1 **Cradle-to-grave carbon footprint of dried organic pasta:**

2 **Assessment and potential mitigation measures**

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18 **Cradle-to-grave carbon footprint of dried organic pasta**

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 of 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}), that 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.

43 **Key words:** Business-to-consumer carbon footprint; cooking phase;
44 decorticated organic durum wheat; dry organic pasta;
45 paperboard boxes, polypropylene or polyethylene bags;
46 sensitivity analysis.

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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 tonnes of pasta are annually produced worldwide, the 22.7% and 14.0% of which being produced in Italy and 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 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 ones 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 Declarations¹²⁻²⁰ have been published and revised so far. As shown in the electronic supplement (Table S1), the estimated cradle-to-distribution centre (business-to-business) carbon footprint (CF_{CDC}) of dried durum wheat semolina pasta ranged from 0.57 to 1.7 kg of 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 (e.g., pasta and pizza margherita).²¹ Actually, pasta cooking for an average time of 10 min involves a consumption of about 10 L of water and 2.3 kWh per each kg of dried pasta, respectively.^{17, 22} Thus, depending on the use of a gas or electric hob, further GHG emissions in the range of 0.6¹³ to 3.1¹⁸ 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 different operating variables and yield factors used.

Despite 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 product carbon footprint, it is crucial to rely on appropriate and transparent emission factors. Unfortunately, the numerous Environmental Product Declarations 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 Calculator³¹ 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. Thus, the first aim of this study was to develop a life-cycle assessment 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 2050 standard method,³²⁻³³ and was based on transparent processing and packaging consumption yields, as well as

144 emission factors. Then, a sensitivity analysis of CF_{CG} was carried out to assess
145 the influence of different parameters (such as, origin of durum wheat and its
146 cultivation methods, GHG emissions per kWh of electric or thermal energy
147 generated by fossil and/or renewable sources, distribution logistics,
148 transportation by road, rail or sea, cooking modes, etc.), and thus identify the
149 most promising strategy to mitigate the GHG emissions associated with the
150 overall dried pasta life cycle.

METHODOLOGY

The life-cycle analysis (LCA) was performed in compliance with the PAS 2050 standard method,³²⁻³³ 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 PAS 2050.

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 hot spots.

Functional unit

The analysis was referred to a *functional unit* defined as one kg of dried decorticated organic durum wheat semolina pasta packed in 0.5-kg polypropylene (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 the 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 by-products 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 method.³²

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 by-products, 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 life cycle assessment by means of CO₂ credits. In addition, all CO₂ credits from recycling of renewable and non-renewable materials were included.

Data gathering and data quality

According to 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 by-products, as well as dough and dried pasta discarded fractions, were used as animal feed, this giving rise to a CO_{2e} credit. Distribution center (DC), 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 to the Italian electric energy production by renewable and non-renewable sources, ³⁴ LCA software (i.e., Simapro 8.2 v.2, Prè Consultants, Amersfoort, NL), and several databases (such as BUWAL 250, Ecoinvent 2.0, Franklin USA 98) using the method developed by IPCC, ³⁵ as well other technical reports. ^{30, 33}

INVENTORY ANALYSIS

In this stage of the LCA procedure all the 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 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.³⁶

About 70% of the nominal non-irrigated land was dedicated to durum wheat cultivation, while the remaining 30% to fodder legume one. In this way, the only soil undergoing legume cultivation was managed using aged poultry manure compost with an average total nitrogen content of 1.3%.³⁷ 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 N₂O emissions.³⁵ The above ground residues AG_{DM}, that is straw, as well as below ground ones (BG_{DM}), were estimated in accordance with IPCC procedures.³⁵ According to EPD®,³⁸ 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 the 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); ³² 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. Fig. 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 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. Such 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 one (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 middlings (different in sizes and composition) were 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 circa 0.38 kg per each kg of input grains was produced (Fig. 2).

All the wheat dockage fractions resulting from the precleaning and cleaning phases, and bran particles derived from the decortication (FDF) and grinding (GB) steps were converted into the so-called wheat feed pellets (WFP), their overall amount being of 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 $\pm 10\%$, as shown in the electronic supplement (Table S2). In this way, durum wheat milling gave rise to an overall yield for the three types of semolina of ~ 0.867 kg per kg of 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, RWDWS) were used to produce three different dried organic pastas. Fig. 3 shows the block diagram of their pasta making process.

Each 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-coated dies to obtain long- (LP) or short-cut (SP) extruded pasta. Despite extrusion barrels had 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 $\sim 0.31 \text{ kg kg}^{-1}$. The average amount of discarded dough as such or extruded (KW) was approximately the 0.4% of D.

A final drier was then used to reduce the moisture content of extruded pasta to $0.1125 \text{ kg kg}^{-1}$ 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 to 10 h, depending on the pasta shape. As 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 $\pm 10 \%$, as shown in the electronic supplement (Table S3).

Pasta Packaging

The 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 self-seal laminating polypropylene (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 being then labeled and sealed with a scotch tape. The tertiary one involved a 120x80-EPAL wood pallet over which different layers of cartons were stacked. The effect of other packages (i.e., 0.5-kg paperboxes, and 3-kg polyethylene, PE, bags for catering service) was also assessed.

Fig. 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

359 tertiary packages. (i.e., plastic bags or paperboxes, cartons, adhesive labels,
360 scotch tape, stretch and shrink film, pallet, etc.).

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Processing Aids

Milling and pasta making equipment needs to be cleaned and lubricated. The average consumption of detergents and lubricant oils was of about 0.020 and 0.037 L per each Mg of dried pasta produced, respectively. Moreover, all the other materials used in minimum quantities (that is, 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).³²

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.
- Paperboxes (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 back 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 of $\sim 484 \text{ mg O}_2 \text{ L}^{-1}$) per Mg of dried pasta were produced and submitted to aerobic digestion to lower their COD value to approximately $175 \text{ mg O}_2 \text{ L}^{-1}$ 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} of dried pasta.

Wheat milling by-products (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 to the production of soybean meal (having a minimum raw protein content of 0.44 g g^{-1}).³⁹ In the case of no land use changes, the carbon footprint of soybean meal ranged from ~ 0.6 to $0.95 \text{ kg CO}_{2e} \text{ kg}^{-1}$,⁴⁰ this being equivalent to $1.4\text{-}2.2 \text{ kg CO}_{2e} \text{ kg}^{-1}$ protein. Since the raw protein contents 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 $-0.22 \text{ kg CO}_{2e} \text{ kg}^{-1}$.

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 to dehydrate wet extruded pasta.

Table 3 shows the specific energy needs, as derived from factory measurements or extracted from the literature.^{9, 41-43}

In the year 2016 or 2017, the 20 or 24% of the electricity used by the pasta factory in question was absorbed by the Italian mean voltage (20,000 V) grid, while the remaining 80 or 76% 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 2017.⁴⁴ As concerning the thermal energy requirements, in the years 2016 or 2017 the 41 or 43% of the overall duty was satisfied by the cogeneration plant, while the 57 or 59% using 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 2016.³⁴ 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 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 centres, 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).³²⁻³³

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 the distance of one hundred kilometers from the pasta factory of concern, the distance travelled by the empty pallets was circa 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 2016,⁴⁵ 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 (Ronchi and Nepi, 2017),⁴⁶ as reported in the electronic supplement (Table S6).

Use phase

Dry pasta is stored at ambient temperature. To cook 1 kg of pasta, 10 liters of boiling water laced with 70 g of table salt (TS)¹³ are usually needed, as reported in the EPD®⁴⁷ and PEF²² category rules for dry pasta. The default energy requirements for boiling 1 kg of water is 0.18 kWh, while for cooking 1 kg of pasta is 0.05 kWh per minute of cooking. By assuming an average cooking time of 10 min, the overall energy requirements would be 2.3 kWh per kg of dry pasta, of which (0.18 x 10=) 1.80 kWh to boil 10 L of water and (0.05 x 10=) 0.5 kWh to cook pasta. Electricity or gas is used to cook dry pasta. In the European Union, the 83% of the domestic cookers are gas-fired, while the remaining 17% 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 a 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 the 12% of what had been cooked⁴⁸ was wasted probably because it was not used in time or prepared too much. The effect of such 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.⁴⁹ 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, ⁴⁵ 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 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 the GHG emissions associated to 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 in mass, energy, 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 density, 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.³⁵ Fig. 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 spot (43.1%), diesel fuel consumption for management practices the secondary one (26.6%), and direct and indirect N₂O 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, that 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 with conventional one in Switzerland⁵⁰ or Southern Italy⁵¹, 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 one using a rotation between cereals and fodder legumes ensued a 31% less average crop yield of 2.7 ± 0.1 Mg ha⁻¹.³⁶ Also, the crop rotation test performed by Barilla in 13 farms, located in the most important areal 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 of durum wheat in the 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.

Fig. 6 shows the contribution of the different life cycle phases to the cradle-to- distribution centre, excluding (CF_{CDC'}) or including (CF_{CDC}) the CO_{2e} credits due to the feed use of processing byproducts, or -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 to 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 to 69 g CO_{2e} kg⁻¹. Thus, CF_{CDC} and CF_{CG} scores totaled 1.12 and 1.81 kg CO_{2e} kg⁻¹ (Table 4).

If the pasta scraps were as high as the 12% of dried pasta cooked,⁴⁸ CF_{CG} increased by 5.2% to 1.90 kg CO_{2e} kg⁻¹.

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

Table 4 shows the sensitivity of dried organic pasta CF_{CG} towards the pasta types (i.e., short and long goods) and packing formats (i.e., 0.5-kg PP bags or 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 paperboard boxes, CF_{CG} for short or long goods increased by 10.5 or 7.5% with respect to their 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 versus 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 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

Because of 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 or 0.5-¹⁷ kg PP bags, respectively.

The impact of the milling phase ranged from 35¹⁶ to 270¹⁵ g CO_{2e} kg⁻¹. In the pasta factory examined here, in 2016 the specific electric energy consumption was about 54 kWh per Mg of durum wheat milled, 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 third⁴¹ or one half⁴² of that stated by other authors (Table 3).

The contribution of packaging materials was mainly affected by the primary packaging type, that included both 0.5- or 5-kg PP bags,^{12, 14-20} and 0.5-kg paperboard boxes.¹³ It ranged from quite an improbable value of less than one¹⁸ to 410¹⁴ g CO_{2e} kg⁻¹.

The contribution of pasta production and packaging phase fluctuated from 142¹⁹ to 815¹⁶ g CO_{2e} kg⁻¹. Although the drying times for short-cut extruded pasta (2-3 h) are definitively much shorter than those (4-5 h) for the long

counterpart, especially when using the ultra-high 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,⁵² milk,⁵³ or beer,⁵⁴ 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 per Mg of dried pasta (Table 3), and was in line with that (289 kWh Mg⁻¹) measured in a Sicilian pasta factory producing annually about 23 Mg of dry pasta,⁴³ but resulted to be about the double of that testified by Notarnicola and Nicoletti,⁹ and higher by 10 to 60% of that given by Carlsson-Kanyama and Faist.⁴¹

On the other hand, the specific thermal energy consumption registered in this work varied from 281 to 304 kWh per Mg of dried pasta (Table 3), this interval of values falling within that indicated by Carlsson-Kanyama and Faist,⁴¹ and being about the 53-57% of that reported by other authors,^{9, 43} probably because they referred to pasta factories of smaller size than that examined here.

The impact of transportation varied from as low as 12¹⁶ to 189¹⁴ 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 1,500 km and a Euro4 (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} per kg of 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 by-products as feed material embodied approximately the 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 ⁵⁵ the mass-basis allocation procedure was used to account for the GHG emissions associated to both straw and grinding middling production. On the contrary, in other studies ^{6, 56} 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 Eq. (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 i-th independent variable (X_i) with respect to its basic value (X_{iR}) while keeping all the other parameter (X_j) constant for j≠i. ⁵⁷

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 by Ruini et al.,¹¹ that involved a crop yield of 7.5 Mg ha⁻¹ and a product carbon footprint (PCF) of 0.36 kg CO_{2e} kg⁻¹, was compared to the conventional tillage system with a crop yield of 6.907 Mg ha⁻¹ and a PCF of 0.915 kg CO_{2e} kg⁻¹,⁵⁸ and 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⁻¹.⁵⁹

ii) Durum wheat grown locally or in some European countries at an average supply distance of 50 or 1,500 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 0.422³⁰ or 0.029⁶⁰ kg CO_{2e} kWh⁻¹, respectively.

v) Transport modality for palletized pasta by railway or container ships 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 1,500 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-to-pasta ratio (WPR) of 12 L kg⁻¹ with water heating and pasta cooking carried out both at the maximum power rating of 2 kW, this being typical of the so-called hurried cooker,⁶¹ 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.⁴⁹ These cooking procedures resulted in a specific cooking energy consumption of 4.70⁶¹ or 0.39⁴⁹ 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}) was 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

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

In this way, the intrinsic linearity of Eq. (1) was immediately checked for. Then, the higher m_i the higher the sensitivity of CF_{CG} towards 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 ($m_i\sim+0.212$) energy. In spite of their antagonistic effects, CF_{CG} resulted to be slightly affected not only by the transport modality and deliver distance of final product from the factory gate to the distribution centers ($m_i\sim+0.045$), but also by the processing waste disposal scenario ($m_i=-0.039$). In any case, the use of such a 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 in principle possible to adopt the simple and stepwise approach suggested by Morawicki.⁶² Firstly, one should improve all processing efficiencies and replace gradually usage of fossil energy with renewable one 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 firm-oriented, such an approach might result in mitigation actions exerting a minimum reduction in the product carbon footprint, as previously assessed in the case of lager beer production.⁶³ Thus, a few mitigation opportunities were scheduled on the rationale that one should

prioritize the life cycle stages with the highest contribution to the product carbon footprint. 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 ⁴⁹ might cut the CF_{CG} by 29% with respect to the reference case (RC). Use of organic durum wheat cultivated using the following sequential 4-yr crop rotation (tomato, durum wheat, maize, and soft wheat) as 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 ⁵⁹ 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 7.4% further. 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 one, 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 the reference case (RC), from 1.81 to 0.77 kg CO_{2e} kg^{-1} (Table 6). All the other options examined in Table 6 exerted an extra reduction of 5% in 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, respectively, achieved; whereas CF_{CG} further reduced by 1.4 or 1.1%

as 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 Product Environmental Footprint 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 semolinas as packed in 0.5-kg PP bags amounted to $1.12 \text{ kg CO}_{2e} \text{ kg}^{-1}$, 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 approximately represented the 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 $1.81 \text{ kg CO}_{2e} \text{ kg}^{-1}$. 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 ($1.74 \text{ kg CO}_{2e} \text{ kg}^{-1}$), that corresponded to long goods packed in 3-kg PE bags for catering service.

The one-factor-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 needed to limit energy and water usage. This finding should, on one side, ask for the replacement of the domestic appliances and cookware sets currently used today with novel energy-saving pasta cookers, and, on the other one, 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 to organic durum wheat production with 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 $0.675 \text{ kg CO}_{2e} \text{ kg}^{-1}$. 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 of other environmental impact categories.

LIST OF SYMBOLS

1PEoL Primary packaging end of life.

795	2-3PEoL	Secondary and tertiary packaging end of life
796	AG _{DM}	Above ground residues [kg ha ⁻¹]
797	AT	Articulated truck
798	BC	Byproduct credit
799	BG _{DM}	Below ground residues [kg ha ⁻¹]
800	CA	Cartons [kg]
801	CAL	Carton labels [kg]
802	CALW	Carton label waste [kg]
803	CAW	Carton waste [kg]
804	CDW	Cleaned durum wheat [kg]
805	CE	Cooking energy needs
806	CF _{CDC}	Cradle-to-distribution center carbon footprint of a functional unit
807		including the CO _{2e} credits due to the feed use of processing
808		byproducts [kg CO _{2e} kg ⁻¹]
809	CF _{CDC'}	Cradle-to-distribution center carbon footprint of a functional unit,
810		excluding the CO _{2e} credits due to the feed use of processing
811		byproducts [kg CO _{2e} kg ⁻¹]
812	CF _{CG}	Cradle-to-grave carbon footprint of a functional unit [kg CO _{2e} kg ⁻¹],
813		as defined by Eq. (1)
814	CF _{CGR}	Reference value for the cradle-to-grave carbon footprint of a
815		functional unit [kg CO _{2e} kg ⁻¹]
816	CHP	Combined heat and power system
817	COD	Chemical Oxygen Demand
818	CP	Consumer phase

819	D	Pasta dough [kg]
820	DC	Distribution center
821	DDWK	Decorticated durum wheat kernels [kg]
822	DKPC	Pre-cleaning Dockage [kg]
823	DKC	Cleaning Dockage [kg]
824	FDF	First debrannig fraction [kg]
825	DIW	Water used to prepare the dough [kg]
826	DP	Dried pasta [kg]
827	DPB	Dried pasta in primary packs [kg]
828	DPC	Dried pasta in secondary packs [kg]
829	DPP	Dried pasta in tertiary packs [kg]
830	DPW	Dried pasta wastes [kg]
831	DW	Durum wheat [kg]
832	DWLS	Local supply of durum wheat [km]
833	DWS	DW semolina [kg]
834	DWSD	DW supply distance [km]
835	E _e	Electric energy
836	EF ₁	N ₂ O-N emissions per N fertilizer mass [kg N ₂ O-N (kg N) ⁻¹]
837	EF ₄	N ₂ O-N emissions per unit mass of NH ₃ and N oxides emitted, both
838		expressed in N mass [kg N ₂ O-N (kg NH ₃ -N+kg NO _x -N-emitted) ⁻¹]
839	EF ₅	N ₂ O-N emissions per unit mass of N leached off [kg N ₂ O-N (kg N
840		leaching off) ⁻¹]
841	EF _i	Emission factor for the generic i-th activity, expressed in [kg CO _{2e}
842		kg ⁻¹], [kg CO _{2e} kWh ⁻¹] or [kg CO _{2e} Mg ⁻¹ km ⁻¹]

843	EoL	End-of-life
844	EPD	Environmental Product Declaration
845	EPMC	Euro pallet managing center
846	ESCP	Eco-sustainable cooking procedure
847	E _T	Thermal energy
848	ETBG	Thermal energy from biogas
849	EV	Water evaporated during dough extrusion [kg]
850	F _{CR}	Specific N content of crop residues [kg N ha ⁻¹ yr ⁻¹]
851	FDF	First decortication fraction [kg]
852	FP	Field phase
853	Frac _{GASF}	NH ₃ - and NO _x -emissions per unit N fertilizer mass [kg NH ₃ -
854		N+NO _x -N (kg N) ⁻¹]
855	Frac _{LEACH}	N leaching off per unit N fertilizer mass [kg N (kg N) ⁻¹]
856	F _{SN}	Specific N content of organic fertilizer [kg N ha ⁻¹ yr ⁻¹]
857	GHG	Greenhouse gas
858	GB	Grinding bran particles [kg]
859	GWP	Global Warming Potential
860	HERS	High-extraction rate semolina [kg]
861	HRT	Heavy rigid truck
862	ISS	Impurities, stones, and straw [kg]
863	KW	Pasta dough discarded during kneading [kg]
864	LCA	Life-cycle assessment
865	LP	Long extruded pasta
866	MAL	Multiple axle lorry

867	MI	Milling phase
868	m_i	Slope of the relative variation of CF_{CG} ($\Delta CF_{CG}/CF_{CGR}$) as referred
869		to the relative variation of each independent parameter X_i
870		($\Delta X_i/X_{iR}$), as defined by Eq. (2) [dimensionless]
871	MLBF	Milling light branny fraction [kg]
872	ORCS	Organic rotation cropping system
873	PAS	Publicly Available Specification
874	PB	Paperboard box [kg]
875	PCDW	Precleaned DW [kg]
876	PCF	Product Carbon Footprint
877	PE	Polyethylene
878	PEE	Photovoltaic electric energy
879	PEF	Product Environmental Footprint
880	PM	Packaging manufacture
881	PP	Polypropylene
882	PPB	PP bag or paperboard box [kg]
883	PPDD	Palletized pasta delivery distance [km]
884	PPP	Pasta production and packaging
885	PPTM	Palletized pasta transport modality
886	PPW	PP bag or paperboard box wastes [kg]
887	PRD	Regional distribution of pasta
888	PRM	Packaging raw material
889	PRT	Pasta rail transport
890	PS	Pasta scraps [kg]

891	PST	Pasta shipping transport
892	PV	Water evaporated during pasta drying [kg]
893	PWM	Processing waste management
894	Q_e	Specific electric energy consumption [kWh Mg ⁻¹]
895	Q_T	Specific thermal energy consumption [kWh Mg ⁻¹]
896	R_{BG-BIO}	Below ground-to above-ground biomass ratio [dimensionless]
897	RC	Reference case
898	RWDWS	Recombined whole durum wheat semolina [kg]
899	RT	Light-medium rigid truck
900	SDF	Secondary decortication fraction [kg]
901	SC	Carton scotch tape [kg]
902	SCW	Carton scotch tape waste [kg]
903	SP	Short-cut extruded pasta
904	TR	Transportation
905	TRfp	Transport of final product
906	TRpaw	Transport of packaging and auxiliary materials, and wastes
907	TS	Table salt [kg]
908	TW	Tempering Water [kg]
909	WCC	Waste collection center
910	WCDW	Wet cleaned durum wheat [kg]
911	WDP	Wet extruded product [kg]
912	WDWS	Whole durum wheat semolina [kg]
913	WE	Water evaporated [kg]
914	WEP	Wet extruded pasta [kg]

915	WFP	Wheat feed pellets [kg]
916	WP	Wooden pallet [kg]
917	WPF	Wooden pallet wrap film [kg]
918	WPFW	Wooden pallet wrap film waste [kg]
919	WPL	Wooden pallet label [kg]
920	WPLW	Wooden pallet label waste [kg]
921	WPR	Cooking water-to-pasta ratio [L kg ⁻¹]
922	WPW	Wooden pallet waste [kg]
923	X _i	Generic i-th independent variable
924	X _{iR}	Reference value for any generic i-th variable X _i
925	ΔCF _{CG}	Relative variation of CF _{CG} with respect to the reference value
926		(CF _{CG} -CF _{CGR}) [kg CO _{2e} kg ⁻¹]
927	ΔX _i	Relative variation of each independent parameter X _i with respect
928		to the corresponding reference value (X _{iR})
929	Ψ _i	Entity of the i-th activity [kg, J or Mg km]

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932 **Appendix A. Supplementary data**

933 Supplementary data related to this article can be found online at <http://>

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FIGURE 1

Dried pasta system boundary showing the main processes as divided into upstream, core and downstream ones. All symbols were listed in the *List of Symbol* section.

1195 **Figura 2**

1196 Flowchart of the process of decortication and milling of durum wheat (DW) with
1197 production of durum wheat semolina (DWS), whole durum wheat semolina
1198 (HERS) and recombined one (RWDWS). All symbols were listed in the *List of*
1199 *Symbol* section.

1200

FIGURE 3

Flowchart of the dried pasta making process using durum wheat (DWS), high-extraction rate (HERS) or recombined whole durum wheat (RWDWS) semolinas. All symbols were listed in the *List of Symbol* section.

FIGURE 4

Schematic diagram of the packaging process for each dried pasta type examined in this work. All symbols were listed in the *List of Symbols* section.

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

Contribution of the different life cycle stages to the cradle-to-distribution center (CF_{CDC}) or -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. Item list: FP, field phase; MI, milling; PPP, pasta production and packaging; PM, packaging manufacture; TRpaw, transport of packaging and auxiliary materials, and wastes; TRfp, transport of final product; 2-3PEoL, secondary and tertiary packaging end of life; BC, byproduct credit; CP, consumer phase; PS, pasta scraps; 1PEoL, primary packaging end of life.

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, $\square$) and supply distance (DWSD, $\bullet$); thermal (E_T , $\triangle$), and electric (E_e , $\circ$) energy emission factors; palletized pasta transport modality (PPTM, $\blacksquare$) and delivery distance (PPDD, $+$); processing waste management (PWM, $*$); and cooking energy needs (CE, $\blacklozenge$).

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 the LCA model (1). All symbols used are listed in the *List of Symbols* section and Table 6.

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. ³⁵

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 ₂ O ₅	kg ha ⁻¹ yr ⁻¹	0
Potassium fertilizer as K ₂ O	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 DM) ⁻¹	0.0067
Percentage of straw baling	%	80
Percentage of straw left in the field	%	20
Below ground-to above-ground biomass ratio (R _{BG-BIO})	kg kg ⁻¹	0.24
Belowground residues (BG _{DM})	Mg DM ha ⁻¹ yr ⁻¹	1.44-1.63
N content of below-ground residues	kg N (kg DM) ⁻¹	0.009
Crop residues (F _{CR})	kg N ha ⁻¹ yr ⁻¹	18.1-20.4

NH ₃ - and NO _x -emissions (Frac _{CGASF})	kg NH ₃ -N+NO _x -N (kg N) ⁻¹	0.1 (0.03-0.3)
N leaching off (Frac _{CLEACH})	kg N (kg N) ⁻¹	0.3 (0.1-0.8)
EF ₁	kg N ₂ O-N (kg N) ⁻¹	0.01 (0.003-0.03)
EF ₄	kg N ₂ O-N (kg NH ₃ -N+kg NO _x -N-emitted) ⁻¹	0.01 (0.002-0.05)
EF ₅	kg N ₂ O-N (kg N leaching off) ⁻¹	0.0075 (0.0005-0.025)
Direct N ₂ O emissions [(F _{SN} +F _{CR}) EF ₁ 44/28]	kg N ₂ O ha ⁻¹ yr ⁻¹	0.89-0.92
Indirect N ₂ O emissions from NH ₃ and NO _x -emissions [=F _{SN} Frac _{CGASF} EF ₄ 44/28]	kg N ₂ O ha ⁻¹ yr ⁻¹	0.12
Indirect emissions form N leaching off [(F _{SN} +F _{CR}) Frac _{CLEACH} EF ₅ 44/28]	kg N ₂ O ha ⁻¹ yr ⁻¹	0.32-0.33

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

Packaging format	PP Bags		Paperboard Box		PE Bags		Unit
Pasta type	SP	LP	SP	LP	SP	LP	
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 x Width x Height	105x38x170	310x80x30	130x65x175	270x70x34	420x320x70	335x250x45	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 x Width x Depth	380x220x220	300x175x285	545x220x195	300x190x290	400x300x285	340x170x285	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 x (2.42±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. Secondary Packages	10	16	20	16	8	8	-
No. Layer 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 x (3.11±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 to durum wheat (DW) milling and dry pasta (DP) making, as collected in the pasta factory or extracted from literature.

Processing step	Specific consumption		References
	Q_e	Q_T	
	[kWh Mg ⁻¹ DW]	[kWh Mg ⁻¹ DW]	
Durum wheat milling			
	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	-	⁴¹
	83.33	2.22	⁴²
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	⁴¹
	289	511	⁴³

Table 4

Percentage contribution of the different life cycle phases to the cradle-to-distribution center, excluding (CF_{CDC}) or including (CF_{CDC}) by-product credits, and -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 or PB boxes, and 3-kg PE bags.

Life Cycle Phases		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	
		[#]	[%]	[#]	[%]	[#]	[%]	[#]	[%]	[#]	[%]	[#]	[%]
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, auxiliary materials & 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 byproducts 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
Beer production including byproducts 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

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 Eq. (2).

Parameter X_i	Ref.	Value	Unit	CF_{CG} [g CO _{2e} kg ⁻¹]	m_i [-]
Reference Value	This work			1807.3	
<i>- Effect of durum wheat carbon footprint and crop yield</i>					
Organic crop rotation system	11	0.360	kg CO ₂ kg ⁻¹	1580.2	0.317
No tillage – low nitrogen addition	59	0.259	kg CO ₂ kg ⁻¹	1466.2	
conventional tillage farming	58	0.915	kg CO ₂ kg ⁻¹	2242.0	
<i>- Effect of durum wheat supply distance</i>					
Local grains	This work	50	km	1786.9	0.017
EU grains	This work	1500	km	2082.1	
<i>- Effect of the electricity emission factor</i>					
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	
<i>- Effect of the thermal energy emission factor</i>					
Biogas	60	0.029	kg CO _{2e} kWh ⁻¹	1358.9	0.270
Lignite (brown coal)	30	0.422	kg CO _{2e} kWh ⁻¹	2230.8	
<i>- Effect of transport modality for palletized pasta</i>					
Rail	Ecoinvent	0.0474	kg CO _{2e} (Mg km) ⁻¹	1771.5	0.045
Inland waterway shipping	Ecoinvent	0.0353	kg CO _{2e} (Mg km) ⁻¹	1759.9	
<i>- Effect of delivery distance for palletized pasta</i>					
Regional distribution	This work	250	km	1748.6	0.045
European distribution	This work	1500	km	1862.3	
<i>- Effect of processing waste management</i>					
Landfilling	33	0.800	kg CO ₂ kg ⁻¹	2058.0	-0.039

Composting	Ecoinvent	0.106	kg CO ₂ kg ⁻¹	1900.6	
<i>- Effect of cooking energy needs</i>					
Induction hob eco-sustainably operating with WPR=2 L kg ⁻¹	49	0.400	kg CO ₂ kg ⁻¹	1282.6	0.351
Induction hob at the maximum power rating and WPR=12 L kg ⁻¹	61	4.700	kg CO ₂ kg ⁻¹	2470.0	

24

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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 relative percentage variation (ΔCF_{CG}) with respect to that pertaining to the reference case. The sequential step-wise 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]	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 km) ⁻¹	0.731	-59.5
Pasta shipping transport	PST	0.0353	kg CO _{2e} (Mg 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

SUPPLEMENTARY MATERIAL

Table S1

Contribution of the different life cycle phases to the carbon footprint from cradle-to-distribution centers (CF_{CDC}) of a functional unit (1 kg) of dried long (LP) and short (SP) pasta differently packed (5-kg catering PE bags, 5PEB; 0.5-kg paperboard boxes, 0.5PAB; 0.5-kg or 1-lb PP bags, 0.5PPB or 1-lbPPB), as extracted from several EPD® studies.

Carbon Footprint	(g CO _{2e} kg ⁻¹)												
Pasta type	LP	LP&SP	LP&SP	LP	SP	LP&SP	SP ¹	SP ²	SP	PL	LP&SP	SP	
Pack format	5PEB	0.5PAB	0.5PAB	1-lbPPB		0.5PPB		5PEB	5PEB	0.5PPB	0.5PPB	5PEB	0.5PPB
Production & Consumption sites	Italy	USA	Italy	Italy	Italy	Italy	Italy	Italy	Italy	Italy	Greece	Italy	Italy
	Italy	USA	Italy	USA	USA	Italy	USA	Italy	Italy	Italy	Greece	Italy	Italy
Life cycle stage													
Field phase	557	610	564	767	767	775	775	618	618	800	762	259	503
Milling	51	205	48	44	44	270	270	35	35	-	97	103	58
Packaging Production	61	62	21	114	410	76	101	21	20	40	<1	30	18
Pasta Production	198	262	198	308	312	294	294	815	338	110	360	142	241
Transportation	31	152	65	176	189	62	164	17	12	30	31	33	54
Packaging end of life	-	40	17	<1	<1	13	11	20	19	-	<1	-	7
CF _{CDC}	898	1331	913	1409	1722	1489	1615	1526	1042	980	1251	567	881
References	12	13		14		15		16		17	18	19	20

¹ Pasta production line capacity of 135 kg/h;

² Pasta production line capacity of 850 kg/h.

Table S2

Inputs and outputs for producing durum wheat semolina (DWS), whole durum wheat semolina (HERS), and recombined whole durum wheat semolina (RWDWS), as referred to the flowchart shown in Fig. 2 and determined on the industrial scale using an initial amount of raw durum wheat grains of 277.78 Mg. All yields were affected by an average coefficient of variation of $\pm 10\%$.

Input-Output	Amount	Unit
Raw durum wheat grains	100.00	kg
<i>Pre-cleaning</i>		
Impurities, stones and straw (ISS)	0.02	kg
Pre-cleaned wheat dockage (DKPC)	0.87	kg
Precleaned durum wheat (PCDW)	99.11	kg
<i>Cleaning</i>		
Wheat dockage (DKC)	4.10	kg
Cleaned durum wheat (CDW)	95.01	kg
<i>Tempering</i>		
Tempering Water (TW)	6.87	kg
Wet Cleaned durum wheat (WCDW)	101.88	kg
<i>Decortication</i>		
First decortication fraction (FDF)	5.01	kg
Second decortication fraction (SDF)	4.01	kg
Decorticated durum wheat kernels (DDWK)	91.13	kg
Water evaporated during decortication (WE)	1.74	kg
<i>Grinding</i>		
Ground bran particles (GB)	8.40	kg
Milling light branny fraction (MLBF)	6.63	kg
Durum wheat semolina (DWS)	72.87	kg
High-extraction rate semolina (HERS)	3.23	kg
<i>Semolina Assembling</i>		
Durum wheat semolina (DWS)	45.51	kg

High-extraction rate semolina (HERS)	3.23	kg
Re-combined whole durum wheat semolina (RWDWS)	38.00	kg
<i>Milling byproducts</i>		
Wheat feed pellets (WFP)	18.38	kg

Table S3

Inputs and outputs for producing dried pasta (DP) using durum wheat semolina (DWS), high-extraction rate semolina (HERS), and recombined whole durum wheat semolina (RWDWS), as referred to the flowchart shown in Fig. 3. All yields were affected by an average coefficient of variation of $\pm 10\%$.

Input-Output	Amount	Moisture fraction
	[kg]	[kg kg ⁻¹]
HERS, DWS, or RWDWS	100.0	0.135
<i>Kneading</i>		
Mixing water (DIW)	34.0	
Dough waste (KW)	0.5	0.354
Dough (D)	133.5	0.354
<i>Extrusion</i>		
Water evaporated (EV)	8.6	1.000
Wet extruded pasta (WEP)	124.9	0.310
<i>Drying</i>		
Water evaporated (PV)	27.8	1.000
Dried pasta (DP)	97.1	0.1125

Table S4

Percentage fraction of the processing and packaging materials discarded, as collected in the pasta factory examined in this work.

Processing and Packaging Materials discarded	Discarded Fraction (%)
Dough waste (KW)	0.40
Dried Pasta waste (DPW)	0.25
PP bags or paperboxes (PPW)	1.50
Cartons (CAW)	1.00
Adhesive labels (CALW)	0.30
Scotch tape waste (SCW)	0.30
Stretch & shrink film waste (WPFW)	0.20
Wooden pallet label waste (WPLW)	0.20
Damaged wooden pallet (WPW)	1.00

Table S5

Brief description of the logistics of raw, processing aid, packaging materials, processing wastes and byproducts, and finished product from production sites to factory gate or from factory gate to distribution (DC), Euro pallet managing (EPMC) and waste collection (WCC) centers including the transport means used, their load capacity and average distance travelled.

Inventory	from	to	Means of Transport	Load Capacity [Mg]	Distance [km]
<i>Raw Materials and Processing Aids</i>					
Organic durum wheat seeds	Collection site	Field	RT	3.5 - 7.5	10
Diesel oil and oil lubricants		Field	RT	3.5 - 7.5	10
Poultry manure compost		Field	AT	16 - 32	50
Durum wheat grains	Field	Grain accumulator	AT	16 - 32	50
	Grain accumulator	Factory gate	AT	16 - 32	100
Detergents	Production site	Factory gate	RT	3.5 - 7.5	500
Lubricants	Production site	Factory gate	RT	3.5 - 7.5	300
<i>Packaging Materials</i>					
PP bags	Production site	Factory gate	HRT	7.5 – 16	22
Cartons	Production site	Factory gate	HRT	7.5 – 16	78
Carton and pallet labels	Production site	Factory gate	HRT	7.5 – 16	98
Carton scotch tape & pallet wrap film	Production site	Factory gate	HRT	7.5 – 16	100
Regenerated wood pallets	DCs via EPMCs	Factory gate	AT	16 – 32	900
<i>Processing wastes and Byproducts</i>					
Wheat Feed Pellets (WFP)	Factory gate	Cattle farm	HRT	7.5 – 16	107
Dough waste (KW)	Factory gate	Cattle farm	RT	3.5 - 7.5	30
Dried pasta wastes (DPW)	Factory gate	Cattle farm	RT	3.5 - 7.5	107
Wood pallet wastes (WPW)	Factory gate	EPMC	RT	3.5 - 7.5	105

Plastic wastes (PPW+SCW+WPF)	Factory gate	WCC	RT	3.5 - 7.5	100
Paper and cardboard wastes (CAW+CALW+WPLW)	Factory gate	WCC	RT	3.5 - 7.5	100
<i>Distribution Phase</i>					
Palletized Dried Pasta (DP)	Factory gate	DC	MAL	<32	895
Pasta cartons	DC	Retailer	RT	3.5 - 7.5	100
Pasta loss and secondary and tertiary packaging wastes	DC	WCC	RT	3.5 - 7.5	50
<i>Post-consumer Phase</i>					
Pasta loss and primary packaging wastes	Consumer	WCC	RT	3.5 - 7.5	50

Table S6

Overall Italian waste management scenarios for pasta losses and primary, secondary and tertiary packaging wastes resulting after the distribution and consumer phases in the year 2016.

Waste Management Scenarios Waste	Landfill [%]	Recycling [%]	Incineration [%]	References
Dried and cooked pasta wastes	28	52	20	45
Paper and cardboard wastes	11.8	79.7	8.5	46
Wood wastes	36	61	3	46
Plastic wastes	14	41	45	46

Table S7

Default values of the GHG emission factors for the energy sources; means of transport; raw and packaging materials, detergents, and processing aids; use phase; waste disposal; and byproduct uses, applied in this carbon footprint exercise, as extracted from several databases (i.e., BUWAL250, Ecoinvent, Franklin USA 98) of the LCA software Simapro 8.2 v. 2.0 (Prè Consultants, Amersfoort, NL) and technical references.

Emission Factor	Default Value	Unit	Ref.
<i>Energy source</i>			
Electricity, medium voltage, fossil fuels, at grid/IT	0.5129	kg CO _{2e} kWh ⁻¹	34
Electricity, medium voltage, renewable and no-renewable sources, at grid/IT	0.3213	kg CO _{2e} kWh ⁻¹	34
Electricity supplied by Italian CHP systems	0.3491	kg CO _{2e} kWh ⁻¹	34
Thermal energy supplied by Italian CHP systems	0.2327	kg CO _{2e} kWh ⁻¹	34
Photovoltaic electricity	0.055	kg CO _{2e} kWh ⁻¹	30
Diesel oil (upstream+combustion)	3.487	kg CO _{2e} kg ⁻¹	30
Natural gas (upstream+combustion)	0.231	kg CO _{2e} kWh ⁻¹	30
<i>Means of transport</i>			
Transport, lorry >32 Mg, EURO5 (Multiple axle lorry, MAL)	0.0845	kg CO _{2e} Mg ⁻¹ km ⁻¹	Ecoinvent 2.0
Transport, lorry 16-32 Mg, EURO5 (Articulated truck, AT)	0.171	kg CO _{2e} Mg ⁻¹ km ⁻¹	Ecoinvent 2.0
Transport, lorry 7.5-16 Mg, EURO5 (Heavy Rigid truck, HRT)	0.221	kg CO _{2e} Mg ⁻¹ km ⁻¹	Ecoinvent 2.0
Transport, lorry 3.5-7.5 Mg, EURO5 (Light-Medium Rigid truck, RT)	0.526	kg CO _{2e} Mg ⁻¹ km ⁻¹	Ecoinvent 2.0
Transport, freight, rail/RER U	0.0474	kg CO _{2e} Mg ⁻¹ km ⁻¹	Ecoinvent 2.0
Freight transoceanic ship, RER U	0.0116	kg CO _{2e} Mg ⁻¹ km ⁻¹	Ecoinvent 2.0
Freight, inland waterways, barg, RERU	0.0353	kg CO _{2e} Mg ⁻¹ km ⁻¹	Ecoinvent 2.0
<i>Raw Materials, Ingredients, Detergents, Processing Aids</i>			
Wheat Seeds	0.522	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Poultry manure, dried, at regional storehouse/CH S	0.106	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Tap water, at user/CH S	0.154	kg CO _{2e} m ⁻³	Ecoinvent 2.0

Detergents (Chlorine, liquid, production mix, at plant/RER U)	1.08	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Lubricating oil, at plant/RER U	1.07	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Packaging Materials			
Cartons	2.33	kg CO _{2e} kg ⁻¹	Franklin USA 98
Paperboard 100% Recycled FAL	2.6	kg CO _{2e} kg ⁻¹	Franklin USA 98
Packaging LDPE film	2.6	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Polypropylene bags	2.39	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
EUR-flat pallet/RER U	-1.4	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Use Phase			
Tap water, at user/CH S	0.154	kg CO _{2e} m ⁻³	Ecoinvent 2.0
Sodium chloride, powder at plant/RER U	0.203	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Waste disposal			
Landfill			
Disposal, polyethylene, 0.4% water, to sanitary landfill/CH S	0.113	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Disposal, polypropylene, 15.9% water, to sanitary landfill/CH S	0.0968	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH S	0.0897	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Disposal, packaging paper, 13.7% water, to sanitary landfill/CH S	1.34	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Disposal, packaging cardboard, 19.6% water, to sanitary landfill/CH S	1.73	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Disposal, wood untreated, 20% water, to sanitary landfill/CH S	0.0857	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Urban and biological wastes	0.8	kg CO _{2e} kg ⁻¹	³³
Incineration			
Disposal, PE sealing sheet, 4% water, to municipal incineration/CH S	2.55	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Disposal, polypropylene, 15.9% water, to municipal incineration/CH S	2.53	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH S	2.35	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Disposal, packaging paper, 13.7% water, to municipal incineration/CH S	1.48	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Disposal, packaging cardboard, 19.6% water, to municipal	1.60	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0

incineration/CH S			
Disposal, wood untreated, 20% water, to municipal incineration/CH S	1.47	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Disposal, municipal solid waste, 22.9% water, to municipal incineration/CH S	1.23	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
<i>Recycling</i>			
Recycling PE B250	-0.332	kg CO _{2e} kg ⁻¹	BUWAL250
Recycling PP B250	0.0459	kg CO _{2e} kg ⁻¹	BUWAL250
Recycling Plastics (excl. PVC) B250	-0.332	kg CO _{2e} kg ⁻¹	BUWAL250
Recycling paper/RER U	-0.0635	kg CO _{2e} kg ⁻¹	BUWAL250
Recycling cardboard/RER S	0	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Recycling wood/RER U	0	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
Composting organic waste/RER U	0	kg CO _{2e} kg ⁻¹	Ecoinvent 2.0
<i>Byproduct uses</i>			
Wheat Feed Pellets (WF) at 17% RP	-0.31	kg CO _{2e} kg ⁻¹	This work
Dough waste (KW) at 9 % RP	-0.16	kg CO _{2e} kg ⁻¹	This work
Dried Pasta waste (DPW) at 12.3% RP	-0.22	kg CO _{2e} kg ⁻¹	This work