, cardboard) developed over the product shelf-life. These drawbacks are generally attributed to the use of the conventional milling process, while the use of decorticated durum wheat semolina is expected to give rise to pasta or bakery products with an appearance and texture more similar to standard semolina pasta.[33]

Thus the first aim of this study was to develop an LCA model to estimate the cradle-to-grave (business-to-consumer) carbon footprint (CF_{CG}) of the industrial production and distribution of dry decorticated organic durum wheat semolina pasta in 0.5 kg polypropylene (PP) bags. This model complied with the Publicly Available Specification (PAS) 2050 standard method[34,35] and was based on transparent processing and packaging consumption yields, as well as emission factors. Then a sensitivity analysis of CF_{CG} was carried out to assess the influence of different parameters (such as origin of durum wheat and its cultivation methods, GHG emissions per kWh of electric or thermal energy generated by fossil and/or renewable sources, distribution logistics, transportation by road, rail or sea, cooking modes, etc.) and thus identify the most promising strategy to mitigate the GHG emissions associated with the overall dried pasta life cycle.

METHODOLOGY

The LCA was performed in compliance with the PAS 2050 standard method,[34,35] and involved the following stages: goal and scope definition, inventory analysis, impact assessment and interpretation of results. The scope of this study was to assess the cradle-to-grave environmental impact of decorticated organic durum wheat semolina pastas, this conforming a business-to-consumer study in accordance with the PAS 2050.

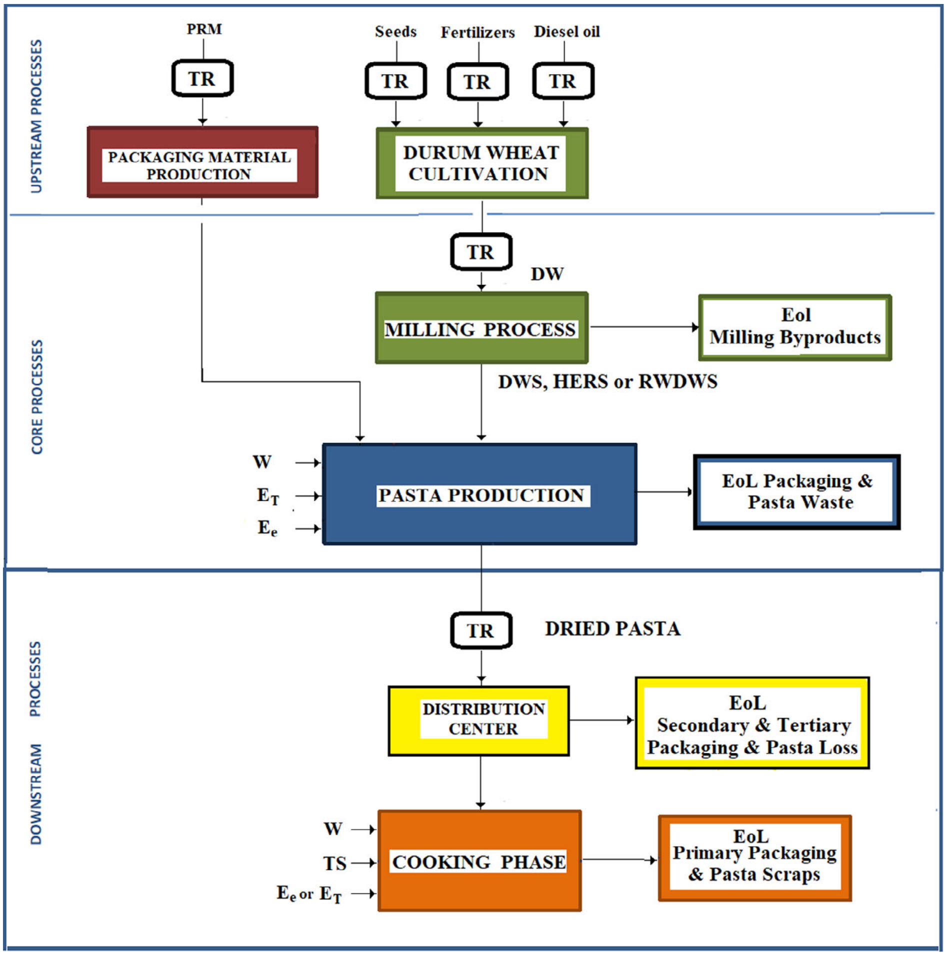

Figure 1. Dried pasta system boundary showing the main upstream, core and downstream processes. All symbols are defined in 'List of symbols'.

Goal and scope

The goal for this study was to develop an LCA model to assess the carbon footprint of dried organic pasta made of decorticated durum wheat semolina and produced from a medium-sized pasta factory located in the South of Italy, as well as to identify its life cycle hotspots.

Functional unit

The analysis was referred to a *functional unit* defined as 1 kg of dried decorticated organic durum wheat semolina pasta packed in 0.5 kg PP bags.

System boundary

The system boundary for this study included three different life cycle stages, i.e. upstream processes (from cradle to gate), core processes (from gate to gate) and downstream processes (from gate to grave). It is shown in Fig. 1, where all the identification items used are given in 'List of symbols'.

More specifically, the upstream processes consisted of:

U1) organic durum wheat cultivation;
U2) seed production;
U3) fertilizer production;
U4) electricity and fuel used in the upstream module;
U5) production of auxiliary products (i.e. lubricants, detergents for cleaning, etc.);
U6) manufacturing of primary, secondary and tertiary packaging.

The core processes entailed:

C1) decortication and milling of durum wheat kernels, pasta manufacture and packaging;
C2) disposal of processing wastes and byproducts generated during pasta manufacturing;
C3) electricity and fuels used in the core module.

The production of capital goods (machinery, equipment and energy wares), any travel of personnel, research and development activities, as well as consumer transport to and from the retail shop, were excluded from the system boundary, as specified by Section 6.5 of PAS 2050.[34]

Finally, the following downstream processes were encompassed:

D1) transportation of palletized product to distribution center (DC) and retailer (R) platforms;
D2) consumer use of dried pasta;
D3) end-of-life processes of any wasted fraction of cooked pasta;
D4) end-of-life processes of packaging waste.

Boundaries to nature are defined as flows of material and energy resources from nature into the system. Emissions to air, water and soil cross the system boundary when they are emitted from or leaving the product system. Milling byproducts, which occurred during grain decortication and milling processes, as well as dough wastes and dried pasta scraps that resulted from pasta manufacture, were considered as an avoided production of cattle feed. This was accounted for in the LCA by means of CO_2 credits. In addition, all CO_2 credits from recycling of renewable and non-renewable materials were included.

Data gathering and data quality

According to the PAS 2050 (Section 7.2), the following was stated.

i. *Geographic scope*: this LCA study focused on the Italian production and distribution of dried decorticated organic durum wheat semolina pasta.
ii. *Time scope*: the reference time period for assessing the carbon footprint values included the years 2016 and 2017. The overall dried pasta production in both years was approximately constant and equal to 125 ± 2 Gg yr^{-1}, the change in pasta production being of the order of 1.3%.
iii. *Technical reference*: the process technology underlying the datasets used in this study reflected process configurations, as well as technical and environmental levels, typical for industrial-scale dried pasta processing in the reference period.
iv. *Primary data* for this PAS 2050-compliant study were collected from a medium-sized pasta factory. Consumption rates of input materials and electrical and thermal energy, as well as input material supply and finished product delivery logistics, were assessed at the pasta factory (primary data). All solid residues resulting from processing were separated into plastic, paper and cardboard, or wood wastes and recycled. Milling byproducts, as well as dough and dried pasta discarded fractions, were used as animal feed, this giving rise to a CO_{2e} credit. Distribution center, retailer and post-consumer wastes underwent differentiated waste collection.
v. *Secondary data* were sourced from the Italian Institute for Environmental Protection and Research as concerning the GHG emissions associated with the Italian electric energy production by renewable and non-renewable sources,[36] LCA software (i.e. Simapro 8.2 v.2, Prè Consultants, Amersfoort, The Netherlands) and several databases (such as BUWAL 250, Ecoinvent 2.0, Franklin USA 98) using the method developed by IPCC,[37] as well other technical reports.[30,35]

INVENTORY ANALYSIS

In this stage of the LCA procedure, all resource and energy inputs and yield outputs for organic durum wheat cultivation, durum wheat decortication and milling, pasta making, packaging and transportation, consumer phase and post-consumption waste management were gathered as reported below.

Farm production of organic durum wheat

Table 1 shows the main inputs for the cultivation system used, where durum wheat was subjected to rotation with alfalfa (*Medicago sativa* L.) in an area bordering the Campania, Basilicata and Apulia Regions of Italy. Such a flowering plant in the legume family Fabaceae allowed the enrichment of the soil through the nitrogen fixation process, and improvement of its organic structure and biotic activity, as well as reduced the risk of fungal infections and parasitic attacks and decreased weeds also in the organic farming.[38]

About 70% of the nominal non-irrigated land was dedicated to durum wheat cultivation, and the remaining 30% to fodder legume. In this way, the only soil undergoing legume cultivation was managed using aged poultry manure compost with an average total nitrogen content of 13 g kg^{-1}.[39] Thus the organic cultivation of durum wheat avoided using pesticides and fertilizers of fossil origin. Table 1 shows all the parameters and emission factors used to calculate direct and indirect N_2O emissions.[37] The above ground residues AG_{DM}, i.e. straw, as well as the below ground residues BG_{DM} were estimated in accordance with IPCC procedures.[37] According to EPD®,[40] the allocation factor proposed for the organic cultivation method was 93.1% for durum wheat grains and 6.9% for straw. Since about 80% of straw was harvested and sold as a byproduct, while the residual 20% as well as all below ground residues were left on the ground, the allocation factor to straw was reduced to 5.5%. The agricultural stage of concern included reduced tillage, seeding, harrowing, harvesting and baling with an overall consumption of diesel fuel and lubricant oils of 100–150 and 5 L ha^{-1} yr^{-1} respectively (Table 1). No postharvest drying of grains was performed, since their average moisture content was less than 120 g kg^{-1}.

Finally, durum wheat was cultivated on land which had been used for agricultural purposes for longer than 20 years (PAS 2050, Section 5.5);[34] therefore the GHG emissions arising from land use change were not considered.

Wheat milling

Once the durum wheat grains had been transported to the pasta factory, they were directly milled and then conveyed to the pasta making unit, with no further transport step. Figure 2 shows the block diagram of the milling process used. Grains with an average moisture content of 108 g kg^{-1} were pre-cleaned to remove impurities, like stones and straw (ISS), and pre-cleaned wheat dockage (DKPC), as weed seeds, weed stems and chaff; cleaned to remove further wheat dockage (DKC), as underdeveloped, shriveled and small pieces of wheat kernels and/or grain other than wheat; tempered up to a mean moisture content of 170 g kg^{-1}; and then conveyed to an abrasive decorticator. This debranning machine was primarily used for bran removal and included two operating sections. As wheat kernels entered at the top of the machine and moved into the abrasion section, they were firstly abraded between the rotating special abrasion stones and slotted screens, then entered at the bottom of the friction section, where a series of lifter paddles moved the grains upward to the discharge gate, causing friction between the kernels and a special screen. Wheat debranning was the pre-milling treatment that allowed a controlled and progressive removal of grain external layers so as to reduce the risk of damaging the endosperm with starch loss into the debranning fractions. The first fraction (FDF) was used as animal feed, while the second fraction (SDF) was collected. Decorticated durum wheat kernels (DDWK) resulted also to be degerminated by impaction and partially dehydrated to a moisture content of 156 g kg^{-1}. After several break passages, the mixture of vmiddlings (different in sizes and composition) was sorted and cleared (removing of residual bran particles) in the plansifter and purifier. It was possible to recover approximately 0.032 kg kg^{-1} of input grains of *high extraction rate semolina* (HERS) and 0.73 kg kg^{-1} of *durum wheat semolina* (DWS). By combining a fraction of the latter with the branny fractions resulting from the decortication (SDF) and milling (MLBF) steps (Fig. 2), a *recombined whole durum wheat semolina* (RWDWS) of ∼0.38 kg kg^{-1} input grains was produced (Fig. 2).

All wheat dockage fractions resulting from the pre-cleaning and cleaning phases and bran particles derived from the decortication

Table 1. Inputs and outputs for the organic durum wheat (DW) cultivation system examined in this work and referred to a nominal land area of 1 ha. All emission factors were extracted from IPCC[37]

Parameter	Unit	Amount
Nominal non-irrigated land used	ha	1
Land used to cultivate durum wheat	%	70
Set-aside land	%	30
Input		
Organic wheat seed density	kg ha^{-1}	180–240
Seed delivery distance	km	10
Diesel fuel used for all agricultural treatments	L ha^{-1} yr^{-1}	100–150
Lubricant oil	L ha^{-1} yr^{-1}	5
Nitrogen fertilizer	kg ha^{-1} yr^{-1}	0
Phosphate fertilizer as P_2O_5	kg ha^{-1} yr^{-1}	0
Potassium fertilizer as K_2O	kg ha^{-1} yr^{-1}	0
Aged poultry manure compost (1.3% N)	Mg ha^{-1} yr^{-1}	10
Pesticides	kg ha^{-1} yr^{-1}	0
Output		
Organic durum wheat grains	Mg ha^{-1} yr^{-1}	3.5–4.0
Average moisture content at harvest	g kg^{-1}	108
Above ground residues (AG_{DM})	Mg DM ha^{-1} yr^{-1}	3.82–4.29
N content of above ground residues	kg N kg^{-1} DM	0.0067
Percentage of straw baling	%	80
Percentage of straw left in the field	%	20
Below ground/above ground biomass ratio (R_{BG-BIO})	kg kg^{-1}	0.24
Below ground residues (BG_{DM})	Mg DM ha^{-1} yr^{-1}	1.44–1.63
N content of below ground residues	kg N kg^{-1} DM	0.009
Crop residues (F_{CR})	kg N ha^{-1} yr^{-1}	18.1–20.4
NH_3 and NO_x emissions ($Frac_{GASF}$)	kg NH_3-N + NO_x-N kg^{-1} N	0.1 (0.03–0.3)
N leaching off ($Frac_{LEACH}$)	kg N kg^{-1} N	0.3 (0.1–0.8)
EF_1	kg N_2O-N kg^{-1} N	0.01 (0.003–0.03)
EF_4	kg N_2O-N kg^{-1} NH_3-N + NO_x-N emitted	0.01 (0.002–0.05)
EF_5	kg N_2O-N kg^{-1} N leaching off	0.0075 (0.0005–0.025)
Direct N_2O emissions (= ($F_{SN} + F_{CR}$) EF_1 44/28)	kg N_2O ha^{-1} yr^{-1}	0.89–0.92
Indirect N_2O emissions from NH_3 and NO_x emissions (= F_{SN} $Frac_{GASF}$ EF_4 44/28)	kg N_2O ha^{-1} yr^{-1}	0.12
Indirect emissions form N leaching off (= ($F_{SN} + F_{CR}$) $Frac_{LEACH}$ EF_5 44/28)	kg N_2O ha^{-1} yr^{-1}	0.32–0.33

(FDF) and grinding (GB) steps were converted into the so-called wheat feed pellets (WFP), their overall amount being about 0.184 kg kg^{-1}.

All yield factors of the milling process used in this study were determined on the industrial scale on durum wheat lots of approximately 278 Mg and were characterized by an average coefficient of variation of ±10%, as shown in the electronic supplement (Table S2). In this way, durum wheat milling gave rise to an overall yield for the three aforementioned types of semolina of ~0.867 kg kg^{-1} input grains. On the contrary, by conventional milling of the same durum wheat variety, the average yield for durum wheat semolina was 0.71 kg kg^{-1}, while further recombination gave rise to a yield for durum wheat semolina and whole durum wheat semolina of 0.632 and 0.131 kg kg^{-1} respectively.[6]

Pasta making

The above three types of semolina (HERS, DWS and RWDWS) were used to produce three different dried organic pastas. Figure 3 shows the block diagram of their pasta making process.

Each 1 kg of any semolina type was mixed with ~0.34 kg of water in a trough operating under vacuum to yield a dough (D) having a moisture content of approximately 0.354 kg kg^{-1} and a lumpy consistency. D was then transferred to the extruder and forced through bronze dies provided with Teflon® to obtain long- (LP) or short- (SP) cut extruded pasta. Despite extrusion barrels having been equipped with water cooling jackets to dissipate the heat generated during the extrusion process and keep the dough temperature roughly constant around 51 °C, the moisture content of extruded products (WEP) reduced to ~0.31 kg kg^{-1}. The average amount of discarded dough as such or extruded (KW) was approximately 0.4% of D.

A final drier was then used to reduce the moisture content of extruded pasta to 0.1125 kg kg^{-1} so that the finished product (DP) could retained its shape and be stored without spoiling. Proper drying is critical in the pasta making process. Thus, wet pasta was dried in a continuous drying chamber for 3–10 h, depending on the pasta shape. When DP had been cooled, it was fed to the packaging unit.

All yield factors for the pasta making process used were determined on the industrial scale and were characterized by an average coefficient of variation of ±10%, as shown in the electronic supplement (Table S3).

Pasta packaging

Around 90% of dried pasta is nowadays packed in plastic film bags and the remaining 10% in cardboard boxes.[22] In this study, dried pasta of the short (SP) or long (LP) type was packed in 0.5 kg

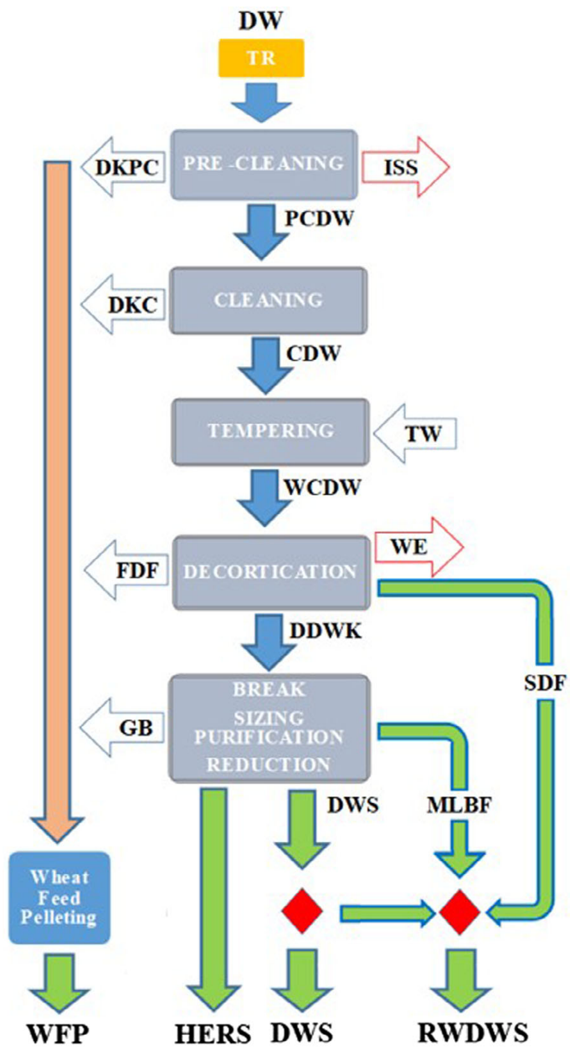

Figure 2. Flowchart of the process of decortication and milling of durum wheat (DW) with production of durum wheat semolina (DWS), whole durum wheat semolina (HERS) and recombined whole durum wheat semolina (RWDWS). All symbols are defined in 'List of symbols'.

self-seal laminating (PP) bags having a top closure that could be repeatedly opened and closed. The secondary package consisted of several bags assembled in a carton, the latter then being labeled and sealed with scotch tape. The tertiary package involved a 120 cm × 80 cm EPAL wood pallet over which different layers of cartons were stacked. The effect of other packages (i.e. 0.5 kg paperboard boxes and 3 kg polyethylene (PE) bags for catering service) was also assessed.

Figure 4 shows the block diagram for the packaging process examined in this work, showing also all the solid wastes generated. Table 2 lists the amounts of packaging materials and aids needed to prepare the primary, secondary and tertiary packages. (i.e. plastic bags or paperboard boxes, cartons, adhesive labels, scotch tape, stretch and shrink film, pallet, etc.).

Processing aids

Milling and pasta making equipment needs to be cleaned and lubricated. The average consumption of detergents and lubricant oils was about 0.020 and 0.037 L Mg^{-1} dried pasta produced respectively. Moreover, all the other materials used in minimum quantities (i.e. other minor chemicals and process equipment wastes, etc.) were not included in the system boundaries, since their potential influence on the analysis results was assumed as negligible, being smaller than 1% (PAS 2050, Section 6.3).[34]

Waste management

All wastes arising from the pasta making operations were disposed of as follows:

- Plastic bags (PPW), scotch tape (SCW) and stretch wrap films (WPFW) discarded during primary, secondary and tertiary packaging, respectively, were amassed for plastic recycling.
- Paperboard boxes (PPW) and cartons discarded (CAW), as well as labels rejected during secondary (CALW) and tertiary (WPLW) packaging, were collected and used as feedstock for recycled paper.
- Wooden pallets (WPW) damaged during either tertiary packaging or collection at the distribution centers were gathered and returned to the original producer in order to be repaired and made available again to the pasta factory.

The percentage fraction for each packaging item discarded during the pasta making process was determined in the pasta factory under study, as detailed in the electronic supplement (Table S4).

About 84 L of process wastewaters (having an initial chemical oxygen demand (COD) of ∼484 mg O_2 L^{-1}) per 1 Mg of dried pasta were produced and submitted to aerobic digestion to lower their COD value to approximately 175 mg O_2 L^{-1} in order to be disposed of in the municipal sewer system. The electric energy consumed for wastewater pumping and aeration operations was about 0.28 kWh Mg^{-1} dried pasta.

Wheat milling byproducts (WFP) and pasta making (KW) and packaging (DPW) wastes were used as animal feed. In this way, they represented an avoided environmental load. It was estimated by referring to the environmental burden associated with the production of soybean meal (having a minimum raw protein content of 0.44 g g^{-1}).[41] In the case of no land use changes, the carbon footprint of soybean meal ranged from ∼0.6 to 0.95 kg CO_{2e} kg^{-1},[42] this being equivalent to 1.4–2.2 kg CO_{2e} kg^{-1} protein. Since the raw protein content of WFP, KW and DPW was 170, 90 and 123 g kg^{-1}, respectively, their average avoided environmental burden was quantified as −0.31, −0.16 and −0.22 kg CO_{2e} kg^{-1}, respectively

Energy sources

The energy resources employed in pasta making comprised electricity and natural gas. Electric energy was used to drive process machines and equipment as well as to run plant utilities and electric forklifts, while thermal energy was used to dehydrate wet extruded pasta.

Table 3 shows the specific energy needs as derived from factory measurements or extracted from the literature.[9,43–45]

In the year 2016 or 2017, 20 or 24% of the electricity used by the pasta factory in question was absorbed by the Italian mean voltage (20 000 V) grid, with the remaining 80 or 76% coming from a nearby combined heat and power (CHP) system with a gas turbine. The electric energy absorbed from the Italian grid was corrected for the average electric energy loss (∼5.8%) in 2017.[46] Concerning the thermal energy requirements, in the year 2016 or 2017, 41 or 43% of the overall duty was satisfied by the cogeneration plant,

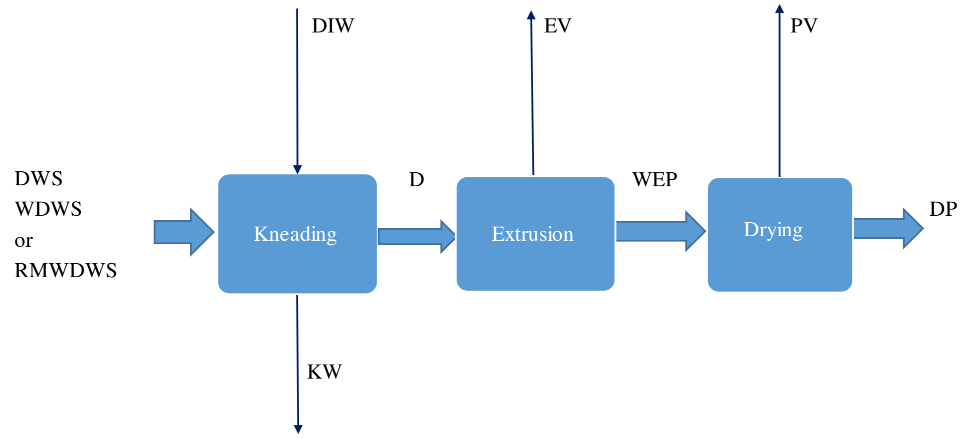

Figure 3. Flowchart of the dried pasta making process using durum wheat semolina (DWS), high extraction rate semolina (HERS) or recombined whole durum wheat semolina (RWDWS). All symbols are defined in 'List of symbols'.

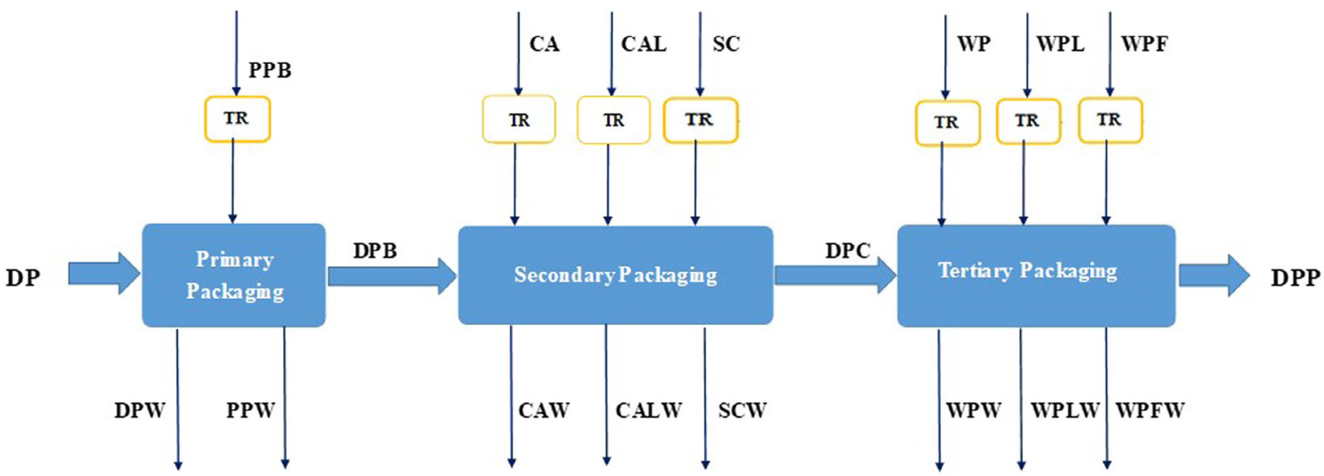

Figure 4. Schematic diagram of the packaging process for each dried pasta type examined in this work. All symbols are defined in 'List of symbols'.

with the remaining 57 or 59% coming from methane-fired boilers, these having an overall efficiency of 88%.

The GHG emission factor for electricity withdrawn from the national grid (512.9 g CO_{2e} kWh^{-1}) was related to the average Italian electric production from non-renewable sources in 2017, while those for the electric (349.1 g CO_{2e} kWh^{-1}) and thermal (232.7 g CO_{2e} kWh^{-1}) energy directly supplied by the CHP system coincided with the average values for the Italian natural gas-fired cogeneration plants in 2016.[36] Finally, the emission factor for the methane used (231 g CO_{2e} kWh^{-1}) included the combustion and upstream processes.[30]

Transportation and distribution stage

The only transport modality for raw materials, processing aids and packaging materials from their production sites to the pasta factory gate and for processing wastes and byproducts from the factory gate to Euro pallet managing (EPMC) and waste collection (WCC) centers was by road using Euro 5 means, as specified in the electronic supplement (Table S5). The final product transport included the delivery from the factory gate to the distribution centers and then to the selling points (Table S5). On the contrary, the GHG emissions arising from the transport of consumers to and from the point of retail purchase were excluded from the system boundary (PAS 2050, Section 6.5).[34,35]

Once dried pasta had been delivered on wooden pallets, the distributor or trader collected the empty pallets to allocate them back to the original producer, where defected pallets were repaired and made available again to the pasta factory. Since the average distance travelled by the final product was approximately 900 km (Table S5), and the pallet operator was at a distance of 100 km from the pasta factory of concern, the distance travelled by the empty pallets was ~800 km.

During distribution, about 1% of pasta is generally wasted owing to package breakage.[22] Its disposal was assumed as coinciding with the overall Italian management scenarios for solid urban wastes in 2016,[47] these being detailed in the electronic supplement (Table S6).

The secondary and tertiary packaging wastes generated at the distribution centers and retail points were managed in accordance with the overall Italian waste management scenarios for paper and cardboard, mixed plastic and wood wastes in the year 2016,[48] as reported in the electronic supplement (Table S6).

Use phase

Dry pasta is stored at ambient temperature. To cook 1 kg of pasta, 10 L of boiling water laced with 70 g of table salt (TS)[13] is usually needed, as reported in the EPD®[49] and PEF[22] category rules for dry pasta. The default energy requirement for boiling 1 kg of water

Table 2. Mass of any component of primary, secondary and tertiary packages for dried short- (SP) or long- (LP) cut extruded pasta as referred to different packaging formats

Packaging format	PP bags		Paperboard box		PE bags		
Pasta type	SP	LP	SP	LP	SP	LP	Unit
Primary packaging							
Capacity	0.5	0.5	0.5	0.5	3.0	3.0	kg
Mass	7.1 ± 0.3	3.6 ± 0.2	30 ± 0.6	23.0 ± 0.5	25.2 ± 0.5	18.7 ± 0.1	g
Length × width × height	105 × 38 × 170	310 × 80 × 30	130 × 65 × 175	270 × 70 × 34	420 × 320 × 70	335 × 250 × 45	mm
Primary packaging overall mass	0.507	0.504	0.530	0.523	3.025	3.019	kg
Secondary packaging							
No. of primary packages	20	24	12	20	4	6	–
Length × width × depth	380 × 220 × 220	300 ×175 × 285	545 × 220 × 195	300 × 190 × 290	400 × 300 × 285	340 × 170 × 285	mm
Carton mass	296.2 ± 0.7	207.0 ± 0.5	296 ± 0.9	219 ± 0.6	650 ± 1	277.6 ± 0.7	g
Adhesive label for cartons	0.617 ± 0.005			0.68 ± 0.01			g
Scotch strip			$2 \times (2.42 \pm 0.13)$				g
Pasta mass per carton	10	12	6	10	12	18	kg
Secondary packaging overall mass	10.44	12.30	6.66	10.69	12.76	18.4	kg
Tertiary packaging			Euro pallet				
No. of secondary packages	10	16	20	16	8	8	–
No. of layers per pallet	8	6	9	6	6	6	–
Overall height of pallet	1.904	1.854	1.899	1.884	1.854	1.854	m
Pallet label			$2 \times (3.11 \pm 0.05)$				g
Stretch & shrink film	401 ± 4	390 ± 6	400 ± 6	397 ± 7	390 ± 5	390 ± 6	g
Pallet mass			25				kg
Pasta mass per pallet	800	1152	1080	960	576	864	kg
Tertiary packaging overall mass	860.9	1206.1	1224.5	1051.1	637.7	908.4	kg

Table 3. Specific consumption for electric (Q_e) and thermal (Q_T) energy associated with durum wheat (DW) milling and dry pasta (DP) making, as collected in the pasta factory or extracted from the literature

	Specific consumption		
Processing step	Q_e	Q_T	Reference
Durum wheat milling	(kWh Mg^{-1} DW)	(kWh Mg^{-1} DW)	
	54.2	–	This work as referred to the year 2016
	44.7	–	This work as referred to the year 2017
	47.6	–	9
	117–150	–	43
	83.33	2.22	44
Dry pasta making	(kWh Mg^{-1} DP)	(kWh Mg^{-1} DP)	
	277.7	281.0	This work as referred to the year 2016
	317.1	303.9	This work as referred to the year 2017
	162.1	551.7	9
	194–250	250–472	43
	289	511	45

is 0.18 kWh, while for cooking 1 kg of pasta it is 0.05 kWh min^{-1}. Assuming an average cooking time of 10 min, the overall energy requirement would be 2.3 kWh kg^{-1} dry pasta, i.e. ($0.18 \times 10 =$) 1.80 kWh to boil 10 L of water and ($0.05 \times 10 =$) 0.5 kWh to cook 1 kg of pasta. Electricity or gas is used to cook dry pasta. In the European Union, 83% of domestic cookers are gas-fired, while the remaining 17% are of the electric type.[22]

Post-consumer waste disposal

Pasta loss at the consumer phase was assumed of the order of 2% of the quantity cooked.[22] However, according to research carried out by Last Minute Market, a spin-off from the University of Bologna (Italy), the cooked pasta wasted by Italian families would be about six times more than the above default value. Thus, up to 12% of what had been cooked[50] was wasted, probably because it was not used in time or too much was prepared. The effect of this scenario was also accounted for.

The mass of residual cooking water or *pasta water* is generally discarded into sinks. The contribution of pasta water disposal to the overall carbon footprint of pasta cooking was disregarded, since it was found to be insignificant with respect to that resulting from the energy consumption.[51] On the contrary, by accounting for the overall Italian management scenarios for solid urban wastes in 2016, cooked pasta waste was assumed to be 28% landfilled, 20% incinerated and 52% composted or recycled,[47] as shown in the electronic supplement (Table S6). Finally, the primary packaging waste after the use phase was disposed of in accordance with the overall Italian waste management scenarios for plastic, paper and cardboard wastes in the year 2016, as described in the electronic supplement (Table S6).

Carbon footprint assessment

To assess the cradle-to-grave carbon footprint (CF_{CG}) of the functional unit chosen, all GHG emissions associated with the dry pasta life cycle were estimated as follows:

$$CF_{CG} = \sum_i (\Psi_i \, EF_i) \quad (1)$$

where Ψ_i is the amount of each specific activity parameter (expressed on mass, energy or mass-km basis) and EF_i its corresponding emission factor, expressed in kg CO_{2e} emitted over a time horizon of 100 years, as listed in the electronic supplement (Table S7) to make transparent the CF_{CG} estimation. Since all activity data were referred to 1 kg of dry pasta, the resulting carbon footprint was expressed in kg CO_{2e} kg^{-1}.

RESULTS AND DISCUSSION

Carbon footprint of dried organic pasta

The carbon footprint of organic durum wheat was estimated by accounting for the different seed densities, diesel fuel uses and yield factors shown in Table 1 by accounting for the default values of the emission factors EF_1, EF_4 and EF_5 characterizing nitrogen fertilizer application.[37] Figure 5 shows the specific contribution of the emissions resulting from the use of seeds, aged manure, diesel fuel, lubricant, and crop residues and manure itself to the carbon footprint associated with organic durum wheat production (0.565 ± 0.050 kg CO_{2e} kg^{-1}). In this case, the aged manure production represented the primary hotspot (43.1%), diesel fuel consumption for management practices the secondary one (26.6%) and direct and indirect N_2O emissions the third one (24.8%). Thus the overall GHG emissions allocated to grains amounted to 0.53 ± 0.05 kg CO_{2e} kg^{-1}.

When comparing the GHGs emitted per hectare of organic and conventional durum wheat cultivation, a net positive reduction was generally observed, which was however reverted when accounting for the carbon footprint per unit of grain produced. In fact, durum wheat yield with organic cropping system was found to be 14 or 21% lower than that with conventional one in Switzerland[52] or Southern Italy[53], respectively. Moreover, in 20 representative farms of the Sicilian hilly hinterland, conventional farming resulted in an average crop yield of 3.9 ± 0.4 Mg ha^{-1}, while organic farming using a rotation between cereals and fodder legumes ensued a 31% lower average crop yield of 2.7 ± 0.1 Mg ha^{-1}.[38] Also, a crop rotation test performed by Barilla on 13 farms, located in the most important areas for durum wheat cultivation in Italy, reported an average crop yield and carbon footprint of 7.4 ± 0.2, 4.6 ± 1.0 or 4.2 ± 1.2 Mg ha^{-1} and 0.44 ± 0.07, 0.44 ± 0.17 or 0.54 ± 0.14 kg CO_{2e} kg^{-1} for durum wheat in Northern, Central or Southern Italy respectively.[11] Consequently, the carbon footprint of the organic durum wheat cultivation investigated in this work appeared to be in line with previous findings.

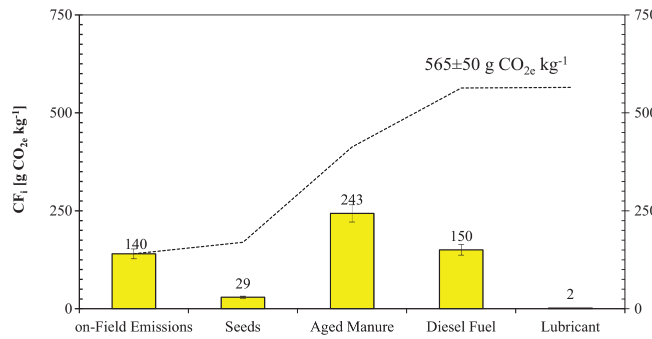

Figure 5. Contribution of the different life cycle stages to the overall carbon footprint of organic durum wheat, as well as its cumulative score.

Figure 6 shows the contribution of the different life cycle phases to the cradle-to-distribution center, excluding ($CF_{CDC'}$) or including (CF_{CDC}) the CO_{2e} credits due to the feed use of processing byproducts, or cradle-to-grave (CF_{CG}) carbon footprint of dried organic short-cut extruded pasta as packed in 0.5 kg PP bags. The primary hotspot coincided with the use and post-consume phases (0.684 kg CO_{2e} kg^{-1}), while the secondary one corresponded to durum wheat cultivation (0.666 kg CO_{2e} kg^{-1}). In particular, such a score was referred to 1 kg of dry pasta and included seed and grain transportation. The GHG emissions associated with durum wheat milling, packaging materials, pasta processing and packaging, and transportation amounted to about 52, 107, 201 and 148 g CO_{2e} kg^{-1} respectively. The contribution of packaging waste management at the factory, distribution centers and selling points was of the order of 19 g CO_{2e} kg^{-1}, while the CO_{2e} credit equaled 69 g CO_{2e} kg^{-1}. Thus CF_{CDC} and CF_{CG} scores totaled 1.12 and 1.81 kg CO_{2e} kg^{-1} respectively (Table 4).

If the pasta scraps were as high as 12% of the dried pasta cooked,[50] CF_{CG} increased by 5.2% to 1.90 kg CO_{2e} kg^{-1}.

Effects of pasta type and packaging format on CF_{CG}

Table 4 shows the sensitivity of dried organic pasta CF_{CG} toward the pasta types (i.e. short and long goods) and packing formats (i.e. 0.5 kg PP bags or paperboard (PB) boxes and 3 kg PE bags) used.

Owing to the greater packaging density of long goods with respect to short ones, the smaller contribution of packaging materials and transportation allowed CF_{CG} to be reduced by 3.5% from 1.81 to 1.74 kg CO_{2e} kg^{-1}.

When using 0.5 kg PB boxes, CF_{CG} for short or long goods increased by 10.5 or 7.5% with respect to the corresponding pasta type packed in PP bags respectively (Table 4).

Finally, when referring to 3 kg PE bags for catering service, CF_{CG} for short-cut pasta exhibited a slight increase of 3.0% with respect to that estimated in the case of 0.5 kg PP bags, probably because of the smaller overall mass of the tertiary packages (638 *vs* 861 kg) used (Table 2). On the contrary, for long-cut pasta, the effect of the aforementioned PE bags for catering service on CF_{CG} was negligible (−0.3%), as shown in Table 4.

Thus, depending on the pasta types and packaging formats, the cradle-to-grave carbon footprint was found to vary from +0.3

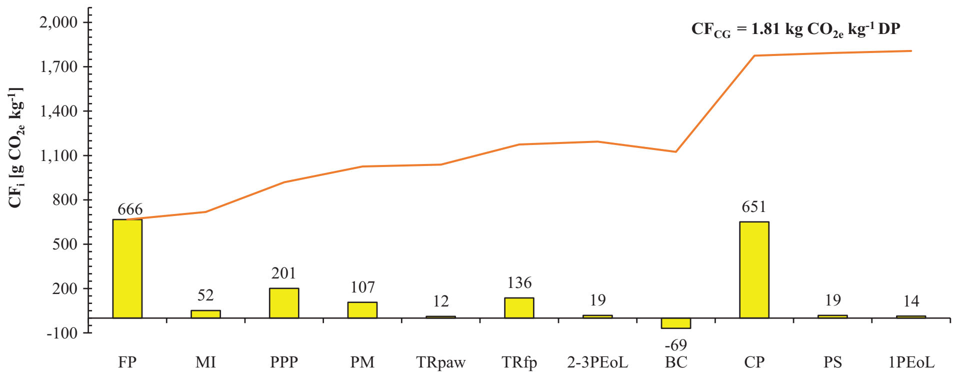

Figure 6. Contribution of the different life cycle stages to the cradle-to-distribution center (CF_{CDC}) or cradle-to-grave (CF_{CG}) carbon footprint of a functional unit (1 kg) of dried organic pasta packed in 0.5 kg PP bags in a medium-sized pasta factory, and its cumulative score. All symbols are defined in 'List of symbols'.

Table 4. Percentage contribution of the different life cycle phases to the cradle-to-distribution center, excluding ($CF_{CDC'}$) or including (CF_{CDC}) byproduct credits, and cradle-to-grave (CF_{CG}) carbon footprint of a functional unit (1 kg) of dried short (SP) and long (LP) pasta packed in 0.5 kg PP bags and PB boxes and 3 kg PE bags

	Carbon footprint for different packaging formats											
Primary packaging of dried organic pasta	0.5 kg PP bags				0.5 kg PB boxes				3 kg PE bags			
Pasta type	SP		LP		SP		LP		SP		LP	
Life cycle phase	(#)	(%)	(#)	(%)	(#)	(%)	(#)	(%)	(#)	(%)	(#)	(%)
Field phase (FP)	666.4	36.9	666.4	38.2	666.4	33.4	666.4	35.5	666.4	35.8	666.4	38.3
Milling phase (MI)	51.6	2.9	51.6	3.0	51.6	2.6	51.6	2.8	51.6	2.8	51.6	3.0
Pasta production and packaging (PPP)	201.2	11.1	201.2	11.5	201.2	10.1	201.2	10.7	201.2	10.8	201.2	11.6
Packaging materials (PM)	106.9	5.9	60.2	3.4	277.9	13.9	175.5	9.4	152.6	8.2	54.7	3.1
Transport of packaging and auxiliary materials and wastes (TR_{paw})	12.0	0.7	9.9	0.6	11.9	0.6	11.0	0.6	14.9	0.8	10.9	0.6
Transport of final product (TR_{fp})	136.3	7.5	133.1	7.6	144.1	7.2	139.0	7.4	139.6	7.5	133.3	7.7
Secondary and tertiary packaging end of life (2-3PEoL)	18.8	1.0	15.0	0.9	24.7	1.2	16.5	0.9	26.0	1.4	14.4	0.8
Pasta production excluding byproduct credits ($CF_{CDC'}$)	**1193.3**		**1137.4**		**1377.9**		**1261.3**		**1252.5**		**1132.7**	
Byproduct credits (BC)	−69.3	−3.8	−69.3	−4.0	−69.3	−3.5	−69.3	−3.7	−69.3	−3.7	−69.3	−4.0
Pasta production including byproduct credits (CF_{CDC})	**1124.0**		**1068.2**		**1308.6**		**1192.0**		**1183.2**		**1063.4**	
Consumer phase (CP)	650.7	36.0	650.7	37.3	650.7	32.6	650.7	34.7	650.7	35.0	650.7	37.4
Pasta scraps (PS)	18.9	1.0	18.9	1.1	18.9	0.9	18.9	1.1	18.9	1.1	18.9	1.1
Primary packaging end of life (1PEoL)	13.6	0.8	6.9	0.4	18.9	0.9	14.5	0.8	8.8	0.5	6.6	0.4
Cradle-to-grave pasta production (CF_{CG})	**1807.3**	**100.0**	**1744.7**	**100.0**	**1997.1**	**100.0**	**1876.1**	**100.0**	**1861.7**	**100.0**	**1739.6**	**100.0**

= g CO_{2e} kg^{-1}.

to +14.8% with respect to the minimum score estimated, this coinciding with the CF_{CG} of organic spaghetti packed in 3 kg PE bags for catering service.

Sensitivity analysis

Owing to the many assumptions needed to calculate CF_{CG}, it is difficult to compare the estimated scores even in the case of the same type of product. Not only are the technological processes different, but also the emission factors used are unknown in almost all the Environmental Product Declarations EPD® available online (http://www.environdec.com/). However, by comparing the CF_{CDC} values estimated in this work and those listed in Table S1, it was possible to observe that the main difference concerned the carbon footprint of durum wheat, which varied from 259 to 800 g CO_{2e} kg^{-1} in the case of pasta packed in 5[19] and 0.5[17] kg PP bags, respectively.

The impact of the milling phase ranged from 35[16] to 270[15] g CO_{2e} kg^{-1}. In the pasta factory examined here, the specific electric energy consumption was ~54 kWh Mg^{-1} durum wheat milled in 2016, while in the subsequent year, after the decorticator installation, it reduced to ~45 kWh Mg^{-1}, as shown in Table 3. Both the aforementioned values for the specific milling electricity needs agreed with that reported by Notarnicola and Nicoletti,[9] but resulted to be one-third[43] or one-half[44] of that stated by other authors (Table 3).

The contribution of packaging materials was mainly affected by the primary packaging type, which included both 0.5 or 5 kg PP bags[12,14–20] and 0.5 kg PB boxes.[13] It ranged from quite an improbable value of <1[18] to 410[14] g CO_{2e} kg^{-1}.

The contribution of pasta production and packaging phase fluctuated from 142[19] to 815[16] g CO_{2e} kg^{-1}. Although the drying times for short-cut extruded pasta (2–3 h) are definitively much shorter than those for the long counterpart (4–5 h), especially when using the ultrahigh temperature drying process, such a contribution seemed to be independent of the pasta type,[13,18] or difficulty discernable when collecting primary data, as in this case. On the contrary, the pasta production line capacity appeared to affect significantly the GHG emissions associated with this stage. As reported by Granarolo,[16] the estimated carbon footprint of this phase reduced from 815 to 338 kg CO_{2e} kg^{-1} as the pasta production capacity was increased from 135 to 850 kg h^{-1} (Table S1). Such a finding paralleled the remarks about the increase in the carbon footprint of bread,[54] milk[55] or beer[56] as the scale of bakery, dairy or brewery decreased.

In the pasta factory under study, the specific electric energy consumed during this phase varied from 278 to 317 kWh Mg^{-1} dried pasta (Table 3) and was in line with that (289 kWh Mg^{-1}) measured in a Sicilian pasta factory producing annually about 23 Gg of dry pasta,[45] but resulted to be about double that testified by Notarnicola and Nicoletti[9] and higher by 10–60% than that given by Carlsson-Kanyama and Faist.[43]

On the other hand, the specific thermal energy consumption registered in this work varied from 281 to 304 kWh Mg^{-1} dried pasta (Table 3), this interval of values falling within that indicated by Carlsson-Kanyama and Faist[43] and being about 53–57% of that reported by other authors,[9,45] who probably referred to pasta factories of smaller size than that examined here.

The impact of transportation varied from as low as 12[16] to 189[14] g CO_{2e} kg^{-1}. As suggested by the PEF category rules for dry pasta,[22] final product logistics might involve an average distance of 1500 km and a Euro 4 (16–32 Mg) truck as means of transport. In the circumstances, the default contribution for this stage would be of the order of 250 g CO_{2e} kg^{-1} dry pasta. In accordance with the final product logistics described in Table S5, such a phase involved GHG emissions of 133–144 g CO_{2e} kg^{-1} (Table 4).

Finally, the average GHG credits due to the use of processing byproducts as feed material embodied approximately 3.5–4.0% of CF_{CG} (Table 4). In the great majority of the CF studies listed in Table S1, the environmental impact of such byproducts was not clearly stated, being probably allocated on a mass or economic basis. For instance, in a carbon footprint study by Sgambaro[57] the mass-basis allocation procedure was used to account for the GHG emissions associated with both straw and grinding middling production. On the contrary, in other studies[6,58] the CO_{2e} credit was assumed as coincident with the GHG emissions related to the production of a typical animal feed (e.g. soybean meal) under constant raw protein content.

To improve the scientific value of this CF_{CG} assessment exercise, it was decided to resort to transparent data (see Tables 1–3 and S2–S7) and to study how the uncertainty in the output of the LCA model defined by Eqn (1) might be attributed to different sources of uncertainty in its input variables, especially in the emission factors EF_i of any activity parameter. Since such a model is linear, CF_{CG} sensitivity was quantified by registering the changes with respect to a basic value as resulting from the variation of the generic ith independent variable (X_i) with respect to its basic value (X_{iR}) while keeping all other parameters (X_j) constant for $j \neq i$.[59]

Therefore, to provide perspectives on the key drivers to the CF_{CG} of 1 kg of dried organic short-cut pasta packed in 0.5 kg PP bags, its sensitivity was assessed by changing the following activities.

i. Durum wheat cultivated under quite different crop management practices. In particular, the most effective crop rotation system used in Emilia-Romagna to cultivate organic durum wheat,[11] which involved a crop yield of 7.5 Mg ha^{-1} and a PCF of 0.36 kg CO_{2e} kg^{-1}, was compared with a conventional tillage system with a crop yield of 6.907 Mg ha^{-1} and a PCF of 0.915 kg CO_{2e} kg^{-1},[60] and a reduced tillage one with low input of N fertilizer (30 kg ha^{-1}), a crop yield of 4.755 Mg ha^{-1} and a PCF of 0.259 kg CO_{2e} kg^{-1}.[61]
ii. Durum wheat grown locally or in some European countries at an average supply distance of 50 or 1500 km respectively. In both cases, it was delivered at the factory gate by road using the same means of transport shown in Table S5.
iii. Electricity generated by solar photovoltaic or coal-fired power plants with an overall emission factor of 0.055 or 0.864 kg CO_{2e} kWh^{-1}, respectively.[30]
iv. Thermal energy deriving from the combustion of lignite (brown coal) or biogas produced anaerobically from organic resources and waste with an overall emission factor of 0.422[30] or 0.029[62] kg CO_{2e} kWh^{-1}, respectively.
v. Transport modality for palletized pasta by railway or container ship with an overall emission factor of 0.0474 or 0.0353 kg CO_{2e} Mg^{-1} km^{-1}, respectively (see Table S7).
vi. Regional and European distribution of palletized pasta with an average delivery distance of 250 and 1500 km, respectively.
vii. Management of processing wastes according to different disposal scenarios such as landfilling or composting with an overall emission factor of 0.8 or 0.106 kg CO_{2e} kg^{-1}, respectively (see Table S7).
viii. Home pasta cooking using an induction hob under different cooking procedures, namely use of a high cooking water/pasta ratio (WPR) of 12 L kg^{-1} with water heating and pasta cooking both carried out at the maximum power rating of 2 kW, this being typical of the so-called hurried cooker,[63] or use of the eco-sustainable pasta cooking procedure with WPR 2 L kg^{-1} and water heating and pasta cooking performed at 2 and 0.4 kW levels respectively.[51] These cooking procedures resulted in a specific cooking energy consumption of 4.70[63] or 0.39[51] kWh kg^{-1} respectively.

The main results of such a sensitivity analysis are shown in Table 5.

In Fig. 7, the relative variation of CF_{CG} (ΔCF_{CG}) with respect to the reference value (CF_{CGR}) is plotted against the relative variation of each independent parameter X_i accounted for (ΔX_i) with respect to the corresponding reference value (X_{iR}) so as to assess its slope m_i defined as

$$m_i = \left(\Delta CF_{CG}/CF_{CGR}\right) / \left(\Delta X_i/X_{iR}\right) \qquad (2)$$

In this way, the intrinsic linearity of Eqn (1) was immediately checked for: the higher m_i, the higher the sensitivity of CF_{CG} toward

Table 5. Sensitivity analysis of the cradle-to-grave carbon footprint (CF_{CG}) of dry organic pasta made of decorticated durum wheat semolina and packed in 0.5 kg PP bags (reference case): effect of the relative variation of a series of independent parameters X_i with respect to their reference value (X_{iR}) on CF_{CG} and corresponding slope m_i as defined by Eqn (2)

Parameter X_i	Reference	Value	Unit	CF_{CG}(g CO_{2e} kg^{-1})	m_i(–)
Reference value	This work			1807.3	
Effect of durum wheat carbon footprint and crop yield					
Organic crop rotation system	11	0.360	kg CO_2 kg^{-1}	1580.2	0.317
No tillage – low nitrogen addition	61	0.259	kg CO_2 kg^{-1}	1466.2	
Conventional tillage farming	60	0.915	kg CO_2 kg^{-1}	2242.0	
Effect of durum wheat supply distance					
Local grains	This work	50	km	1786.9	0.017
EU grains	This work	1500	km	2082.1	
Effect of electricity emission factor					
Solar photovoltaic energy	30	0.055	kg CO_{2e} kWh^{-1}	1505.2	0.212
Coal-fired power plant	30	0.864	kg CO_{2e} kWh^{-1}	2122.6	
Effect of thermal energy emission factor					
Biogas	62	0.029	kg CO_{2e} kWh^{-1}	1358.9	0.270
Lignite (brown coal)	30	0.422	kg CO_{2e} kWh^{-1}	2230.8	
Effect of transport modality for palletized pasta					
Rail	Ecoinvent	0.0474	kg CO_{2e} Mg^{-1} km^{-1}	1771.5	0.045
Inland waterway shipping	Ecoinvent	0.0353	kg CO_{2e} Mg^{-1} km^{-1}	1759.9	
Effect of delivery distance for palletized pasta					
Regional distribution	This work	250	km	1748.6	0.045
European distribution	This work	1500	km	1862.3	
Effect of processing waste management					
Landfilling	33	0.800	kg CO_2 kg^{-1}	2058.0	−0.039
Composting	Ecoinvent	0.106	kg CO_2 kg^{-1}	1900.6	
Effect of cooking energy needs					
Induction hob eco-sustainably operating with WPR of 2 L kg^{-1}	51	0.400	kg CO_2 kg^{-1}	1282.6	0.351
Induction hob at maximum power rating and WPR of 12 L kg^{-1}	63	4.700	kg CO_2 kg^{-1}	2470.0	

the relative variation of X_i will be. In brief, CF_{CG} resulted to be mainly controlled by the cooking energy needs, its slope being equal to +0.351. The carbon footprint and crop yield of durum wheat resulted to be the second most effective parameter (m_i = +0.317), such a slope being independent of the farming system applied. Then CF_{CG} was influenced by the emission factor of the source used to generate the thermal (m_i = +0.270) or electric (m_i = +0.212) energy. In spite of their antagonistic effects, CF_{CG} resulted to be slightly affected not only by the transport modality and delivery distance of the final product from the factory gate to the distribution centers (m_i = +0.045) but also by the processing waste disposal scenario (m_i = −0.039). In any case, the use of such waste as cattle feed had an environmental burden definitively smaller than landfilling and composting. Finally, CF_{CG} was by far less sensitive to durum wheat supply distance (m_i = 0.017).

Effect of a few mitigation options on dry organic pasta CF_{CG}

To improve the sustainability of dry organic pasta, it would be possible in principle to adopt the simple and stepwise approach suggested by Morawicki.[64] Firstly one should improve all processing efficiencies and gradually replace usage of fossil energy with renewable energy by purchase or self-generation. Then one should sequentially minimize the environmental impact of all transport steps, crop farming, and post-consumer packaging wastes and pasta scraps. Despite being firm-oriented, such an approach might result in mitigation actions exerting a minimum reduction in the PCF, as previously assessed in the case of lager beer production.[65] Thus a few mitigation opportunities were scheduled on the rationale that one should prioritize the life cycle stages with the highest contribution to the PCF. In this work, the hotspots were identified thanks to the sensitivity analysis shown in Fig. 7. By using technologies nowadays feasible for the pasta sector, Table 6 shows the effect of such alternatives on dried organic pasta CF_{CG}.

The diffusion of the eco-sustainable pasta cooking procedure with WPR 2 L kg^{-1} previously assessed[51] might cut the CF_{CG} by 29% with respect to the reference case (RC). Use of organic durum wheat cultivated using the sequential four-year crop rotation (tomato, durum wheat, maize and soft wheat) tested by Ruini *et al.*[11] enabled CF_{CG} to be decreased by another 12.6%. On the contrary, use of conventional durum wheat, cultivated under reduced tillage and low N input[61] in the neighboring region of the pasta factory examined, reduced CF_{CG} by 19% with respect to RC. By replacing the methane needed for the steam generating boilers with biogas, CF_{CG} reduced by a further 7.4%. A quasi zero-carbon alternative for electricity generation is solar-photovoltaic electricity. In this specific case, such a shift affected not only the pasta production step but also its cooking, and lessened CF_{CG} by 8.6%. Thus such mitigation options allowed the cradle-to-grave carbon footprint of dry pasta to be reduced by approximately 58% with respect to RC, from 1.81 to 0.77 kg CO_{2e} kg^{-1} (Table 6). All other options examined in Table 6 exerted an extra reduction of 5% in

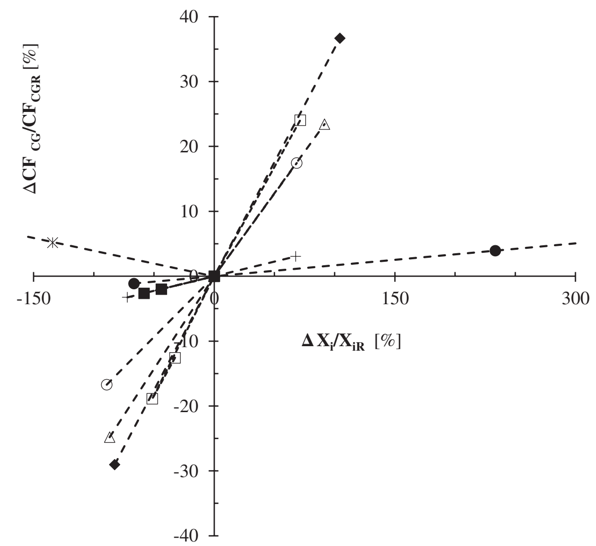

Figure 7. Effect of the relative variation ($\Delta CF_{CG}/CF_{CGR}$) of the cradle-to-grave carbon footprint with respect to its reference value for a functional unit (1 kg) of dry organic pasta packed in 0.5 kg PP bags against the relative variation ($\Delta X_i/X_{iR}$) of a few parameters X_i, namely durum wheat cultivation method (DW, □) and supply distance (DWSD, ●), thermal (E_T, △) and electric (E_e, ○) energy emission factors, palletized pasta transport modality (PPTM, ■) and delivery distance (PPDD, +), processing waste management (PWM, ⁎) and cooking energy needs (CE, ♦).

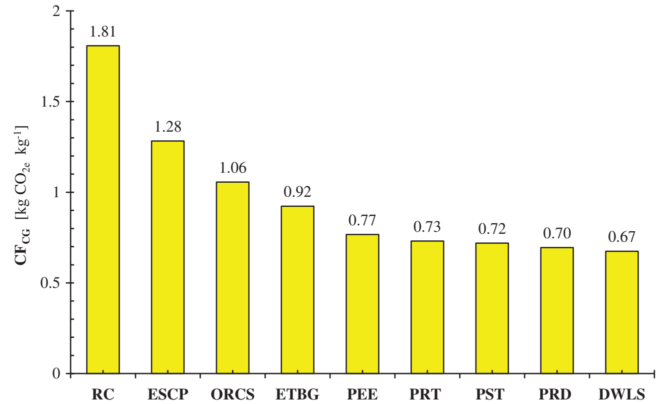

Figure 8. Marginal abatement curves of the cradle-to-grave carbon footprint (CF_{CG}) as resulting from the sequential mitigation strategies adopted to alleviate the environmental load of the most impactful life cycle phase of the production of a functional unit (1 kg) of dry organic pasta in 0.5 kg PP bags in a medium-sized pasta factory, as estimated using the LCA model (1). All symbols are defined in 'List of symbols'.

CF_{CG}. In particular, by shifting from road to rail or sea freight transport, a supplementary 2 or 2.6% reduction in CF_{CG} was achieved respectively, while CF_{CG} further reduced by 1.4 or 1.1% when the final product or grain delivery distance was as low as 250 or 50 km respectively.

As shown in Fig. 8, such a sequential series of mitigation options allowed CF_{CG} to be totally reduced by about 63% with respect to RC. On the contrary, use of conventional durum wheat under the aforementioned reduced management practices would have overall cut CF_{CG} by approximately 69% with respect to RC.

This sequential procedure might be applied to ascertain the most effective improvement opportunities along the life cycle phases. A further step should be focused on examining other environmental impacts in the product life cycle, especially eutrophication and acidification categories, as recommended by the PEF category rules for dry pasta.[22]

CONCLUSIONS

By referring to fully transparent primary and secondary data, the estimated business-to-business carbon footprint (CF_{CDC}) of dry short-cut extruded pasta made of decorticated organic durum wheat semolina and packed in 0.5 kg PP bags amounted to 1.12 kg CO_{2e} kg^{-1}, including the CO_{2e} credits resulting from the use of all processing byproducts as cattle feed. Excluding such credits, the contribution of the field phase, milling, pasta production and packaging, packaging materials, transport and packaging waste end of life represented approximately 56, 4, 17, 9, 12 and 2% of CF_{CDC} respectively. As the contribution of the use and post-consume phases was accounted for, the business-to-consumer carbon footprint (CF_{CG}) increased to 1.81 kg CO_{2e} kg^{-1}. Thus the last mentioned life cycle phases resulted to be the primary hotspot. This was more or less affected by the pasta types (i.e. short and long goods) and packing formats used (i.e. 0.5 kg PP bags or PB boxes and 3 kg PE bags), since CF_{CG} was found to vary from +0.3 to +14.8% with respect to the minimum score estimated (1.74 kg CO_{2e} kg^{-1}), which corresponded to long goods packed in 3 kg PE bags for catering service.

The one-factor-at-a-time sensitivity analysis revealed that three promising strategies might be applied to reduce the overall GHG emissions. Firstly, more eco-sustainable cooking practices are

Table 6. Effect of the sequential mitigation strategies used to minimize the cradle-to-grave carbon footprint (CF_{CG}), as referred to the production of 1 kg of dry organic pasta packed in 0.5 kg PP bags in the large-sized pasta factory accounted for, and its cumulative percentage variation (ΔCF_{CG}) with respect to that pertaining to the reference case. The sequential stepwise procedure started from the most impactful parameter as resulting from the sensitivity analysis shown in Fig. 7

Mitigation strategy	Parameter varied	Value	Unit	CF_{CG} (kg CO_{2e} kg^{-1})	ΔCF_{CG} (%)
Reference case	RC		–	1.807	0
Eco-sustainable cooking procedure	ESCP	0.400	kWh kg^{-1}	1.283	−29.0
Organic rotation cropping system	ORCS	0.360	kg CO_{2e} kg^{-1}	1.056	−41.6
Thermal energy from biogas	ETBG	0.029	kg CO_{2e} kWh^{-1}	0.923	−49.0
Photovoltaic electric energy	PEE	0.055	kg CO_{2e} kWh^{-1}	0.767	−57.6
Pasta rail transport	PRT	0.0474	kg CO_{2e} Mg^{-1} km^{-1}	0.731	−59.5
Pasta shipping transport	PST	0.0353	kg CO_{2e} Mg^{-1} km^{-1}	0.720	−60.2
Regional distribution of pasta	PRD	250	km	0.695	−61.5
Local supply of durum wheat	DWLS	50	km	0.675	−62.7

needed to limit energy and water usage. This finding should, on one side, ask for the replacement of the domestic appliances and cookware sets used today with novel energy-saving pasta cookers and, on the other side, drive the pasta manufacturers to develop for instance new pre-gelatinized pasta products requiring a smaller cooking energy consumption. Secondly, the field phase resulted to be the second hotspot, this making the application of less environmentally impacting cultivation techniques vital to minimize the emissions associated with organic durum wheat production under the constraint of maximizing the crop yield. Thirdly, the use of renewable resources was demanded for generating the thermal and electric energy needed to manufacture and cook dry pasta.

Finally, a simple and stepwise approach was applied to minimize the cradle-to-grave carbon footprint by resorting to the LCA model developed here on the rationale that one should prioritize the life cycle stages with the highest impact on CF_{CG} according to the sensitivity analysis mentioned above. Thus the resulting mitigation options allowed the cradle-to-grave carbon footprint of dry organic pasta to be reduced by approximately 63% with respect to the reference case down to 0.675 kg CO_{2e} kg^{-1}. A further reduction of 5% in CF_{CG} might be achieved by shifting the transport modality from road to rail and shortening the supply logistics of dry pasta and grains. This might involve also the delocalization of pasta production sites.

A cost/benefit analysis is lastly looked for pinpointing the most effective opportunities to reduce the product environmental impact with minimum effect on the overall dry pasta operating costs, or alternatively to assess other environmental impact categories.

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SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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