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Cradle-to-Grave Environmental Profile of Organic Dry Pasta: Assessment and Mitigation Measures

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Cradle-to-Grave Environmental Profile of Organic Dry Pasta: Assessment and Mitigation Measures

Abstract

In this PhD thesis, the cradle-to-grave carbon footprint of 1 kg of organic durum wheat semolina dry pasta, packed in 0.5 kg polypropylene bags, was firstly assessed in compliance with the PAS 2050 methodology and found to be equal to 1.98±0.16 kg CO_{2e} kg^{-1}. The life cycle assessment (LCA) pointed out that the field and cooking phases were the primary and secondary hotspots. To improve the environmental performance of the cooking phase, an induction hob was controlled by a low-cost, open-source electronic platform, piloted via smartphone, and equipped with an S-shaped mixer and tested using both long and short pastas. By using such a novel eco-sustainable pasta cooker, it was possible to keep cooked pasta quality practically constant by reducing the cooking water-pasta ratio and electric energy consumed from 10 to 3 L kg^{-1} and from 1.55±0.04 to 0.55±0.01 W h g^{-1}, respectively. Finally, by using a well-known LCA software (SimaPro), it was possible evaluate the environmental profile of dry pasta in compliance with the IMPACT 2002^{+} methodology. An overall weighted damage score (OWDS) of 832±23 μpt kg^{-1} of dry pasta was thus estimated. The damage category of “Ecosystem quality” was that mostly affected (45.2 % of OWDS), while that of “Climate change”, “Resource depletion”, or “Human health” represented 20.9, 20.0, or 13.9 % of OWDS, respectively. Use of the eco-sustainable pasta cooker allowed the cradle-to grave carbon footprint of organic dry pasta to be reduced to 1.61±0.17 kg CO_{2e} kg^{-1}, and its OWDS to 764±22 μpt. Future research activities should be directed not only towards a more sustainable organic durum wheat cultivation, but also to favor the replacement of the current domestic appliances and cookware sets with novel energy-saving pasta cookers.

Key words: Carbon footprint; cooked pasta quality; cooking water-to-dried pasta ratio; eco-sustainable cooker; IMPACT 2002^{+}; Life Cycle Analysis; overall weighted damage score; PAS 2050.

Profilo ambientale dalla culla alla tomba della pasta secca biologica: valutazione ed azioni di mitigazione

Riassunto

In questa tesi di dottorato, l'impronta di carbonio dalla culla alla tomba di 1 kg di pasta secca di semola biologica di grano duro, confezionata in sacchetti di polipropilene da 0,5 kg, è stata valutata in conformità con la metodologia PAS 2050, risultando pari a 1,98±0,16 kg CO_{2e} kg^{-1}. L'analisi del ciclo di vita (LCA) ha evidenziato che le fasi più emissive erano in sequenza la coltivazione del grano duro e la cottura domestica della pasta. Per migliorare le prestazioni ambientali della fase di cottura, un fornello ad induzione commerciale è stato controllato tramite una piattaforma elettronica open source a basso costo, pilotato tramite *smartphone* e dotato di appropriato miscelatore, valutandone l'efficacia con pasta sia lunga che corta. Utilizzando detto cuoci-pasta eco-sostenibile, è stato possibile mantenere praticamente costante la qualità della pasta cotta, riducendo, rispettivamente, il rapporto acqua-pasta e l'elettricità consumata da 10 a 3 L kg^{-1} e da 1,55±0,04 a 0,55±0,01 Wh g^{-1}. Infine, utilizzando un noto software LCA (SimaPro), è stato possibile valutare il profilo ambientale della pasta secca in conformità con la metodologia IMPACT 2002^{+}. Si è stimato un indicatore di danno complessivo ponderato (OWDS) di 832±23 μpt kg^{-1} di pasta secca. La categoria di danno inerente la *Qualità dell'ecosistema* era quella maggiormente colpita (45,2 % di OWDS), mentre quella relativa ai *Cambiamenti climatici*, all'*Esaurimento delle risorse* od alla *Salute umana* rappresentava rispettivamente il 20,9, il 20,0 o il 13,9 % di OWDS. L'uso del cuoci-pasta ecosostenibile ha permesso di ridurre l'impronta di carbonio a 1,61±0,17 kg CO_{2e} kg^{-1} e l'indicatore OWDS a 764±22 μpt.

Le future attività di ricerca dovrebbero essere orientate non solo a rendere più sostenibile la coltivazione biologica del grano duro, ma anche favorire la sostituzione dei piani di cottura e del pentolame attualmente in uso con nuovi cuoci-pasta a ridotto consumo energetico.

Parole chiave: Analisi del ciclo di vita; fornello ecosostenibile; IMPACT 2002^{+}; impronta del carbonio; indicatore di danno ponderato complessivo; PAS 2050; qualità della pasta cotta; rapporto acqua di cottura/pasta secca.

Cradle-to-Grave Environmental Profile of Dry Pasta: Assessment and Mitigation Measures

Extended Abstract

1. Introduction

The main aims of this PhD thesis were as follows:

i) Assessment of the cradle-to-grave carbon footprint of 1 kg of organic durum wheat semolina dry pasta (CF_{CG}) packed in 0.5-kg polypropylene (PP) bags using the *Publicly Available Specification* (PAS 2050) method (BSI, 2008), as well as the contribution of each product life cycle stage.

ii) Development a novel sustainable pasta cooking system to minimize the energy and water needs and assure an appropriate instrumental and sensorial quality of cooked pasta.

iii) Characterize the environmental profile of organic dry pasta using the IMPACT 2002^{+} methodology (Jolliet et al., 2003) to suggest a more sustainable dried pasta production.

2 State of the art

Since the current food system is regarded as ecologically unsustainable, the food and drink industry are looking for improving its environmental performance. Dry pasta is a basic food mostly produced and consumed worldwide. The cradle-to-grave carbon footprint (CF_{CG}) of 1 kg of dried pasta was estimated as equal to 1.93 or 3.03 kg carbon dioxide equivalents (CO_{2e}), depending on the use of a gas or electric stove, respectively (Barilla, 2017). Durum wheat cultivation represented 32 or 20 % of CF_{CG}, while pasta cooking 31 or 56 % of CF_{CG}. Such a great contribution was due to the great volume of water (i.e., 10-12 L) that has to be boiled to cook 1 kg of dried pasta. Thus, the greenhouse gas (GHG) emissions associated with the cooking of pasta should be primarily reduced.

The environmental performance of food and drink production may be assessed by various standard methods (Cimini and Moresi, 2018a). Some of them (i.e., PAS 2050; Bilan Carbone®; GHG Protocol) make use of only the impact category of climate change (CC) and give no hint about the overall environmental impact of the products, even if the emissions from direct land-use changes over the previous 20 years are generally included. Other LCA-compliant standard methods refer to several impact categories, which are estimated at the first stages in the cause-effect chain (i.e., midpoint categories) or up to the endpoint (Jolliet et al., 2003). For instance, the *Life Cicle Assessment*, LCA, and *Environmental Product Declaration* (EPD®) account for seven midpoint impact categories, whereas the IMPACT 2002^{+} method evaluate15 mid-point impact categories that are used to measure the potential damages to human health (HH), ecosystem quality (EQ), and depletion of natural resources (RD). Moreover, the *Product Environmental Footprint* (PEF) assesses 14 midpoint impact categories, that are then normalized and weighted to yield an overall weighted score (Sala et al., 2017, 2018).

Any generic impact category (IC_j) is estimated by summing up the release to air, water or soil (Ψ_i, expressed in mass, energy, mass-km basis) associated to the system boundaries times its corresponding characterization factor ($F_{i,j}$). There is, thus, a strong need for reliable databases to assess a product life cycle environmental performance, as observed by the food and drink companies involved in several PEF pilot tests (FoodDrinkEurope, 2017).

3. Materials and methods

3.1 Assessment of the environmental impact of dried pasta

The life-cycle analysis was sequentially performed in compliance with the PAS 2050 (BSI, 2008) and IMPACT 2002+ (Jolliet et al., 2003) standard methods. All the four LCA canonical stages complied with the recommendations by the ISO 14040 series and were referred to a functional unit consisting of 1 kg of dried pasta, produced in a medium-sized pasta factory located in the South of Italy in the years 2016 and 2017, and packed in 0.5-kg PP bags.

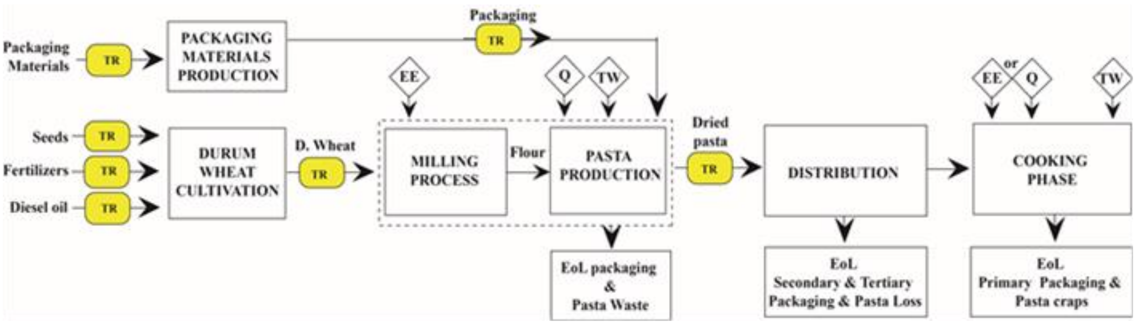

Figure 1 Dry pasta system boundaries, as adapted from Cimini et al. (2019d): EE, electric energy; Q, thermal energy; TR, transport; TW, process water.

The system boundaries for this study included the upstream, core and downstream processes (Fig. 1). The former implied the organic durum wheat cultivation, and organic fertilizer, electricity, fuel, and packaging material production. In the core processes wheat milling, and pasta making and packaging were considered. The downstream ones included the distribution, use and post-consumer waste management phases. Primary data were collected from the above pasta factory, while secondary ones from several technical reports and databases embedded in the professional tool SimaPro 9.0.0.41 (PRé Consultants, Amersfoort, NL), as detailed by Cimini et al. (2019d). The CF_{CG} of the functional unit chosen was estimated by accounting for the 100-year time horizon global warming potentials (IPCC, 1996). The 15 impact categories (ICs) accounted for of the IMPACT 2002+ method were calculated using their specific characterization factors F_{ij}. Such ICs were then grouped into four damage categories (DCs) to underpoint the environmental compartments damaged by dry pasta in its life cycle. The effect on human health (HH) derived from different ICs (i.e., “carcinogens”, “non-carcinogens”, “respiratory inorganics and organics”, “ionizing radiation”, and “ozone layer depletion”) and was expressed in *disability-adjusted life years* (DALY), these indicating the amount of years (of life) lost due to premature mortality and/or disability, after an exposure to toxic chemicals. The impact on the Ecosystem Quality (EQ) resulted from several ICs (i.e., “aquatic and terrestrial eco-toxicity”, “acidification”, “eutrophication”, and “land use”) and was measured in *potentially disappeared fraction* (PDF) of biological species that have a high probability of not surviving in the geographical area where dry pasta is produced. Since the impact of CC on EQ and HH is not accurate enough to derive reliable damage characterization factors, the global warming (CC) was considered as a stand-alone endpoint category by referring to a 500-yr time horizon to account for both short- and long-term effects (Jolliet et al., 2003). Finally, the environmental impact resulting from the depletion of non-renewable resources (RD) was measured by the additional primary energy required to extract a unit of mineral and of total non-renewable primary energy for energy carriers. The assessment was extended to the endpoint approach via the phases of *normalization* and *weighing*. The HH, EQ, CC and RD normalization factors of 0.0071 DALY, 13,700 PDF m^2 yr, 9,900 kg CO_{2e}, and 152,000 MJ per person by year were obtained as the ratio between the overall results for all pollutants, potentially damaged fraction of species, total GHG emissions and non-renewable energy consumption in Western Europe, and Western European population, respectively. Then, a default weighting factor of one was used to aggregate such damage categories (Jolliet et al., 2003).

3.2 Assessment of cooked pasta quality

Several commercial brands of durum wheat semolina dried pasta of the *Spaghetti* and *Penne* types were used. Their labelled raw protein content and recommended cooking time ranged from 108 to 139 g kg^{-1}, and 9 to 10-12 min, respectively. Their composition was previously reported (Cimini et al., 2019abc), while the pasta cooking system and procedure used, as well as the cooking water and energy balances during pasta cooking, were described by Cimini and Moresi (2017) and Cimini et al. (2019c). Several cooking tests were performed by varying the water-to-pasta ratio (WPR) from 2 to 12 L kg^{-1}. To limit pasta adhesion during cooking, a mechanical stirrer was kept rotating at 50 rev min^{-1} for 30 s, but resting for the subsequent 90, 60 or 30 s at WPR equal to 6, 4, or 3 L kg^{-1}, respectively. Cooked pasta properties were characterized by assessing the relative water uptake (WU) and cooking loss, starch gelatinization degree, hardness at 90 (F_{90}) or 98 (F_{98}) % deformation using a Universal Testing Machine UTM mod. 3342 (Instron Int. Ltd., High Wycombe, UK) equipped with a 1000-N load cell, and a few sensory attributes (i.e., Firmness, Stickiness, Bulkiness, Overall Cooking Quality) by a panel of six trained judges, as detailed by Cimini et al. (2019abc). The carbon footprint of pasta cooking (CF_{PC}) was evaluated by multiplying the overall electric energy consumed by its corresponding emission factor of 323.6 g CO_{2e} kWh^{-1} (ISPRA, 2018). The novel eco-sustainable pasta cooker (EPC) developed here consisted of a commercial induction-plate stove, that was controlled via the programmable Arduino® hardware platform using a digital temperature sensor to detect the water temperature and a current sensor to monitor the energy consumption to heat water, and cook and mix pasta. For further details refer to Cimini et al. (2019f). All data were shown as average±standard deviation, and analyzed by Tukey test at a probability level (α) of 0.05.

4. Results and discussion

4.1 The cradle-to-grave carbon footprint of organic dry pasta

As shown in Fig. 2, the CF_{CG} of 1 kg of organic dry pasta amounted to ~1.8 kg CO_{2e} kg^{-1}, while the contribution of all the life cycle phases was ranked as follows: field phase (666 g CO_{2e} kg^{-1}), home pasta cooking (651 g CO_{2e} kg^{-1}), pasta production and packaging (201 g CO_{2e} kg^{-1}), transportation (148 g CO_{2e} kg^{-1}), packaging material manufacture (107 g CO_{2e} kg^{-1}), durum wheat milling (52 g CO_{2e} kg^{-1}), end of life of packaging materials (33 g CO_{2e} kg^{-1}) and pasta losses (19 g CO_{2e} kg^{-1}). Wheat milling by-products, and pasta making and packaging wastes were used as cattle feed and gave rise to a CO_{2e} credit of 69 g CO_{2e} kg^{-1} (Cimini et al., 2019d). Thus, the sustainability of dry pasta might be improved by reducing the contribution of the consumer, field, and transportation life cycle phases.

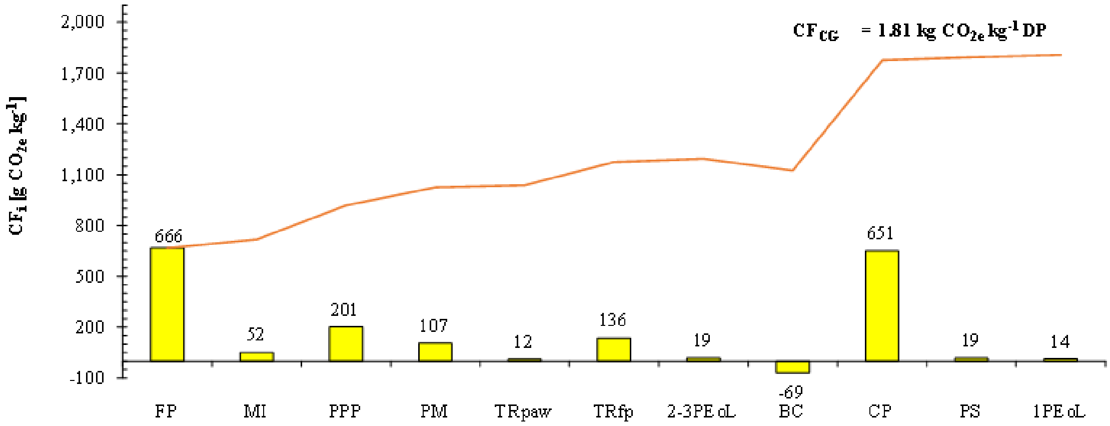

Figure 2 Contribution of the different life cycle stages to the CF_{CG} of 1 kg of dried organic pasta, as extracted from Cimini et al. (2019d), and its cumulative score (see continuous line): 1PEoL, primary packaging end of life; 2-3PEoL, secondary and tertiary packaging end of life; BC, byproduct credit; CP, consumer phase; FP, field phase; MI, milling phase; PM, packaging material manufacture; PPP, pasta production and packaging; PS, pasta scraps; TRfp, transport of final product; TRpaw, transport of packaging and auxiliary materials, and wastes.

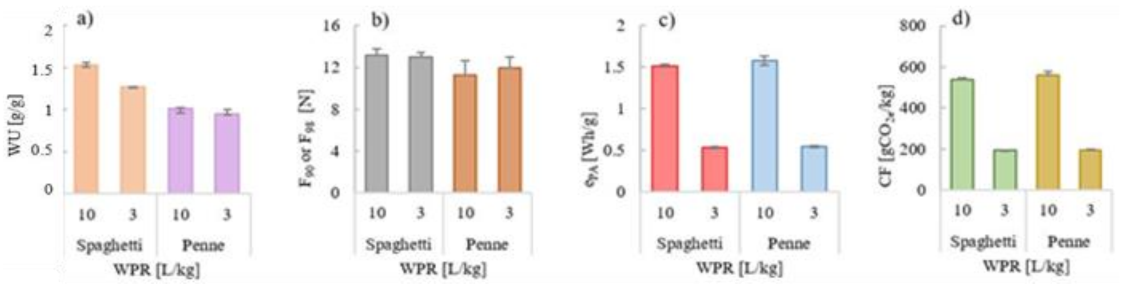

Figure 3 Effect of WPR on the **a)** relative water uptake (WU); **b)** hardness at 90 or 98% deformation (F_{90} or F_{98}), **c)** specific pasta cooking energy consumption (e_{PA}), and **d)** carbon footprint (CF_{PC}) for the long and short pasta formats examined.

4.2 Eco-sustainable pasta cooking system

The effect of WPR on the cooking quality of long and short pasta types was assessed using an induction hob (Cimini et al., 2019abc) or a gas-fired one (Cimini et al., 2019e). The induction hob was set at its maximum power rating (P_H=2 kW) to heat water up to the boiling point, and at a power rating (P_C) of just 0.4 kW during pasta cooking (Cimini and Moresi, 2017; Cimini et al., 2019abc). The main cooking quality parameters (WU, F_{90} or F_{98}) of two commercial pasta types, both with a raw protein content of about 135 g kg^{-1}, as well as the specific pasta cooking energy consumption (e_{PA}) and carbon footprint (CF_{PC}) were compared at two WPR levels, as shown in Fig. 3. As WPR was reduced from 10 to 3 L kg^{-1}, the water uptake and cooking loss (data not shown for brevity) by cooked penne was practically constant, while those for cooked spaghetti reduced by circa 17% (Fig. 3a). On the contrary, cooked pasta hardness (F_{90} or F_{98}) was not statistically different at α=0.05 (Fig. 3b). In all cases tested, the energy efficiency of the induction hob (η_C) was practically constant (67±3 %), while both e_{PA} and CF_{PC} decreased from 1.55±0.04 to 0.55±0.01 Wh g^{-1} (Fig. 2c), and from 0.55 to 0.19 kg CO_{2e} kg^{-1} (Fig. 2d), respectively. At WPR=3 L kg^{-1}, the mixing energy consumed to avoid pasta sticking (~0.0011 Wh g^{-1}) was definitively negligible with respect to e_{PA}. Thus, instead of cooking 1 kg of dried pasta in 10 L of water, as commonly suggested by pasta manufacturers, the cooking procedure tested with WPR=3 L kg^{-1} would about halve the climate change impact of the current Italian consumption pasta of dried pasta (~1.61×10^6 Mg yr^{-1}).

4.3 *The environmental profile of organic dry pasta*

Table 1 shows the environmental profile of 1 kg of dry pasta as resulting from the framework provided by the Impact 2002+ V2.14 life cycle impact assessment method embedded in SimaPro 9.0.0.41. The environmental impact of the great majority of the mid-point ICs firstly raised from the field phase (i.e., “non-carcinogens”, “respiratory inorganics and organics”, “ionizing radiation”, “ozone layer depletion”, “terrestrial eco-toxicity”, “terrestrial and aquatic acidification and nitrification”, “land occupation” and “mineral extraction”), and secondly from the cooking one (i.e., “global warming”, and “non-renewable energy”), as pointed out by the underscore and italics characters in Table 1, respectively. Even if this method referred to a time horizon of 500 years, the global warming effects were still dominated by the cooking phase.

Table 1 Environmental profile of 1 kg of dried organic pasta as estimated using the IMPACT 2002+ method: percentage contribution of the different life cycle stages (symbols as in Fig. 2), and overall score of each mid-point impact category (IC_j).

Impact category (IC_j)	**Life Cycle Phase Contribution (%)**						**IC_j Score**	**Unit**
	FP	**MI+PPP**	**PM**	**TR**	**CP**	**EoLPM**		
Carcinogens	15.7	41.2	44.2	7.9	10.7	-19.8	1.27×10^{-2}	kg $C_2H_3Cl_e$
Non-carcinogens	45.6	14.8	11.7	*21.7*	12.6	-6.4	1.44×10^{-2}	kg $C_2H_3Cl_e$
Respiratory inorganics	50.9	17.5	4.6	11.9	*19.8*	-4.6	1.07×10^{-3}	kg $PM_{2.5e}$
Respiratory organics	45.2	13.5	10.5	17.1	*17.9*	-4.2	4.53×10^{-4}	kg C_2H_{4e}
Ionizing radiation	62.5	14.1	2.8	4.8	*16.2*	-0.4	22.2	Bq $^{14}C_e$
Ozone layer depletion	38.9	23.2	3.0	*19.4*	16.6	-1.0	1.32×10^{-7}	kg CFC-11_e
Aquatic ecotoxicity	*24.6*	13.6	40.9	13.6	12.6	-5.2	117.5	kg TEG water
Terrestrial ecotoxicity	30.9	11.4	26.1	*27.5*	8.7	-4.6	43.8	kg TEG soil
Terr. acidification/nutr.ion	53.3	18.5	2.6	6.2	*20.8*	-1.3	4.08×10^{-2}	kg SO_{2e}
Aquatic acidification	46.3	20.5	3.5	7.1	*24.4*	-1.9	6.96×10^{-3}	kg SO_{2e}
Aquatic eutrophication	91.5	2.7	1.3	1.8	*4.3*	-1.6	9.38×10^{-4}	kg PO_4^{3-}
Land occupation	99.7	0.07	*0.3*	0.2	0.1	-0.3	4.36	m^2 org. arable
Global warming	*35.0*	15.3	3.7	8.4	37.8	-0.2	1.62	kg CO_{2e}
Non-renewable energy	*30.1*	16.7	6.5	8.9	40.1	-2.3	25.7	MJ primary
Mineral extraction	48.2	8.3	4.0	10.3	*30.9*	-1.8	2.17×10^{-2}	MJ surplus

The 15 ICs shown in Table 1 were then grouped into four damage categories (DCs) to underpin the environmental compartments damaged by dry pasta in its life cycle. As shown by the underscore and italics characters in Table 2, the damage impact on HH and EQ mainly derived from the field phase, while that on CC and RD from the cooking one, respectively. The assessment was extended to the endpoint approach via the phases of *normalization* and *weighing* (Table 2). EQ was the damage category mostly affected (45.6 % of the overall weighed score), followed by RD (20.5 %) and CC (19.9 %), while HH was that suffering the lowest environmental damage (14.2 %). The dry pasta life cycle

phase exerting the greatest percentage contributions to the overall weighted damage score (825 μpt) was the cultivation one (63.1 %), followed by the cooking phase (18.8 %), grain milling and pasta making (9.5 %), transportation (6.2 %), and packaging material manufacture (4.0 %). The end of life of packaging material wastes had the effect of lowering the OWDS by -1.5%.

Table 2 IMPACT 2002$^+$ damage assessment related to the production of 1 kg of dried organic pasta packed in 0.5-kg PP bags: percentage contribution of the different life cycle stages (symbols as in Fig. 2), single (SSj) and weighted scores (WSj) of each damage category (DC_j), and overall weighted damage score (OWDS).

Damage category (DC_j)	**Life Cycle Stages Contribution (%)**						**SS_j**	**Unit**	**WS_j (μpt)**
	FP	**MI+PPP**	**PM**	**TR**	**CP**	**EoLPM**			
Human Health (HH)	49.2	18.3	6.6	12.1	*19*	-5.3	8.28×10^{-7}	DALY	117
Ecosystem Quality (EQ)	94.6	1	2.08	*2.09*	0.8	-0.6	5.15	PDF m^2 yr	376
Climate Change (CC)	*35*	15.3	3.7	8.4	37.8	-0.2	1.62	kg CO_{2e}	164
Resource Depletion (RD)	*30.1*	16.7	6.5	8.9	40.1	-2.3	25.7	MJ primary	169
OWDS	63.1	9.5	4.0	6.2	*18.8*	-1.5			***825***

4.4 *Options to reduce the environmental profile of dry pasta*

To improve the sustainability of dry organic pasta, any mitigation action should *a priori* aim at reducing firstly EQ and secondly CC and RD. Quite a large number of studies have demonstrated that organic farming for durum wheat cultivation in Italy is a low-carbon agriculture with lower GHG emissions per hectare, but higher ones per unit product, with respect to the conventional wheat cultivation, owing to its lower productivity. By accounting for the grain yields and land occupation in rotation crop experiments conducted in Italy and more specifically in Southern Italy by Ruini et al. (2013) and Fagnano et al. (2012), the organic durum wheat used here was characterized by greater grain yield (3.75±0.27 Mg ha^{-1}) and land occupation (0.7 ha yr^{-1}). Thus, no further mitigation option on the organic farming system was accounted for. Thus, the novel Arduino®-based eco-sustainable pasta cooker (EPC), operating with a cooking water-to-pasta ratio of 3±1 L $kg^{-1}$and an overall electricity consumption of 0.6±0.1 kWh kg^{-1} appeared to be proper for lessening the environmental impact of the pasta cooking phase. In the circumstance, the GHG emissions associated to each life cycle phase did not change, except those from the consumer use one that reduced to 0.269 kg CO_{2e} kg^{-1}. Altogether, CF_{CG} reduced to 1.61±0.17 kg CO_{2e} kg^{-1}, this being about 19 % lower than the reference case (RC). By using the EPC, the scores of RD and CC reduced by ca. 22 % each; that of EQ was unaltered whereas that of HH slightly increased by 6 %. Altogether, the overall weighted damage score approximately decreased by 8 % to 764±22 μpt.

5. Conclusions and Future Perspectives

The business-to-consumer carbon footprint (CF_{CG}) of 1 kg of dry pasta made of decorticated organic durum wheat semolina was estimated and found to be primarily and secondarily controlled by the use and field phases, respectively. Since the cooking energy requirements accounted for a significant share of the energy consumed along the product life cycle, a more eco-sustainable pasta cooker was developed to limit energy and water usage. The environmental profile of the product was assessed in compliance with the

IMPACT 2002$^+$ methodology and the ecosystem quality resulted to be the damage category mostly affected. Among the product life cycle phases, the cultivation and cooking ones exerted the highest contributions. By resorting to the eco-sustainable pasta cooker developed here, it was possible to cut CF_{CG} and OWS by 19 and 8 %, respectively.

Since the characterization of the environmental profile of a single product is quite expensive, and the climate change impact category is by far more reliable than all the other ones accounted for in this PhD thesis (Wolf et al., 2012), the carbon footprint assessment seems to be the cheaper tool to identify the major hotspots of the product life cycle stages. Thus, it is probably the best method to start improving the sustainability of the 99 % of the food and beverage small- and medium-sized enterprises.

To reduce the energy consumption and improve the environmental performance of dry pasta, future research activities should firstly explore the organic farming potentials in order to improve organic durum wheat yields, and secondly drive the pasta manufacturers to evaluate if novel pre-gelatinized pasta products might be a feasible option. Finally, it is high time for the pasta makers to start selling not only pasta products, but also their specialized pasta cookers in order to allow even unskilled pasta cooks to prepare high quality cooked pasta in a very reproducible and quick way with as small as possible environmental impact.

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INTRODUCTION

The current food system is regarded as ecologically unsustainable (Church, 2005; FoodDrinkEurope, 2012; WRI, 2013), since fossil fuels are essential requirements not only for running crop production, animal husbandry, food production and distribution, but also for constructing and maintaining machinery and processing equipment, transportation vehicles, and infrastructures.

The greenhouse gas (GHG) emissions associated with food production and consumption represent 19-29 % of the global GHG emissions (Vermeulen et al., 2012). Actually, the food, drink, tobacco and narcotics area of consumption in the EU-25 should be responsible for 20-30 % of the main impact categories, namely “climate change”, “ozone depletion layer”, “photochemical ozone creation”, “acidification”, “eutrophication”, “resource depletion”, “human toxicity”, and “eco-toxicity” (Tukker et al., 2006).

Among the numerous studies on the long-term sustainability of the current agro-food system, the EU Standing Committee on Agriculture Research (SCAR) observed that food production is near to exceed environmental limits (European Commission, 2011). The average USA and EU diet is too rich in meat, fat and sugar, and is a risk for the individual health, social systems and environment. Since the world population is expected to grow from about 7 billion to 9.6 billion people in 2050, the promotion of healthy diets is a prerequisite for reducing the environmental impact of food consumption, while food processing and retail industries are to improve the environmental impact of food production (European Commission, 2011; FAO, 2018; Moresi and Valentini, 2010; WRI, 2013).

The food and beverage industry is a major contributor to the EU economy (FoodDrinkEurope, 2018), followed by the automotive, machinery and equipment, and chemical industries. As of 2015, it was the major driver of the economy, with turnover of € 1.109 trillion, employment of 4.57 million employees with 294,000 total number of companies. Actually, 99.1% (i.e., 280,000) of the companies are small and medium-sized enterprises (SMEs), these generating 48.1% (i.e., €538 billion) of the overall turnover, 48.4% (i.e., €107 billion) of the value added and 61.3% (i.e., 2.8 million employees) of employments. Owing to its environmental and economic importance, an intergovernmental set of 17 Sustainable Development Goals has already been identified in the food sector (FoodDrinlEurope, 2019), this being a core part of the 2030 Agenda for

Sustainable Development (UN, 2015). Not only GHG emissions, waste generation, and water and energy consumption are to be decreased, but also sustainable industrialization (i.e., Goal 9) is to be stimulated, even if what type of innovation should be promoted to foster transition towards a more sustainable food system should be also deeply analyzed (El Bilali, 2018).

Dry pasta is a basic food mostly produced worldwide (i.e., about 14.3 million metric tonnes). About 23 % and 14 % of which is produced in Italy and USA, respectively (UNAFPA, 2015). 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}) (UNAFPA, 2015).

The application of life cycle assessment methodologies to basic cereals, as well as their main derived products, was recently reviewed by (Renzulli et al., 2015). 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 (Lo Giudice et al., 2011) (Moresi, 2015) (Röös et al., 2011), and just a few ones a cradle-to-grave one (Bevilacqua et al., 2007) (Notarnicola et al., 2001) (Notarnicola et al., 2004). Nevertheless, probably because of the great number of assumptions made, and different operating variables and yield factors used, these studies did not enable the environmental impact of dry pasta to be directly compared. According to Barilla (2017), the cradle-to-grave carbon footprint (CF_{CG}) of 1 kg of dried pasta was of the order of 1.9 or 3.0 kg of carbon dioxide equivalents (CO_{2e}), depending on the use of a gas or electric stove, respectively. Durum wheat cultivation represented 32 or 20 % of CF_{CG}, while pasta cooking, embodying 31 or 56 % of CF_{CG}, should be the most impacting phase of the overall life cycle of dried pasta.

Within this context, the main aims of this PhD thesis were as follows:

i) Assess the cradle-to-grave carbon footprint of 1 kg of organic durum wheat semolina dry pasta (CF_{CG}) packed in different packages using the *Publicly Available Specification* (PAS 2050) method (BSI, 2008), and the contribution of each product life cycle stage to identify a series of mitigation actions to minimize the GHG emissions associated with organic pasta production and consumption. This activity was fully described in Chapter 1.

ii) Develop a novel sustainable pasta cooking system to minimize the energy and water needs and assure an appropriate instrumental and sensorial quality of cooked pasta.

To this end, a series of tests was sequentially carried out to assess the effect of the water-to-pasta ratio (WPR) in the range 2 to 12 L kg^{-1} on the main chemico-physical and sensory characteristics of commercial long (i.e. spaghetti) or short (i.e., Penne rigate) pasta made of higher or lower quality durum wheat semolina. These results allowed an empirical relationship to be develop to evaluate the minimum WPR ratio sufficient to avoid short or long pasta strands sticking to each other. Finally, a novel eco-sustainable pasta cooker (EPC), controlled by a low-cost, open-source electronic platform and piloted via smartphone, was finally developed to minimize the carbon footprint of domestic pasta cooking. These activities were detailed in Chapter 2.

iii) Characterize the environmental profile of organic dry pasta in order to cope with the quite large intervals of variation in the estimated business-to business scores of the main four environmental impact categories for dry pasta, as extracted from the Environmental Product Declations EPD® currently available. To this end, the business-to-consumer life-cycle assessment (LCA) model of the industrial production and distribution of an organic dry durum wheat semolina pasta, detailed in Chp. 1, was developed in the well known LCA software (SimaPro 9.0.0.41: PRé Consultants, Amersfoort, NL) to assess the environmental profile of dry pasta using the IMPACT 2002+ (Jolliet et al., 2003) methodology, as pointed in Chapter 3.

CHAPTER 1

The cradle-to-grave carbon footprint of organic dry pasta

1.1 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 (Miao et al., 2015). 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 (UNAFPA, 2015). 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}) (UNAFPA, 2015).

The application of life cycle assessment methodologies to basic cereals, as well as their main derived products, was recently reviewed by (Renzulli et al., 2015). 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 (Lo Giudice et al., 2011) (Moresi, 2015) (Röös et al., 2011), and just a few ones a cradle-to-grave one (Bevilacqua et al., 2007) (Notarnicola et al., 2001) (Notarnicola et al., 2004).

The agricultural phase was generally the primary hotspot, owing to the environmental impacts (i.e., climate change, eutrophication, acidification, 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 (Ruini et al., 2019).

In addition, several Environmental Product Declarations have been published and revised by several pasta makers, such as Barilla, CANE, De Cecco, Granarolo, Lantmännen, Misko, Sgambaro and Voiello. As shown Table 1.1, 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 of carbon dioxide equivalent (CO_{2e}) kg^{-1}.

Table 1.1 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	5 PEB	0.5 PAB	0.5 PAB	1-lb PPB		0.5 PPB		5 PEB	5 PEB	0.5 PPB	0.5 PPB	5 PEB	0.5 PP
Production & Consumption sites	Italy Italy	USA USA	Italy Italy	Italy USA		Italy Italy	Italy USA	Italy Italy	Italy Italy	Italy Italy	Greece Greece	Italy Italy	Italy Italy
Life Cycle Stage													
Field phase	557	610	546	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	Barilla (2013)	Barilla (2017)		CANE (2017)		De Cecco (2017)		Granarolo (2017)		Lantmännen (2011)	Misko (2017)	Sgambaro (2018)	Voiello (2017)

1 Pasta production line capacity of 135 $kg\ h^{-1}$;

2 Pasta production line capacity of 850 $kg\ h^{-1}$.

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 were accounted for, the contribution of pasta consumption seemed to be highly relevant in terms of energy consumption and associated impacts.

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) (Aldaya et al., 2010). 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 (UNAFPA, 2018). Thus, depending on the use of a gas or electric hob, further GHG emissions in the range of 0.6 to 3.1 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 (Barilla, 2013, 2017; CANE, 2017; De Cecco, 2017; Granarolo, 2017; Lantmännen, 2011; Misko, 2017; Sgambaro, 2018; Voiello, 2017), 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. 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 (Cimini et al., 2018a; Finkbeiner et al., 2014; Lehmann et al., 2016), industry (ACEA, 2013; BDI, 2015), policy-makers (BMUB/UBA/TUB, 2019, and consumer associations (ANEC, 2019). 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. Thus, since numerous independent studies have shown that climate change is the impact category with the lowest uncertainty level (Wolf et al., 2012), 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.

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® and Australian Wine Carbon Calculator 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 Table 1.1 the environmental performance of dried organic pasta using semolina 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 (USDA/USDHHS, 2019). 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 quite similar to standard semolina pasta (Arlotti et al., 2014).

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 (BSI, 2008) 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.

1.2 METHODOLOGY

The life-cycle analysis (LCA) was performed in compliance with the PAS 2050 standard method (BSI, 2008), 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.

1.2.1 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.

1.2.2 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.

1.2.3 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. 1.1, where all the identification items used are given in the List of Symbols. More specifically:

The upstream processes:

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 downstream processes:

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.

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.

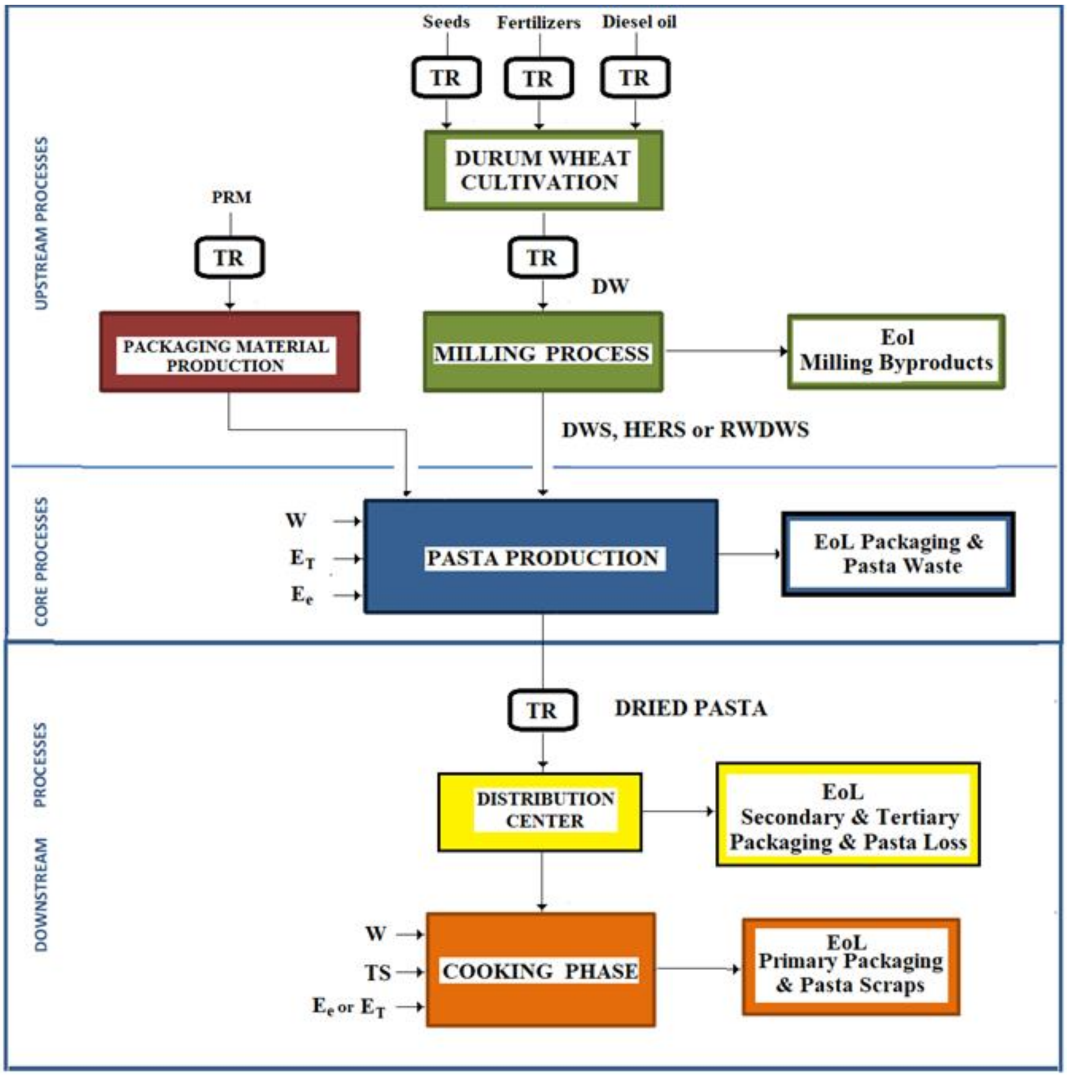

Figure 1.1. Dried pasta system boundary showing the main processes as divided into upstream, core and downstream ones. All symbols were listed in the *List of Symbol* section.

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 CO_2 credits. In addition, all CO_2 credits from recycling of renewable and non-renewable materials were included.

1.2.4 *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 (ISPRA, 2018), 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 (IPCC, 2007) as well other technical reports.

1.3 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.

1.3.1 Farm production of organic durum wheat

Table 1.2 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 (Tudisca et al., 2014).

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 13 g kg^{-1}. Thus, the organic cultivation of durum wheat avoided using pesticides and fertilizers of fossil origin. Table 1.2 shows all the parameters and emission factors used to calculate direct and indirect N_2O emissions (IPCC, 2007). The above ground residues AG_{DM}, that is straw, as well as below ground ones (BG_{DM}), were estimated in accordance with IPCC procedures (IPCC, 2007). According to EPD® (EPD, 2013), 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 $ha^{-1}\cdot yr^{-1}$, respectively (Table 1.2). No postharvest drying of grains was performed since their average moisture content was less than 120 $g\cdot kg^{-1}$.

Table 1.2 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.

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	$kg \cdot ha^{-1}$	180-240
Seed delivery distance	km	10
Diesel fuel used for all agricultural treatments	$L \cdot ha^{-1} \cdot yr^{-1}$	100-150
Lubricant oil	$L \cdot ha^{-1} \cdot yr^{-1}$	5
Nitrogen fertilizer	$kg \cdot ha^{-1} \cdot yr^{-1}$	0
Phosphate fertilizer as P_2O_5	$kg \cdot ha^{-1} \cdot yr^{-1}$	0
Potassium fertilizer as K_2O	$kg \cdot ha^{-1} \cdot yr^{-1}$	0
Aged poultry manure compost (1.3 % N)	$Mg \cdot ha^{-1} \cdot yr^{-1}$	10
Pesticides	$kg \cdot ha^{-1} \cdot yr^{-1}$	0
Output		
Organic durum wheat grains	$Mg \cdot ha^{-1} \cdot yr^{-1}$	3.5-4.0
Average moisture content at harvest	$g \cdot kg^{-1}$	108
Above ground residues (AG_{DM})	$Mg_{DM} \cdot ha^{-1} \cdot yr^{-1}$	3.82-4.29
N content of above-ground residues	$kg\ N \cdot (kg_{DM})^{-1}$	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})	$kg \cdot kg^{-1}$	0.24
Belowground residues (BG_{DM})	$Mg_{DM} \cdot ha^{-1} \cdot yr^{-1}$	1.44-1.63
N content of below-ground residues	$kg\ N \cdot (kg_{DM})^{-1}$	0.009
Crop residues (F_{CR})	$kg\ N \cdot ha^{-1} \cdot yr^{-1}$	18.1-20.4
NH_3- and NO_x-emissions ($Frac_{GASF}$)	$kg\ NH_3\text{-}N\text{+}NO_x\text{-}N \cdot (kg\ N)^{-1}$	0.1 (0.03-0.3)
$N_{leaching\ off}$ ($Frac_{LEACH}$)	$kg\ N \cdot (kg\ N)^{-1}$	0.3 (0.1-0.8)
EF_1	$kg\ N_2O\text{-}N \cdot (kg\ N)^{-1}$	0.01 (0.003-0.03)
EF_4	$kg\ N_2O\text{-}N \cdot (kg\ NH_3\text{-}N\text{+}kg\ NO_x\text{-}N\text{-}_{emitted})^{-1}$	0.01 (0.002-0.05)

EF_5	kg N_2O-N · (kg N $_{\text{leaching off}}$)$^{-1}$	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

Finally, durum wheat was cultivated on land which had been used for agricultural purposes for longer than 20 years (PAS 2050: Section 5.5) (BSI, 2008); therefore, the GHG emissions arising from land use change were not considered.

1.3.2 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, whit no further transport step. Fig. 1.2 shows the block diagram of the milling process used.

Grains with an average moisture content of 108 g kg^{-1} were precleaned 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. 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 determinated 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. 1.2), a recombined whole durum wheat semolina (RWDWS) of circa 0.38 kg per each kg of input grains was produced (Fig. 1.2).

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 ±10 %, as shown in Table 1.3. In this way, durum wheat milling gave rise to an overall yield for the three aforementioned 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.

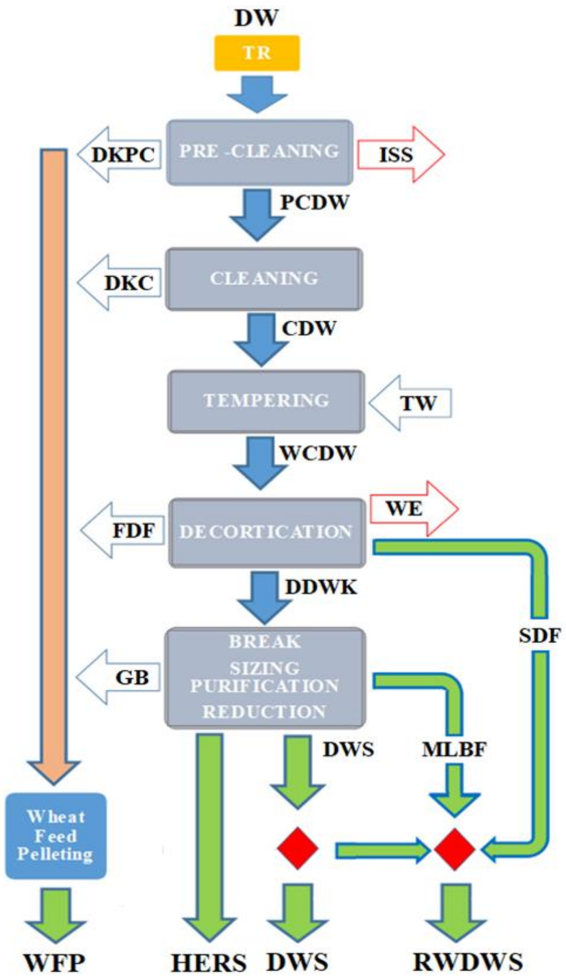

Figure 1.2. Flowchart of the process of decortication and milling of durum wheat (DW) with production of durum wheat semolina (DWS), whole durum wheat semolina (HERS) and recombined one (RWDWS). All symbols were listed in the *List of Symbol* section.

Table 1.3 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. 1.2 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 ±10%.

Input-Output	**Amount**	**Unit**
Raw durum wheat grains	100.00	kg
Pre-cleaning		
Impurities, stones and straw (ISS)	0.02	kg
Pre-cleaned wheat dockage (DKPC)	0.87	kg
Precleaned durum wheat (PCDW)	99.11	kg
Cleaning		
Wheat dockage (DKC)	4.10	kg
Cleaned durum wheat (CDW)	95.01	kg
Tempering		
Tempering Water (TW)	6.87	kg
Wet Cleaned durum wheat (WCDW)	101.88	kg
Decortication		
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
Grinding		
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
Semolina Assembling		
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
Milling byproducts		
Wheat feed pellets (WFP)	18.38	kg

1.3.3 Pasta Making

The above three types of semolina (HERS, DWS, RWDWS) were used to produce three different dried organic pastas. Fig. 1.3 shows the block diagram of their pasta making process.

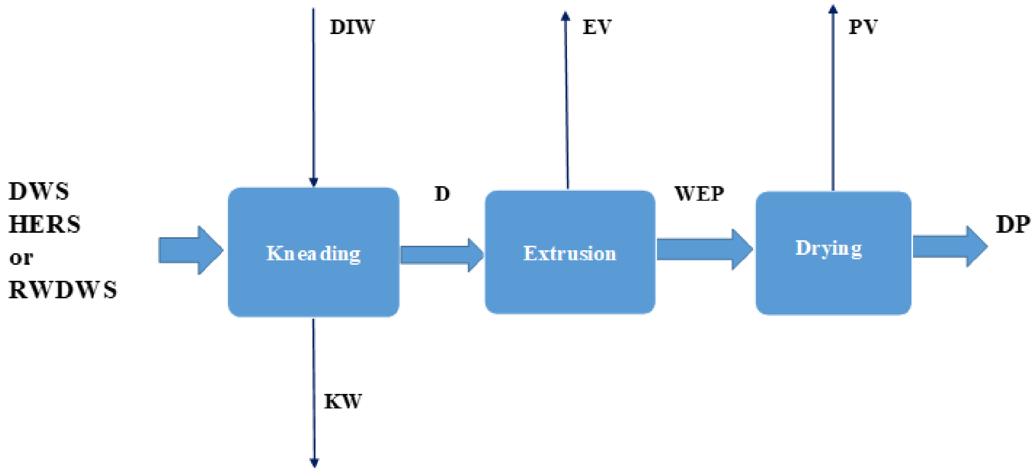

Figure 1.3. Flowchart of the dried pasta making process using durum wheat (DWS), high-extraction rate (HERS) or recombined whole durum wheat (RWDWS) semolinas. All symbols were listed in the *List of Symbol* section.

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 ~0.31 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 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 ±10 %, as shown in the Table 1.4.

Table 1.4 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. 1.3 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 ±10%.

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

1.3.4 Pasta Packaging

The 90% of dried pasta is nowadays packed in plastic film bags and the remaining 10% in cardboard boxes (UNAFPA, 2018). 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. 1.4 shows the block diagram for the packaging process examined in this work, showing also all the solid wastes generated. Table 1.5 lists the amounts of packaging materials and aids needed to prepare the primary, secondary and tertiary packages. (i.e., plastic bags or paperboxes, cartons, adhesive labels, scotch tape, stretch and shrink film, pallet, etc.).

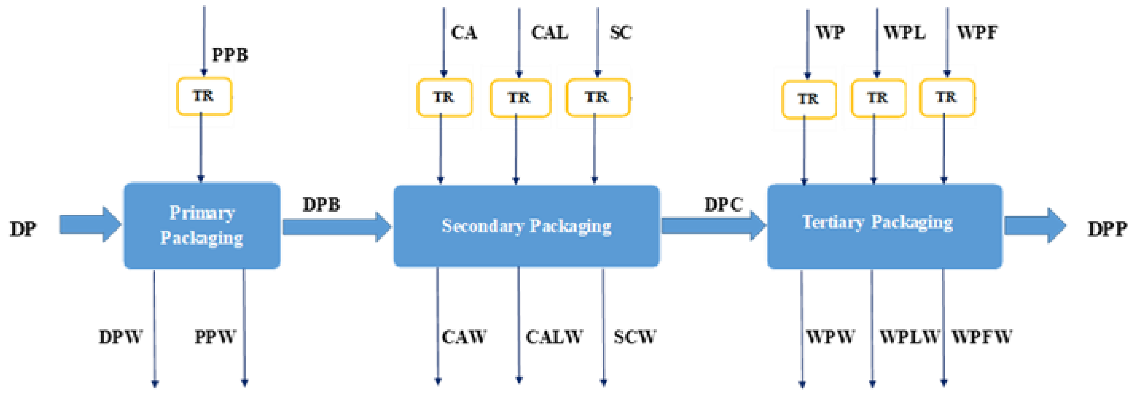

Figure 1.4. Schematic diagram of the packaging process for each dried pasta type examined in this work. All symbols were listed in the List of Symbols section.

Table 1.5 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**		**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

1.3.5 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) (BSI, 2008).

1.3.6 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 table 1.6.

Table 1.6 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

About 84 L of process wastewaters (having an initial Chemical Oxygen Demand of ~484 mg O_2 L^{-1}) per 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} 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}). 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} (Dalgaard et al., 2008), this being equivalent to 1.4-2.2 kg CO_{2e} 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 kg CO_{2e} kg^{-1}.

1.3.7 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 1.7 shows the specific energy needs, as derived from factory measurements or extracted from the literature.

Table 1.7 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		Reference
	Q_e	Q_T	
Durum wheat milling	[kWh Mg^{-1} DW]	[kWh Mg^{-1} DW]	
	54.2	-	This work was referrred to the year 2016
	44.7	-	This work was referrred to the year 2017
	47.6	-	(Notarnicola et al,. 2001)
	117-150	-	(Carlsson-Kanyama et al,. 2000)
	83.33	2.22	(O'Shaughnessy et al,. 2013)
Dry pasta making	[kWh Mg^{-1} DP]	[kWh Mg^{-1} DP]	
	277.7	281.0	This work was referrred to the year 2016
	317.1	303.9	This work was referrred to the year 2017
	162.1	551.7	(Notarnicola et al,. 2001)
	194-250	250-472	(Carlsson-Kanyama et al,. 2000)
	289	511	(Panno et al,. 2007)

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 (Sistan-Terna, 2017). 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 (ISPRA, 2018). Finally, the emission factor for the methane used (231 g CO_{2e} kWh^{-1}) included the combustion and upstream processes (ADEME, 2007).

1.3.8 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 table 1.8.

The final product transport included the delivery from the factory gate to the distribution centers, and then to the selling points (Table 1.8). 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).

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 1.8), 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 (UNAFPA, 2018), solid urban wastes in 2016 (Hera Group, 2019), these being detailed in the table 1.9.

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 et al,. 2017), as reported in Table 1.9.

Table 1.8 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]**
Raw Materials and Processing Aids					
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
Packaging Materials					
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	DC_s via $EPMC_s$	Factory gate	AT	16 – 32	900
Processing wastes and Byproducts					
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
Distribution Phase					
Palletized Dried Pasta (DP)	Factory gate	DC	MAL	<32	895
Pasta cartons	DC	Retailer	RT	3.5 - 7.5	100
Pasta loss & secondary and tertiary pack.ing wastes	DC	WCC	RT	3.5 - 7.5	50
Post-consumer Phase					
Pasta loss and primary packaging wastes	Consumer	WCC	RT	3.5 - 7.5	50

Table 1.9 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	Hera Group (2019)
Paper and cardboard wastes	11.8	79.7	8.5	Ronchi et al. (2017)
Wood wastes	36	61	3	Ronchi et al. (2017)
Plastic wastes	14	41	45	Ronchi et al. (2017)

1.3.9 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) (Barilla, 2017), are usually needed, as reported in the EPD® and PEF (UNAFPA, 2018) 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 (UNAFPA, 2018).

1.3.10 Post-consumer waste disposal

Pasta loss at the consumer phase was assumed of the order of 2% of the quantity cooked (UNAFPA, 2018). 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 (GCF, 2015). Thus, up to the 12 % of what had been cooked 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 (Cimini et al., 2019d). 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

(Hera Group, 2019), as shown in the Table 1.9. 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 Table 1.9.

In this Life Cycle Inventory, the waste packaging recycling was mainly modeled by using the allocation at the point of substitution, generally known as APOS system model. The latter follows the attributional approach in which burdens are attributed proportionally to specific processes. Consequently, plastic and paper packaging waste recycling would involve a CO2e credit for the provision of such recyclable packaging materials. However, the Ecoinvent v. 2.0 database used the system model allocation, cut-off by classification, (i.e., cut-off system model). According to such an approach, a producer is fully responsible for the disposal of its wastes, and does not receive any credit for the provision of any recyclable materials. As shown in Table 1.10, the APOS system model was applied for plastic and paper packaging waste recycling by referring to the BUWAL250 database. Such a database gave no information about the credits associated with cardboard and wood recycling, as well as organic waste composting. Thus, for such wastes the cut-off system model was applied in compliance with the Ecoinvent v. 2.0 database.

1.3.11 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:

$$CF_{CG} = \sum_{i} (\Psi_i \; EF_i) \qquad (1.1)$$

where Ψi 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 Table 1.10 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 CO2e kg^{-1}.

Table 1.10 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.
Energy source			
Electricity, medium voltage, fossil fuels, at grid/IT	0.5129	kg CO_{2e} kWh^{-1}	36
Electricity, medium voltage, renewable and non-renewable sources, at grid/IT	0.3213	kg CO_{2e} kWh^{-1}	36
Electricity supplied by Italian CHP systems	0.3491	kg CO_{2e} kWh^{-1}	36
Thermal energy supplied by Italian CHP systems	0.2327	kg CO_{2e} kWh^{-1}	36
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
Means of transport			
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, RER U	0.0353	kg CO_{2e} Mg^{-1} km^{-1}	Ecoinvent 2.0
Raw Materials, Ingredients, Detergents, Processing Aids			
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 incineration/CH S	1.60	kg CO_{2e} kg^{-1}	Ecoinvent 2.0
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
Recycling			
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
Byproduct uses			
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

1.4 RESULTS AND DISCUSSION

1.4.1 Carbon footprint of dried organic pasta

The carbon footprint of organic durum wheat was estimated by accounting for the different seed density, diesel fuel used, and yield factors shown in Table 1.20 by accounting for the default values of the emission factors EF_1, EF_4 and EF_5 characterizing nitrogen fertilizer application (IPCC, 2007). Fig. 1.5 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 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}.

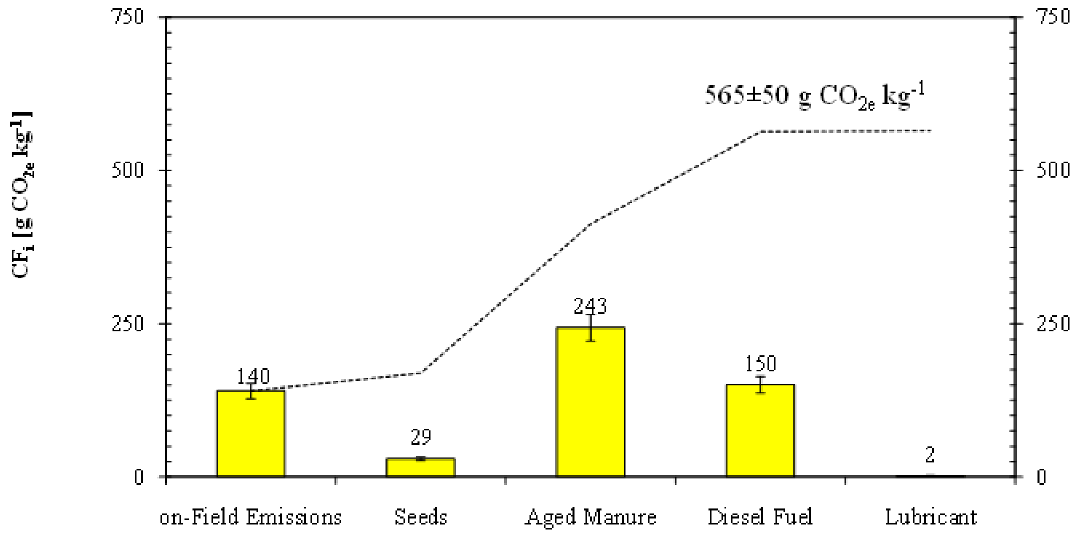

Figure 1.5. Contribution of the different life cycle stages to the overall carbon footprint of organic durum wheat, as well as its cumulative score.

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 Switzerland (Mader et al., 2007) or Southern Italy (Fagnano et al,. 2012), 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} (Tudisca et al., 2014). 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 (Ruini et al., 2013). Consequently, the carbon footprint of the organic durum wheat cultivation investigated in this work appeared to be in line with previous findings.

Fig. 1.6 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 -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}).

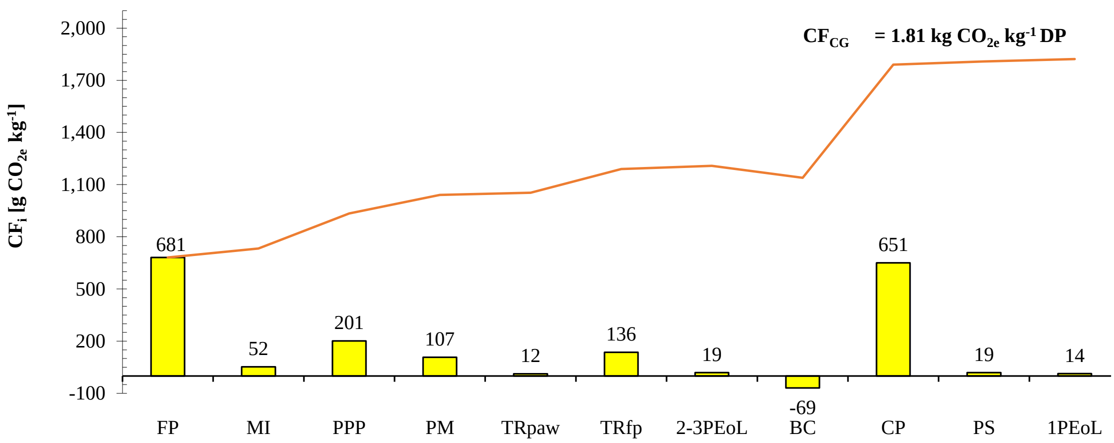

Figure 1.6. Contribution of the different life cycle stages to the cradle-to-distribution center (CF_{CDC}) or -grave (CF_{CG}) carbon footprint of a functional unit (1 kg) of dried organic pasta packed in 0.5-kg PP bags in a medium-sized pasta factory, and its cumulative score. Item list: FP, field phase; MI, milling; PPP, pasta production and packaging; PM, packaging manufacture; TR_{paw}, transport of packaging and auxiliary materials, and wastes; TR_{fp}, 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.

In particular, such a score, as referred to 1 kg of dry pasta, 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 1.11).

If the pasta scraps were as high as the 12 % of dried pasta cooked (CGF, 2015), CF_{CG} increased by 5.2% to 1.90 kg CO_{2e} kg^{-1}.

Table 1.11 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}.

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

Table 1.11 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 3.10.

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. 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 1.11.

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.

1.4.3 *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 1.1, 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- (Sgambaro, 2018) or 0.5- (Lantmännen, 2011) kg PP bags, respectively.

The impact of the milling phase ranged from 35 (Granarolo, 2017) to 270 (De Cecco, 2017) 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 1.7. Both the aforementioned values for the specific milling electricity needs agreed with that reported by Notarnicola and Nicoletti, but resulted to be one third (Catlsson-Kanyama et al., 2000) or one half (O'Shaughnessy et al., 2013) of that stated by other authors Table 1.7.

The contribution of packaging materials was mainly affected by the primary packaging type, which included both 0.5- or 5-kg PP bags, and 0.5-kg paperboard boxes. It ranged from quite an improbable value of less than one to 410 g CO_{2e} kg^{-1}.

The contribution of pasta production and packaging phase fluctuated from 142 to 815 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, 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, 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 1.1). Such a finding paralleled the remarks about the increase in the carbon footprint of bread (Andersson, 1998), milk (Høgaas Eide, 2000), or beer (Cimini and Moresi, 2018), 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 1.7), and was in line with that (289 kWh Mg^{-1}) measured in a Sicilian pasta factory producing annually about 23 Gg of dry pasta, but resulted to be about the double of that testified by Notarnicola and Nicoletti, and higher by 10 to 60% of that given by Carlsson-Kanyama and Faist.

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 1.7), this interval of values falling within that indicated by Carlsson-Kanyama and Faist, and being about the 53-57 % of that reported by other authors, who probably referred to pasta factories of smaller size than that examined here.

The impact of transportation varied from as low as 12 to 189 g CO_{2e} kg^{-1}. As suggested by the PEF category rules for dry pasta, 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 1.11).

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 1.11). In the great majority of the CF studies listed in table 1.1, 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 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 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, 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 quantitied 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 $j \neq i$.

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] 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} (Sørensen et al., 2014) 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} (Alhajj et al., 2015).

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 1.8.

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.

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 (ADEME, 2007) or 0.029 (Lien et al., 2013) 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 (Table 1.10).

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 (Table 1.10).

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 (Cimini et al., 2017) 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. These cooking procedures resulted in a specific cooking energy consumption of 4.70 or 0.39 kWh kg^{-1}, respectively.

The main results of such a sensitivity analysis are shown in Table 1.12.

In Fig. 1.7 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

$$m_i = \frac{\left(\frac{\Delta CF_{CG}}{CF_{CGR}}\right)}{\left(\frac{\Delta X_i}{X_{iR}}\right)} \qquad (1.2)$$

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=+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 (mi=+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).

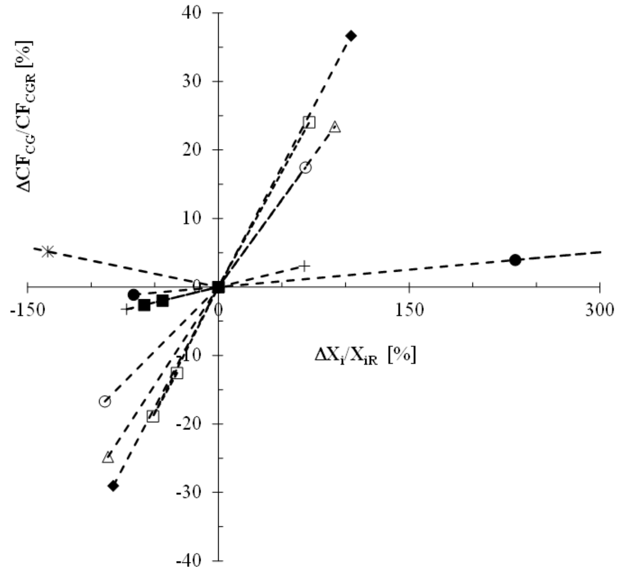

Figure 1.7. Effect of the relative variation ($\Delta CF_{CG}/CF_{CGR}$) of the cradle-to-grave carbon footprint with respect to its reference value for a functional unit (1 kg) of dry organic pasta packed in 0.5-kg PP bags against the relative variation ($\Delta X_i/X_{iR}$) of a few parameters X_i, 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, ◆).

Table 1.12 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 mi 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	
- *Effect of durum wheat carbon footprint and crop yield*					
Organic crop rotation system	(Ruini et al., 2013)	0.360	kg CO_2 kg^{-1}	1580.2	0.317
No tillage – low nitrogen addition	(Alhajj et al., 2015)	0.259	kg CO_2 kg^{-1}	1466.2	
Conventional tillage farming	(Sørensen et al., 2014)	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 the electricity emission factor*					
Solar photovoltaic energy	(ADEME, 2007)	0.055	kg CO_{2e} kWh^{-1}	1505.2	0.212
Coal-fired power plant	(ADEME, 2007)	0.864	kg CO_{2e} kWh^{-1}	2122.6	
- *Effect of the thermal energy emission factor*					
Biogas	(Lien et al., 2013)	0.029	kg CO_{2e} kWh^{-1}	1358.9	0.270
Lignite (brown coal)	(ADEME, 2007)	0.422	kg CO_{2e} kWh^{-1}	2230.8	
- *Effect of transport modality for palletized pasta*					
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	
- *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	(Arlotti et al., 2014)	0.800	kg CO_{2e} $(Mg\ km)^{-1}$	2058.0	-0.039

1.4.4 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. 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 (Cimini et al., 2018). 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. 1.7. By using technologies nowadays feasible for the pasta sector, table 1.13 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 (Cimini et al., 2019) 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., 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 (Alhajj et al., 2015) 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 1.13). All the other options examined in table 1.13 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.

Table 1.13 Percentage fraction of the processing and packaging materials discarded, as collected in the pasta factory examined in this work. 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. 1.7.

Mitigation strategy	**Parameter varied**	**Value**	**Unit**	$\mathbf{CF_{CG}}$ [kg CO_{2e}/kg]	$\mathbf{\Delta CF_{CG}}$ [%]
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

As shown in Fig. 1.8, 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 overally 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.

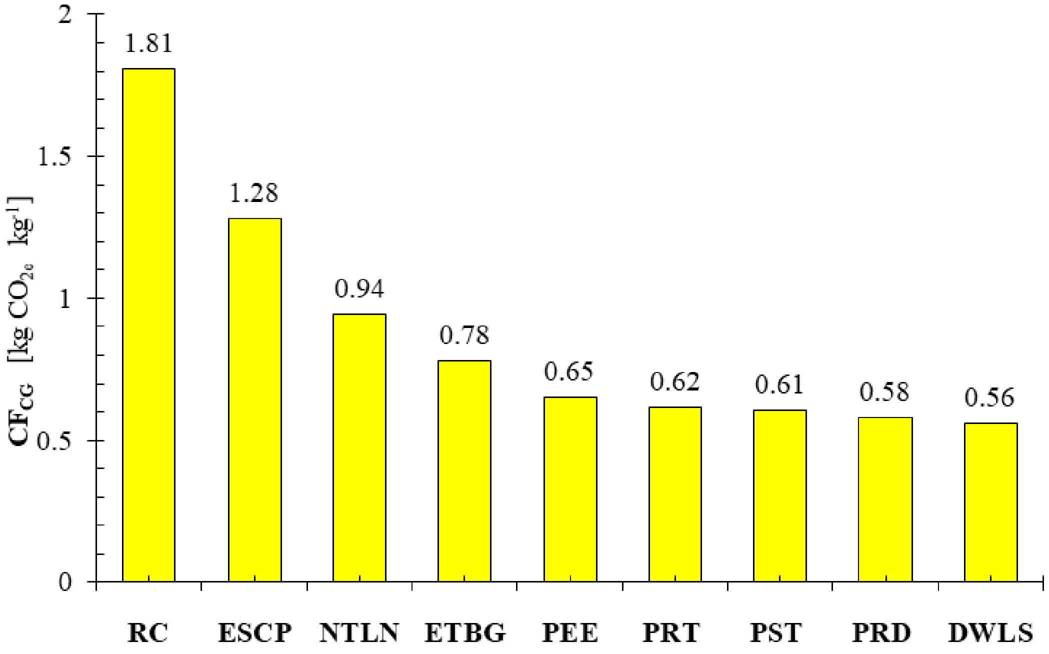

Figure 1.8. Marginal abatement curves of the cradle-to-grave carbon footprint (CF_{CG}) as resulting from the sequential mitigation strategies adopted to alleviate the environmental load of the most impactful life cycle phase of the production of a functional unit (1 kg) of dry organic pasta in 0.5-kg PP bags in a medium-sized pasta factory, as estimated using the LCA model (1). All symbols used are listed in the *List of Symbols* section and Table 1.13.

1.5. 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 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 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 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}), 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 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}. 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.

CHAPTER 2

Eco-sustainable pasta cooking system

2.1 INTRODUCTION

In Chapter 1 it was assessed that the cradle-to-grave carbon footprint (CF_{CG}) of dried pasta was mainly controlled by the pasta cooking phase (CF_{PC}). Thus, any attempt to improve the sustainability of dry pasta should be firstly aimed at cutting the GHG emissions associated with its cooking.

Dry pasta is generally cooked in boiling water, such a temperature being required to enhance convective motions within the water-pasta suspension and thus increase heat and mass transfer from the bulk to the pasta surface throughout the cooking phase (Piazza *et al*., 1994; Sicignano *et al*., 2015). Such motions, as well as pasta mixing, are essential to cook homogeneously pasta with no agglomerates and/or partly cooked areas.

The pasta cooking energy needs are not only dependent on the home appliance (i.e., gas-fired or electric stoves), but also on the cooking water-to-pasta ratio (WPR) used. The overall energy efficiency (η_C) of dried pasta cooking using gas-fired and induction hobs was found to vary from 30 to 46 %, respectively (Cimini and Moresi, 2017). In particular, the induction hob resulted to be the most efficient cooking system and thus was regarded as an option for cleaner and safer cooking way in developing countries (Banerjee *et al*., 2016). Moreover, its usage, as coupled to an environmentally sustainable pasta cooking practice previously set up, allowed useless water evaporation to be limited and, consequently, pasta cooking carbon footprint to be reduced to 0.67±0.04 kg CO_{2e} per kg of dry pasta (Cimini and Moresi, 2017). Greater energy saving might be achieved if the cooking water-to-pasta ratio (WPR) were reduced from the values generally recommended by pasta makers (i.e., 10-12 L kg^{-1}) to as low as possible. In principle, the minimum WPR value should vary with the pasta shape. In particular, the shapes (i.e., spaghetti with an average diameter of 2 mm) exhibiting a greater external surface-to-volume ratio than others (i.e., rigatoni or helicoidal having an outer diameter of 15-19 mm) are generally more liable to come across and adhere to each other. The importance of such a problem is low at the aforementioned conventional WPRs, but it enhances as WPR is reduced.

In order to minimize the energy consumption throughout the pasta cooking process, a series of tests was sequentially carried out:

i) The effect of WPR in the range 2 to 12 L kg^{-1} on the cooking quality of one of the highest sold format of durum wheat semolina dry pasta (i.e., Spaghetti no. 5

Barilla) was initially assessed together with the electric energy needs and cooking water utilization.

ii) The effect of WPR at two levels (i.e., 3 and 10 L kg^{-1}) on the main chemico-physical and sensory characteristics of three commercial spaghetti made of higher or lower quality durum wheat semolina was then assessed.

iii) The effect of WPR at 4 levels (i.e., 3, 4, 6, and 10 L kg^{-1}) on just the chemico-physical cooking quality of three commercial durum wheat semolina dried pastas of the *Penne rigate* type, all being extruded through the same bronze die and dried under almost the same thermo-hygrometric conditions, was also determined.

iv) An empirical relationship was then empirically developed to evaluate the minimum WPR ratio sufficient to avoid short or long pasta strands sticking to each other.

v) A novel eco-sustainable pasta cooker (EPC), controlled by a low-cost, open-source electronic platform and piloted via smartphone, was finally developed to minimize the carbon footprint of domestic pasta cooking and its performance tested with two commercial dried pasta of the short or long type by setting WPR at 10 L kg^{-1} and a minimum water-to-pasta ratio (WPR^*), as roughly estimated on the basis of the pasta geometric characteristics and specific water uptake.

2.2 MATERIALS AND METHODS

2.2.1 Raw materials

Different types of commercial durum wheat semolina dried pasta were used.

Spaghetti no. 5, made by Barilla G. e R. F.lli SpA (Parma, Italy), packed in 1-kg paperboard boxes and purchased in a local supermarket (lot no. 017096) was used to assess the effect of WPR in the range of 2-12 L kg^{-1}. They had a diameter of 1.94±0.05 mm, a length of 257±1 mm, composition as extracted from the label and reported in parentheses in g kg^{-1} (moisture: <125; raw protein: 125; total carbohydrates: 702; fat: 20; total fiber: 30; ash: 0.13), specific energy content of 15.21 MJ kg^{-1}, and set time of 9 min.

Three commercial brands of spaghetti of different semolina quality were bought in the local supermarket and were used to assess the effect of WPR at two levels (i.e., 3 and 10 L kg^{-1}) on the main chemico-physical and sensory characteristics of cooked pasta. Their main characteristics are summarized in Table 2.1.

Three commercial brands of short pasta of the *Penne rigate* type, kindly provided by De Matteis Agroalimentare Spa (Flumeri, AV, Italy), were used to assess the effect of WPR at four levels (i.e., 3, 4, 6, and 10 L kg^{-1}) on the main chemico-physical characteristics of cooked pasta. These products were made of different quality semolina, extruded using the same bronze die (external diameter 600 mm; thickness 140 mm; Teflon® insert no. 330; hole diameter 10.1 mm) and dried under almost the same thermo-hygrometric conditions. Their main characteristics are summarized in Table 2.2.

Two commercial brands of short (*Cannerone*) and long (*Spaghetti alla chitarra*) pasta, kindly provided by De Matteis Agroalimentare Spa (Flumeri, AV, Italy), were used to assess the effect of WPR at two levels (i.e., WPR^* and 10 L kg^{-1}) on the main chemico-physical characteristics of cooked pasta. All samples were made of the same *Armando* durum wheat semolina and had the same composition, as extracted from their commercial labels, that is moisture (125 g kg^{-1}), raw protein as Nx6.25 (135 g kg^{-1}), starch (676 g kg^{-1}), soluble sugars (32 g kg^{-1}), total fiber (27 g kg^{-1}), fat (13 g kg^{-1}), and salt (0.05 g kg^{-1}). The dough was extruded through bronze dies equipped with Teflon® inserts and dried under almost the same thermo-hygrometric conditions. Their main characteristics are summarized in Table 2.3

All chemicals and solvents used were of analytical grade and purchased from Carlo Erba (Milan, Italy) and from Sigma-Aldrich Srl (Milan, Italy).

Table 2.1 Main characteristics and chemical composition of the three commercial spaghetti brands used.

Spaghetti Brand	**Cuore Mediterraneo n. 5**	**Barilla n. 5**	**Rummo n. 3**
Main Characteristics			
Raw spaghetti length [mm]	263±3	257±1	257±1
Raw spaghetti diameter [mm]	1.90±0.05	1.94±0.05	2.00±0.05
Factory suggested cooking time [min]	9	9	9
White core disappearance time [min]	11.00	11.50	14.50
Total organic matter (TOM)	1.41 ± 0.04	1.29 ± 0.05	0.95 ± 0.03
Chemical Composition **(g/100 g)**			
Moisture	11.3± 0.07	10.5 ± 0.07	10.6 ± 0.07
Raw protein (N x 6.25)	11.5 ± 0.19	13.5 ± 0.06	13.9 ± 0.04
Starch	64.9 ± 1.98	65.1 ± 3.74	62.4 ± 3.04
Fat	2.30 ± 0.03	1.60 ± 0.04	1.80 ± 0.08
Ash	0.76 ± 0.01	0.85 ± 0.01	0.77 ± 0.03

Table 2.2 Main production conditions, characteristics and chemical composition of the three commercial *penne rigate* brands used.

Pasta Brand	**Donna Vera**	**Borges**	**Baronia**
Main Characteristics			
Penne length, L_p [mm]	36±2	36±2	34±2
Penne internal diameter, d_i [mm]	5.08±0.07	5.07±0.08	5.02±0.06
Penne external diameter, d_{Ru} [mm]	8.88±0.04	8.94±0.05	8.93±0.06
Above rib thickness, t_{Ru} [mm]	1.90±0.04	1.94±0.05	1.96±0.04
Below rib thickness, t_{Rb} [mm]	1.50±0.14	1.42±0.18	1.43±0.20
100-piece weight [g]	150±8	158±13	149±9
Cooking time suggested by pasta maker [min]	10-12	10-12	10-12
White core disappearance time [min]	11.00	11.50	14.50
Total organic matter, TOM [g kg^{-1}]	6.9 ± 0.8	6.5 ± 0.5	6.2 ± 0. 5
Chemical Composition **[g kg^{-1}]**			
Moisture	124 ± 0.5	114 ± 0.4	116 ± 2
Raw protein (Nx6.25)	108 ± 2	119.0 ± 0.2	131 ± 1
Starch	665 ± 3	682 ± 7	657 ± 2
Soluble sugars	37.0 ± 1.5	32.0 ± 0.5	31.0 ± 0.4
Total fibres	26 ± 3	25.0 ± 0.6	27.0 ± 1.5
Fat	21 ± 4	13.0 ± 0.3	17.0 ± 0. 9
Ash	5.2 ± 0.3	5.1 ± 0.5	5.3 ± 0.3

Table 2.3 Main geometric characteristics, specific water uptake (WU) at the conventional (10 L kg^{-1}) and minimum (WPR*) water-to-pasta ratios., and pasta cooking times as suggested by the maker or estimated in accordance with ISO (2016) of the two commercial short and long pasta types used.

Pasta type	***Cannerone***	***Spaghetti alla chitarra***
Pasta description	Small-length smooth tubes, orthogonally cut at both ends.	Spaghetti-like pasta with a square cross section.
Length of each piece, L_p [mm]	18.2±0.9	251±4
External perimeter of each piece [mm]	36.7±0.3	-
Equivalent external diameter (d_{ee}) of the circular cross-section [mm]	11.7±0.1	-
Side of the square cross-section [mm]	-	2.02±0.03
Piece thickness, t [mm]	1.5±0.2	-
100-piece weight [g]	105±5	138±3
S_p [mm^2]	766.7	2038.2
V_c [mm^3]	1058.2	0.0
WU @ 10 L kg^{-1} [g g^{-1}]	0.94	1.34
WPR* [L kg^{-1}]	2.7	2.8
Cooking time suggested by pasta maker [min]	7-8	11-12
Optimal cooking time (OCT) @ 10 L kg^{-1}[min]	11	15
White core disappearance time @ 10 L kg^{-1} [min]	12	17
Optimal cooking time (OCT) @ WPR* [min]	11	15
White core disappearance time @ WPR* [min]	12	19

2.2.2 Equipment and experimental procedure

Pasta cooking process was carried out using:

- a 3-L magnetic stainless-steel pan model Oumbärlig no. 502.864.20 (Inter IKEA Systems B.V. 1999-2014, Sweden) with a bottom diameter and height of 145 mm and 130 mm, respectively;
- a 2-kW 190-mm induction-plate stove (Melchioni INDU, Melchioni Spa, Milan, Italy);
- a mechanical stirrer EURO-ST P CV (IKA®-Werke GMBH, Staufen, D), that was kept rotating at the minimum stirring rate attainable (50 rev min^{-1}) either continuously or intermittently depending on the WPR used.
- a digital scale of the series PCE-BSH 10000 (CE Italy srl, Capannori, LU, Italy) with a load range of 0.6 g to 10 kg, and a reading accuracy of 0.2 g, this resulting in a percentage error of 0.2% on a 100-g mass reading;
- a custom-made data logger based on an Arduino Nano 3.0 (ATmega328) board;

- a digital power meter type RCE MP600 (RCE Srl, Salerno, Italy), characterized by an accuracy of ±1.0% when measuring power in the range of 0.4-3,999 W.

Any cooking test was started by setting the aforementioned pan over the cooking system, as shown Fig. 2.1a. The latter was placed on digital scale and both on induction hob. The lid was drilled twice, as shown Fig. 2.1b. The 10-mm axial hole A allowed inserting a S-shaped non-magnetic stainless-steel impeller to avoid pasta from sticking, while the 8-mm lateral one B allowed lodging a thermocouple so as to measure the cooking water temperature (T_{WM}) near the pan axis at mid-height of the water level.

a) **b)**

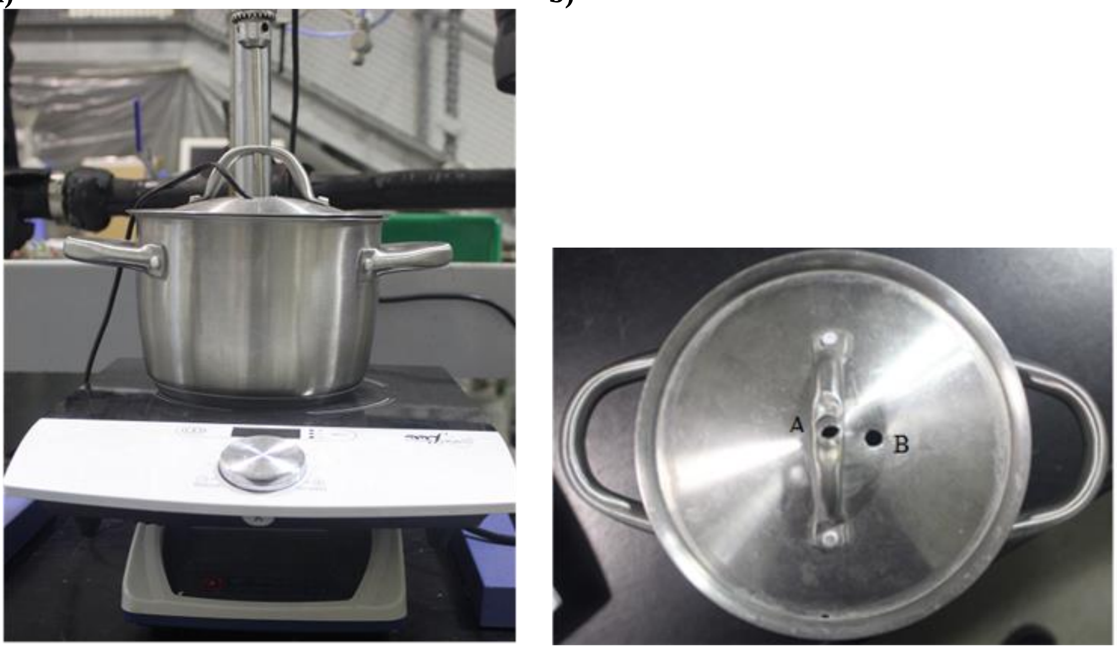

Figure 2.1. Pictures of (**a**) the cooking system used in this work, consisting of a pan closed with its lid, mixer, thermocouple, and induction hob, both being placed over a technical balance, and (**b**) the lid with the central and lateral holes used to insert the mixer and thermocouple.

The induction hob was firstly regulated to its maximum setting (2.0 kW) to bring as quickly as possible the cooking de-ionized water (m_{W0}) from 20±1 °C to about 98 °C in accordance with Cimini et al. (2017). Once the dried pasta (m_{PA}) had been added to the boiling water and the latter had restarted to boil, the hob control knob was adjusted to 0.4 kW to keep the cooking temperature around 98 °C for as long as the optimal cooking time. Such a power level was selected after a few preliminary tests carried out as reported previously, but not shown for the sake of simplicity (Cimini *et al.*, 2017). Thus, by referring to the overall mass (m_{T0}) of the water-pasta suspension used previously, namely 1.625 kg, the nominal specific power was calculated ($e_{C,nom}$≈0.246 W g^{-1}) and kept constant for WPR ranging from 2 to 12 L kg^{-1}. Thus, once WPR had been set, the initial amounts of dried pasta (m_{PA}) and cooking water (m_{W0}) were estimated as follows:

$$m_{PA} = \frac{P_{C,nom}}{e_{C,nom}\,(1+WPR)} \tag{2.1}$$

$$m_{W0} = m_{PA0}\,WPR \tag{2.2}$$

At the highest WPR used here (i.e., 10 L kg^{-1}), the cooking tests were carried out in the absence of stirring. To avoid spaghetti sticking together during cooking at WPR=2 L/kg, the aforementioned stirrer was continuously kept rotating at its minimum level (50 rev min^{-1}). For all the other pasta formats, the aforementioned stirrer was kept rotating at 50 rev min^{-1} for 30 s, but resting for the subsequent 90, 60 or 30 s at WPR equal to 6, 4, or 3 L kg^{-1}, respectively.

2.2.3 Eco-sustainable pasta cooker (EPC)

The novel eco-sustainable pasta cooker (EPC) was using the aforementioned induction-plate stove (Melchioni INDU, Melchioni Spa, Milan, Italy), that was properly modified to make the energy supply controllable in terms of power and time, as well as the hot plate temperature variable from 60 to 240 °C, via a programmed microcontroller. In this way, the power supplied throughout the entire cooking process was controlled by accounting for the difference between the instantaneous water temperature and its reference value (i.e., 98 °C) either during the water heating or pasta cooking phases. To favor pasta rehydration, a 12-V, 30-rev min^{-1} direct current electric motor model GW370 (dispatched from Yueqing, Zhejiang, China) was welded to the pot lid and connected to a stainless-steel rod mixer. The microprocessor used to control the induction hob was the programmable Arduino® hardware platform, based on the 8-bit automatic voltage regulator (AVR) microcontroller ATmega168/328 (Microchip Technology Inc., Chandler, AZ, USA). It was integrated into the circuit board of the induction cooker, from which it picked up the current for powering and controlling its ignition, shutdown and mixer motor. Arduino® is a card that converts analog and digital inputs, as picked up and transmitted by sensors, into actions according to the instructions that have been encoded and imparted in a specially written program using the open source Arduino's programming language, namely an integrated development environment (IDE) software using the Language of C^{++}. The input sensors used were the following:

i) A WIRE digital temperature sensor - DS18B20 (Maxim Integrated Products San Jose, CA, USA). It was used to detect the water temperature with a precision from 9- to 12-bit in a temperature range between -55 and +125 °C with an approximation of ±0.5 °C and a temperature conversion time to 12-bit word of 750 ms. The sensor was housed inside a stainless-steel cockpit welded to the pot lid that ended just 5 mm above the pot bottom surface.

ii) A current sensor - SCT 013-020 (Yashuadechang Electronic, Bejjing, China). It was used to monitor the energy consumed by the induction hob. By connecting it to one of the user cables, it was possible to measure an output voltage in the range of 0-1 V over the included sampling resistance. Such a voltage was proportional to the current flowing across the cable itself with a maximum nonlinearity of 3 %.

The entire system was managed and programmed via an application installed on a smartphone with android system. This application was implemented by using a human-machine interface (HMI) platform (for android) (Virtuino), that allowed the creation of a graphical interface for the management, monitoring, and recording of the input and output data of the Arduino® microprocessor. Communication between the smartphone and microprocessor was via Bluetooth v. 2.0 + Enhanced Data Rate (EDR), a faster short-range wireless data exchange modulation scheme operating at a frequency of 2.4 GHz with the module HC-05, that had a range of 10 m.

Figure 2.2 shows all the items of the eco-sustainable paste cooker developed here, while Figure 2.3 displays the application installed on a smartphone with all the function keys.

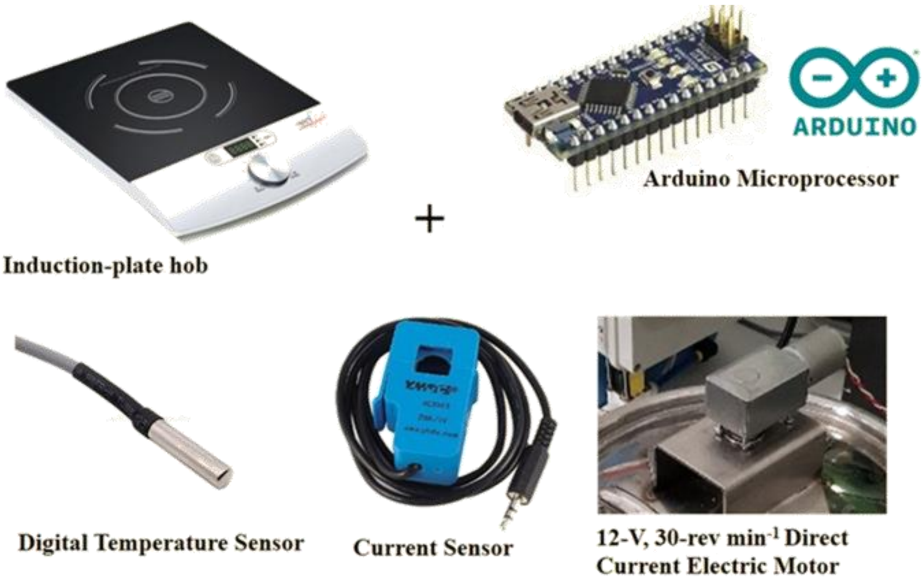

Figure 2.2 Main items of the eco-sustainable pasta cooker (EPC) developed in this work.

Figure 2.3 Picture of the application installed on a smartphone with description of all the function keys during the pasta cooking phase.

As shown in Fig. 2.3, the simple graphical interface included the main *Power* and *Menu* buttons, these replacing the physical ones present on the induction hob, as well as some other function keys, such as the *Turn off* key to switch off the hob, and the *Agitator* one to activate the mixer inside the pot. Such an operation can be performed in the manual (i.e., the user turns on and off the mixer) or automatic (i.e., once the agitation has been started, the mixer is activated and stopped at previously prefixed time intervals by the user) mode. The instantaneous cooking water temperature was shown by the digital display on the upper right side, as well as by the central chart in the graphical interface. Similarly, four separate displays allowed the instantaneous electric power absorbed (expressed in W), current (in A), energy consumed (in W h), and CO_{2e} emitted during cooking to be monitored. The time course of the electric energy consumed was also plotted in the lower central chart. The electric energy supplied by the induction hob (E_S) was also independently measured using a digital power meter type RCE MP600 (RCE Srl, Salerno, Italy).

With the EPC all cooking tests were carried out using a given amount (m_{W0}) of bottled still mineral water with a fixed residue at 180 °C of about 300 mg L^{-1}, as suggested by ISO (2016). Once the induction hob had been connected to the power supply, the microprocessor was activated using the aforementioned application. The prefixed amount of water (m_{W0}) was added to the pot, the latter was lidded, and the water heating phase was started by pressing the *Power* button in the application. As the microprocessor had set the induction hob at its maximum power (2,000 W), the word *Heating* appeared on the app central display (Fig. 2.3). In the meantime, the application asked for the duration of the pasta cooking process. In this work, the optimal cooking time (OCT) for each pasta type examined, as determined below, was entered. Alternatively, the cooking time recommended in the package label by the pasta maker might be accounted for. As the water temperature had reached 98 °C, the microprocessor beeped and automatically lowered the power rating to its minimum value (i.e., 200 W), this making the word *Boiling* appear on the app display (Fig. 2.3). Once the pot had been unlidded, the prefixed amount of dried pasta (m_{PA}) was added to the boiling water. Thereafter, the lid was newly closed, and the *Pasta cooking timer* and *Mixer* buttons were pressed on the app interface (Fig. 2.3). To limit pasta adhesion during cooking, the aforementioned stirrer was automatically activated 30 s after the addition of dry pasta to allow it to become just flexible, kept rotating at 30 rev min^{-1} for 10 s, and resting for the subsequent 20 s. As the microprocessor had detected a drop in the water temperature, it started to increase the power supplied by the induction hob. Actually, during the pasta cooking phase, the microprocessor system acquired the water temperature every 10 s, and automatically increased the power rating of 200 W, whether the current cooking water temperature differed from the reference one (98 °C). After 10 s, if the above temperature difference was still negative, the microprocessor increased the power setting to 600 W, and then step by step up to the maximum power setting of 2,000 W. The same procedure was used to reduce the power setting if the cooking water temperature was greater than the reference one. As the prefixed cooking time had elapsed, the app switched off the induction hob and beeped. Figure 2.4 shows some pictures of the EPC during its operation.

(a) b) c)

Figure 2.4 Pictures of the EPC at (**a)** the beginning of the cooking process, (**b**) during the pasta cooking phase, and (**c**) the end of pasta cooking phase with the pan unlidded.

2.2.4 Dried pasta analyses

Raw pasta samples were milled using a refrigerated laboratory mill model IKA A10 (IKA-WERKE GmbH and CO KG, Staufen, Germany). Their chemical composition was assayed by the standard *International Association for Cereal Science and Technology* (ICC) procedures, namely moisture (ICC Standard method No. 110/1), total protein (ICC Standard method No.105/2), and ash (ICC Standard method No. 104/1). In particular, the raw protein content was calculated as total Kjeldahl nitrogen × 6.25. Fat was determined according to AACC method 30-20. Total starch was analyzed by K-TSTA assay kit by Megazyme (Megazyme Bray, Co. Wicklow, Ireland).

2.2.5 Cooked pasta physico-chemical analyses

Each spaghetti sample was weighed, broken in half, and cooked in boiling deionized water. The effects of cooking water (Cubadda *et. al.,* 2009; Sozer *et. al.,* 2007), pH and hardness on stickiness and cooking loss of spaghetti were deeply assessed (Dexter *et. al.,* 1983; D'Egidio *et. al.,* 1981; Malcolmson *et. al.,* 1993). In particular, quite small differences in the above parameters were observed when considering deionized or tap water, especially for pasta samples made of durum wheat semolina (Malcolmson *et. al.,* 1993). Cooking properties of pasta samples were assessed by collecting several strands of long or short pasta with a colander. Such strands were cooled by rinsing under running tap water for 60 s. After excess water had been removed by shaking the colander for 10 s, the samples were immediately used for the following analyses.

The AACC Method 66-50.01 was used to monitor the central white core of spaghetti, cooked with different WPRs for as long as the aforementioned set time of 9 min, and up to the disappearance of the central white core, when a spaghetti strand was gently squeezed between two glass plates. After collecting the short pasta strands at different cooking times up to and beyond the set time suggested by the pasta maker, they were immediately cut at right angles with a cutter to detect the presence of the central white annular portion. The time required for such a continuous white line to disappear represented the so-called optimum cooking time (ISO, 2016). Actually, when a broken white line was visible, the cooking process was regarded as completed, the resulting pasta being described as cooked "al dente". All three commercial brands of Penne rigate were cooked al dente after a cooking time of 11 min.

The amount of total organic matter (TOM) found in washing water after spaghetti or *penne rigate* cooking with a nominal WPR of 10 L/kg was determined following the ICC Standard method n. 153 (ICC, 1995).

Whatever the WPR used, cooking loss (CL) was evaluated by determining the amount of solid dispersed in the cooking water used. Once pasta water had been recovered with a colander and transferred into a graduated cylinder, the empty pot was accurately washed with deionized water to recover all adhering materials and finally the pasta water mass was brought back to its initial amount (m_{W0}) (D'Egidio *et. al.,* 1990). Under very vigorously stirring, a few aliquots (~10 g) were collected and dried at 105 °C overnight. The cooking loss (CL) was referred to the initial mass of dried pasta used (m_{PA}) and expressed as grams of matter loss per g of dry pasta.

$$CL = \frac{x_{RS}\, m_{CW0}}{m_{PA}} \tag{2.3}$$

Because of water absorption, the increase in cooked pasta mass was gravimetrically assessed as the difference between the masses of cooked pasta (m_{CPA}) and dried pasta (m_{PA}). The relative water uptake (WU) was expressed as grams of water per g of dry pasta.

$$WU = \frac{m_{PC} - m_{PA}}{m_{PA}} \tag{2.4}$$

Starch gelatinization was estimated via the colorimetric measurement of starch–iodine complex formed in an aqueous suspension of the cooked pasta sample as such and after complete starch gelatinization (Cocci *et. al.,* 2008; Dalla Rosa *et. al.,* 1989). Two samples A and B of cooked pasta ~ (0.6 g), as cooked using a given WPR value, were collected at different cooking times and were homogenized with de-ionized water (20 mL) using a Ultraturrax at 13,000 rpm for 1 min. Any resulting suspension was carefully recovered and brought to a final volume of 30 mL.

Sample A was centrifuged at 3,000 rev min^{-1} for 10 min using a centrifuge Beckman mod. TJ-6 equipped with a 55-mm radius rotor. Then, 0.1 mL of sample A was diluted with 1.9 mL of deionized water and integrated with 0.02 mL of an aqueous solution containing potassium iodide (4 g) and iodine (1 g) in 100 mL of deionized water. Two standard optical polystyrene cuvettes (10-mm light path, 1.5 mL volume) were filled with the aforementioned sample and the iodine solution, respectively, and their net absorbance

(ΔA_A) was measured at 600 nm with a Thermofisher Scientific mod. Evolution 60S spectrophotometer.

Before being centrifuged, Sample B was transferred into a Sovirel screw-capped tube to avoid water evaporation and subsequently thermally treated in a water bath kept at 100 °C for 15 min to achieve the complete gelatinization of starch. Such a treatment was found to be equivalent to that carried out in an autoclave at 135 °C for 1 h by AACC Method 76-11 (AACC International, 1995), as verified in this work and by Dalla Rosa et al. (1989). Thereafter, each tube was promptly cooled using tap water, centrifuged as reported above, and spectrophotometrically assayed as the sample A to determine the net absorbance ΔA_B. The degree of starch gelatinization (SGD), representing the ratio of gelatinized starch to total gelatinized starch in cooked pasta at a given cooking time and WPR value, was calculated as:

$$SGD = \frac{\Delta A_A}{\Delta A_B} x\, 100 \quad (2.5)$$

where ΔA_A or ΔA_B is the net absorbance of the iodine complexes prepared from the aqueous suspension before or after thermal starch gelatinization.

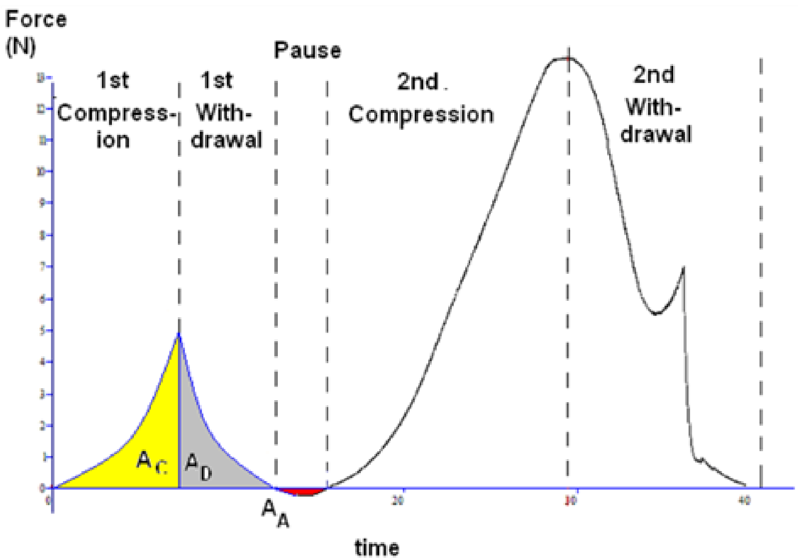

Figure 2.5. Typical TPA curve as determined in accordance with the standard TPA test set up by Barilla Group. All parameters were listed in the Nomenclature section.

The textural characteristics of cooked pasta were determined using a Universal Testing Machine UTM mod. 3342 (Instron Int. Ltd., High Wycombe, UK) equipped with a 1000-N load cell and connected to a personal computer (PC) via a controller 3300 (version 01-v2,02/03-b6,58/EFI- v1.36) and operated via a specially designed software (Bluehill 2.33.893-hotfix). The Fig. 2.5 shows a typical TPA curve generated by UTM.

Seventeen strands of cooked spaghetti were aligned over a stainless-steel compression platen Fig. 2.6a to avoid spaghetti sticking to it, as well as to clean easily the platen itself, and tested using the cutting probe, shown in Fig. 2.63b-c.

For a time, interval smaller than 10 min, the difference among TA parameters was found to be statistically insignificant at the probability level of 0.05. The average cooked spaghetti diameter (d_{CP}) was calculated as the difference between the total displacement of the probe at the contact points with the platen and pasta samples, both revealed by a trigger force of 0.05 N. Each TA test was carried out in accordance with the Barilla Group standard test (Ballestrieri *et. al.*, 2015). By setting the probe speed at 1 mm s^{-1}, a first bite was performed by submitting the strands to a 30% compression. The probe was then moved upward to reach its initial position. After a pause of 5 s, it was newly moved downward to submit the specimens to a second 90% compression and then moved upward to return to its initial position. The height of the force peak on the first and second compression cycles was defined as the pasta hardness at 30% (F_{30}) and 90% deformation (F_{90}). The force-vs-time area (A_D) during the 1st withdrawal of the compression divided by the force-vs-time area (A_C) of the 1st compression (see Fig. 2.5) was defined as the cooked pasta resilience (R_{CP}), this measuring how well the cooked pasta can regain its original form (Haraldsson *et. al.*, 2010). The upstroke actions during the first and second bites represented the work necessary to pull the compressing probe away from the spaghetti strands and the force-vs-time area was defined as adhesiveness (A_A). In almost all tests carried out, A_A was found to be negligible, as shown in Fig. 2.5.

Three pieces of cooked short pasta were inserted into three stainless steel bars (Fig. 2.7b), and tested using the cutting probe, shown in Fig. 2.7a. Each Texture Analysis (TA) test was performed as described by (Ballestrieri *et. al.*, 2015). The difference between the total displacement of the probe at the contact points with the three aligned bars and pasta samples, both revealed by a trigger force of 0.05 N, allowed the average thickness (s_{CP}) of cooked *Penne rigate* to be estimated.

a) b) c)

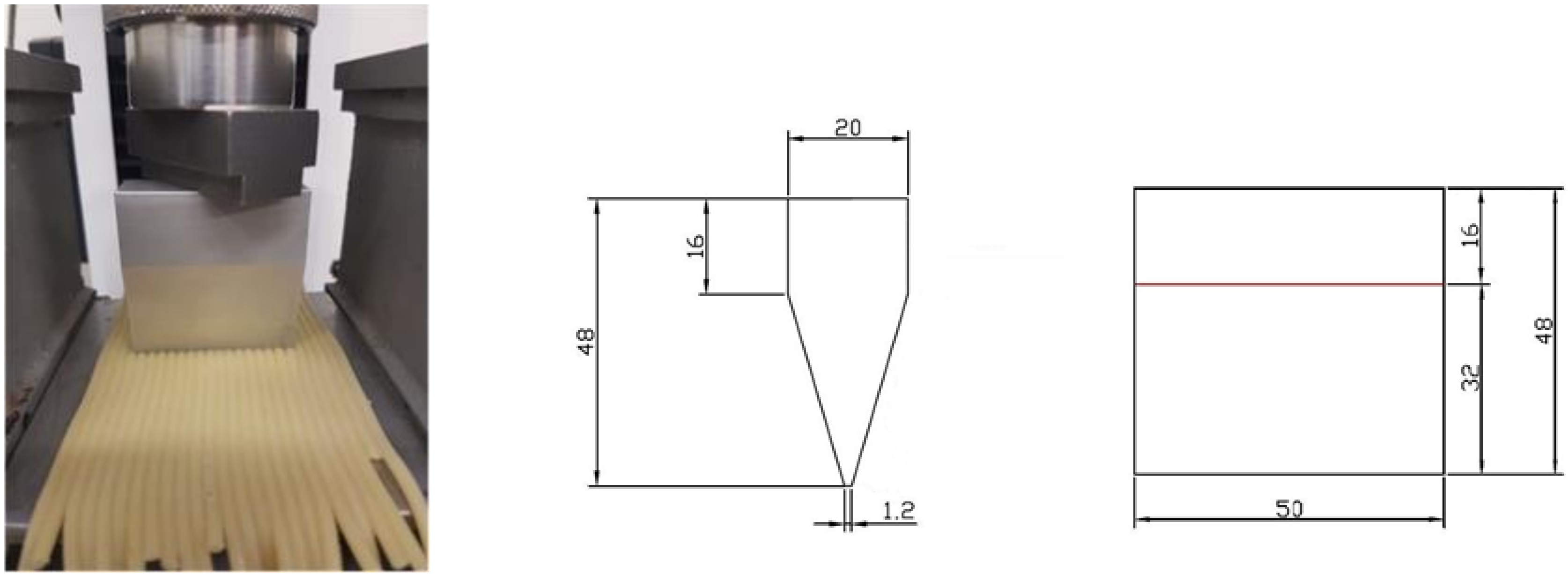

Figure 2.6. Picture (**b**), front (**c**) and side (**a**) views of the cutting probe used to perform the Texture Profile Analysis of 17 strands of cooked spaghetti aligned over a Teflon compression platen. All dimensions are in mm.

a) **b)**

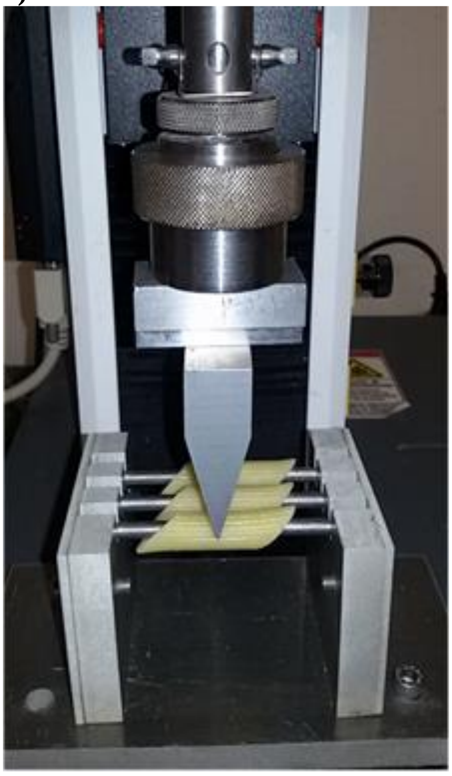

Figure 2.7 Picture (**a**) of the TA system used to measure the instrumental quality of three short strands of cooked pasta with details of the three stainless-steel bars (**b**).

After setting the probe speed at 1 mm s^{-1}, a first compression cycle was carried out to submit the pasta pieces to a 40% compression with respect to s_{CP} (first bite). The probe was then lifted up to its initial position. After a pause of 5 s, it was moved downward to submit the pasta pieces to a second 98% compression (second bite). Finally, the cutting probe was raised to reach again its initial position. The force peak on the 1^{st} or 2^{nd} compression cycle represented the pasta hardness at 40% (F_{40}) or 98% (F_{98}) deformation. The cooked pasta resilience (R_{CP}) was estimated as in the case of spaghetti.

Each TA test with long or short pasta was repeated three to five times.

When testing the EPC, the short and long cooked pasta strands were submitted to two consecutive compression cycles, the first and second ones up to a 30 % and 90 % compression to compare the TA data.

2.2.6 Cooked pasta sensory analysis

A panel of six trained judges evaluated the sensory properties of the cooked spaghetti samples using the following traits defined as follows (Cubadda *et. al.,* 1988):

- *Firmness,* as the resistance of cooked pasta when chewed or flattened between the fingers or sheared between the teeth.
- S*tickiness,* as the state of surface disintegration of cooked pasta following visual inspection.
- *Bulkiness,* as the degree of adhesion of cooked spaghetti strands on the basis of visual and manual inspection.
- *Overall cooking quality* (CQ), as estimated by averaging the scores obtained for the above three sensory attributes.

In Italy, such attributes were considered quite reliable to judge the pasta cooking quality (Cubadda *et. al.,* 2007; Marconi *et. al.,* 2012). Moreover, they are strictly related to those (namely, firmness, liveliness, and starch release) used by the international standard method ISO (2016).

Sensory profiling was performed using a 100-point category scale (Cubadda *et. al.,* 1988). A printed response sheet with written instructions for the test was given to each panelist at the start of each session. More specifically, spaghetti was regarded of poor quality with $CQ \leq 40$, not completely satisfactory ($40 < CQ \leq 50$), fair ($50 < CQ \leq 70$), good ($70 < CQ \leq 80$), and excellent ($CQ > 80$). One of the samples was presented to panelists at each session, and 18 sessions were held so that each of the three spaghetti specimens cooked at both WPR levels was evaluated three times by each judge. The order of sample presentation was completely randomized, and the samples were identified with three random numbers.

2.2.7 Cooking water and energy balances

The pasta cooking process was subdivided into two distinct phases. The first one was aimed at heating the cooking water up to its boiling point, while the second one was the real pasta cooking phase. To check for the cooking water balance during such a process, the block diagram shown in Fig. 2.8 was used.

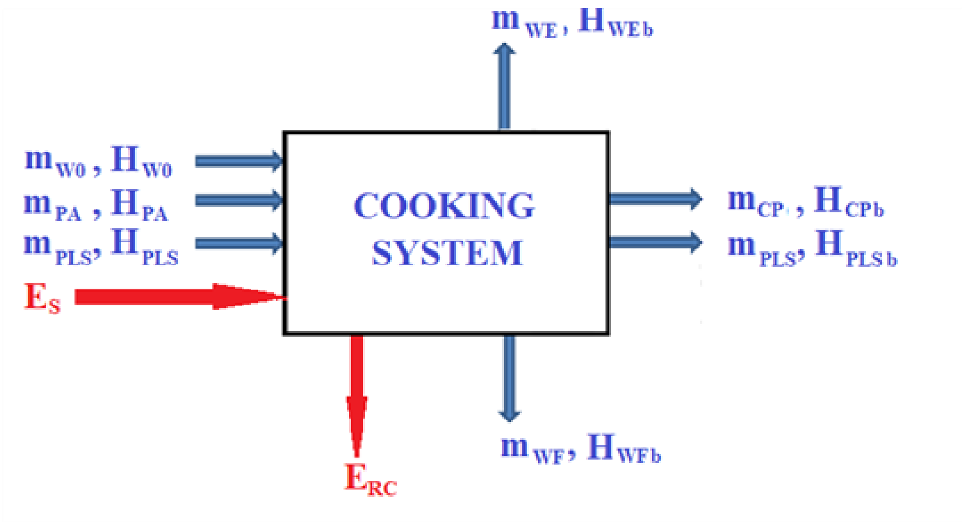

Figure 2.8 Block diagram of the pasta cooking system used to establish the mass and energy balances. All symbols were listed in the Nomenclature section.

To this end, the following data were collected:

- The initial mass of cooking water (m_{W0}).
- The cooking water mass at the boiling point (m_{WBP}) to estimate the mass of water evaporated throughout the cooking water heating phase:

$$m_{We} = m_{W0} - m_{WBP} \qquad (2.6)$$

- The cooking water mass as soon as the pan has been unlidded (m_{WLO}), just before dried pasta adding (m_{PA}). As the lid was removed, there was a sudden release of water vapor (adiabatic flash), its mass being equal to:

$$m_{WAF1} = m_{WBP} - m_{WLO} \qquad (2.7)$$

- The masses of residual cooking water or *pasta water* (m_{Wf}), and cooked pasta (m_{CPA}), once water-pasta mixture has been fractionated with a colander. In this way, the mass of water absorbed by pasta (m_{WPA}), or adiabatically flashed (m_{WAF2}) at the end of the cooking process when the lid has been newly removed, was estimated as:

$$m_{WPA} = m_{CPA} - m_{PA} \qquad (2.8)$$

$$m_{WAF2} = m_{W0} - m_{We} - m_{WAF1} - m_{WPA} - m_{Wf} \qquad (2.9)$$

Such data allowed to trace which fraction of m_{W0} was evaporated (η_{WE}), adiabatically flashed as the pan had been unlidded (η_{WAFi}), absorbed by cooked pasta (η_{PA}), and unused (η_{Wf}) at the end of the pasta cooking process.

The energy balance was expressed as follows:

$$H_{W0}+H_{PA}+H_{PLS}+E_S = H_{WEb}+H_{CPb}+H_{PLSb}+H_{WFb}+m_{PA}\ x_S\ \Delta H_{gel}+E_{RCC} \quad (2.10)$$

where H_{W0}, H_{PA}, and H_{PLS} are the enthalpies of cooking water, raw pasta, and pan, lid and stirrer, all at the initial temperature T_0; E_S is the energy supplied by the induction hob; H_{WEb}, H_{CPb}, H_{PLSb}, and H_{WFb} are the enthalpies of water evaporated, cooked pasta, pan, lid and stirrer, and pasta water, all at the boiling point T_b; E_{RCC} is the energy dissipated by radiation, convection and conduction from the pan and heating source. Since pasta cooking involves starch gelatinization, the heat of starch gelatinization was estimated as the mass fraction of starch (x_S) in raw pasta times its mass (m_{PA}) and enthalpy of wheat starch gelatinization (ΔH_{gel}=11.9 J g^{-1}), the latter being extracted from (Ratnayake *et al.* 2009). The energy efficiency (η_C) of the pasta cooking system was calculated as the enthalpy change for cooking water, raw pasta, as well as pan, lid and stirrer, from T_0 to T_b, plus the heat of starch gelatinisation divided by E_S.

2.2.8 Carbon footprint of pasta cooking

According to the Product Environmental Footprint category rules for dry pasta (UNAFPA, 2018), the carbon footprint of pasta cooking (CF_{PC}) is mainly dependent on the electric energy requirements to cook pasta. Thus, it was estimated by multiplying the overall electric energy consumed (E_{PC}) by its 100-year time horizon Global Warming Potential factor (GWP_{EE}):

$$CF_{PC} = E_{PC}\ GWP_{EE} \quad (2.11)$$

with

$$E_{PC} = e_{PA}/(1-\eta_{IG}) \quad (2.12)$$

where e_{PA} is the specific energy consumed to cook 1 kg of raw pasta, while GWP_{EE} (=0.3213 kg CO_{2e} kWh^{-1}) and η_{IG} (≈5.8 %) were referred to the average thermo-electric production from non-renewable and renewable sources and electric energy loss of the Italian grid in 2016, as extracted from ISPRA (2018). In compliance with the PAS 2050 standard method (BSI, 2008), the production of capital goods (machinery, equipment and energy wares) was excluded from the system boundary.

2.2.9 Statistical analysis of data

Each pasta cooking test was replicated four times to assess the average values and standard deviations of a series of variables, such as cooking water mass, electric energy consumption, cooking loss, specific water absorption, TA parameters, and sensory attributes. Any set of data was shown as average ± standard deviation and was analyzed by Tukey test at a significance level of 0.05. Analysis of variance was used to assess the statistical effects of raw pasta diameter (d_{RP}) and protein content (x_{RP}), and cooking-to-dried pasta ratio on CL, WU, and TA and sensory parameters using SYSTAT version 8.0 (SPSS Inc., 1998). Any linear regression was estimated using the least squares method and the goodness of fit was evaluated by means of its coefficient of determination (r^2).

2.3 RESULTS

2.3.1 Effect of WPR on spaghetti cooking

Whatever the water-to-pasta ratio WPR used, each spaghetti cooking test was carried out as reported in §2.2.2. In all conditions, the electric power absorbed by the stirrer was practically constant (5.8±0.3 W). By accounting for the different rest intervals used, the overall mixing energy consumed was calculated as equal to 0.870, 0.435, or 0.218 Wh for WPR=2, 3, or 6 L kg^{-1}, respectively. The resulting specific energy requirement was thus negligible with respect to that (E_{cons}) needed to cook pasta (Table 2.4).

The time needed to heat the different initial masses of cooking water used up to the boiling point decreased from about 350 to 253 s as WPR was reduced from 12 to 2 L kg^{-1} dry pasta (Fig 2.9). This time interval was proportional to the amount of cooking water used (m_{W0}), the energy efficiency of the induction hob used being approximately constant.

The main results of the cooking and TA tests, the former being quadricated and the latter repeated from 10 to 22 times, were summarized in Table 2.4.

Table 2.4 Barilla Spaghetti no. 5 cooking tests carried out under constant power supplied by the induction hob during water boiling (P_H) and spaghetti cooking (P_C) when using different amounts of dried pasta (m_{PA}) and cooking water (m_{W0}): effect of WPR on the overall energy consumed (E_{cons}); cooking energy efficiency (η_C); effective power supplied per unit mass of cooking water and dried pasta (e_{CE}); energy consumed per unit mass of dried pasta (e_{PA}); percentage fractions of water evaporated (η_{WE}), adiabatically flashed before pasta addition (η_{WAF1}) and drainage (η_{WAF2}), absorbed by cooked pasta (η_{WPA}), and remaining after cooking (η_{Wf}); relative water uptake by cooked pasta (WU); starch gelatinization degree (SGD); cooking loss (CL); main TA parameters (F_{30}, F_{90}, R_{CP}); and diameter of cooked spaghetti (d_{CP}). All cooking tests were replicated 4 times, while TA ones from 10 to 22 times.

WPR	m_{W0}	m_{PA}	P_H	P_C	E_{cons}	η_C	e_{CE}	e_{PA}	η_{WE}	η_{WAF1}	η_{WPA}	η_{WAF2}	η_{Wf}	WU	SGD	CL	F_{30}	F_{90}	R_{CP}	d_{CP}
[L kg^{-1}]	[g]	[g]	[kW]	[kW]	[Wh]	[%]	[W kg^{-1}]	[Wh g^{-1}]	[%]	[%]	[%]	[%]	[%]	[g g^{-1}]	[%]	[g g^{-1}]	[N]	[N]	[-]	[mm]
11.98 ± 0.01^{a}	1500.2 ± 0.0^{a}	125.2 ± 0.1^{a}	1.99 ± 0.01^{a}	0.24 ± 0.01^{a}	242 ± 5^{a}	65 ± 1^{a}	151 ± 3^{a}	1.93 ± 0.04^{a}	2.1 ± 0.3^{a}	0.63 ± 0.01^{a}	10.8 ± 0.1^{a}	2.4 ± 0.1^{a}	84.0 ± 0.5^{a}	1.30 ± 0.01^{a}	12.0 ± 0.2^{a}	0.045 ± 0.001^{a}	5.6 ± 0.4^{a}	13.8 ± 0.5^{a}	0.64 ± 0.02^{a}	2.6 ± 0.1^{a}
10.02 ± 0.03^{b}	1477 ± 5^{b}	147.6 ± 0.3^{b}	1.83 ± 0.01^{b}	0.24 ± 0.01^{a}	225 ± 3^{b}	70 ± 2^{b}	145 ± 4^{a}	1.52 ± 0.02^{b}	2.3 ± 0.2^{a}	0.7 ± 0.2^{a}	15.2 ± 0.3^{b}	-0.1 ± 0.3^{b}	81.8 ± 0.5^{b}	1.53 ± 0.03^{b}	11 ± 2^{a}	0.042 ± 0.001^{b}	5.1 ± 0.3^{a}	13.2 ± 0.6^{a}	0.64 ± 0.01^{a}	2.65 ± 0.03^{a}
6.0 ± 0.0^{c}	1392.9 ± 0.1^{c}	232 ± 0^{c}	1.95 ± 0.01^{c}	0.25 ± 0.01^{a}	238 ± 2^{a}	64 ± 1^{a}	156 ± 4^{ab}	1.02 ± 0.01^{c}	2.5 ± 0.2^{a}	1.1 ± 0.2^{b}	20.8 ± 0.2^{c}	2.9 ± 0.3^{c}	72.7 ± 0.1^{c}	1.25 ± 0.01^{c}	11.2 ± 0.3^{a}	0.041 ± 0.000^{2b}	6.3 ± 0.5^{b}	13.9 ± 0.6^{a}	0.62 ± 0.01^{a}	2.66 ± 0.03^{a}
3.0 ± 0.0^{d}	1218.5 ± 0.1^{d}	406 ± 0^{d}	1.96 ± 0.01^{c}	0.25 ± 0.01^{a}	222 ± 2^{b}	65 ± 1^{a}	153 ± 7^{ab}	0.54 ± 0.01^{d}	3.4 ± 0.2^{b}	0.20 ± 0.1^{c}	42.2 ± 0.1^{d}	3.0 ± 0.7^{c}	51.1 ± 0.5^{d}	1.27 ± 0.01^{d}	11.5 ± 0.4^{a}	0.035 ± 0.001^{c}	6.1 ± 0.3^{b}	13.0 ± 0.4^{b}	0.62 ± 0.01^{a}	2.70 ± 0.03^{a}
2.0 ± 0.00^{e}	1083.1 ± 0.1^{e}	542 ± 0^{e}	1.90 ± 0.02^{d}	0.26 ± 0.01^{a}	213 ± 6^{c}	65 ± 1^{a}	159 ± 5^{ab}	0.39 ± 0.01^{e}	6.5 ± 0.6^{a}	0.0 ± 0.0^{d}	70.2 ± 0.9^{e}	3 ± 1^{c}	20 ± 2^{e}	1.37 ± 0.06^{a}	9.8 ± 0.6^{b}	0.022 ± 0.002^{d}	6.0 ± 0.4^{b}	12.3 ± 0.8^{b}	0.62 ± 0.01^{a}	2.59 ± 0.06^{b}

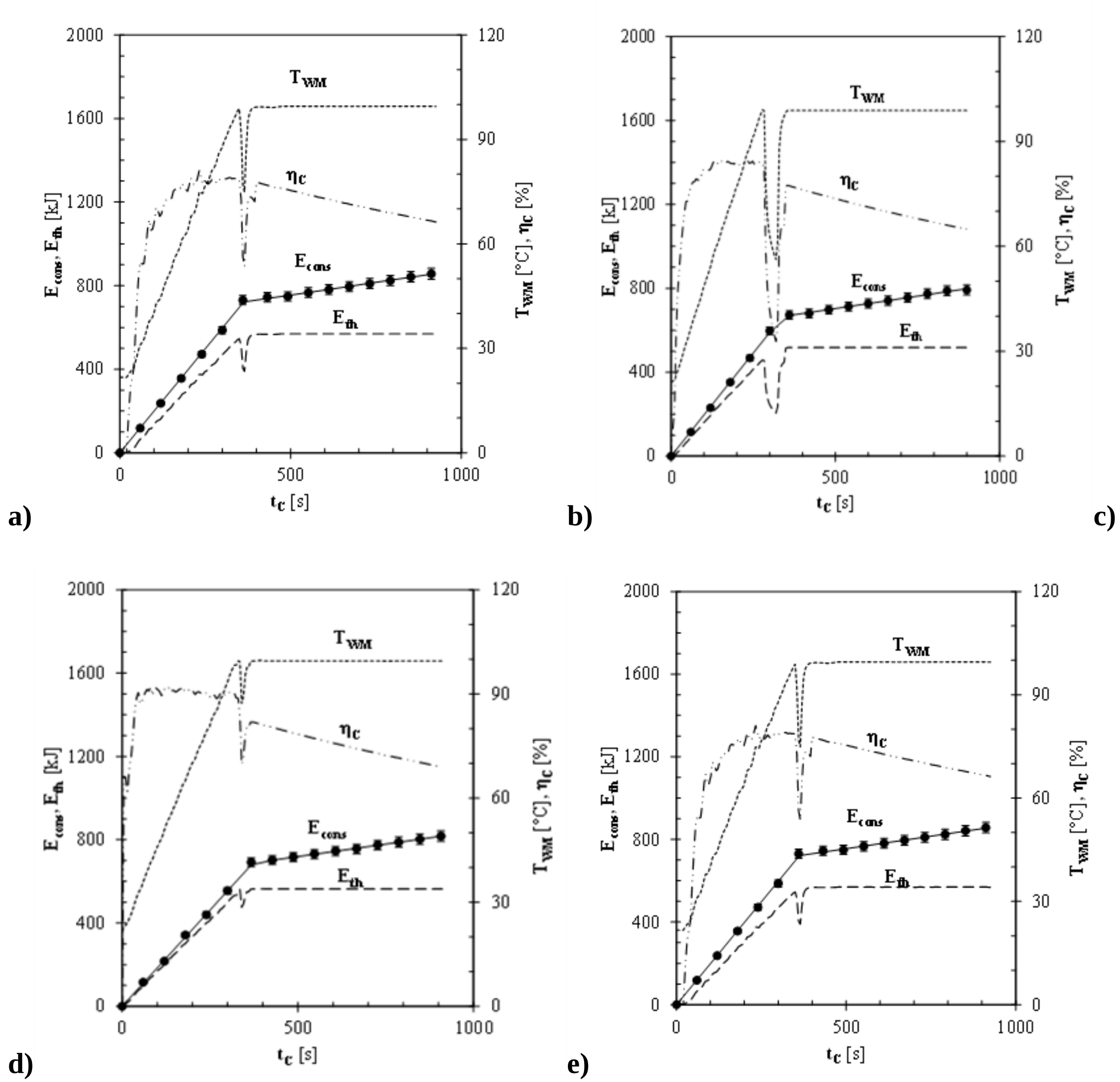

Figure 2.9 Effect of cooking time (t_C) on the cooking water temperature at mid-height (T_{WM}: **- - -**), energy theoretically (E_{th}: — —) and effectively (E_{cons}: ——) consumed, and energy efficiency (η_C: — · · —, — · · —) during pasta cooking with different WPR values [**a**) WPR=2; **b**) 3; **c**) 6; **d**) 10: **e**) 12 L kg^{-1} dry pasta] and the hob control knob set at the nominal power of 2 kW during the cooking water heating phase and at 0.4 kW during the pasta cooking one.

Energy aspects

Fig. 2.10 shows the effect of WPR on the parameters related to the energy aspects of the process. Firstly, it was checked for the effective electric power (E_{cons}) supplied by the induction hob during either the cooking water heating phase (P_H) or pasta cooking one (P_C). By using the aforementioned multimeter, the measured E_{cons} values were linearly related to the cooking time (t_C), as follows:

$$E_{cons}(t) = \alpha \cdot t_C + \beta \qquad (2.13)$$

where α and β are empiric constants estimated using the least squares method. All regressions were characterized by coefficients of determination (r^2) greater than 0.995, while the estimated slopes (α) by coefficients of variation ranging from 0.3 to 3%. Thus, the effective power supplied per unit mass of the water-pasta suspension undergoing cooking ($e_{C,e}$) was found to be practically constant (153±5 W kg^{-1}) whatever WPR (Table 2.4). Same situation for the overall cooking energy efficiency (η_C=66±2 %). On the contrary, the specific energy consumed per unit mass of dried pasta (e_{PA}) reduced almost linearly from about 1.93 to 0.39 Wh g^{-1} as WPR was reduced from 12 to 2 L kg^{-1}:

$$e_{PA} = (0.160 \pm 0.004)\ WPR \qquad (r^2=0.997) \qquad (2.14)$$

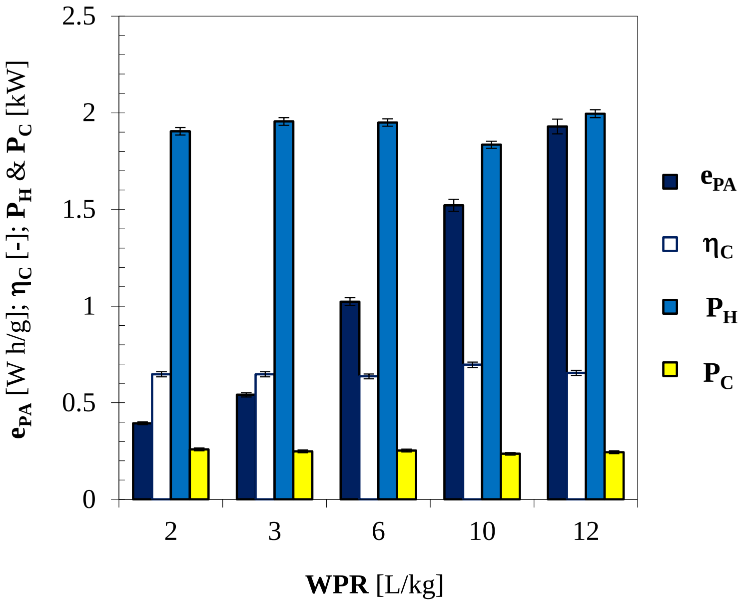

Figure 2.10 Specific energy consumed to cook dry pasta (e_{PA}); dimensionless cooking energy efficiency (η_C); power supplied to heat the cooking water (P_H) or cook pasta (P_C) against WPR.

Utilization of cooking water

Fig 2.11 shows the effect of WPR on the percentage utilization of the water used to cook spaghetti. The fraction of water evaporated during the cooking process (η_{WE}) slightly increased from 2.1 to 2.5 % for WPR halving from 12 to 6 L kg^{-1}, but enhanced to 3.4 and 6.5 % as WPR was further reduced to 3 and 2 L kg^{-1}, respectively. The cooking water adiabatically flashed (η_{WAF12}), anytime the pot was unlidded during the pasta cooking process, was practically independent of WPR (r^2=0.180) and of the order of 3±1 %. On the contrary, the cooking water absorbed by cooked pasta (η_{WPA}) was about the 11 % of the water initially added into the pot (m_{W0}) when dry pasta was cooked in a great excess of water (WPR=12 L kg^{-1}), but doubled to 21% of m_{W0} when WPR was halved to 6 L kg^{-1}. As WPR was reduced to 3 or 2 L kg^{-1}, such a water uptake jumped to 42 or 70% of m_{W0}, respectively. Consequently, by diminishing WPR from 12 to 2 L kg^{-1}, the so-called *pasta water*, that is the cooking water leftover after recovering cooked pasta with a colander, lessened from 84 to 21% of m_{W0}.

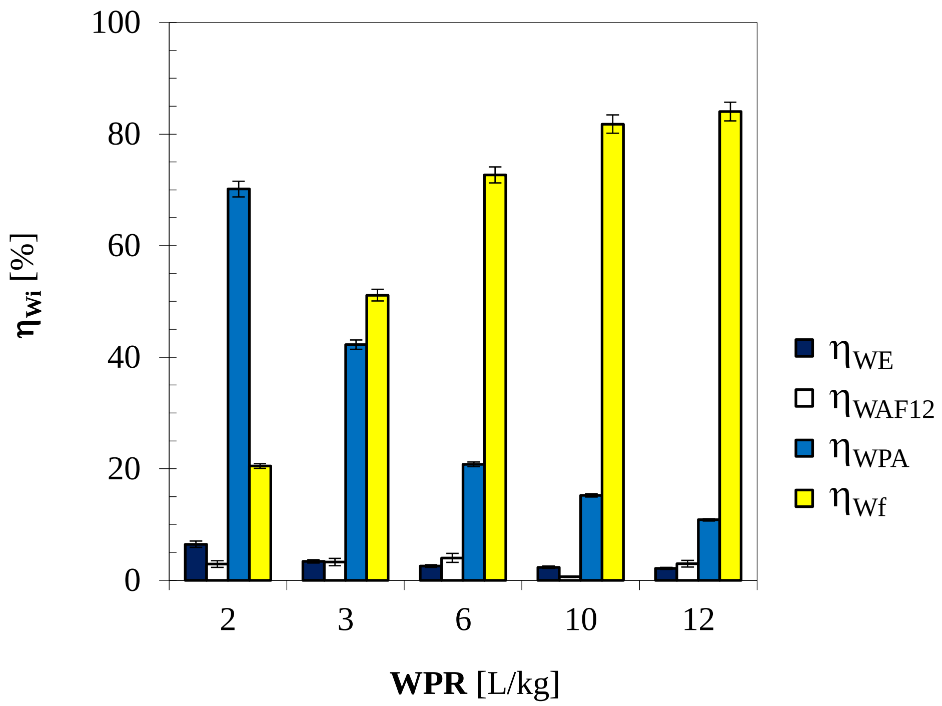

Figure 2.11 Percentages of water evaporated during the cooking process (η_{WE}), released as vapor when the pot is unlidded firstly to add dried pasta and then to drain cooked pasta (η_{WAF12}), absorbed by cooked pasta (η_{WPA}), and leftover upon pasta drainage (η_{Wf}) *versus* WPR.

Cooked spaghetti quality

Fig 2.12 shows the effect of WPR on cooked spaghetti quality. In particular, the relative increase in cooked pasta mass as due to water absorption (WU) was not related to WPR (r^2=0.090), but about constant (1.3±0.1 g g^{-1}) as WPR was decreased from 12 to 2 L kg^{-1}. The starch gelatinization degree (SGD) lessened from 12 to 9.8%, while the cooking loss (CL) tended to decrease as WPR was decreased (r^2=0.69). Actually, the loss of solid matter dissolved in the cooking water was about 0.042 g per g of dried pasta for WPR ranging from 12 to 6 L kg^{-1}. For WPR=3 or 2 L kg^{-1}, such amount dropped to 0.035 or 0.022 g g^{-1}, respectively.

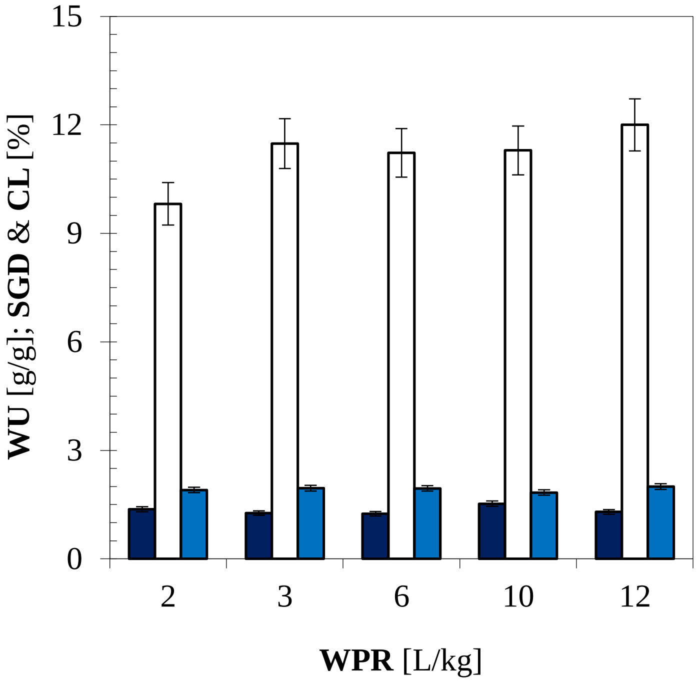

Figure 2.12 Relative increase in cooked pasta mass (WU: ■RICPM), starch gelatinization degree (SGD: □), and cooking loss (CL: ■) against WPR.

TA parameters of cooked spaghetti

Fig. 2.13 clearly shows the negligible effect of WPR on the three TA parameters accounted for. More specifically, throughout all TA tests the spaghetti strand diameter, and cooked pasta hardness upon either 30% or 90% deformation were practically constant, and equal to 2.6±0.1 mm, 5.8±0.5 N, or 13.2±0.6 N, respectively. Finally, cooked pasta resilience (R_{CP}) was about linearly related to WPR (r^2=0.890), even if its derivate with respect to WPR was so small (0.0022±0.0004) that it might be for the sake of simplicity regarded as constant (0.63±0.01).

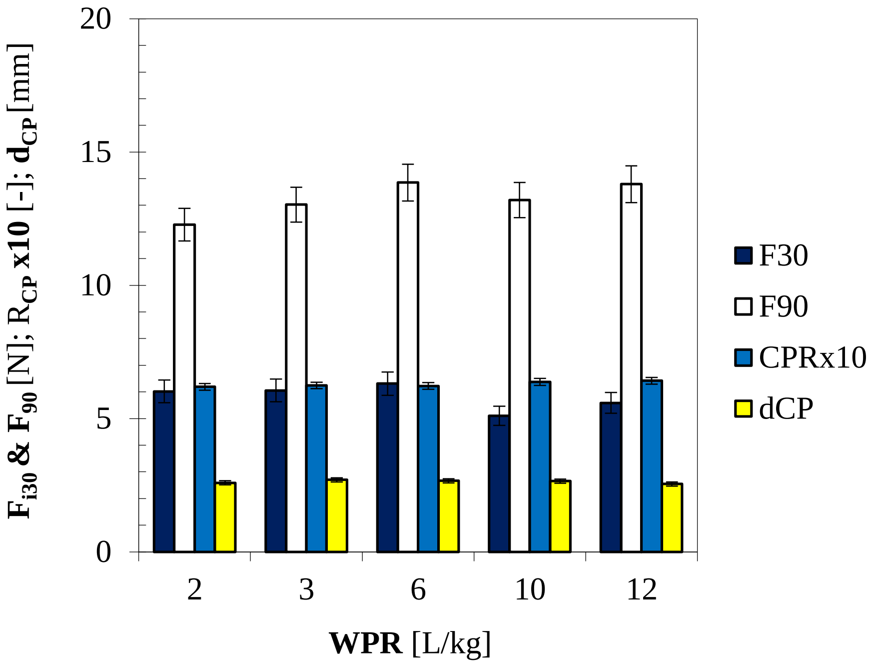

Figure 2.13 Cooked pasta hardness at 30% (F_{30}) and 90% (F_{90}) deformation; cooked pasta resilience (CPR); and cooked spaghetti diameter (d_{CP}) *versus* WPR.

Carbon footprint of spaghetti cooking

Fig. 2.14 shows the effect of WPR on the carbon footprint (CF_{PC}) of home spaghetti cooking according to the eco-sustainable cooking procedure used here. Firstly, CF_{PC} was linearly related to WPR (r^2=0.995) and any reduction in WPR would positively reduce the climate change potential of pasta cooking.

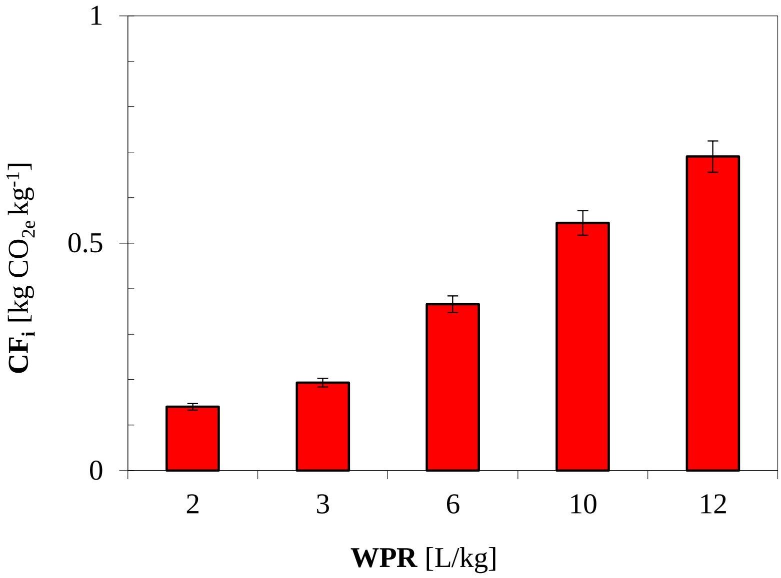

Figure 2.14 Effect of the cooking water-to-dry pasta ratio (WPR) on the carbon footprint (CF_{PC}) of spaghetti cooking as referred to the eco-sustainable cooking procedure used here.

2.3.2 *Effect of WPR on the cooking quality of three commercial spaghetti*

The physico-chemical characteristics of the three commercial spaghetti brands examined in this PhD thesis are shown in Table 2.1

Moisture, starch, fat and ash contents were in line with those characteristics of typical durum wheat semolina spaghetti. The raw protein content (x_{RP}) and diameter (d_{RP}) for the spaghetti samples under study varied from 11.5 to 13.9 g/(100 g), and 1.9 to 2.0 mm, respectively.

Total organic matter (TOM) test was used to measure *a priori* spaghetti stickiness by determining the amount of material leached by exhaustive rinsing of drained, cooked spaghetti. Samples 1, 2 and 3 resulted to be of fair, good, and excellent quality, respectively.

Electric power supplied

For WPR=3 L kg^{-1}, the electric power supplied by the mechanical stirrer was found to be practically constant (6.1±0.5 W). By accounting for the amount of raw pasta used (~406 g), the specific stirring energy consumed (0.0011 Wh/g) resulted to be totally negligible with respect to the specific cooking energy (e_{PA}).

As shown in the Fig. 2.15, the time course of the cooking process was substantially similar in all the cases examined, except for the time needed to heat the different initial masses of cooking water used up to the boiling point. As WPR was reduced from 10 to 3 L kg^{-1}, such a time interval decreased from about 340 to 275 s. This reduction was, of course, proportional to the reduction in the mass of cooking water used, the energy efficiency of the induction hob being practically constant in both cases tested. The main results of all cooking tests were summarized in the Table 2.5.

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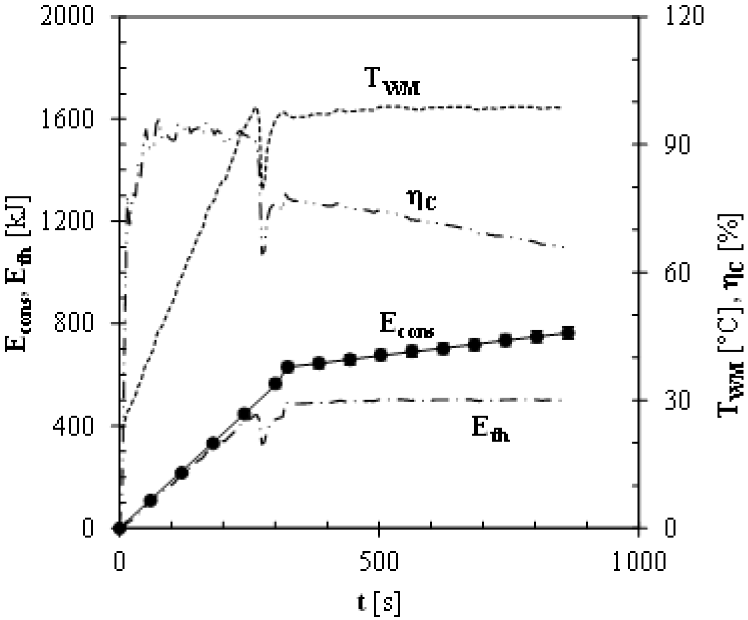
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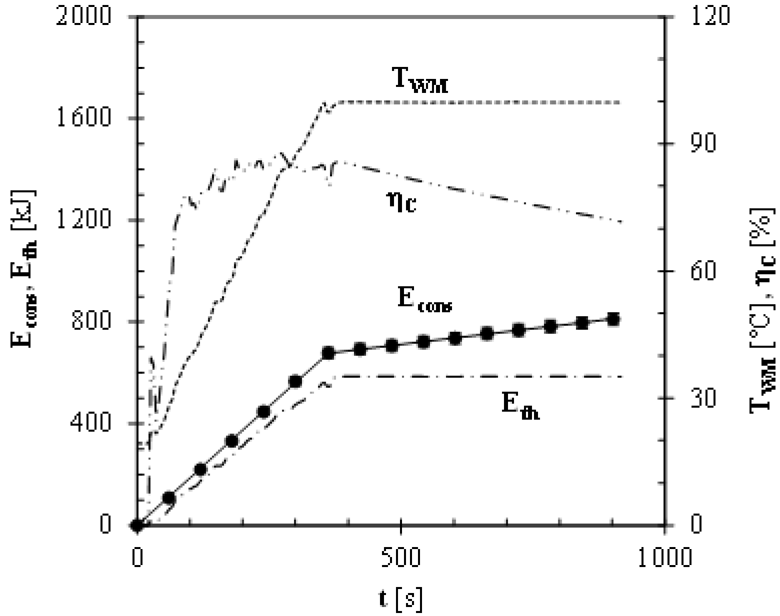
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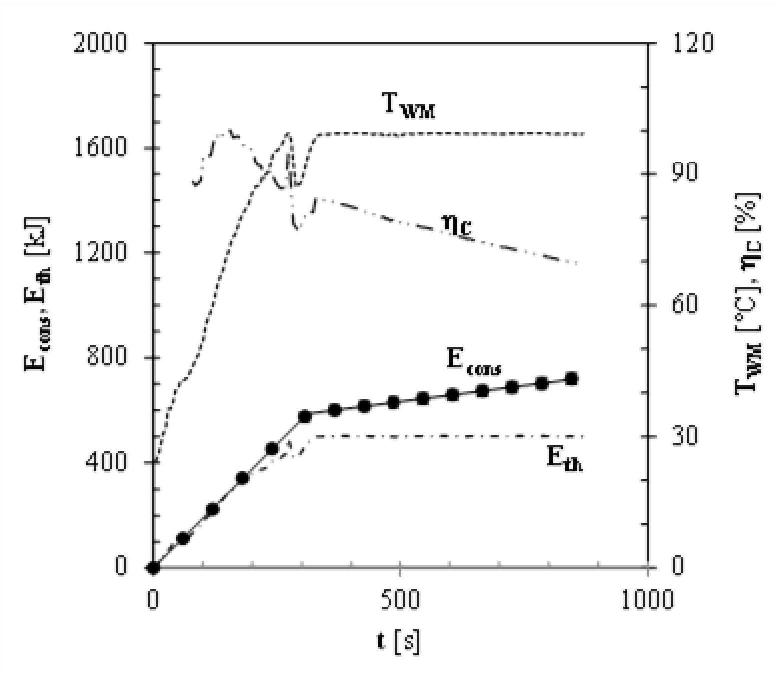

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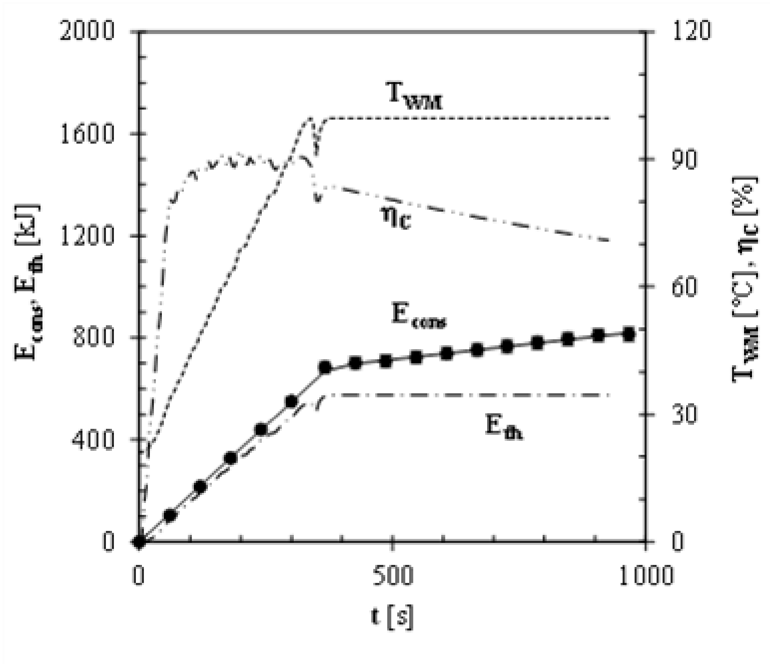

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η_C
E_{cons}
E_{th}

3a) **3b)**

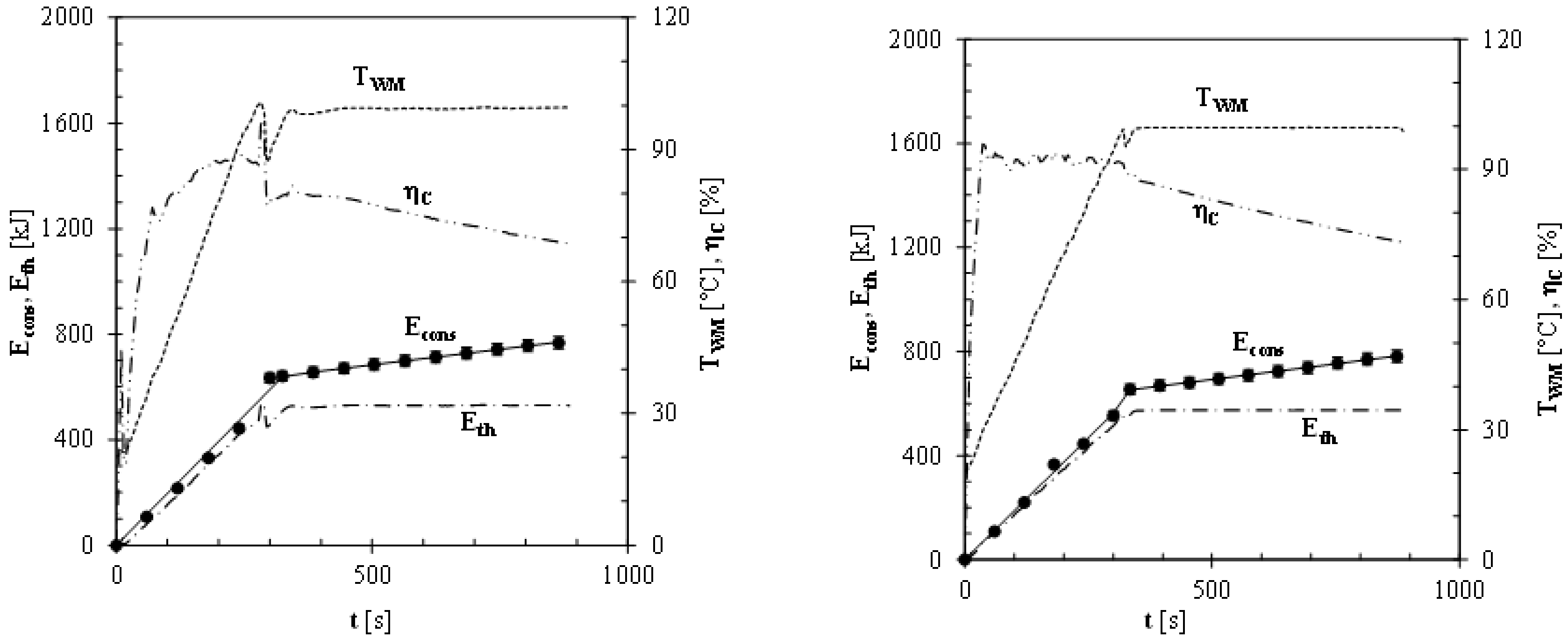


Figure 2.15 Effect of cooking time (t) on the cooking water temperature at mid-height (T_{WM}: **- - -**), energy theoretically (E_{th}: — . —) and effectively (E_{cons}: ——) consumed, and cooking energy efficiency (η_C: — · · —, — · · —) during cooking of the three spaghetti brands labelled **1**, **2,** or **3** with 3 (**a**) or 10 (**b**) L of water per kg of dried pasta, and the hob control knob set at the nominal power of 2 kW during the cooking water heating phase and at 0.4 kW during the pasta cooking one.

Table 2.5 Spaghetti cooking tests carried out under constant power supplied by the induction hob during water boiling (P_H) and spaghetti cooking (P_C) when using different amounts (m_{PA}) of three different amounts of spaghetti brands labelled Cuor Mediterraneo, Barilla, or Rummo and cooking water (m_{W0}): effect of the water-to-dried pasta ratio (WPR) on the mean value and standard deviation of several parameters characterizing the cooking pasta process, that is the overall energy consumed (E_{consT}), cooking energy efficiency (η_C); effective power supplied per unit mass of cooking water and dried pasta ($e_{C,e}$); energy consumed per unit mass of dried pasta (e_{PA}); percentage fractions of water evaporated (η_{WE}), adiabatically flashed before pasta addition (η_{WAF1}) and drainage (η_{WAF2}), absorbed by cooked pasta (η_{WPA}), and remaining after cooking (η_{Wf}); relative water uptake by cooked pasta (WU); cooking loss (CL); and main TA parameters (F_{30}, F_{90}, CPR, d_{CP}). All cooking tests were quadruplicated, while TA tests were repeated 20 times.

Spaghetti label / Parameter	Cuor Mediterraneo 1		Barilla 2		Rummo 3	
WPR [L/kg]	10.0±0.0	3.0±0.0	10.02±0.03	3.0±0.0	10.0±0.0	3.0±0.0
m_{W0} [g]	1477.5±0.3	1218.3±0.1	1477±5	1218.5±0.1	1477.4±0.2	1218.2±0.1
m_{PA} [g]	147.7±0.0	406.1±0.1	147.6±0.3	406±0	147.7±0.0	406.3±0.0
P_H [kW]	1.88±0.04 ^{a}	1.89±0.05 ^{a}	1.83±0.01 ^{a}	1.96±0.01 ^{b}	1.88±0.02 ^{a}	1.93±0.03 ^{a,b}
P_C [kW]	0.25±0.01 ^{a}	0.25±0.01 ^{a}	0.24±0.01 ^{a}	0.25±0.01 ^{a}	0.24±0.01 ^{a}	0.24±0.01 ^{a}
$E_{cons,T}$ [Wh]	218±9 ^{a}	214±2 ^{a,b}	225±3 ^{a}	222±2 ^{a}	220±3 ^{a}	212±3 ^{b}
η_C [%]	71±0 ^{a}	68±2 ^{b}	70±2 $^{a.b}$	65±1 ^{c}	72±1 ^{d}	68±0 ^{b}
$e_{C,e}$ [W/kg]	151±3 ^{a}	152±1 ^{a}	145±4 ^{a}	153±7 ^{a}	146±7 ^{a}	147±3 ^{a}
e_{PA} [Wh/g]	1.47±0.06 ^{a}	0.53±0.01 ^{b}	1.52±0.02 ^{a}	0.54±0.01 ^{b}	1.49±0.02 ^{a}	0.52±0.01 ^{b}
η_{WE} [%]	2.3±0.1 ^{a}	3.2±0.7 ^{b}	2.3±0.2 ^{a}	3.4±0.2 ^{b}	2.2±0.1 ^{a}	4.8±2.2 ^{a,b}
η_{WAF1} [%]	0.3±0.1 ^{a}	0.6±0.1 ^{b}	0.7±0.2 ^{b}	0.2±0.1 ^{a}	0.5±0.4 $^{a, b}$	0.6±0.7 $^{a, b}$
η_{WAF2} [%]	2.5±0.6 ^{a}	3.9±0.9 ^{b}	-0.1±0.3 ^{c}	3.0±0.7 ^{a,b}	2.2±0.9 ^{a}	2.3±1.4 ^{a,b}
η_{WPA} [%]	12.8±0.3 ^{a}	44.4±1.3 ^{d}	15.2±0.3 ^{b}	42.2±0.1 ^{e}	11.1±0.8 ^{c}	37.5±0.6 ^{f}
η_{Wf} [%]	82.2±0.6 ^{a}	47.9±1.6 ^{c}	81.8±0.5 ^{a}	51.1±0.5 ^{d}	84.0±0.2 ^{b}	54.8±1.2 ^{e}
WU [g/g]	2.96±0.03 ^{a}	1.95±0.04 ^{b}	1.53±0.03 ^{c}	1.27±0.00 ^{d}	2.80±0.08 ^{e}	1.74±0.02 ^{f}
CL [g/100 g]	4.2±0.3 ^{a}	3.6±0.1 ^{b}	4.2±0.1 ^{a}	3.5±0.1 ^{b}	4.5±0.1 ^{a}	4.4±0.1 ^{a}
F_{30} [N]	5.1±0.3 ^{a}	4.2±0.4 ^{b}	5.1±0.3 ^{a}	6.1±0.3 ^{b}	8.4±0.3 ^{a}	6.9±0.4 ^{b}
F_{90} [N]	12.0±0.5 ^{a}	11.0±0.6 ^{b}	13.2±0.6 ^{a}	13.0±0.4 ^{a}	16.4±0.6 ^{a}	15.4±0.5 ^{b}
CPR [-]	0.64±0.01 ^{a}	0.65±0.01 ^{b}	0.64±0.01 ^{a}	0.62±0.01 ^{b}	0.58±0.01 ^{a}	0.60±0.01 ^{b}
d_{CP}[mm]	2.56±0.02 ^{a}	2.44±0.03 ^{b}	2.65±0.03 ^{a}	2.70±0.03 ^{b}	2.86±0.02 ^{a}	2.79±0.02 ^{b}

- Different lowercase letters indicate statistically significant difference among the parameter means of the same spaghetti label cooked at different WPRs at the probability level of 0.05.

Energy-related parameters

Fig. 2.16 shows the effect of WPR on the parameters related to the energy aspects of the cooking process. Firstly, the effective electric energy supplied by the induction hob (E_{cons}) during both the cooking water heating and pasta cooking phases was linearly related to t using Eq. (2.13). All regressions were characterized by coefficients of determination (r^2) greater than 0.995. Moreover, the estimated slopes (α) represented the effective power supplied (P_H and P_C) during the above phases and their dispersion was measured by coefficients of variation ranging from 0.3 to 3%. Thus, the effective power supplied per unit mass of the water-pasta suspension undergoing cooking ($e_{C,e}$) was about constant (149±3 W kg^{-1}), as shown in Tab. 2.5. The overall cooking energy efficiency (η_C) was about constant (69±3 %) for both WPRs examined. On the contrary, the specific energy consumed per unit mass of dried pasta (e_{PA}) reduced from about 1.49±0.02 to 0.53±0.01 Wh g^{-1} as WPR was reduced from 10 to 3 L kg^{-1} of dried pasta.

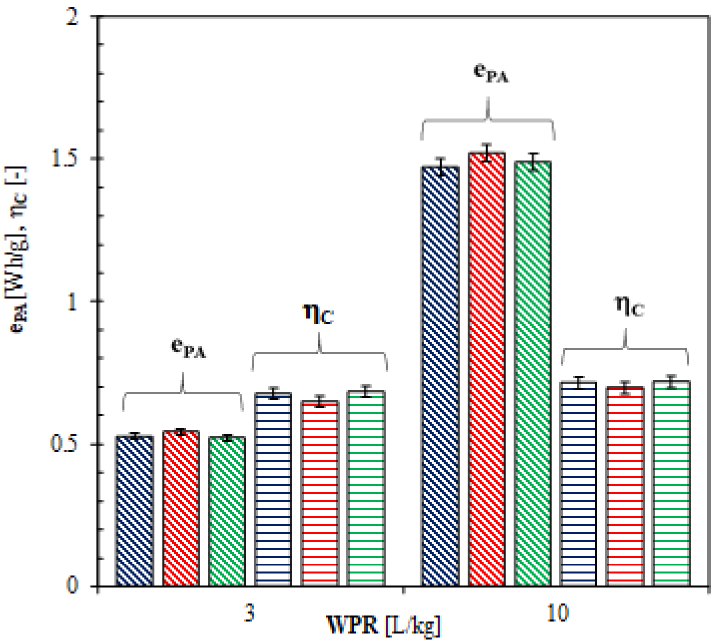


Figure 2.16 Effect of the cooking water-to-dried pasta ratio (WPR) on some energy-related and quality parameters characterizing the pasta cooking process of the three spaghetti brands labelled **1** (blue color), **2** (red color), or **3** (green color) under study: Specific energy consumed to cook dry pasta (e_{PA}: ▧), and dimensionless cooking energy efficiency (η_C: ▤) *versus* WPR.

Cooking water utilization

Fig 2.17 shows the percentage utilization of the water used to cook spaghetti at the two WPRs assayed. By reducing WPR from 10 to 3 L kg^{-1}, the fraction of water evaporated during the cooking process (η_{WE}) or adiabatically flashed (η_{WAF12}) anytime the pot was unlidded slightly increased from 2.3±0.1 to 3.8±0.9 %, or from 2±1 to 3.5±0.8 %, respectively. On the contrary, the fraction of cooking water absorbed by cooked pasta (η_{WPA}) was the 13±2 % of that initially added into the pot (m_{W0}) when dry pasta was cooked in a great excess of water (WPR=10 L kg^{-1}), but it approximately tripled to 41±4 % of m_{W0} for WPR=3 L kg^{-1}. Thus, even at such a low WPR the pasta cooking process appeared to have been performed with no shortage of water. In fact, after having recovered the cooked pasta with a colander, drained water, generally named as *pasta water*, declined from 83±1 to 51±3 % of m_{W0}, but not tended to zero.

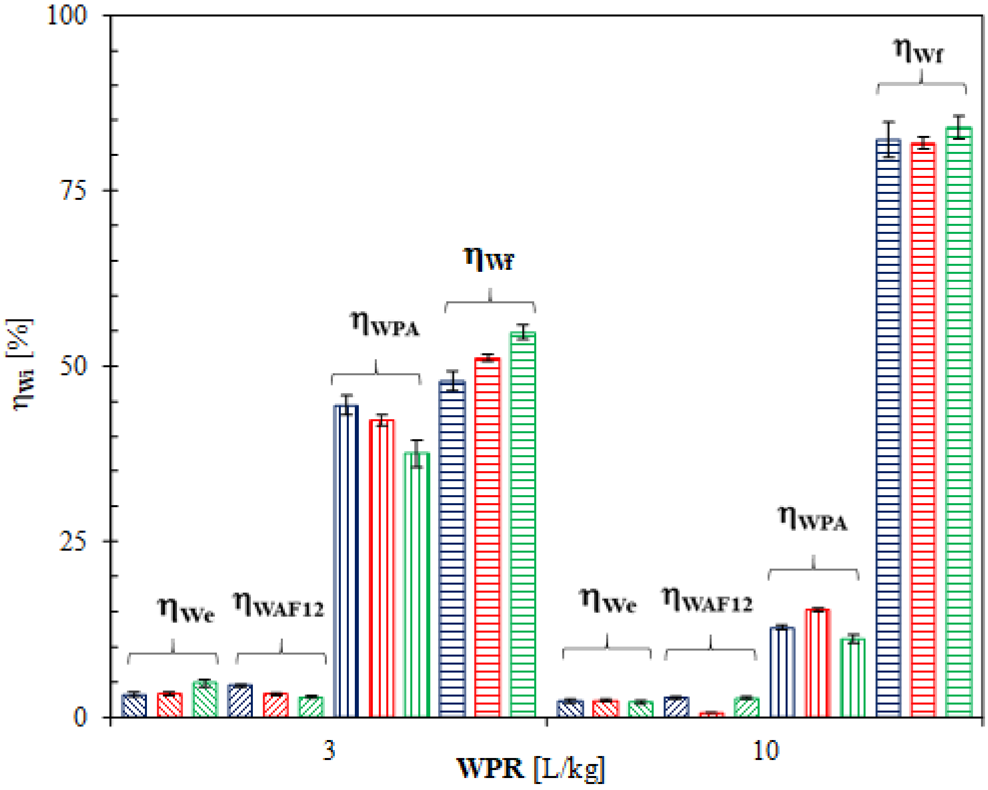


Figure 2.17 Percentages of water evaporated (η_{WE}:), released as vapor when the pot is unlidded firstly to add dried pasta and then to drain cooked pasta (η_{WAF12}:), adsorbed by cooked pasta (η_{WPA}:), and leftover upon pasta drainage (η_{Wf}:) against WPR. Same symbols as in Fig. 2.16.

Cooked spaghetti quality

Fig 2.18 shows the effect of WPR on cooked spaghetti quality. As WPR was reduced from 10 to 3 L kg^{-1}, the relative increase in cooked pasta mass as due to water absorption (WU) tended to reduce by about one third, except for spaghetti brand 2, its WU reducing by circa 17% (Tab. 2.5). Altogether, such a brand exhibited the lowest increase in cooked pasta mass. Since it was the most widespread pasta brand in the Italian supermarkets in 2017, its high production output was in all probability associated with a very high temperature drying process. Even the solid matter dissolved in the cooking water tended to decrease slightly with WPR.

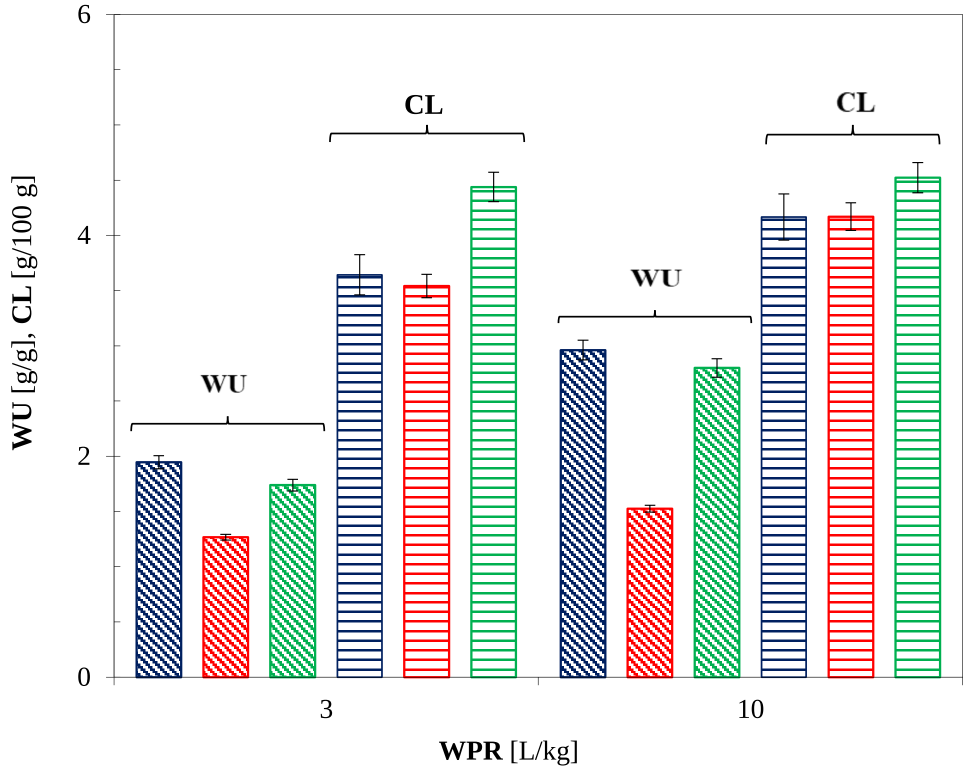


Figure 2.18 Relative increase in cooked pasta mass (WU: ▧), and cooking loss (CL: ☰) against WPR. Same symbols as in Fig. 2.16.

TA parameters of cooked spaghetti

The main results of the TA tests are shown in Fig. 2.19. Whatever the spaghetti brand tested, the three TPA parameters, as well as the diameter of cooked spaghetti (d_{CP}), tended to increase slightly with WPR, this increase being statistically significant at the probability level of 0.05 (Table 2.5). However, Fig. 2.19 clearly shows that for each spaghetti type examined the variability of TA parameters with WPR was of little entity.

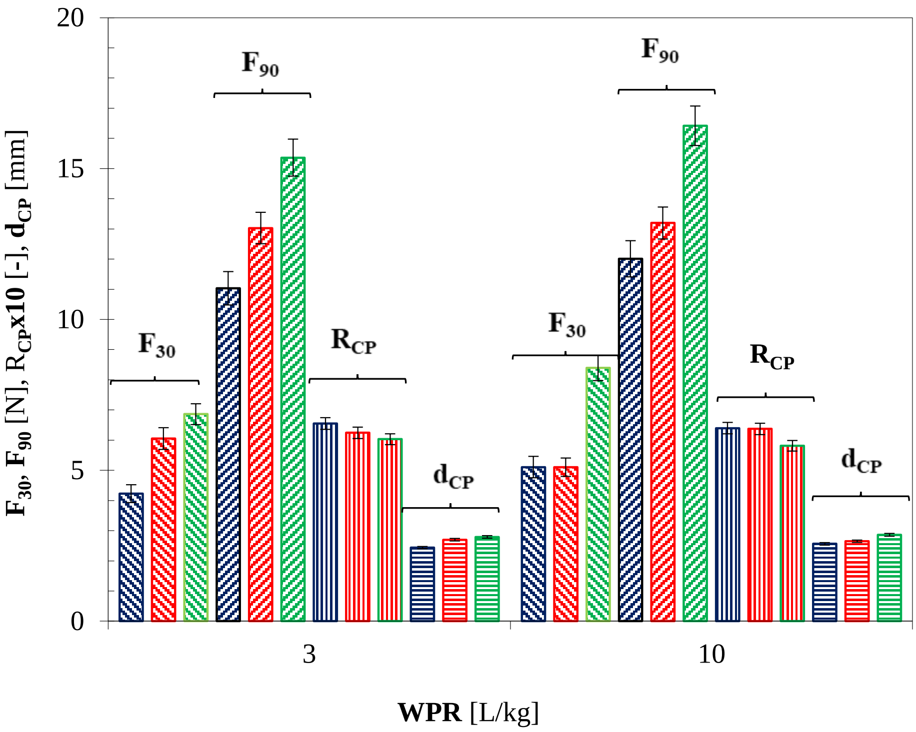


Figure 2.19 Cooked pasta hardness at 30% (F_{30}:) and 90% (F_{90}:) deformation, resilience (R_{CP} x10:), and diameter (d_{CP}:) *versus* WPR. Same symbols as in Fig. 2.16.

Sensory properties of cooked spaghetti

The difference in the three sensory attributes of the samples studied at the two WPRs tested was found to be statistically negligible at the 95% confidence level (Table 2.6). In particular, for spaghetti brand 1, 2, or 3, the resistance of cooked pasta to be chewed (Firmness) was regarded as quite sufficient, good, or excellent, whereas both the state of surface disintegration (Stickiness) and degree of adhesion (Bulkiness) of cooked spaghetti strands were considered as high, rare, or almost absent, respectively. Finally, their overall cooking quality was respectively retained as not completely satisfactory, fair, and excellent, being the average CQ score smaller than 50, and 70, but greater than 80 (Cubadda R *et al.*, 1988). Thus, the cooking quality of such spaghetti paralleled their corresponding TOM values (Table 2.1).

Table 2.6 Effect of water-to-dried pasta ratio (WPR) on the mean values and standard deviations of the sensory attributes of Firmness, Stickiness, Bulkiness, and Overall Cooking Quality, as evaluated by 6 trained judges, of the three cooked commercial spaghetti brands labelled Cuor Mediterraneo, Barilla, or Rummo. All sensory tests were repeated 18 times.

Parameter \ Spaghetti label	Cuor Mediterraneo		Barilla		Rummo	
WPR [L/kg]	10	3	10	3	10	3
Firmness [-]	56± 9 [a]	59±14 [a]	78± 6 [b]	78± 6 [b]	100± 0 [c]	94± 8 [c]
Stickiness [-]	57±11 [a]	54±12 [a]	61± 5 [b]	71±10 [b]	88± 4 [c]	84± 9 [c]
Bulkiness [-]	32±10 [a]	33±12 [a]	48± 9 [b]	52± 6 [b]	85± 3 [c]	66± 12 [c]
Overall Cooking Quality [-]	48±8 [a]	49±11 [a]	63±4 [b]	67±5 [b]	91±2 [c]	83±5 [c]

- Different lowercase letters indicate statistically significant difference among the parameter means of the spaghetti brands cooked at different WPRs at the probability level of 0.05

Analysis of variance for the instrumental and sensory properties of cooked spaghetti

To account for the different diameter (d_{RP}) and raw protein content (x_{PR}) of the spaghetti used (Table 2.1), all instrumental and sensory properties were submitted to analysis of variance, as shown in Table 2.7.

WU resulted to be firstly affected by x_{PR} ($p= 0.003$), then by WPR ($p=0.038$), and finally by d_{RP} ($p=0.091$). On the contrary, the solid matter dissolved in the cooking water was significantly influenced by all the aforementioned variables, even if the main effect of d_{RP} was greater than that of WPR, which was on turn about three times greater than that of x_{PR} (Table 2.7).

The observed reduction in CL was already detected as WPR was lessened from 30.8 to 8.3 L/kg (de la Peña *et al.*, 2014). The greater the amount of pasta in water, the greater the probability of spaghetti strands to attach longitudinally to each other becomes. As agglomerates of two-to-four spaghetti strands forms, the surface of pasta exposed to the water reduces, this limiting the rehydration kinetics, as well as the cooking loss into the cooking water. Nevertheless, for the sake of simplicity, an average cooking loss of 4.1±0.4 g per 100 g of dried pasta was accounted for.

Table 2.7 Analysis of variance for the relative water uptake by cooked pasta (WU), cooking loss (CL), main TA parameters (F_{30}, F_{90}, R_{CP}, d_{CP}) and sensory attributes (Firmness, Stickiness, Bulkiness, Overall Cooking Quality).

Parameter	Source	df	Mean-Square	F-ratio	p value
WU	d_{RP}	2	3.309	2.749	0.091
	x_{PR}	1	13.834	11.493	0.003
	WPR	1	6.009	4.993	0.038
	Error	18	1.204		
CL	d_{RP}	1	4.731	221.172	0.000
	x_{PR}	2	1.388	64.872	0.000
	WPR	1	4.284	200.253	0.000
	Error	61	0.021		
F_{30}	d_{RP}	18	0.480	1.247	0.244
	x_{PR}	7	1.972	5.124	0.000
	WPR	1	1.574	4.088	0.046
	Error	85	0.385		
F_{90}	d_{RP}	18	144.466	5.764	0.000
	x_{PR}	7	1640.067	65.438	0.000
	WPR	1	0.030	0.001	0.972
	Error	86	25.063		
R_{CP}	d_{RP}	18	0.375	5.987	0.000
	x_{PR}	7	3.319	52.963	0.000
	WPR	1	0.023	0.366	0.547
	Error	86	0.063		
d_{CP}	d_{RP}	18	6.206	5.880	0.000
	x_{PR}	7	61.803	58.554	0.000
	WPR	1	0.141	0.134	0.716
	Error	86	1.055		
Firmness	d_{RP}	18	2724.936	1.649	0.066
	x_{PR}	7	41307.809	24.996	0.000
	WPR	1	4335.473	2.624	0.109
	Error	86	1652.552		
Stickiness	d_{RP}	18	2114.381	1.655	0.064
	x_{PR}	7	33260.024	26.036	0.000
	WPR	1	1219.766	0.955	0.331
	Error	86	1277.468		
Bulkiness	d_{RP}	18	1044.653	0.982	0.488
	x_{PR}	7	18339.866	17.232	0.000
	WPR	1	4270.425	4.012	0.048
	Error	86	1064.303		
Overall Cooking Quality	d_{RP}	18	1837.951	1.321	0.195
	x_{PR}	7	29404.382	21.139	0.000
	WPR	1	3512.761	2.525	0.116
	Error	86	1391.033		

As concerning the TA parameters, the analysis of variance showed that cooked pasta hardness at 90% deformation (F_{90}), resilience (R_{CP}), and diameter (d_{CP}) were affected firstly by the protein content (x_{PR}) and then by the original diameter (d_{RP}) of the spaghetti brands examined, the effect of WPR being found statistically negligible (Table 2.7). Only in the case of F_{30}, the effect of WPR was found be more important than that of d_{RP} (Table 2.7). Such results confirmed that at both WPR levels tested there was no shortage of water at the spaghetti surface and thus no relevant effect on TA parameters. Moreover, as the protein content of raw pasta increased from 11.5 to 13.9 g/(100 g), the cooked pasta hardness at 90% deformation increased from about 11.5 to 16 N (Fig. 2.19 and Table 2.5).

As regarding the sensory attributes, the analysis of variance showed that all the attributes of Firmness, Stickiness, Bulkiness, and Overall Cooking Quality were mainly affected by the protein content (x_{PR}) of the spaghetti brands examined. The raw spaghetti diameter and WPR exerted the secondary and tertiary effects on Firmness and Stickiness, while they exhibited a reverted importance on Bulkiness and CQ.

Finally, as shown in Fig. 2.20, cooked pasta hardness at 90% deformation (F_{90}) was linearly related to the corresponding overall cooking quality (CQ):

$$CQ = (-47 \pm 12) + (8.4 \pm 0.9)\, F_{90} \qquad (r^2 = 0.96) \qquad (2.15)$$

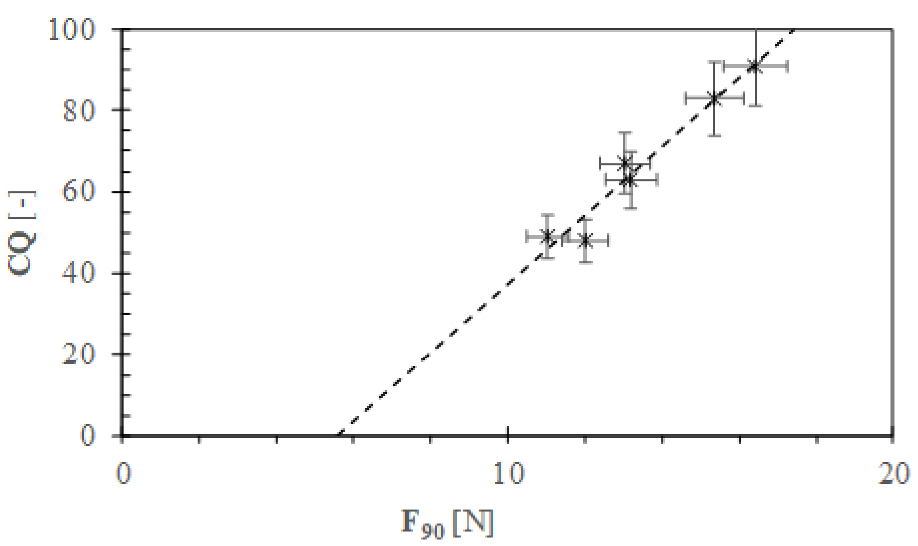


Figure 2.20 Overall cooking quality (CQ) of cooked commercial spaghetti *versus* the corresponding hardness at 90% deformation (F_{90}). Le broken line was plotted using Eq. (2.15). The horizontal and vertical bars refer to the average coefficients of variation of both data.

2.3.3 Effect of WPR on the cooking quality of three commercial short pasta brands

All pasta samples were dried at temperatures falling within the typical range (85-96 °C) used in the very-high-temperature pasta drying processes (Milatovich and Mondelli, 1990; Zweifel *et al*., 2003). They were extruded through the same bronze die, equipped with Teflon® inserts, and thus exhibited almost the same internal and external diameters, and length, these being approximately equal to 5.0, 8.9, and 36 mm, respectively. Their 100-piece weight was about 150 g for samples 1 and 3, and 158 g for sample 2 (Table 2.2).

The raw protein content was expressed as total nitrogen x 6.25, as reported in pasta labels (EU Regulation No. 1169/2011) and was found to vary from 108 to 131 g kg^{-1} The average moisture, raw protein, starch, fat and ash contents did not differ from those of typical durum wheat semolina dry pasta (Biernacka *et al*., 2018; Pasqualone *et al*., 2014; Piwińska *et al*., 2016).

The amount of total organic matter (TOM) leached after thorough rinsing of drained, cooked pasta was determined as an indirect measure of the sensory attributes of stickiness and overall cooking quality (Cubadda *et al.*, 2007, 2009). Since all TOM values shown in Table 2.2 were by far smaller than 14 g kg^{-1} (ICC Standard no. 153, 1995), all samples appeared to be of good quality. As the raw protein content increased from 108 to 131 g kg^{-1}, the time at which the central white core of a short strand of cooked pasta fully disappeared increased from 11.0 to 14.5 min (Table 2.2). Moreover, the short strands of pasta type 3 exhibited almost the same broken central white line after about 11 min whatever the cooking water-to-dried pasta ratio used (i.e., 10, 6 or 3 L kg^{-1}), as shown in Fig. 2.21.

The same optimal cooking time was assessed even for the short strands of the other pasta types examined (data not shown for the sake of simplicity). Thus, all pasta cooking tests lasted 11 min whatever the short pasta type and WPR used.

Figure 2.21 Pictures of a short strand of pasta type 3 as cooked using 1 kg of dried pasta in 10, 6 or 3 L of water for as long as 8, 9, 10, 11, 12 and 13 min, removed from the pan, cooled and cut at right angles with the cutter according to ISO (2016).

Table 2.6 Pasta cooking tests carried out with the induction hob set at the high or low power rating during water heating (P_H) or pasta cooking (P_C), respectively, and different amounts of three commercial short pasta brands (m_{PA}), labelled Donna Vera, Borges, or Baronia, and cooking water (m_{W0}): effect of the water-to-dried pasta ratio (WPR) on the mean value and standard deviation of the overall energy supplied (E_S), cooking energy efficiency (η_C); effective power supplied per unit mass of cooking water and dried pasta (e_{CE}); energy consumed per unit mass of dried pasta (e_{PA}); percentage fractions of water evaporated (η_{WE}), absorbed by cooked pasta (η_{WPA}), and remaining after cooking (η_{WF}); relative water uptake (WU); cooking loss (CL); and starch gelatinisation degree (SGD). All cooking tests were triplicated.

Pasta brand	**WPR**	**m_{W0}**	**m_{PA}**	**P_H**	**P_C**	**E_S**	**η_C**	**e_{CE}**	**e_{PA}**	**η_{WE}**	**η_{WPA}**	**η_{WF}**	**WU**	**CL**	**SGD**
-	[L kg^{-1}]	[g]	[g]	[kW]	[kW]	[Wh]	[%]	[W kg^{-1}]	[Wh g^{-1}]	[%]	[%]	[%]	[g g^{-1}]	[g kg^{-1}]	[%]
Donna Vera A	3.00 ±0.01	1218.5 ±0.2	406.4 ±0.7	1.85 ±0.02^{a}	0.25 ±0.01^{a}	211 ±16	62 ±5^{a}	152 ±8^{a}	0.52 ±0.04^{a}	6.2 ±0.9^{a}	34.5 ±0.4^{a}	59.3 ±0.8^{a}	1.03 ±0.01^{a}	39 ±1^{a}	8.3 ±0.4^{a}
	4.00 ±0.01	1299.7 ±0.1	324.1 ±0.1	1.86 ±0.01^{a}	0.23 ±0.01^{a}	207 ±3	64 ±3^{a}	143 ±1^{a}	0.64 ±0.01^{b}	5.5 ±0.3^{b}	25.6 ±0.1^{b}	69.0 ±0.2^{b}	1.03 ±0.01^{a}	38.7 ±0.9^{a}	9.2 ±2.1^{a}
	5.99 ±0.01	1393.3 ±0.1	232.8 ±0.4	1.85 ±0.02^{a}	0.25 ±0.01^{a}	229 ±1	68 ±2^{b}	151 ±2^{a}	0.99 ±0.01^{c}	4.6 ±0.5^{c}	17.5 ±0.2^{c}	77.9 ±0.4^{c}	1.05 ±0.01^{a}	40.5 ±0.4^{a}	8.3 ±0.1^{a}
	10.02 ±0.04	1477.2 ±0.2	147.4 ±0.5	1.85 ±0.01^{a}	0.25 ±0.01^{a}	231 ±11	67 ±2^{b}	151 ±2^{a}	1.57 ±0.07^{d}	4.4 ±0.3^{c}	10.5 ±0.1^{d}	85.1 ±0.1^{d}	1.05 ±0.01^{a}	40.9 ±0.4^{a}	7.3 ±0.2^{b}
Borges B	3.0 ±0.0	1218.5 ±0.3	406.1 ±0.2	1.88 ±0.02^{b}	0.24 ±0.01^{a}	226 ±4	66 ±2^{a}	150 ±1^{a}	0.56 ±0.01^{a}	6.0 ±0.8^{a}	33.8 ±0.7^{a}	60.2 ±0.6^{a}	1.01 ±0.02^{a}	33.8 ±0.6^{a}	7.7 ±0.4^{a}
	4.00 ±0.01	1299.3 ±0.2	324.6 ±0.1	1.86 ±0.02^{a}	0.23 ±0.01^{a}	206 ±2	67 ±1^{a}	144 ±1^{a}	0.63 ±0.01^{b}	5.6 ±0.6^{a}	24.7 ±0.2^{b}	69.7 ±0.3^{b}	0.99 ±0.01^{a}	35.8 ±0.4^{b}	7.8 ±0.7^{a}
	5.99 ±0.01	1391.9 ±0.8^{b}	232.5 ±0.2^{b}	1.85 ±0.01^{a}	0.25 ±0.01^{a}	230 ±1	67 ±1^{a}	152 ±2^{a}	0.99 ±0.01^{c}	4.8 ±0.5^{b}	17.0 ±0.1^{c}	78.2 ±0.2^{c}	1.02 ±0.01^{a}	36.2 ±0.5^{b}	7.9 ±0.1^{a}
	9.97 ±0.02	1477.1 ±0.1	148.2 ±0.3^{a}	1.82 ±0.11^{a}	0.24 ±0.01^{a}	204 ±28	68 ±1^{b}	151 ±2^{a}	1.37 ±0.19^{d}	4.3 ±0.03^{b}	10.3 ±0.1^{d}	85.4 ±0.4^{d}	1.02 ±0.01^{a}	37.0 ±1^{b}	7.6 ±0.4^{a}
Baronia C	3.0 ±0.0	1218.6 ±0.4	405.9 ±0.6	1.85 ±0.01^{a,b}	0.24 ±0.01^{a}	224 ±3	65 ±1^{a}	147 ±5^{a}	0.55 ±0.01^{a}	7.3 ±2.5^{a}	32 ±2^{a}	61 ±1^{a}	0.95 ±0.05^{a}	27 ±2^{a}	8.9 ±0.5^{a}
	4.00 ±0.01	1299.7 ±0.3	324.5 ±0.7	1.85 ±0.02^{a}	0.24 ±0.01^{a}	208 ±1	65 ±2^{a}	144 ±1^{a}	0.64 ±0.01^{b}	5.3 ±1.1^{b}	24.5 ±0.4^{b}	70.1 ±0.2^{b}	0.98 ±0.02^{a}	33 ±1^{b}	9.3 ±1^{b}
	6.00 ±0.01	1392.9 ±0.2	232.3 ±0.1	1.85 ±0.03^{a}	0.25 ±0.01^{a}	232 ±4	69 ±1^{b}	151 ±1^{a}	1.00 ±0.02^{c}	4.7 ±0.5^{b}	16.4 ±0.1^{c}	78.8 ±0.5^{c}	0.99 ±0.01^{a}	33.4 ±0.8^{b}	7.4 ±0.5^{b}
	10.0 ±0.1	1477.1 ±0.1	147.7 ±0.7	1.85 ±0.01^{a}	0.24 ±0.01^{a}	233 ±6	69 ±1^{b}	148 ±5^{a}	1.58 ±0.05^{d}	4.6 ±0.9^{b}	10.0 ±0.1^{d}	85.4 ±1.0^{d}	1.01 ±0.01^{a}	30.9 ±0.9^{b}	8.3 ±0.5^{a}

Different lowercase Latin letters indicate statistically significant difference among the parameter means of each short pasta brand cooked at different WPRs at the probability level of 0.05.

Electric energy requirements

All the energy-related parameters collected during the cooking tests are listed in Table 2.6.

The electric power supplied by the induction hob (E_S) was found to be a linear function of the cooking time (t), such a relationship being characterized by a coefficient of determination (r^2) greater than 0.99. The proportionality coefficient coincided with the power supplied during the water heating phase (P_H) or pasta cooking one (P_C). As shown in Fig. 2.21, P_H and P_C were approximately constant and equal to 1.85±0.02 or 0.24±0.01 kW, respectively. Moreover, the effective power supplied per unit mass of the water-pasta suspension undergoing cooking (e_{CE}) was nearly constant (149±3 W kg^{-1}) independently of WPR (Table 2.6).

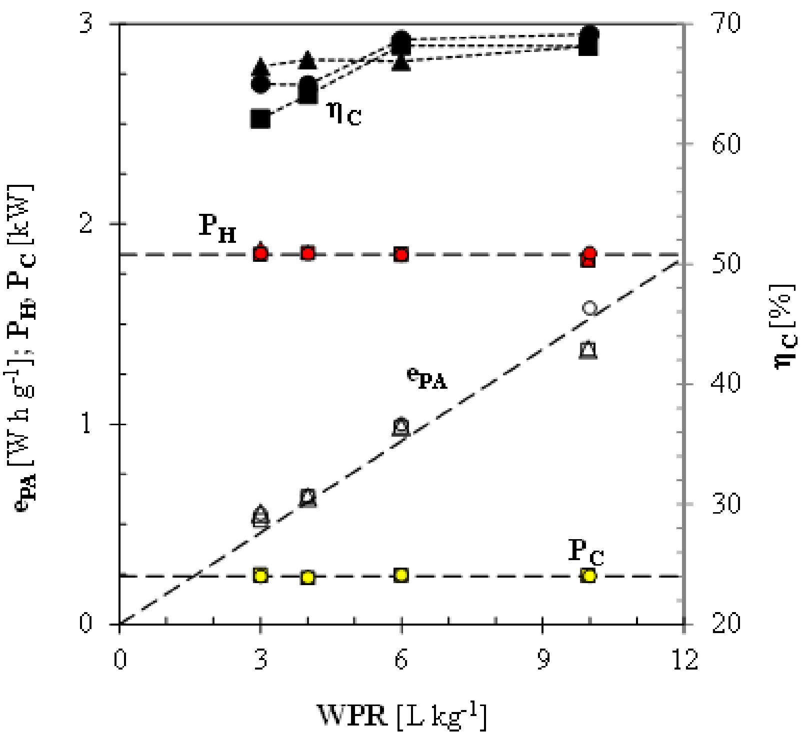


Figure 2.21 Cooking tests using the induction hob set at different power levels during the cooking water heating (P_H: yellow-filled symbols) and pasta cooking (P_C: red-filled symbols) phases with three short pasta brands labelled A (open or closed squares), B (open or closed triangles),and C (open or closed circles): Specific energy consumed to cook dry pasta (e_{PA}: open symbols) and cooking energy efficiency (η_C: closed symbols) *versus* the cooking water-to-dried pasta ratio (WPR). The inclined broken line was plotted using Eq. (11), while the horizontal broken ones represent the average values of P_C and P_H, respectively.

The specific energy consumed per unit mass of raw pasta (e_{PA}) linearly increased from about 0.52 to 1.58 Wh g^{-1} as WPR was increased from 3 to 10 L kg^{-1}. The broken line plotted in Fig. 2.21 represented the least squares regression:

$$e_{PA} = (0.153 \pm 0.004)\ WPR \qquad (r^2=0.992) \qquad (2.16)$$

To prevent short pasta strands from sticking one another, the stirrer was kept rotating at 50 rev min^{-1} for 30 s and resting for the aforementioned times at WPR<10 L kg^{-1}. In all cases, the electric power supplied was of the order of 6.1±0.5 W, as measured via the digital power meter. Thus, the overall mixing energy consumed throughout a cooking time of 11 min was estimated as equal to 0.28, 0.37 or 0.56 Wh for WPR=6, 4, or 3 L kg^{-1}, respectively. The specific stirring energy consumed to cook the different amounts of raw pasta increased from 1.2 to 1.4 Wh kg^{-1}. Thus, the energy needed to stir pasta during its cooking was insignificant with respect to that (e_{PA}) needed to cook it (Table 2.6).

Finally, the overall cooking energy efficiency (η_C) was about constant (67±2 %) whatever the WPR used and agreed with that previously observed when cooking another type of short pasta (i.e., helicoidal) with the same eco-sustainable procedure at WPR=12 L kg^{-1} (Cimini and Moresi, 2017).

Cooking water utilization

As WPR was reduced from 10 to 3 L kg^{-1}, the percentage of water evaporated during the cooking process (η_{WE}) tended to increase from 4.4±0.1 to 6.5±0.7 % of that initially added into the pot (m_{W0}), while that absorbed by cooked pasta (η_{WPA}) increase from 10.2±0.1 to 33±2 % (Fig. 2.22). Conversely, the fraction of *pasta water* (η_{WF}) reduced from 85.4±0.1 to 60.2±0.9 % of m_{W0}. Thus, even at WPR=3 L kg^{-1}, there was no shortage of water at the end of pasta cooking. By referring to commercial spaghetti cooking (§2.3.2), at WPR=3 L kg^{-1} the fraction of water absorbed by cooked spaghetti amounted to 41±4% of m_{W0}, probably because spaghetti exhibited a higher water uptake (i.e., 1.27-2.96 g g^{-1}) than the short pastas used here (see below).

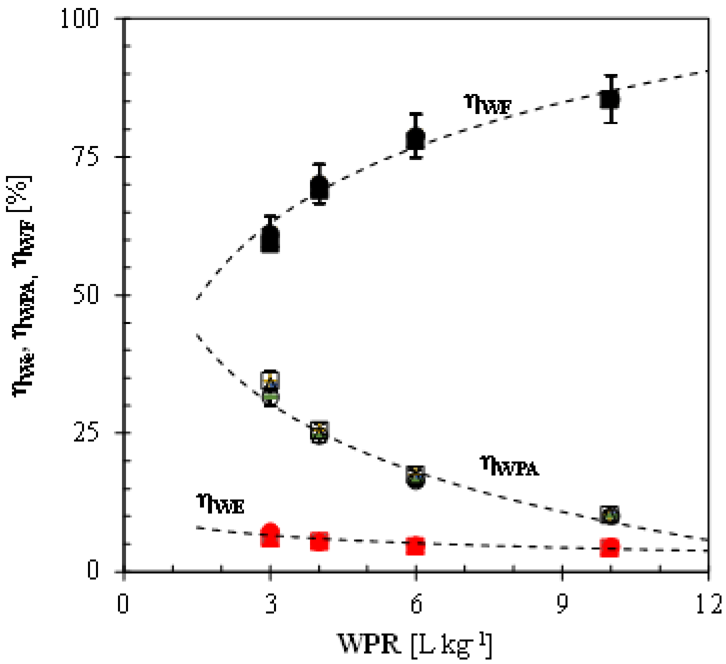


Figure 2.22 Cooking tests carried out with three short pasta brands labelled A (open or closed squares), B (open or closed triangles), and C (open or closed circles): Percentages of water evaporated (η_{WE}: red-filled symbols), adsorbed by cooked pasta (η_{WPA}: open symbols), and recovered as pasta water (η_{WF}: closed symbols) *vs*. WPR. The dashed lines represent the least squares regression lines for the three parameters examined.

Cooked short pasta quality

As concerning cooked pasta quality, Table 2.6 shows the mean values and standard deviations of all parameters determined. As shown in Fig. 2.23, the relative water uptake (WU), degree of starch gelatinization (SGD), and cooking loss (CL) as referred to cooked pasta appeared to be independent of WPR and pasta type, being equal to 1.03±0.01 g g^{-1}, 8.2±0.7 %, and 3.5±0.4 g kg^{-1}, respectively. The observed WU and CL values agreed with those ascertained in good quality pasta by other authors (Pasqualone et al., 2016).

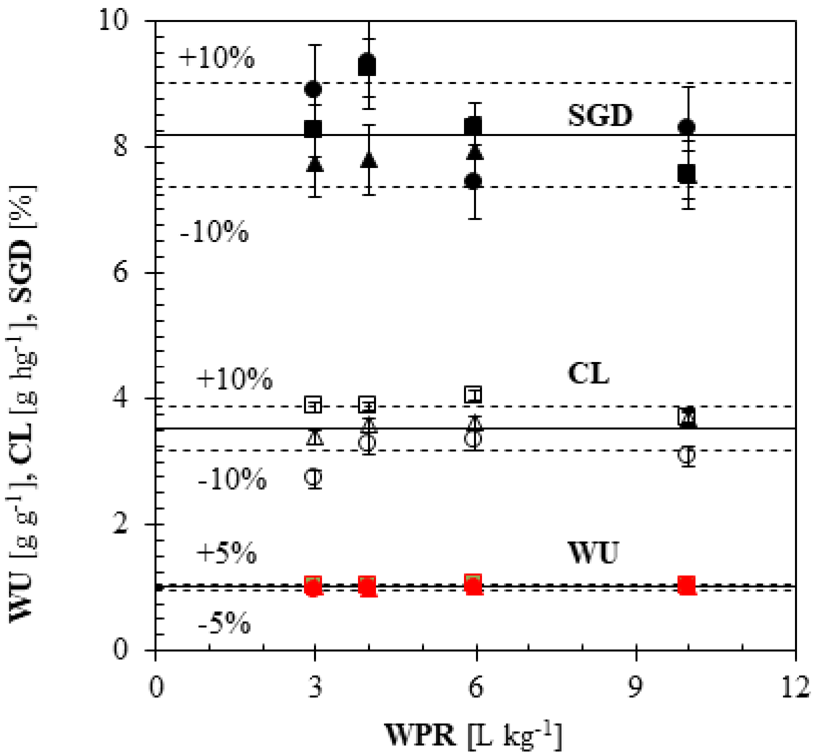


Figure 2.23 Cooking tests carried out with three short pasta brands labelled A (open or closed squares), B (open or closed triangles), and C (open or closed circles): Relative water uptake (WU: red-filled symbols), cooking loss (CL: open symbols), and degree of starch gelatinization (SGD: closed symbols) *vs*. WPR. The continuous lines refer to the mean values of WU, CL, and SGD, while the broken ones to the ±5 or 10% deviation bands

Table 2.7 Effect of water-to-dried pasta ratio (WPR) on the mean values and standard deviations of the main TA parameters (F_{40}, F_{98}, R_{CP}, s_{CP}) of three cooked commercial short pasta brands labelled Donna Vera, Borges, or Baronia. Each TA test was repeated n times.

Pasta brand	WPR	n	F_{40}	F_{98}	R_{CP}	s_{CP}
	[L/kg]		[N]	[N]	[-]	[mm]
Donna Vera	3	15	2.8±0.2 [a]	7.9±0.6 [a]	0.57±0.02 [a,]	2.08±0.06 [a]
	4	15	2.9±0.2 [a]	7.9±0.6 [a]	0.56±0.03 [a]	2.16±0.02 [b]
	6	15	2.9±0.2 [a]	8.8±0.4 [b]	0.58±0.03 [a,b]	2.09±0.05 [a]
	10	15	2.8±0.2 [a]	7.8±0.4 [a]	0.59±0.02 [b]	2.06±0.05 [a]
Borges	3	15	3.4±0.5 [a]	10.2±0.9 [a]	0.54±0.03 [a]	2.12±0.08 [a]
	4	15	3.0±0.8 [a]	9.2±0.7 [b]	0.56±0.04 [a]	2.29±0.05 [b]
	6	15	3.6±0.2 [a]	11.1±0.6 [c]	0.55±0.02 [a]	2.15±0.05 [a]
	10	15	2.8±0.6 [a,b]	8.9±1.6 [b]	0.56±0.04 [a]	2.14±0.04 [b]
Baronia	3	15	4.0±0.3 [a]	12±1 [a]	0.51±0.02 [a]	2.12±0.03 [a]
	4	13	3.7±0.2 [b]	11.3±1.3 [a]	0.53±0.03 [a]	2.32±0.04 [b]
	6	14	3.5±0.4 [b]	11.7±0.7 [a]	0.55±0.03 [b]	2.00±0.24 [a]
	10	28	3.8±0.5 [a,b]	11.3±1.4 [a]	0.51±0.03 [a]	2.19±0.06 [c]

Textural properties of cooked short pasta

Table 2.7 shows the main results of the TA tests.

Within the WPR values examined, all TA parameters, as well as the thickness (s_{CP}) of cooked pasta, exhibited a statistically insignificant variation at the probability level of 0.05 (Table 2.7). However, the cooked pasta hardness at 40 % (F_{40}) or 98 % (F_{98}) compression appeared to be a function of raw pasta formulation. In particular, F_{40} and F_{98} were correlated to the protein content of raw pasta (x_{PR}) by using the least squares method. Both parameters resulted to increase almost linearly with x_{PR}, as shown by the broken lines plotted in Fig. 2.23:

$$F_{40} = (-1.5\pm0.9) + (0.040\pm0.075)\, x_{PR} \qquad (r^2 = 0.76) \qquad (2.17)$$

$$F_{98} = (-8.1\pm0.9) + (0.151\pm0.019)\, x_{PR} \qquad (r^2 = 0.86) \qquad (2.18)$$

This paralleled the relationship between the protein content of raw pasta and cooked pasta firmness, previously established by Cubadda et al. (2007), as well as that relating the sensory attributes of Firmness, Stickiness, Bulkiness, and Overall Cooking Quality of cooked pasta to x_{PR} – see Eq. 2.15.

On the contrary, as shown by the continuous lines plotted in Fig. 2.23, the cooked pasta resilience (R_{CP}) and thickness (s_{CP}) appeared to be independent of x_{PR}, and equal to 0.55±0.02 and 2.14±0.09 mm, respectively.

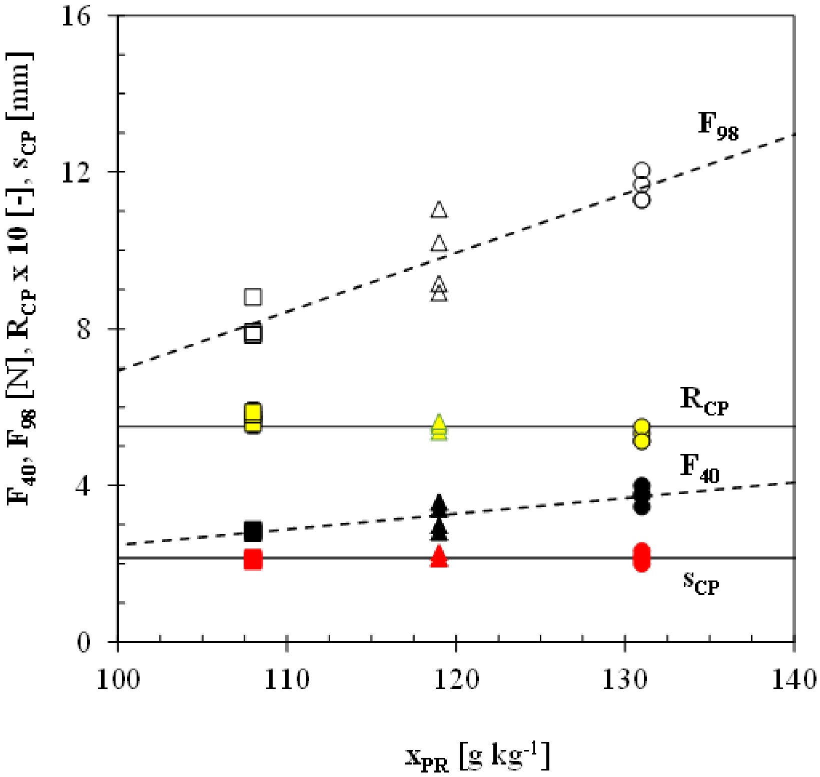


Figure 2.23 Texture Analysis tests carried out with three cooked short pasta brands labelled A (open or closed squares), B (open or closed triangles), and C (open or closed circles): Cooked pasta hardness at 40 % (F_{40}: closed symbols) and 98 % (F_{98}: open symbols) compression, resilience (R_{CP} x10: yellow-filled symbols), and thickness (s_{CP}: red-filled symbols) *vs.* protein content of raw pasta (x_{PR}). The broken lines were plotted using Eq. (6) and (7), while the continuous ones show the mean values of R_{CP}, and s_{CP}.

Carbon footprint of short pasta cooking

Since the carbon footprint of pasta cooking (CF_{PC}) is a linear function of e_{PA}, as shown by Eq.s (2.11) and (2.12), and, in turn, e_{PA} relies on WPR only, as shown by Eq. (2.16), CF_{PC} was predicted as follows:

$$CF_{PC} = (0.052 \pm 0.001)\ WPR \qquad (2.19)$$

By resorting to the eco-sustainable cooking procedure used here, it was possible to reduce CF_{PC} from 0.49±0.04 to 0.18±0.01 kg CO_{2e} kg^{-1} of raw pasta as WPR was lowered from 10 to 3 L kg^{-1}, respectively. The estimated CF_{PC} scores were definitively smaller than those associated to home pasta cooking using a conventional gas- or electric-fired stove (UNAFPA, 2018). More specifically, for WPR=3 L kg^{-1} the cradle-to grave carbon footprint of raw pasta might be practically halved from 3.03 (Barilla, 2017) to 1.51 kg CO_{2e} kg^{-1} and the overall GHG emissions associated with the current Italian consumption of dry pasta (~$1.4x10^6$ Mg/year) might be cut by as much as 2.1 Tg CO_{2e} yr^{-1}, thus approximately halving the climate change potential of dried pasta.

2.3.4 Empirical prediction of the minimum WPR

Theoretically, the minimum volume of water (V_W) to pour into a pan to cook as homogeneously as possible a given type of long or short pasta is related to the packing arrangement of the pasta strands and water uptake (WU) by cooked pasta. Moreover, V_W should also fill all the internal cavities (if present) of each pasta strand. Thus, V_W can be expressed as

$$V_W = n_p V_c + m_{PA} WU/\rho_W \quad (2.20)$$

with

$$m_{PA} = n_p m_p \quad (2.21)$$

where, n_p is the overall number of pasta pieces present in a given amount of raw pasta (m_{PA}), m_p the mass of a single pasta piece, V_c the overall volume of all internal cavities, and ρ_W the density of water. Thus, the minimum cooking water-to-dry pasta ratio (WPR_{min}) can be estimated as:

$$WPR_{min} = V_W/m_{PA} = \frac{V_c}{m_p} + \frac{WU}{\rho_W} \quad (2.22)$$

By referring to the internal diameter (d_i) and length (L_p) of each pasta piece of the three brands used here (Table 2.2), as well as the average specific water uptake (WU) (see Table 2.6), the estimated WPR_{min} ranged from 1.43 to 1.52 L kg^{-1}. By applying Eq. (2.22) to the aforementioned commercial spaghetti with a diameter and WU varying in the ranges of 1.9-2.0 mm, and 1.25-2.96 g g^{-1}, respectively, WPR_{min} fluctuated from about 1.25 to 3.0 L kg^{-1}.

In the circumstances, such a theoretical minimum amount of cooking water does not guarantee a uniform wetting of the external surface of all pasta pieces and, thus, does not avoid pasta sticking during cooking. To assure a good distribution of heat and water over the pasta surface, the external surface (S_p) of each pasta piece was assumed to be covered with a suitable layer (s_F) of water. Consequently, the minimum water volume increases to:

$$V_W^* = n_p\, S_p\, s_F + n_p\, V_c + m_{PA}\, WU/\rho_W \qquad (2.23)$$

and the effective minimum cooking water-to-dry pasta ratio (WPR^*) becomes

$$WPR^* = \frac{S_p\, s_F}{m_p} + \frac{V_c}{m_p} + \frac{WU}{\rho_W} \qquad (2.24)$$

Table 2.8 Schematic representation of the cross section of a pasta piece of the *penne rigate* type and its main geometric characteristics to be directly measured or calculated.

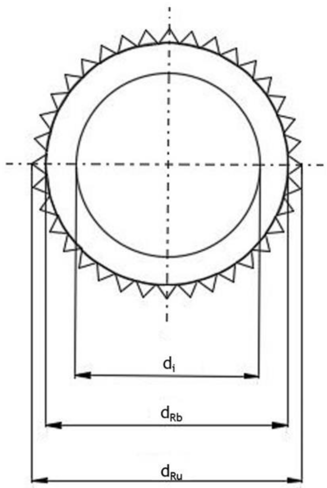
Cross section scheme	
Rib height	$h_R = t_{Ru} - t_{Rb} = d_{Ru} - d_{Rb}$
Number of ribs per piece	$n_R = \left\lvert \frac{\pi\, d_{Rb}}{h_R} \right\rvert$
Rib base	$b_R = \frac{\pi\, d_{Rb}}{n_R}$
Rib hypotenuse	$i_R = \sqrt{\left(\frac{b_R}{2}\right)^2 + h_R^2}$
External surface of each piece	$S_p = 2\, n_R i_R\, L_p + 2\, [\frac{\pi}{4}\, (d_{Rb}^2 - d_i^2) + n_R \frac{b_R h_R}{2}]$
Volume of cylinder cavity	$V_c = \frac{\pi}{4} d_i^2 L_p$

Table 2.8 shows a schematic diagram of the cross section of the pasta type examined in this work, as well as the relationships needed to estimate all the above geometric parameters. By accounting for the geometric characteristics of the three commercial short pastas used (Table 2.2), each pasta piece would have been uniformly covered with 1.51- or 1.58-mm thick layer of water if one kg of raw pasta was cooked with just 3 L of cooking water. In the case of the raw spaghetti 1.94 mm in diameter with WU=1.3±0.1 g g^{-1} as

§2.3.1), s_F would reduce to 1.15 or 0.47 mm if WPR was equal to 3 or 2 L kg^{-1}, respectively.

Whatever the raw short or long pasta type chosen of known geometric characteristics, Eq. (2.24) might, as a rule of thumb, be used to predict the minimum WPR value by assuming that a layer of water 1.0 mm in thickness was sufficient to avoid pasta adhesion during cooking in the presence of a proper agitation degree. It is worth noting that the pasta cooking system used here incorporated a stirrer and allowed to cook pasta in a pan covered by a lid in order to save water and energy, whereas pasta is usually cooked in an open pan (without lid) for allowing frequent manual stirring.

2.3.5 Performance of the eco-sustainable pasta cooker

To test the performance of the Arduino®-based pasta cooker, the short (i.e., *Cannerone*) and long (e.g., *Spaghetti alla chitarra*) pasta strands described in Table 2.3 were used. The former had a length of 18.2 mm with an equivalent external diameter of 11.7 mm and thickness of 1.5 mm, while the latter a length of 251 mm and a square cross-section of 2.02 mm. As shown in Table 2.3, their 100-piece weight ranged from circa 105 to 138 g, respectively.

When such pasta samples were cooked using the conventional WPR of 10 L kg^{-1}, the time at which the central white core of the pasta strands fully disappeared varied from 12 min (*Cannerone*) to 17 min (Sp*aghetti alla chitarra*). As shown in Table 2.3, the time at which the central white nerve appeared as broken (OCT) was shorter, and ranged from 11 min (*Cannerone*) to 15 min (*Spaghetti alla chitarra*).

By referring to the geometric characteristics, as well as the water uptake (WU), measured in an excess of water (WPR=10 L kg^{-1}), for both these pasta types, Eq. (2.24) allowed the prediction of two different WPR* values, namely 2.7 L kg^{-1} for *Cannerone* and 2.8 L kg^{-1} for *Spaghetti alla chitarra* (Table 2.3). Thus, a series of cooking tests of the both pasta types were performed at the conventional and minimum water-to-pasta ratios for as long as their corresponding optimal cooking time. The main results of all cooking tests were summarized in Tables 2.9 and 2.10.

Table 2.9 Pasta cooking tests carried out with the EPC at different power rating during water heating (P_H) or pasta cooking (P_C), respectively, using constant amounts (m_{PA}) of Canneroni (Ca) and Spaghetti alla Chitarra (SC), and cooking water (m_{W0}): effect of the water-to-dried pasta ratio (WPR) on the mean value and standard deviation of the water boiling time (t_H), rate of water heating $(dT/dt)_H$, overall cooking time (t_{CT}), energy consumed per unit mass of dried pasta (e_{PA}); cooking energy efficiency (η_C); percentage fractions of water absorbed by cooked pasta (η_{WPA}), evaporated (η_{WE}), and remaining after cooking (η_{WF}). All cooking tests were triplicated.

Pasta brand	WPR	m_{PA}	m_{W0}	t_H	P_H	$(dT_W/dt)_H$	P_C	t_{CT}	e_{PA}	η_C	η_{WPA}	η_{WE}	η_{PW}
	[L kg^{-1}]	[g]	[g]	[min]	[kW]	[°C/min]	[kW]	[min]	[Wh/g]	[%]	[%]	[%]	[%]
Ca	9.97±0.01	250.7±0.2	2500.3±0.1	9.3±0.3 ^{a}	1.90±0.01 ^{a}	7.9±0.2 ^{a}	0.19±0.06 ^{a}	20.3±0.3 ^{a}	1.31±0.05 ^{a}	72±3 ^{a}	9.5±0.1 ^{a}	1.6±0.5 ^{a}	89±1 ^{a}
	2.70±0.01	250.3±0.5	675.2±0.2	3.1±0.2 ^{b}	1.85±0.01 ^{b}	23.4±0.9 ^{b}	0.14±0.00 ^{a}	14.1±0.2 ^{b}	0.49±0.03 ^{b}	59±4 ^{b}	29.5±0.1 ^{b}	6.5±1.1 ^{b}	64±1 ^{b}
SC	9.99±0.01	250.4±0.1	2500.7±0.9	9.4±0.2 ^{a}	1.91±0.01 ^{a}	8.1±0.2 ^{a}	0.23±0.04 ^{a}	24.4±0.2 ^{a}	1.43±0.00 ^{a}	66±1 ^{a}	13.4±0.0 ^{a}	2.1±0.1 ^{a}	85±1 ^{a}
	2.79±0.00	250.9±0.3	700.9±0.0	3.8±0.4 ^{b}	1.84±0.06 ^{a}	22.4±0.2 ^{b}	0.19±0.07 ^{a}	18.8±0.4 ^{b}	0.66±0.09 ^{b}	45±6 ^{b}	46.8±2.5 ^{b}	9.8±0.6 ^{b}	43±31 ^{b}

- Different lowercase Latin letters indicate statistically significant difference among the parameter means of each pasta brand cooked at the nominal and minimum WPRs at the probability level of 0.05.

Table 2.10 Effect of water-to-dried pasta ratio (WPR) on the mean values and standard deviations of the relative water uptake (WU), cooking loss (CL), main TA parameters (F_{30}, F_{90}, R_{CP}, s_{CP}), and carbon footprint of the cooking phase (CF_{PC}) of Canneroni (Ca) and Spaghetti alla Chitarra (SC). Each TA test was repeated 15 times.

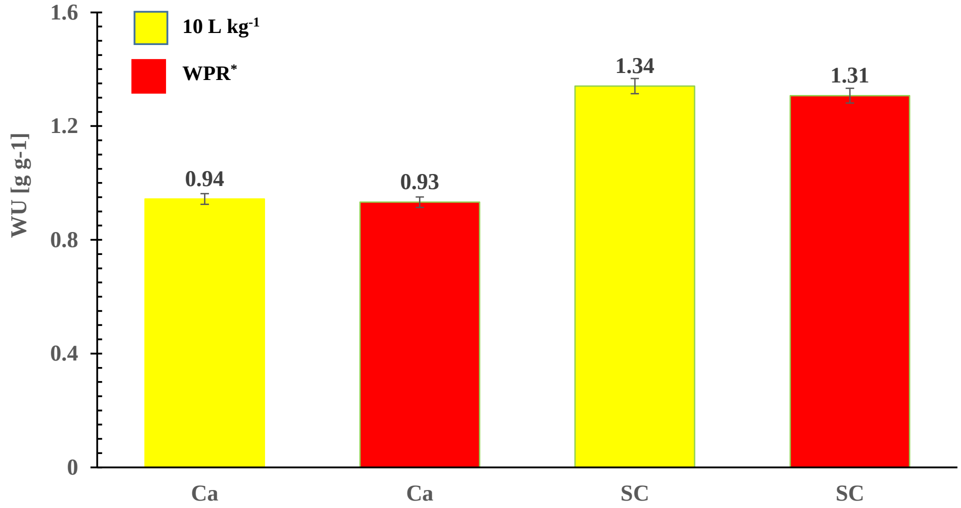
Pasta brand	WPR	WU	CL	F_{30}	F_{90}	R_{CP}	s_{CP}	CF_{PC}
	[L kg^{-1}]	[g g^{-1}]	[g g^{-1}]	[N]	[N]	[-]	[mm]	[kg CO_{2e} kg^{-1}]
Ca	9.97±0.01	0.94±0.01 ^{a}	0.040±0.007 ^{a}	2.8±0.0 ^{a}	9.5±0.4 ^{a}	0.62±0.00 ^{a}	2.08±0.04 ^{a}	0.417±0.005 ^{a}
	2.70±0.01	0.93±0.00 ^{a}	0.032±0.000 ^{b}	2.8±0.1 ^{a}	9.8±0.3 ^{a}	0.62±0.00 ^{a}	2.13±0.03 ^{a}	0.195±0.015 ^{b}
SC	9.99±0.01	1.34±0.00 ^{a}	0.056±0.000 ^{a}	8.3±0.1 ^{a}	14.8±0.4 ^{a}	0.53±0.01 ^{a}	3.16±0.02 ^{a}	0.467±0.000 ^{a}
	2.79±0.00	1.31±0.07 ^{a}	0.036±0.007 ^{b}	7.8±0.2 ^{b}	15.2±0.1 ^{a}	0.55±0.02 ^{a}	3.09±0.04 ^{a}	0.216±0.028 ^{b}

- Different lowercase Latin letters indicate statistically significant difference among the parameter means of each pasta brand cooked at the nominal and minimum WPRs at the probability level of 0.05.

Cooked pasta quality

Fig. 2.24a shows that the relative water uptake (WU) of both cooked pasta types appeared to be independent of WPR at the probability level (p) of 0.05. In particular, WU ranged from 0.93 to 1.34 g g^{-1}, these values being in line with those typical of good quality pasta (Pasqualone et al., 2016). On the contrary, Fig. 2.24b shows that the cooking loss (CL) decreased from 0.050±0.007 to 0.032±0.006 g g^{-1}as WPR was reduced from 10 L kg^{-1} to WPR^*. In fact, the smaller the amount of cooking water the smaller the loss of solid matter dissolved in the cooking water became.

a)



b)

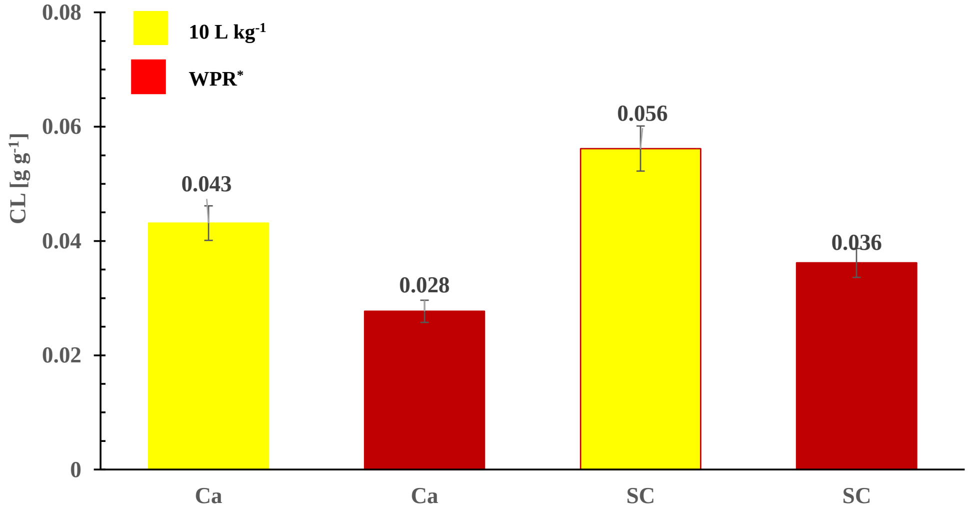


Figure 2.24 Relative water uptake (WU: **a**) and cooking loss (CL: **b**) regarding the short (Ca) and long (SC) pasta brands as cooked with the EPC using the standard (10 L kg^{-1}) and minimum (WPR^*) water-to-pasta ratios.

Textural properties of cooked pasta

Fig. 2.25 shows that the TA parameters (F_{30}, F_{90}) of both cooked pasta brands exhibited a statistically insignificant variation at the probability level of 0.05 within the range of WPR values examined. Thus, the results shown in Table 2.10 did not reveal any difference in their textural properties (F_{30}, F_{90}, s_{CP}), as cooked in the EPC at the conventional or minimum water-to-pasta ratios.

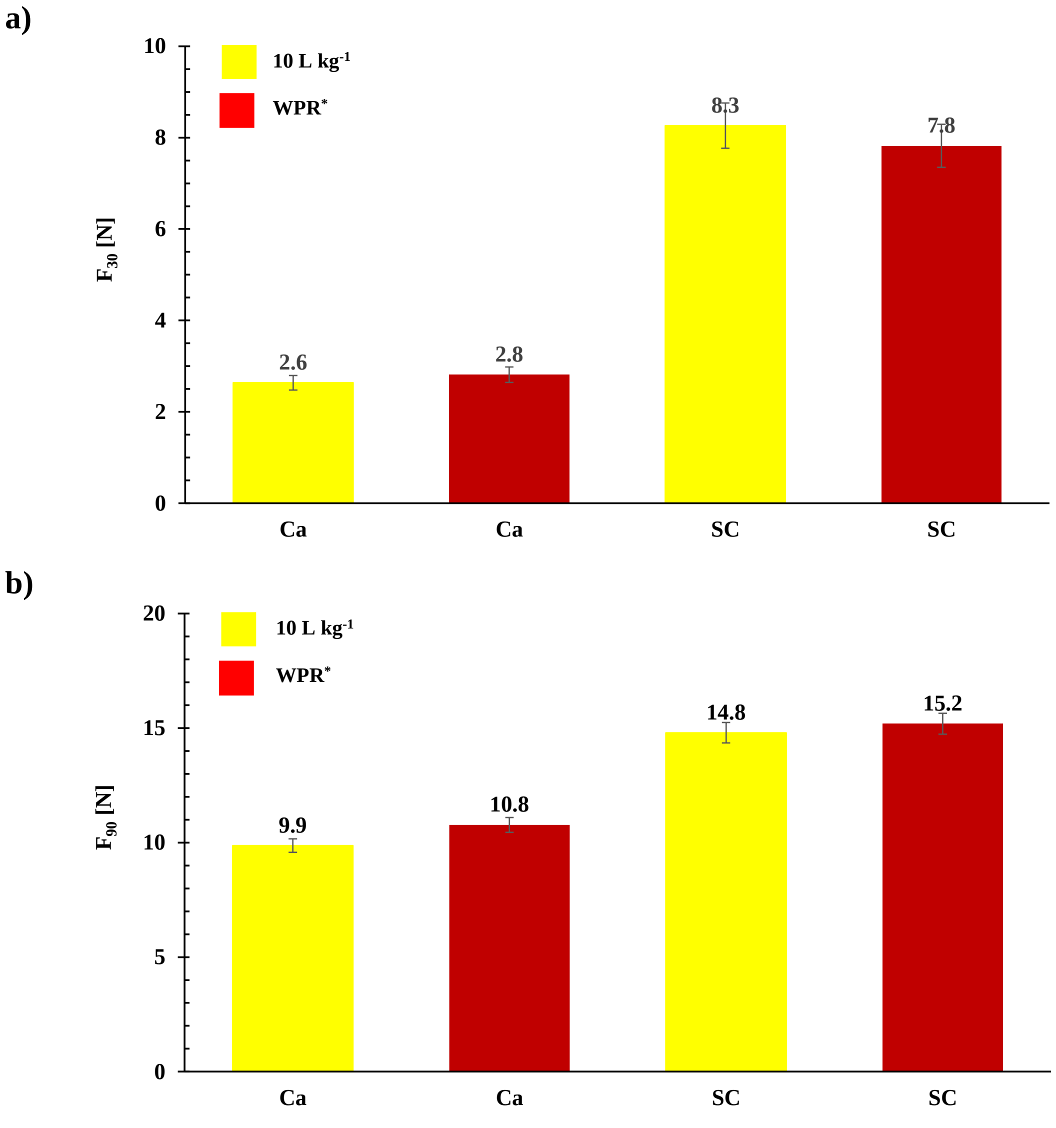


Figure 2.25 Texture Analysis tests carried out with short (*Ca*) and long (*SC*) pasta brands as cooked with the EPC using the standard (10 L kg^{-1}) and minimum (WPR*) water-to-pasta ratios: Cooked pasta hardness at 30 % (F_{30}: **a**) and 90 % (F_{90}: **b**).

Electric energy requirements and cooking water use

The electric energy supplied (E_S) during either the water heating or pasta cooking phase was quite a linear function of the cooking time (t), the corresponding coefficient of determination (r^2) being greater than 0.99. Thus, the power delivered during the water heat phase was approximately constant and equal to 1.88±0.04 kW, while that provided throughout the pasta cooking phase ranged from 0.14 to 0.23 kW with an average value of 0.19±0.04 kW (Table 2.9). Thus, whatever the pasta type used the time needed to make the cooking water boil was equal to 9.2±0.2 min when using 10 L of water to cook 1 kg of dry pasta, but it shortened to 3.1 or 3.8 min when WPR was lowered to 2.7 or 2.8 L kg^{-1} (Table 2.9). In other words, the induction hob provided a constant heating rate of 8.0±01 °C min^{-1} for WPR=10 L kg^{-1}, that increased to ~24 °C min^{-1} when using the WPR^* values given in Table 2.3. Such a greater heating rate made the overall cooking time reduce by about 25% with respect to the default condition (WPR=10 L kg^{-1})m, as shown in Table 2.9.

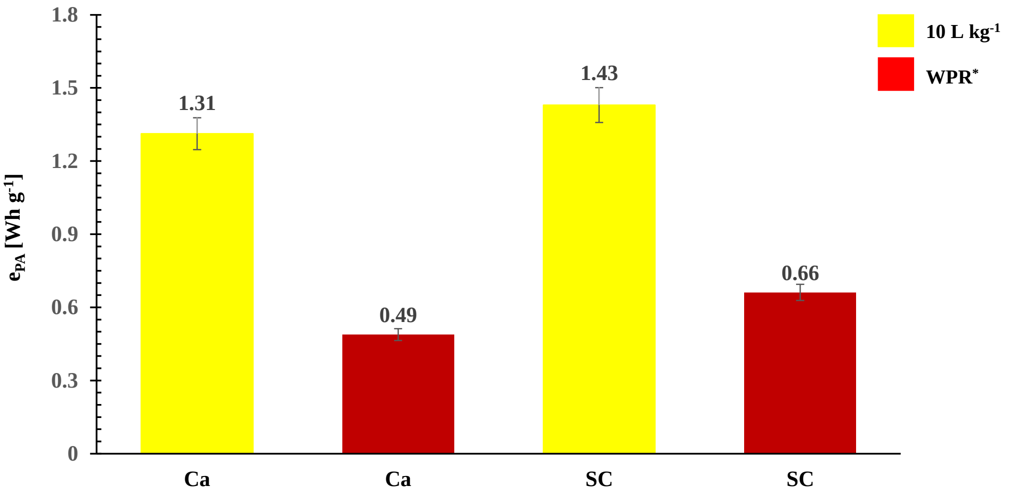


Figure 2.26 Specific energy consumed (e_{PA}) to cook short (Ca) and long (SC) pasta brands with the EPC using the standard (10 L kg^{-1}) and minimum (WPR^*) water-to-pasta ratios.

Fig. 2.26 shows that the specific energy consumed to cook 1 kg of raw pasta (e_{PA}) increased from 0.49 to 1.43 W h g^{-1} as WPR was augmented from 2.7-2.8 to 10 L kg^{-1}. The overall cooking energy efficiency (η_C) of the EPC was about 70 % at WPR of 10 L kg^{-1}, but it reduced to as low as 45 % at WPR^* in consequence of the greater fraction (η_{WE}) of water evaporated (Table 2.9). In details, the percentage of water absorbed by cooked pasta (η_{WPA}) was within 10 and 13 % of the water initially added into the pot

(m_{W0}) at the conventional WPR, but increased to 30-47 % at WPR* (Table 2.9). This made the fraction of pasta water (η_{WF}) reduce from 85-89 % to about 50 % of m_{W0} (Table 2.9). Thus, in all cases tested there was no shortage of cooking water.

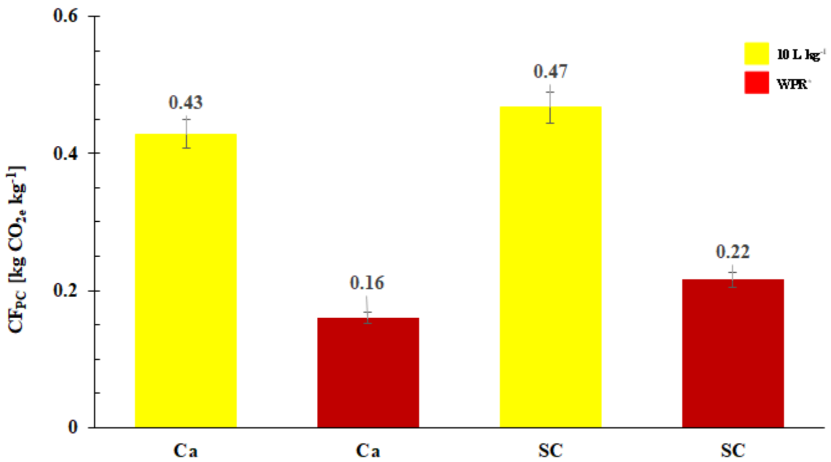


Figure 2.27 Carbon footprint (C_{PC}) to cook short (Ca) and long (SC) pasta brands with the EPC using the standard (10 L kg^{-1}) and minimum (WPR*) water-to-pasta ratios.

Carbon footprint of pasta cooking

By using Eq.s (2.11) and (2.12), the carbon footprint of pasta cooking (CF_{PC}) was estimated, as shown in Table 2.10 and Fig. 2.27.

At WPR of 10 L kg^{-1}, CF_{PC} was 0.42-0.47 kg CO_{2e} kg^{-1}, this being by far smaller than that (1.7 kg CO_{2e} kg^{-1}) generally associated to home pasta cooking using typical electric-fired hobs (UNAFPA, 2018). Only by using the novel EPC developed here with the minimum cooking water-to-pasta ratio estimated via Eq. (2.24), CF_{PC} reduced by about 50% (Table 2.10). If the safety water layer *a priori* assumed as sufficient to avoid pasta adhesion during cooking was halved from 1.0 to 0.5 mm, the minimum water-to-pasta ratio reduced by about 15 or 25 % in the case of the short or long pasta types used, respectively. Under these conditions, CF_{PC} would reduce by 6 to 11 %. Of course, this would hold provided that such variations in WPR* had no effect on the optimal cooking time and, what more important, on the cooking quality of each pasta type examined. In the circumstances, the reduction in the carbon footprint of home pasta cooking CF_{PC} obtained so far was regarded as rather significant with respect to the current impact. Thus, no supplementary cooking tests were carried out to corroborate further the rule of thumb assuming that 1.0-mm layer of water avoided any significant agglomeration of the pasta undergoing cooking with the agitation level ensured by the EPC.

2.4 CONCLUSIONS

Pasta cooking is quite a high resource and energy-intensive process. It is generally carried out in a great excess of boiling water to enhance dry pasta rehydration since this process is mainly controlled by water migration.

The several cooking tests using either long or short pasta strands were performed using the minimum energy consumption cooking procedure developed by Cimini and Moresi (2017). The cooking system was a commercial home induction hob equipped with a S-shaped stirrer to avoid pasta adhering during its cooking, especially when using cooking water-to-pasta ratios lower than the conventional value of 10 L kg^{-1}.

It was assessed that the main chemico-physical properties (i.e., specific water uptake, starch gelatinization degree, and hardness), as well as sensory ones (e.g., Firmness, Stickiness, and Bulkiness), of cooked pasta were practically independent of WPR in the range of 3-10 L kg^{-1}, even if in the case of spaghetti this was true till as low as 2 L kg^{-1}. This was empirically confirmed by developing an empirical relationship capable of estimating the minimum WPR as a function of the surface-to-volume ratio and specific water uptake of the pasta type undergoing cooking.

Finally, an Arduino®-based eco-sustainable pasta cooker EPC, driven by an application installed on a smartphone, was developed and tested with different pasta types, this confirming the possibility of cooking dry pasta with far smaller amounts of water and energy than those used in the most common kitchen appliances. The use of low-cost, credit card–sized, open-source electronics platforms is expected to result in a new generation of kitchen appliances capable of mitigating the carbon footprint of food cooking.

The impact of such a novel pasta cooker on the environmental profile of dry pasta will be evaluated in Chapter 3.

CHAPTER 3

Assessment and mitigation of the cradle-to-grave carbon footprint and environmental profile of dry pasta

3.1 INTRODUCTION

A great number of Environmental Product Declarations for dried pasta are nowadays available, as shown in Table 3.1. It can be noted quite large intervals of variation in the estimated business-to business (B2B) scores of the main four environmental impact categories. In particular, the impact categories of “climate change” (CC), “acidification” (A), “eutrophication” (NP), and “photochemical ozone creation potential” (POCP) varied from 0.57 to 1.72 kg CO_{2e}, from 4.4 to 31.3 g SO_{2e}, from 2.2 to 9.4 g PO_{4e}^{-3}, and from 0.1 to 0.9 g C_2H_{2e} per kg of dry pasta. Durum wheat cultivation, being mainly affected by the manufacture of fertilizers and pesticides, as well as fuel consumption, was the primary hotspot for such impact categories, its contribution ranging from 40 to 64 % for CC, from 62 to 92 % for A, from 80 to 97 % for NP, and from 9 to 71% for POCP. By referring just to the life cycle impacts of dry pasta, packed in 0.5 kg polypropylene (PP) bags and distributed in Italy, as normalized with respect to those of the most widespread pasta brand (i.e., Barilla) in the Italian supermarkets in 2018 (Anon, 2018), the normalized values of CC, A, NP, and POCP differed from 0.9 to 1.6, from 0.8 to 2.7, from 0.5 to 1.2, and from 0.8 to 4.3, respectively, as shown in Fig. 3.1. In all probability, such a great variation in the B2B scores might be associated with several factors, such as the databases used, agricultural techniques, processing conditions and distribution logistics. Hence, a product life cycle environmental performance might be trustfully assessed using not only the specific category rules for dry pasta nowadays available (EPD®, 2016; UNAFPA, 2018), but also more reliable databases, as specifically observed by the food and drink companies involved in several PEF pilot tests (FoodDrinkEurope, 2017),

Thus, the business-to-consumer life-cycle assessment (LCA) model of the industrial production and distribution of an organic dry durum wheat semolina pasta in 0.5-kg PP bags, as detailed in Chp. 1, was developed in the well known LCA software (SimaPro 9.0.0.41: PRé Consultants, Amersfoort, NL). The environmental profile of dry pasta was assessed using either a single- or a multi-environmental issue Life Cycle Impact Assessment method, each one being included in a recent review by Jungbluth (2019) and embedded in the aforementioned software. In particular, the Product carbon footprint was estimated in conjunction with the 5th Assessment Report by IPCC (Myhre et al., 2013), while the IMPACT 2002+ (Jolliet et al., 2003) methodology, as updated by Quantis v.

Q2.21 (Humbert et al. 2014), was selected for it is a comprehensive and valid impact assessment method yielding environmental indicators at the midpoint and endpoint level. Such a method is often used in LCA studies, as in the case of the environmental assessment of durum-wheat bread (Ingrao et al., 2018) and different coffee alternatives (Humbert et al., 2009).

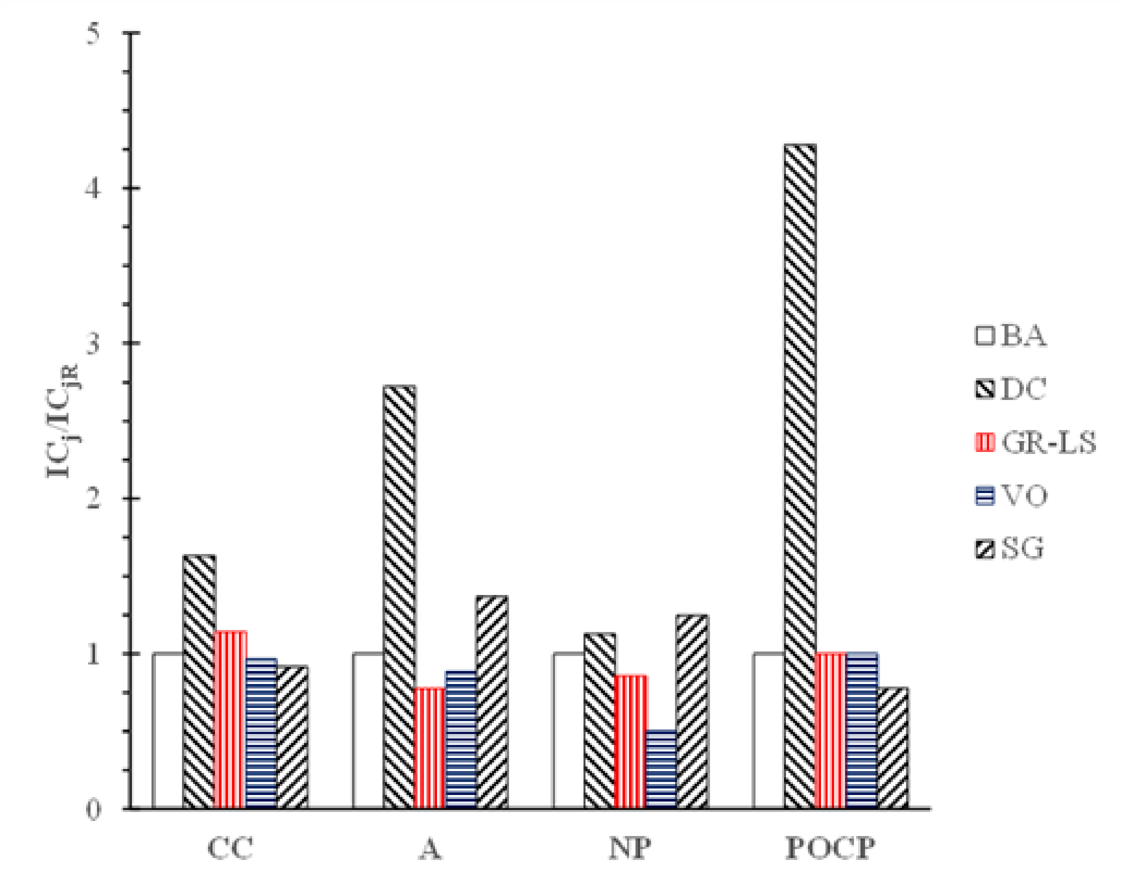


Figure 3.1 Business-to-business life cycle environmental impacts (CC: climate change; A: acidification; NP: eutrophication; POCP, photochemical ozone creation potential) of some Italian brands of dry pasta (BA: Barilla; DC: De Cecco; GR: Granarolo; SG, Sgambaro; VO: Voiello), packed in 0.5 kg PP bags and distributed in Italy, as normalized with respect to those of the most widespread pasta brand (BA) in the Italian supermarkets in 2018.

Table 3.1 Contribution of the different life cycle phases (i.e, FI, Field phase; MI, Milling; PMP, Packaging Material Production; PPP, Pasta Production and Packaging; PDISTR, Transportation; EoLPM, Packaging end of life) to the main environmental impact categories, namely "climate change" (CC), "acidification"(A), "eutrophication" (NP), and "photochemical ozone creation pontential" (POCP), from cradle-to-distribution centers of a functional unit (1 kg) of dried long (LP) and short (SP) pasta differently packed (5PEB, 5-kg catering PE bags; 0.5PAB, 0.5-kg paperboard boxes; 0.5PPB or 1-lbPPB, 0.5-kg or 1-lb PP bags), as extracted from several EPD® studies.

Manufacturer	**Pasta type**	**Pack format**	**Production/DCs**	**Impact Category**	**Life cycle stage**							**Ref.s**
					FI	**MI**	**PMP**	**PPP**	**PDISTR**	**EoLPM**	**Total**	
Barilla	LP	5PEB	Italy/Italy	CC [g CO_{2e} kg^{-1}]	557	51	61	198	31	-	898	Barilla (2013)
				A [g SO_{4e} kg^{-1}]	2.72	0.17	0.17	1.17	0.17	-	4.4	
				NP [g PO_{4e}^{-}kg^{-1}]	4.60	0.05	0.08	0.04	0.04	-	4.81	
				POCP [g C_2H_{2e} kg^{-1}]	0.34	0.03	0.03	0.06	0.02	-	0.48	
	LP&SP	0.5PAB	USA/USA	CC [g CO_{2e} kg^{-1}]	610	205	62	262	152	40	1331	Barilla (2017)
				A [g SO_{4e} kg^{-1}]	9.9	1.41	0.55	1.14	0.94	0.01	13.95	
				NP [g PO_{4e}^{-}kg^{-1}]	7.3	0.2	0.08	0.07	0.17	0.02	7.84	
				POCP [g C_2H_{2e} kg^{-1}]	0.03	0.08	0.06	0.08	0.06	0.01	0.32	
	LP&SP	0.5PAB	Italy/Italy	CC [g CO_{2e} kg^{-1}]	564	48	21	198	65	17	913	Barilla (2017)
				A [g SO_{4e} kg^{-1}]	9.22	0.22	0.39	0.23	0.37	<0.01	10.43	
				NP [g PO_{4e}^{-}kg^{-1}]	6.37	0.03	0.09	0.03	0.07	0.01	6.6	
				POCP [g C_2H_{2e} kg^{-1}]	0.06	0.02	0.04	0.04	0.02	<0.01	0.18	
CANE	LP	1-lbPPB	Italy/USA	CC [g CO_{2e} kg^{-1}]	767	44	114	308	176	<1	1409	CANE (2017)
				A [g SO_{4e} kg^{-1}]	18.2	0.19	0.59	0.92	2.58	<0.001	22.47	
				NP [g PO_{4e}^{-}kg^{-1}]	7.94	0.02	0.11	0.11	0.26	<0.001	8.44	
				POCP [g C_2H_{2e} kg^{-1}]	0.22	<0.01	0.05	0.05	0.08	<0.001	0.40	
	SP	1-lbPPB	Italy/USA	CC [g CO_{2e} kg^{-1}]	767	44	410	312	189	0.12	1722	
				A [g SO_{4e} kg^{-1}]	18.20	0.19	1.59	0.94	2.77	<0.001	23.69	
				NP [g PO_{4e}^{-}kg^{-1}]	7.94	0.02	0.16	0.11	0.28	<0.001	8.51	
				POCP [g C_2H_{2e} kg^{-1}]	0.22	<0.01	0.09	0.05	0.09	<0.001	0.45	
De Cecco	LP&SP	0.5PPB	Italy/Italy	CC [g CO_{2e} kg^{-1}]	775	270	76	294	62	13	1490	De Cecco (2017)
				A [g SO_{4e} kg^{-1}]	22.70	4.12	0.28	0.96	0.34	<0.01	28.40	
				NP [g PO_{4e}^{-}kg^{-1}]	6.32	0.59	0.15	0.25	0.10	0.03	7.44	
				POCP [g C_2H_{2e} kg^{-1}]	0.38	0.25	0.03	0.07	0.04	<.01	0.77	

De Cecco	LP&SP	0.5PPB	Italy/USA	CC [g CO_{2e} kg^{-1}]	775	270	101	294	164	11	1615	De Cecco (2017)
De Cecco				A [g SO_{4e} kg^{-1}]	22.70	4.12	0.47	0.96	3.00	0.01	31.26	
De Cecco				NP [g $PO_{4e}^{-}kg^{-1}$]	6.32	0.59	0.26	0.25	0.41	0.11	7.94	
De Cecco				POCP [g C_2H_{2e} kg^{-1}]	0.38	0.25	0.04	0.07	0.18	<0.01	0.92	
Granarolo[1]	SP	5PEB	Italy/Italy	CC [g CO_{2e} kg^{-1}]	618	35	21	815	17	20	1526	Granarolo (2017)
Granarolo[1]				A [g SO_{4e} kg^{-1}]	7.01	0.13	0.06	2.60	0.08	<0.01	9.88	
Granarolo[1]				NP [g $PO_{4e}^{-}kg^{-1}$]	5.51	0.01	0.01	0.30	0.01	<0.01	5.84	
Granarolo[1]				POCP [g C_2H_{2e} kg^{-1}]	0.08	0.01	0.03	0.18	0.01	<0.01	0.31	
Granarolo[2]	SP	5PEB	Italy/Italy	CC [g CO_{2e} kg^{-1}]	618	35	20	338	12	19	1042	Granarolo (2017)
Granarolo[2]				A [g SO_{4e} kg^{-1}]	7.01	0.13	0.06	0.83	0.06	<0.01	8.09	
Granarolo[2]				NP [g $PO_{4e}^{-}kg^{-1}$]	5.51	0.01	0.01	0.12	0.01	<0.01	5.66	
Granarolo[2]				POCP [g C_2H_{2e} kg^{-1}]	0.08	0.01	0.02	0.07	<0.01	<0.01	0.18	
Misko	PL	0.5PPB	Greece/Greece	CC [g CO_{2e} kg^{-1}]	762	97	<1	360	31	<1	1250	Misko (2017)
Misko				A [g SO_{4e} kg^{-1}]	11.88	0.61	0.11	1.56	0.14	<0.01	14.3	
Misko				NP [g $PO_{4e}^{-}kg^{-1}$]	8.98	0.1	0.03	0.28	0.03	<0.01	9.42	
Misko				POCP [g C_2H_{2e} kg^{-1}]	0.09	0.03	0.02	0.09	0.01	<0.01	0.24	
Sgambaro	LP&SP	5PEB	Italy/Italy	CC [g CO_{2e} kg^{-1}]	259	103	30	142	33	-	567	Sgambaro (2018b)
Sgambaro				A [g SO_{4e} kg^{-1}]	4.98	0.71	0.13	0.37	0.15	<0.01	6.34	
Sgambaro				NP [g $PO_{4e}^{-}kg^{-1}$]	2.4	0.20	0	0.01	0	<0.01	2.61	
Sgambaro				POCP [g C_2H_{2e} kg^{-1}]	0.07	0.02	0.01	0.03	0.01	<0.01	0.14	
Sgambaro	LP&SP	0.5PPB	Italy/Italy	CC [g CO_{2e} kg^{-1}]	539	41	90	142	26	-	838	Sgambaro (2018a)
Sgambaro				A [g SO_{4e} kg^{-1}]	13.10	0.30	0.35	0.37	0.16	<0.01	14.28	
Sgambaro				NP [g $PO_{4e}^{-}kg^{-1}$]	7.90	0.06	0.16	0.07	0.03	<0.01	8.22	
Sgambaro				POCP [g C_2H_{2e} kg^{-1}]	0.07	0.01	0.02	0.03	0.01	<0.01	0.14	
Voiello	SP	0.5PPB	Italy/Italy	CC [g CO_{2e} kg^{-1}]	503	58	18	241	54	7	881	Voiello (2017)
Voiello				A [g SO_{4e} kg^{-1}]	8.03	0.35	0.28	0.25	0.32	<0.01	9.23	
Voiello				NP [g $PO_{4e}^{-}kg^{-1}$]	3.12	0.06	0.05	0.03	0.06	<0.01	3.32	
Voiello				POCP [g C_2H_{2e} kg^{-1}]	0.06	0.02	0.03	0.05	0.02	<0.01	0.18	

[1] Pasta production line capacity of 135 kg h^{-1};
[2] Pasta production line capacity of 850 kg h^{-1}.

3.2 Methodology

The life-cycle analysis (LCA) was performed in compliance with the specific International Standards (ISO, 2006a, b), and included the following stages: Goal and scope definition, inventory analysis, impact assessment, and interpretation of results.

3.2.1 Goal and scope definition

The goal for this study was to develop an LCA model to assess the cradle-to-grave carbon footprint and environmental profile of organic dried durum wheat semolina pasta, produced from the same medium-sized pasta factory mentioned in Chp. 1, as well as to identify its life-cycle hotspots.

The *functional unit* was assumed as 1 kg of organic dried durum wheat semolina pasta packed in 0.5-kg PP bags, while the system boundary comprised the upstream (from cradle to gate), core (from gate to distribution centers, DCE), and downstream (from DCE to grave) processes, as shown in Fig. 1.1.

The reference time period, process technology, primary data, management of solid processing residues and post-consumer packaging material wastes, and allocation criteria were the same accounted for in Chp. 1. Secondary data were sourced from more updated databases (such as Agri-footprint v. 4.0, Ecoinvent v.3.5), all embedded in the software SimaPro 9.0.0.41, using the methods developed by IPCC (Myhre et al., 2013) or Jolliet et al. (2003).

3.2.2 Inventory analysis

The resource and energy inputs and yield outputs for organic dry pasta production reported in Chp. 1 were used to identify five different product stages, namely processes, assembly, reuse, end of life scenarios, and life cycles, and create the dry pasta network using the software SimaPro 9.0.0.41, as shown in Fig. 3.2. Moreover, the parallel life cycles of the primary, secondary, and tertiary packaging materials, and tertiary package (i.e., pallet) were included in order to account for their end of life scenarios. These product stages are summarized in Table 3.2, each one being described in the Appendix (see Tables A.1-A.23).

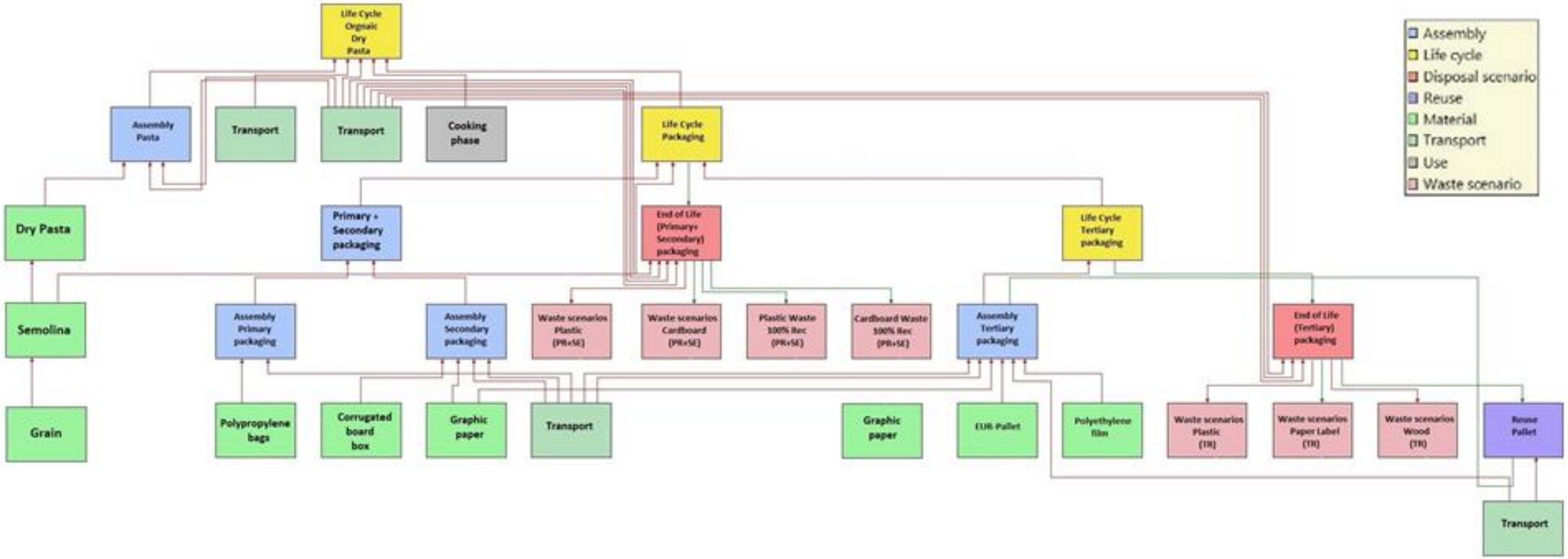


Figure 3.2 Product stages of the dry pasta network developed using the software SimaPro 9.0.0.41, as detailed in Table 3.2.

Table 3.2 Description of the product stages involved in the dried pasta life cycle network according to the Simapro software.

Product stage	Name	Main output	Unit	Table
Process	Durum wheat cultivation	Grain	kg	Table A.1
Process	Durum wheat milling	Semolina	kg	Table A.2
Process	Dry pasta production	Dry pasta	kg	Table A.3
Process	PP bag production	PP bags	kg	Table A.4
Assembly	Assembly of the primary packaging	Ass 1pack	p	Table A.5
Assembly	Assembly of the secondary packaging	Ass 2pack	p	Table A.6
Assembly	Assembly of the tertiary packaging	Ass 3pack	p	Table A.7
Assembly	Assembly of the primary and secondary packaging materials	Ass 1+2pack	p	Table A.8
Assembly	Assembly of dry pasta	Ass pasta	p	Table A.9
Processes	Consumer use phase	Cooked pasta	kg	Table A.10
Disposal scenario	Disposal scenario of plastic of primary and secondary packaging wastes	PW-DS (PR+SE)	kg	Table A.11
Disposal scenario	Disposal scenario of plastic of primary and secondary packaging wastes (100% Recycling)	PW-DS-(100% Rec)	kg	Table A.12
Disposal scenario	Disposal scenario of cardboard and paper of primary and secondary packaging wastes	CPW-DS (PR+SE)	kg	Table A.13
Disposal scenario	Disposal scenario of cardboard and paper of primary and secondary packaging wastes (100% Recycling)	CPW-DS-(100% Rec)	kg	Table A.14
End of life scenario	End of life scenario of the primary and secondary packaging material wastes	EoL-1+2pack	-	Table A.15
Disposal scenario	Disposal scenario of wooden pallet wastes	PAW-DS (TR)	kg	Table A.16
Disposal scenario	Disposal scenario of cardboard and paper of tertiary packaging wastes	CPW-DS (TR)	kg	Table A.17
Disposal scenario	Disposal scenario of plastic of tertiary packaging wastes	PW-DS (TR)	kg	Table A.18
End of life scenario	End of life of the tertiary packaging wastes	EoL-3pack	-	Table A.19
Reuse	Reuse of the wooden pallet	Pallet reuse	p	Table A.20
Life cycle	Life cycle of dry pasta	LC-DP	p	Table A.21
Life cycle	Life cycle of the primary, secondary and tertiary packaging materials	LC1-3pack	p	Table A.22
Life cycle	Life cycle of the tertiary packaging	LC-3pack	p	Table A.23

3.2.3 Impact assessment

The impact assessment was carried out in compliance with IPCC (Myhre et al., 2013) or IMPACT 2002$^+$ v. 2.15 (Jolliet et al., 2003) standard methods embedded in the professional tool SimaPro 9.0.0.41 (PRé Consultants, Amersfoort, NL).

Any generic impact category (IC_j) was estimated by summing up the release to air, water or soil (Ψ_i, expressed in mass, energy, mass-km basis) associated to the system boundaries times its corresponding characterization factor ($F_{i,j}$) as:

$$IC_j = \sum_i (\Psi_{i,j}\ F_{i,j}) \tag{3.1}$$

In particular, the cradle-to-grave carbon footprint (CF_{CG}) of the functional unit chosen was estimated via Eq. (3.1) with any characterization factor coinciding with the corresponding 100-year time-horizon global warming potential, as extracted from Myhre et al. (2013).

The 15 impact categories considered by the IMPACT 2002$^+$ method, namely "carcinogens" (C) and "non-carcinogens" (NC), "respiratory inorganics" (RI) and "organics" (RO), "ionizing radiation" (IR), "ozone layer depletion" (OLD), "aquatic (AE) and terrestrial (TE) eco-toxicity", "terrestrial acidification/nutrification" (TAN), "aquatic acidification" (AA), "aquatic eutrophication" (ANP"; "land occupation" (LO), "global warming" (GW), "non-renewable energy" (NRE), and "mineral extraction" (ME), were calculated using Eq. (3.1) together with the F_{ij} values embedded in the LCA tool used here. Such ICs were then grouped into four damage categories (DC_z) to underline the environmental compartments damaged by dry pasta in its life cycle. The effect on "Human health" (HH) accounted for the impact categories of C, NC, RI, RO, IR, and OLD, and was expressed in disability-adjusted life years (DALY), namely the amount of years (of life) lost as a result of premature mortality and/or disability, after an exposure to toxic chemicals. Similarly, the impact on the "Ecosystem quality" (EQ) was measured by accounting for the contribution of other impact categories (i.e., AE, TE, TANP, and LO) and was measured in potentially disappeared fraction (PDF) of biological species that have a high probability of not surviving in the geographical area where dry pasta is produced. The impact categories "aquatic acidification" and "aquatic eutrophication" were not included in the endpoint EQ, their damage characterization factors being unavailable (Jolliet et al., 2003). Since the impact of "Climate change" (CC) on EQ and

HH is not accurate enough to derive reliable damage characterization factors, the "global warming" was considered as a stand-alone end-point category by referring to a time-horizon of 500 years to account for both short- and long-term effects (Jolliet et al., 2003). Finally, the environmental impact resulting from the "Depletion of non-renewable resources" (RD) was measured by the additional primary energy required to extract a unit of mineral and of total non-renewable primary energy for energy carriers.

Table 3.3 Damage characterization factors of the various reference substances, as extracted from Jolliet et al. (2003).

MID-POINT IMPACT CATEGORY	DAMAGE FACTOR	UNIT
Carcinogens	1.45×10^{-6}	DALY kg^{-1} $C_2H_3Cl_e$
Non-carcinogens	1.45×10^{-6}	DALY kg^{-1} $C_2H_3Cl_e$
Respiratory inorganics	7.00×10^{-4}	DALY kg^{-1} $PM_{2.5e}$
Respiratory organics	2.13×10^{-6}	DALY kg^{-1} C_2H_{4e}
Ionizing radiation	2.10×10^{-10}	DALY/Bq $^{14}C_e$
Ozone layer depletion	1.05×10^{-3}	DALY kg^{-1} CFC-11_e
Aquatic eco-toxicity	8.86×10^{-5}	PDF m^2 yr kg^{-1} TEG water
Terrestrial eco-toxicity	8.86×10^{-5}	PDF m^2 yr kg^{-1} TEG soil
Terrestrial acid/nutrification	1.04	PDF m^2 yr kg^{-1} SO_{2e}
Aquatic acidification	-	
Aquatic eutrophication	-	
Land occupation	1.09	PDF m^2 yr m^{-2} org. arable
Global warming	1.0	kg CO_{2e} kg^{-1} CO_{2e}
Non-renewable energy	45.6	MJ kg^{-1} crude oil
Mineral extraction	5.10×10^{-2}	MJ kg^{-1}iron

Damage characterization factors of any substance was then obtained by multiplying the midpoint characterization potentials with the damage characterization factors of the reference substances, as listed in Table 3.3.

The impact assessment was extended to the end-point approach via the phases of normalization and weighing. In particular, the HH normalization factor of 0.0071 DALY per person by year was obtained by dividing the sum of the results for all pollutants and the European population. The EQ normalization factor of 13,700 PDF m^2 yr (pers yr)$^{-1}$ represented the potential damaged fraction of species in Western Europe. The normalization factor for CC [9,950 kg CO_{2e} (pers yr)$^{-1}$] was based on the total GHG emissions released in Europe per year multiplied by the 500-year time-horizon global warming potentials and divided by the Western European population; while the normalization factor for RD [152,000 MJ (pers yr)$^{-1}$] represented the per capita total non-renewable energy consumption in Western Europe, including nuclear energy consumption. Finally, a default weighting factor of one was used to aggregate such damage categories into an overall weighted damage score (OWDS).

3.3 Statistical analysis of data

The type of uncertainty distribution was related to the primary and secondary data accounted for. The errors in the primary data, concerning for instance the crop and durum wheat semolina yields, mass of packaging materials used and wasted, were assumed to be characterized by a normal distribution and were expressed by reporting the mean values together with their standard deviations (see for instance Table A.1). The N_2O and CO_2 emission factors from managed soils (EPD®, 2013; IPCC, 2006) were assumed to be characterized by a triangular distribution. As these uncertainty distributions had been introduced in the LCA model, it was possible to resort to the well-known Monte Carlo approach (Theodoris, 2015), this analysis being embedded in SimaPro. As the computer took a random variable for each parameter characterized by the uncertainty range specified, CF_{CG}, ICs, DCs and OWDS were recalculated and stored. After repeating the procedure for 2000 times, the resulting 2000 different output values gave rise to an uncertainty distribution.

3.4 Results and discussion

3.4.1 Dry pasta carbon footprint

The carbon footprint of durum wheat was estimated on the basis of the organic fertilizer (poultry manure), seed density, and diesel fuel uses and resulting yield factors, these being summarized in the Appendix A (Table A1), by accounting for the default values of the emission factors characterizing nitrogen and phosphorous fertilizer application (Bouwman et al., 2002; EPD®, 2013; IPCC, 2006).

Fig. 3.3 shows the specific contribution of the different life cycle stages to the carbon footprint associated with organic durum wheat production. In this case, the on-field direct and indirect N_2O emissions represented the primary spot (38.8 %), the poultry manure production the secondary one (27.4 %), diesel fuel consumption for management practices the third one (24.4 %), transportation of manure, seeds, etc. the fourth one (4.6

%), and grain seed cultivation the fifth one (4.4 %). Thus, the overall GHG emissions allocated to grains amounted to 0.62 kg CO_{2e} kg^{-1}.

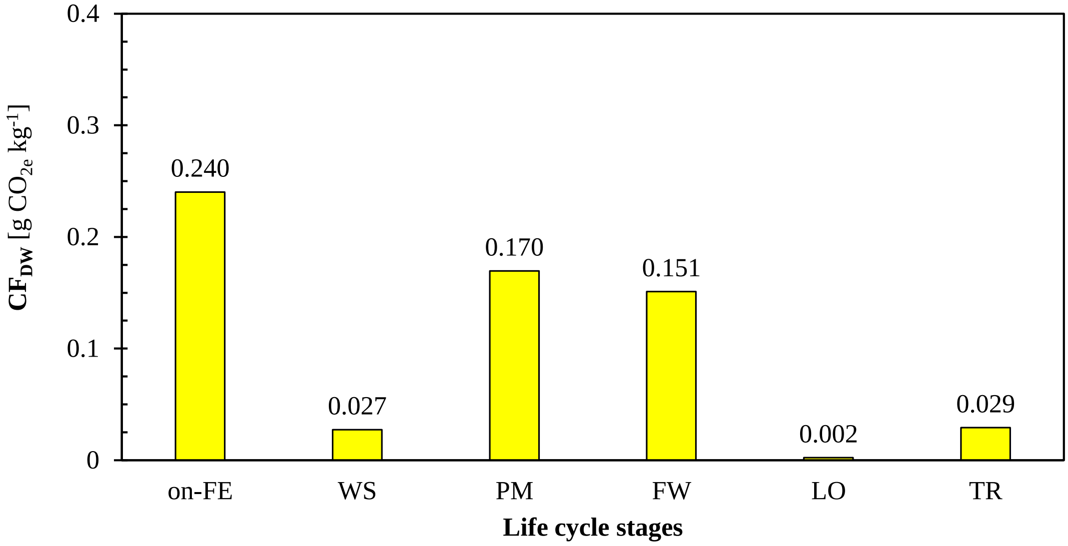


Figure 3.3 Contribution of the different life cycle stages to the overall carbon footprint of organic durum wheat (CF_{DW}): on-FE, on field emissions; WS, wheat seeds; PM, poultry manure; FW, field management, LO, lubricating oil; TR, transport.

In Section §1.4.1, the overall GHG emissions allocated to grains amounted to 0.53±0.05 kg CO_{2e} kg^{-1} with the aged manure production representing the primary spot (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%). In this estimation, the use of the 5th Assessment Report by IPCC (Myhre et al., 2013) instead of the 4th one (Foster et al., 2007) and more updated databases resulted in a greater carbon footprint of durum wheat grains.

As shown in Fig. 3.4, the estimated cradle-to-grave CF_{CG} of 1 kg of dry pasta amounted to about 1.811 kg CO_{2e} kg^{-1}, while the contribution of all the life cycle phases was ranked in the following manner: field phase (0.692 kg CO_{2e} kg^{-1}), home pasta cooking (0.649 kg CO_{2e} kg^{-1}), pasta production (0.188 kg CO_{2e} kg^{-1}), pasta distribution (0.139 kg CO_{2e} kg^{-1}), packaging material manufacture (0.065 kg CO_{2e} kg^{-1}), durum wheat milling (0.049 kg CO_{2e} kg^{-1}), pasta packaging (0.030 kg CO_{2e} kg^{-1}), and end of life of packaging materials (-0.001 kg CO_{2e} kg^{-1}). The estimated CF_{CG} practically coincided with that (1.807 kg CO_{2e} kg^{-1}) previously estimated (Table 1.11) with just limited variation in the contribution of the different life cycle steps.

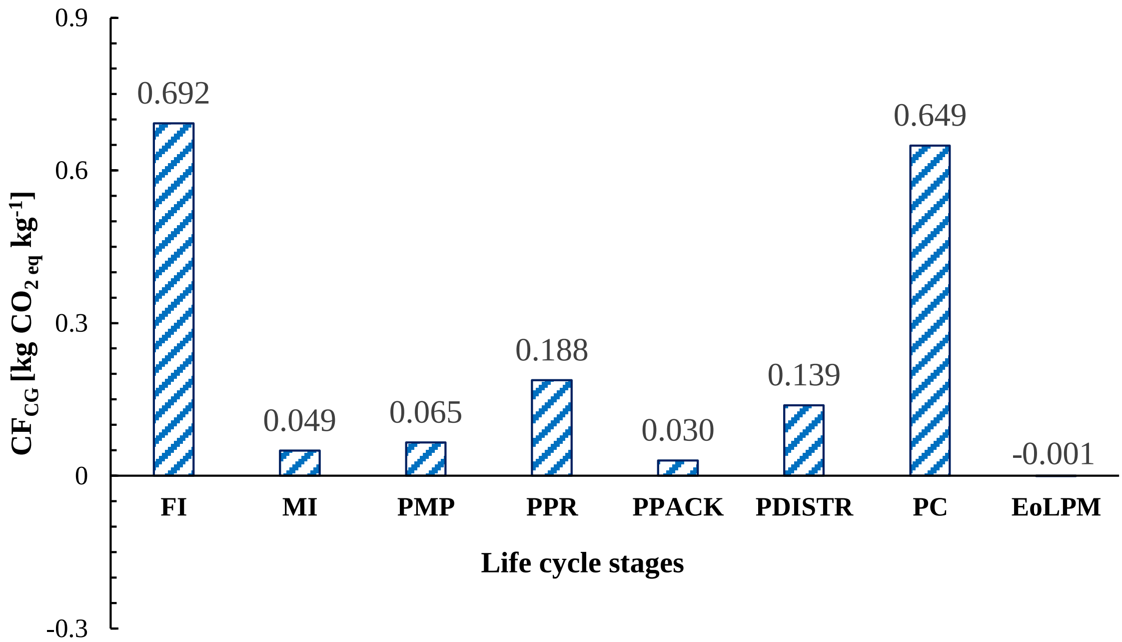


Figure 3.4 Contribution of the different life cycle stages to the cradle-to-grave (CF_{CG}) carbon footprint of a functional unit (1 kg) of dried pasta packed in 0.5-kg PP bags in a medium-sized pasta factory, as estimated by referring to the Ecoinvent v. 3.5 database and 100-year Global Warming Potentials by IPCC (Myhre et al., 2013). Item symbols: FP, field phase; MI, milling; PMP, packaging material manufacture; PPR, pasta production; PPACK, pasta packaging; PDISTR, transport of final product; PC, pasta cooking (consumer phase); EoLPM, end of life of packaging material wastes.

By accounting for the aforementioned triangular and/or normal distribution uncertainty range (§3.3), it was possible to resort to the well-known Monte Carlo approach (Theodoris, 2015), this analysis being embedded in SimaPro. As the computer took a random variable for each parameter characterized by the uncertainty range specified, CF_{CG} was recalculated and stored. After repeating the procedure for 2000 times, the resulting 2000 different CFCG values gave rise to an uncertainty distribution, as that shown for instance in Fig. 3.5.

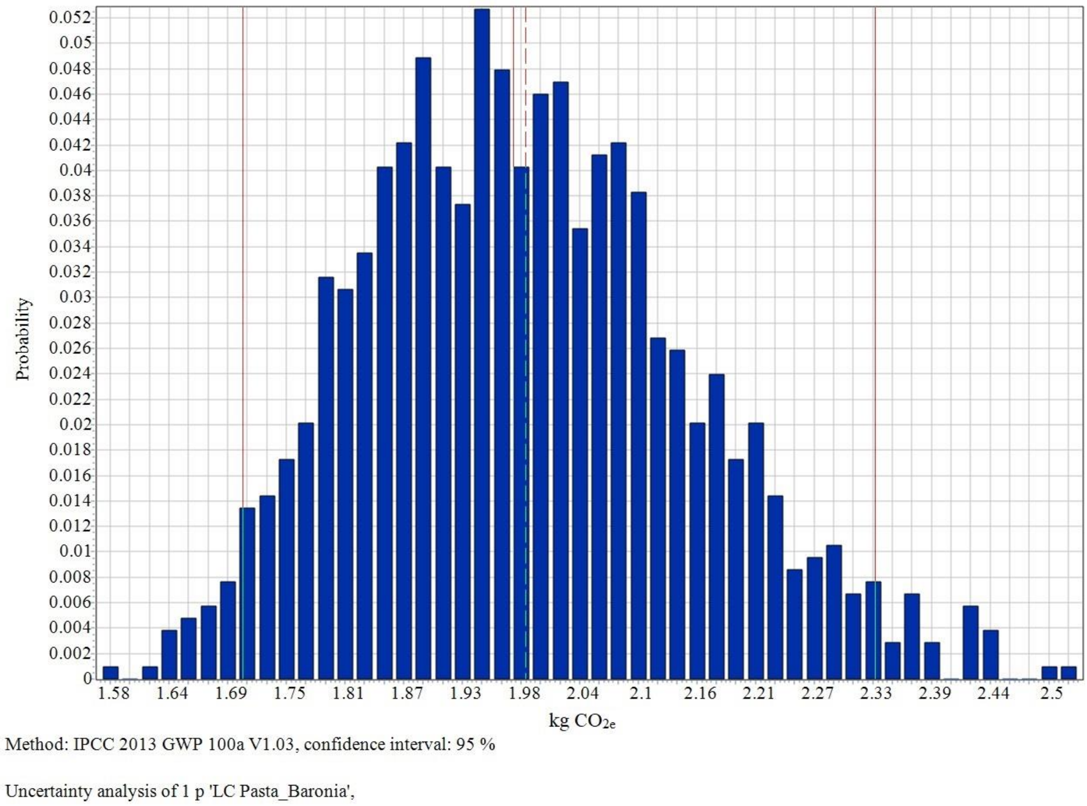


Figure 3.5 Uncertainty distribution of the cradle-to-grave carbon footprint (CF_{CG}) of dry pasta as derived from a Monte Carlo analysis carried out using the Ecoinvent v. 3.5 database and IPCC 5th Assessment Report (Myhre et al., 2013).

The mean value of CF_{CG} was equal to 1.981 kg $CO_{2\ eq}$ kg^{-1}, whereas the standard deviation (sd) and coefficient of variation (CV) were 0.155 kg CO_{2e} kg^{-1} and 7.8 %, respectively.

3.4.2 The environmental profile of dry pasta

Table 3.4 shows the environmental profile of 1 kg of dry pasta as resulting from the framework provided by the Impact 2002$^+$ v.2.15 life cycle impact assessment method, embedded in SimaPro 9.0.0.41. The environmental impact of the great majority of the mid-point impact categories mainly derived from the field and cooking phases, as pointed out by the data in bold- and Italic-types in Table 3.4. Actually, the *durum wheat cultivation* mainly affected, in descending order, the impact categories of "land occupation" (99.7 %), "aquatic eutrophication" (91.5 %), "ionizing radiation" (62.5 %) , "terrestrial acidification and nutrification" (53.3 %), "respiratory inorganics" (50.9 %), "mineral extraction" (48.2 %), "aquatic acidification" (46.3 %), "non-carcinogens" (45.6 %), "respiratory organics" (45.2 %), "ozone layer depletion" (38.9 %) and "terrestrial ecotoxicity" (30.9 %). On the contrary, the *pasta cooking phase* exerted the primary contribution on the impact categories of "non-renewable energy" (40.1 %), and "global warming" (37.8 %), but the secondary one on that of "mineral extraction" (30.9 %), "aquatic acidification" (24.4 %), "terrestrial acidification and nutrification" (20.8), "respiratory inorganics" (19.8 %), "respiratory organics" (17.9 %), and "ionizing radiation" (16.2 %). The *packaging material manufacture* exerted the primary impact on "carcinogens" (44.2 %), and "aquatic eco-toxicity" (40.9 %), as shown in Table 3.4.

Even if the assumed time-horizon in the Impact 2002$^+$ method was 500 years, the global warming effects were still dominated by the cooking phase (37.8 %), as already identified using the PAS 2050 method.

Once the ICs "aquatic acidification" and "aquatic eutrophication" had been excluded, the remaining 13 ICs mentioned above were grouped into four damage categories (DC) to underline the environmental compartments damaged by dry pasta in its life-cycle (Table 3.5). As shown by the data in bold- and Italic types, the damage impact on "Human health" (HH) and "Ecosystem quality" (EQ) mainly derived from the field phase, while that on "Climate Change" (CC) and "Resource Depletion" (RD) from the consumer phase.

Table 3.4 Environmental profile of 1 kg of dried organic pasta packed in 0.5-kg PP bags, as estimated using the IMPACT 2002$^+$ method: Percentage contribution of the different dry pasta life cycle phases, and overall score of each mid-point impact category (IC_j).

Impact category (IC_j)		**Life Cycle Phase Contribution (%)**								**IC_j Score**	**Unit**
		FI	**MI**	**PMP**	**PPR**	**PPACK**	**PDISTR**	**CP**	**EoLPM**		
Carcinogens	C	15.7	2.5	**44.2**	*37.2*	1.5	7.9	10.7	-19.8	1.27×10^{-2}	kg $C_2H_3Cl_e$
Non-carcinogens	NC	**45.6**	4.6	11.7	9.2	1.0	*21.7*	12.6	-6.4	1.44×10^{-2}	kg $C_2H_3Cl_e$
Respiratory inorganics	RI	**50.9**	4.2	4.6	10.6	2.7	11.9	*19.8*	-4.6	1.07×10^{-3}	kg $PM_{2.5e}$
Respiratory organics	RO	**45.2**	3.7	10.5	8.7	1.1	17.1	*17.9*	-4.2	4.53×10^{-4}	kg C_2H_{4e}
Ionizing radiation	IR	**62.5**	2.7	2.8	9.0	2.4	4.8	*16.2*	-0.4	22.2	Bq $^{14}C_e$
Ozone layer depletion	OLD	**38.9**	5.8	3.0	14.7	2.7	*19.4*	16.6	-1.0	1.32×10^{-7}	kg CFC-11_e
Aquatic ecotoxicity	AE	*24.6*	3.6	**40.9**	8.5	1.5	13.6	12.6	-5.2	117.5	kg TEG water
Terrestrial ecotoxicity	TE	**30.9**	5.7	26.1	4.7	1.0	*27.5*	8.7	-4.6	43.8	kg TEG soil
Terrestrial acidification/nutrification	TANP	**53.3**	3.5	2.6	11.8	3.2	6.2	*20.8*	-1.3	4.08×10^{-2}	kg SO_{2e}
Aquatic acidification	AA	**46.3**	3.9	3.5	13.2	3.4	7.1	*24.4*	-1.9	6.96×10^{-3}	kg SO_{2e}
Aquatic eutrophication	ANP	**91.5**	0.6	1.3	1.7	0.4	1.8	*4.3*	-1.6	9.38×10^{-4}	kg PO_4^{3-}
Land occupation	LO	**99.7**	0.03	*0.3*	0.03	0.01	0.2	0.1	-0.3	4.36	m^2 org. arable
Global warming	GW	*35.0*	2.9	3.7	10.7	1.7	8.4	**37.8**	-0.2	1.62	kg CO_{2e}
Non-renewable energy	NRE	*30.1*	3.1	6.5	11.7	1.9	8.9	**40.1**	-2.3	25.7	MJ primary
Mineral extraction	ME	**48.2**	2.4	4.0	5.1	0.8	10.3	*30.9*	-1.8	2.17×10^{-2}	MJ surplus

Table 3.5 IMPACT 2002$^+$ damage assessment related to 1 kg of dried pasta packed in 0.5-kg PP bags: percentage contribution of the different life cycle stages, single (SS_z) and weighted damage scores (WDS_z) of each damage category (DC_z), and overall weighted damage score (OWDS).

Damage category (DC_z)				**LC Stages Contribution (%)**					**SS_z**	**Unit**	**WDS_z**
	FI	**MI**	**PMP**	**PPR**	**PPACK**	**PDISTR**	**CP**	**EoLPM**			**(μpt)**
Human Health (HH)	**49.2**	4.1	6.6	11.7	2.5	12.1	*19.0*	-5.3	8.28×10^{-7}	DALY	117
Ecosystem Quality (EQ)	**94.6**	0.4	2.08	0.5	0.1	*2.09*	0.8	-0.6	5.15	PDF m^2 yr	376
Climate Change (CC)	*35.0*	2.9	3.7	10.7	1.7	8.4	**37.8**	-0.2	1.62	kg CO_{2e}	164
Resource Depletion (RD)	*30.1*	3.1	6.5	11.7	1.9	8.9	**40.1**	-2.3	25.7	MJ primary	169
OWDS	**63.1**	2.0	4.0	6.4	1.1	6.2	*18.8*	-1.5			***825***

Table 3.6 Main results of Montecarlo analysis carried out using the IMPACT 2002$^+$ method as referred to the reference case (RC) or eco-sustainable pasta cooker (EPC) use: mean value (m), standard deviation (sd) and coefficient of variation (CV in %) of each mid-point impact category, aggregated damage category, as such and normalized, and overall weighted damage score (OWDS) of the cradle-to-grave environmental impact of dry pasta.

Case study		**RC**		**EPC**	
Impact Category	**Unit**	**m±sd**	**CV**	**m±SD**	**CV**
Carcinogens	kg $C_2H_3Cl_e$	(1.27±0.29)x10^{-2}	22.7	(1.27±0.23) x10^{-2}	18.1
Non-carcinogens	kg $C_2H_3Cl_e$	(1.43±0.19)x10^{-2}	13.2	(1.41±0.11) x10^{-2}	8.0
Respiratory inorganics	kg $PM_{2.5e}$	(1.07±0.07)x10^{-3}	6.6	(1.13±0.11) x10^{-3}	10.1
Respiratory organics	kg C_2H_{4e}	(4.54±0.41)x10^{-4}	9.0	(4.27±0.39) x10^{-4}	9.2
Ionizing radiation	Bq $^{14}C_e$	22.6±19.3	85.5	19.4±8.9	46.0
Ozone layer depletion	kg CFC-11_e	(1.32±0.32)x10^{-7}	24.2	(1.38±0.31) x10^{-7}	22.5
Aquatic ecotoxicity	kg TEG water	117±19.8	16.9	117±14	12.3
Terrestrial ecotoxicity	kg TEG soil	43.6±4.9	11.3	43.8±3.4	7.7
Terr. acidification/nutrification	kg SO_{2e}	(4.07±0.35)x10^{-2}	8.6	(4.43±0.45) x10^{-2}	10.2
Aquatic acidification	kg SO_{2e}	(6.96±0.54)x10^{-3}	7.8	(7.65±1.06) x10^{-3}	13.9
Aquatic eutrophication	kg PO43-	(9.37±0.79)x10^{-4}	8.4	(1.01±0.39) x10^{-3}	38.2
Land occupation	m^2 org. arable	4.36±0.02	0.5	4.36±0.02	0.6
Global warming	kg CO_{2e}	1.72±0.10	6.1	1.34±0.09	7.0
Non-renewable energy	MJ primary	25.7±1.7	6.5	19.6±1.8	9.2
Mineral extraction	MJ surplus	(2.17±0.36)x10^{-2}	16.5	(2.01±0.29) x10^{-2}	14.6
Damage category					
Human Health (HH)	DALY	(8.22±0.50)x10^{-7}	6.1	(8.7±0.8) x10^{-7}	9.6
Ecosystem Quality (EQ)	PDF m^2 yr	5.15±0.04	0.8	5.15±0.04	0.9
Climate Change (CC)	kg CO_{2e}	1.72±0.10	5.5	1.34±0.09	7.0
Resource Depletion (RD)	MJ primary	25.2±1.4	5.6	19.7±1.8	9.2
Normalized Damage Category					
Human Health (HH)	μpt	116±7	6.1	123±12	9.6
Ecosystem Quality (EQ)	μpt	376±3	0.8	376±3	0.9
Climate Change (CC)	μpt	174±10	5.5	136±10	7.0
Resource Depletion (RD)	μpt	166±9	5.6	129±12	9.2
OWDS	μpt	832±23	2.8	764±22	2.9

To complete the assessment to the end-point approach, the single score (SS_z) of each damage category (DC_z) was firstly normalized using the corresponding normalization factor (see §3.2.3, and then aggregated using the default weighting factor of one (Table 3.5). The assessment pointed out that EQ was the damage category mostly affected (45.5 % of the overall weighted damage score, OWDS), followed by RD, CC, and HH representing 20.5, 19.8 and 14.2 % of OWDS, respectively.

The dry pasta life cycle phase exerting the greatest percentage contribution to the overall weighted damage score (825 micropoint, μpt) was the cultivation one (63.1 %), followed by the pasta cooking (18.8 %), durum wheat milling and pasta manufacture and packing (9.5 %), pasta distribution (6.2 %) and packaging material manufacture (4.0 %). The end of life of packaging material wastes had the effect of lowering the OWDS by -1.5%.

Table 3.6 shows the main results of the Monte Carlo analysis, where the procedure was repeated 2000 times. Some impact categories exhibited an uncertainty level greater than 20 %, namely "carcinogens" (22.7 %), "ozone layer depletion" (24.2 %), and "ionizing radiation" (85.5 %). Other impact categories, such as "aquatic eco-toxicity" (16.9 %), "mineral extraction" (16.5 %), "non-carcinogens" (13.2 %), and "terrestrial eco-toxicity" (11.3 %) were characterized by a coefficient of variation ranging from 10 to 17 %. Thus, according to the Impact 2002+ method, the most relevant impact categories for dry pasta were, in descending order, "land occupation" (0.5 %), "global warming" (6.1 %), "non-renewable energy" (6.5 %), "respiratory inorganics" (6.6 %), "aquatic acidification" (7.8), "aquatic eutrophication (8.4 %), "terrestrial acidification/ nutrification" (8.6 %), and "respiratory organics" (9.0 %), their relative CV being smaller than 10 % (Table 3.6). Such a finding was almost in line with the most relevant impact categories accounted for in the Product Environmental Footprint Category rules for dry pasta (UNAFPA, 2018), except for those concerning "freshwater eco-toxicity" being affected by a CV of 16.9 % and "water resource depletion" not accounted for by IMPACT 2002+. As concerning the normalized damage categories of the Impact 2002+ method, the most significant one was the "Ecosystem quality" (EQ), followed by "Climate change" (CC), "Resource depletion" (RD), and "Human health" (HH), the corresponding CV of which being equal to 0.8, 5.5, 5.6, and 6.1 %, respectively. Altogether, the overall weighted damage score of dry pasta amounted to 832±23 μpt (Table 3.6).

3.4.3 *Comparison of the environmental profiles of organic and conventional dry pasta*

To compare the environmental profile of dry organic pasta, examined in this work, to the profiles of conventional dry pasta, as extracted from the EPDs® and summarized in Table 3.1, the aforementioned LCA model was run using the EPD® (2018) method. The cradle-to-grave scores of the four main impact categories (e.g., "climate change", CC; "acidification", A; "eutrophication", NP; "photochemical ozone creation potential", POCP) were listed in Table 3.7 and compared to the min-max B2B scores of the above impact categories referred to 1 kg of dried pasta differently packed and distributed in Italy and/or abroad.

Table 3.7 Min-max scores of the 4 main impact categories (e.g., "climate change", CC; "acidification", A; "eutrophication", NP; "photochemical ozone creation potential", POCP) characterizing the B2B profiles referred to 1 kg of dried pasta differently packed and shown in Table 3.1, as compared to the B2C profile of 1 kg of dry organic pasta using the EPD® (2018) standard method.

Impact Category	**Main B2B EPDs®**			**B2C EPD®(2018)**	
	Conventional Dry Pasta			Organic Dry Pasta	
	min	max	Unit	Value	Unit
CF	567	1722	g CO_{2e} kg^{-1}	1807	g CO_{2e} kg^{-1}
A	4.4	31.3	g SO_{2e} kg^{-1}	6.9	g SO_{2e} kg^{-1}
NP	2.2	9.4	g PO_{4e}^{-} kg^{-1}	3.0	g PO_{4e}^{-} kg^{-1}
POCP	0.1	0.9	g C_2H_{2e} kg^{-1}	4.6	g $NMVOC_e$ kg^{-1}

Even if the scores for organic dry pasta referred to a cradle-to-grave analysis, those of A and NP tended towards the minimum values displayed in Table 3.7 owing to advantages of organic farming over conventional agriculture for no use of synthetic fertilizers and pesticides, while that of CC was obviously greater since it included the contribution of the consumer phase. In the case of organic dry pasta, the POCP score was expressed in gram of non-methane volatile organic compound equivalents ($NMVOC_e$) kg^{-1} using the ReCiPe 2008 method (EPD®, 2018), whereas in the case of conventional dry pasta it was expressed in g C_2H_{2e} kg^{-1} using the CML method (Benini et al., 2014). In spite of the similar figures for the emissions of CO, SO_2, CH_4, NO_X, and toluene, the CML and ReCiPe characterization methods are different and, hence, the contribution to the impact. In CML, the major contributor are NMVOCs (38%) followed by NO_2 (24%), CO (22%), SO_2 (9%), methane (3%), and toluene (2%). On the contrary, in ReCipe 2008, the major contributors are NO_2 (44.8%) and NMVOC (44.2%), followed by CO (6.5%), SO_2 (2.7%) and CH_4 (0.8%). Thus, such scores were not comparable in absolute values.

In conclusion, none of the environmental profiles of dry pasta assessed so far can be directly compared, mainly because of the great number of assumptions made, different operating variables, yield factors, and what's more life cycle impact assessment methods used.

3.4.4 Options to reduce the environmental profile of dry pasta

Since climate change and resources are generally highly correlated, especially in this case where the contribution of nuclear power energy to the Italian electricity is less than 15 % (Longo, n.d.), the normalized scores of CC and RD may be summed (Humbert et al., 2014), such a combined damage category representing up to 40.9 % of OWDS. Thus, any mitigation action should *a priori* aim at reducing firstly EQ and secondly CC and RD. As shown in Table 3.5, the damage category EQ is mainly controlled by the field phase (94.6 %) and then by the final product distribution (2.09 %) and packaging material manufacture (2.08 %). Moreover, by accounting for the damage characterization factors shown in Table 3.3, EQ is by far affected by the impact category of "land occupation". On the contrary, CC and RD are primarily affected by the pasta cooking phase and secondarily by the field phase (Table 3.5).

Quite a large number of studies have demonstrated that organic farming for durum wheat cultivation in Italy is a low-carbon agriculture with a lower contribution to climate change in terms of GHG emissions per hectare respect to the conventional wheat cultivation (Chiriacò et al., 2017). Unfortunately, the lower productivity of organic agricultural systems with respect to conventional ones asks for more cultivated land. Thus, more research is needed to explore the organic farming potentials and improve organic food production by optimizing the use of resources and yields with the final aim of ensuring sufficient organic food supply at global level.

According to Gan et al. (2011), the carbon footprint (CF) of durum grain, as averaged across a five-year field experiment conducted in Canada, was significantly influenced by the crop rotation system used. Durum produced in the cereal–cereal–durum system had an average CF of 0.42 kg CO_{2e} kg^{-1} of grain. Cropping systems in which durum wheat was preceded by an oilseed crop (canola or mustard) the previous year lowered the CF to 0.34 kg CO_{2e} kg^{-1}, whereas the durum wheat preceded by a pulse crop (chickpea, lentil, or pea) the previous year lowered the CF to 0.30 kg CO_{2e} kg^{-1}. An oilseed and a pulse crop alternately grown the previous two years (pulse-oilseed-durum, oilseed-pulse-durum, or oilseed–oilseed–durum systems) lowered the CF of durum wheat by 25% compared with durum wheat grown in cereal-cereal–durum system. Durum wheat produced in a pulse-pulse-durum system had the lowest carbon footprint (i.e., 0.27 kg CO_{2e} kg^{-1}. In the circumstances, the grain yield when using the cereal-cereal-durum or pulse-pulse-durum system varied from about 2240 to 2660 kg of grain ha^{-1}, but the land occupation was one hectare every three years.

A similar four-year rotation crop experiment was conducted in selected areas of Northern (i.e., Lombardy, Veneto Emilia Romagna regions), Central (i.e., Tuscany, Umbria and Marche regions) and Southern (i.e., Apulia and Sicily) Italy by Ruini et al. (2013). The grain yield was about 7.5 Mg ha^{-1} in Emilia Romagna, but ranged from 4.3 to 5.3 Mg ha^{-1} in Central Italy, and from 4.2 to 5.0 Mg ha^{-1} in Southern Italy (Ruini et al., 2013). The lowest environmental impact involved the rotation of durum wheat with fodder and the land occupation was one hectare every two years.

Moreover, five durum wheat cultivars were grown in Torre Lama (Naples, Italy) under conventional and organic farming preceded by corn crop to evaluate agronomic, technological, sensory, and sanitary quality of grains and pasta (Fagnano et al., 2012). The cultivar Saragolla showed the best results in terms of grain yields (3.62 or 4.09 Mg ha^{-1} in organic or conventional farming) and pasta quality, thus proving to be the cultivar more adapt to organic farming. Even in this case, the land occupation was one hectare every two years.

In this PhD thesis, the organic farming producing durum wheat was preceded by alfalfa (*Medicago sativa* L.) crop and about 70% of the nominal non-irrigated land was dedicated to durum wheat cultivation, while the remaining 30% to fodder legume one (§1.3.1). The average grain yield was 3.75±0.27 Mg ha^{-1} (Table A.1) with a land occupation of 1.4 ha every two years.

In the circumstances, the organic farming carried out in an area bordering Campania, Basilicata and Apulia Regions of Italy to sustain the organic dry pasta production accounted for in this PhD thesis appeared to be more productive than the best one tested by Ruini et al. (2013) in Southern Italy. In fact, the amount of grains recovered from a cultivated area of 1 ha that the year before was dedicated to a fodder crop was 5.0 (Mg ha^{-1}) x 1 (ha)/2 (yr) = 2.5 Mg yr^{-1}. On the contrary, the amount of grains recovered in the case of concern was 3.75 (Mg ha^{-1}) x 0.7 (ha yr^{-1}) ≈ 2.63 Mg yr^{-1}. Thus, having no specific information about the contribution of the main conservation agriculture techniques (e.g., reduction of tillage intensity, organic fertilizers) on the crop yield response in the cultivation areal from which durum wheat grains were harvested to produce the organic dry pasta examined here, no further mitigation option on the organic farming system was accounted for.

Among the mitigation actions examined in §1.4.4, the only eco-sustainable pasta cooking procedure with WPR=2 L kg^{-1} previously assessed (Cimini et al., 2019a) was sufficient to cut the CF_{CG} by 29% with respect to the reference case (RC). On the contrary, the other ones examined, namely replacement of methane with biogas, use of solar-photovoltaic electricity, rail or sea instead of road freight transport, short pasta or grain supply chain, had the effect of lowering CF_{CG} by 7.4, 8.6, 2.0 or 2.6, and 1.4 or 1.1 %, respectively. Thus, the novel Arduino®-based eco-sustainable pasta cooker (EPC), operating with a cooking water-to-pasta ratio of 3±1 L $kg^{-1}$and an overall electricity consumption of 0.6±0.1 kWh kg^{-1} (§2.3.5) appeared to be proper for lessening the environmental impact of the pasta cooking phase.

In the circumstance, the GHG emissions associated to each life cycle phase did not change, except those from the consumer use one that reduced from 0.649 to 0.269 kg CO_{2e} kg^{-1}. Thus, from the Monte Carlo analysis CF_{CG} reduced from 1.98±0.16 to 1.61±0.17 kg CO_{2e} kg^{-1}, this being about 19 % lower than the reference case (RC).

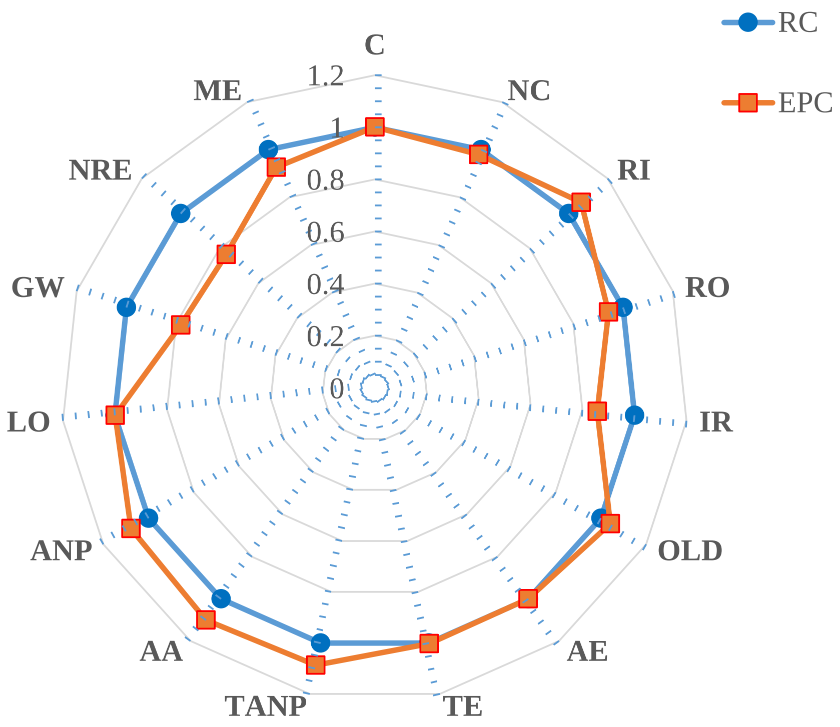


Figure 3.6 Radar chart comparing the impact categories describing the life cycle profile of dry pasta (same acronyms as in Table 3.4) when using the eco-sustainable pasta cooker (EPC: red continuous line and closed squares), as referred to the reference case (blue continuous line and closed circles).

The effects of the above scenario on the 15 impact categories were normalized with respect to those of the base case (Table 3.4) and used to plot a radar chart, as that shown in Fig. 3.6. In this case, the scores of the impact categories of “non-renewable energy”, “global warming”, “ionizing radiation”, “mineral extraction”, “respiratory organics”, and “non-carcinogens” reduced by 24, 22, 14, 7, 6, and 2 % with respect to the reference case (RC), respectively. There was no effect on “land occupation”, “carcinogens”, “aquatic eco-toxicity”, and “terrestrial eco-toxicity”; but an increase in the scores of the impact categories of “ozone layer depletion”, “respiratory inorganics”, “aquatic eutrophication”, “terrestrial acidification/nitrification”, and “aquatic acidification” by 4, 6, 8, 9 and 10 % with respect to RC, respectively. Such increases were in all probability due to the higher electricity needs of the EPC. In the reference case, the overall energy used to cook 1 kg of dry pasta was equal to 2.3 kWh (§1.3.9), 83% of which being of the thermal type (1.91 kWh kg^{-1}) and the remaining 17% of the electric type (0.39 kWh kg^{-1}), as extracted from UNAFPA (2018). Thus, shifting from the average domestic cooker to the EPC involved an increase in the electricity needs from 0.39 (§1.3.9) to 0.6±0.1 kWh kg^{-1} (§2.3.5) kWh kg^{-1}.

Table 3.6 shows the effect of the aforementioned action on the weighted scores of the four damage categories, as well as the overall weighted damage score (OWDS) for dry pasta.

By using the EPC the scores of RD and CC reduced by ca. 22 % each; that of EQ was unaltered whereas that of HH slightly increased by 6 %. Altogether, the overall weighted damage score (OWDS) approximately decreased by 8 % from 832±23 μpt to 764±22 μpt.

In the great majority of the Environmental Product Declarations EPD® currently available (see Table 3.1), the environmental impact of dry pasta was assessed from the cradle to distribution centers, since the contribution of the consumer phase was regarded as external to the production network and uneasy to be improved in the short term (Bevilacqua et al., 2007). Actually, the current drivers of the innovation in the food industry, that is the so-called *care* and *sustainability* ones (Bruin and Jongen, 2003; Moresi, 2016) have not so far attempted to reduce the GHG emissions associated with the great majority of the food cooking operations (Xu et al., 2015). Thus, thanks to the great diffusion of the Easy Serving Espresso (ESE) pods or capsules and associated brewers, it is high time for the pasta makers to start selling not only pasta products, but also their specialized pasta cookers in order to allow even unskilled pasta cooks to prepare high quality cooked pasta in a very reproducible and quick way with an overall reduction in the cradle-to-grave carbon footprint by 19 %, and overall weighted damage score by 8 % with respect to RC.

APPENDIX A

Table A.1
Inventory associated with the organic durum wheat cultivation phase.

Parameters	Amount	Unit	Comment
Output products			
Grain Straw removed	3750±267 3245	kg ha^{-1} kg ha^{-1}	The main output of the cultivation phase is durum wheat grains, their amount varying from 3500 to 4000 kg ha^{-1}. Such crop yield was referred to 70 % of the area cultivated, the remaining 30 % being used to produce alfaalfa. According to EPD® (2013) and IPCC (2006), this gave rise to above- and below-ground crop residues. The allocation factor proposed for the cultivation system was 94.5 % for durum wheat grains and 5.52 % for straw (EPD®, 2013). 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. Thus, the allocation factors used were as follows: 94.5 % were allocated to grains and 5.52 % to straw. The annual amount of N in crop residues returned to soil was estimated in accordance with the Tier I methodology (IPCC, 2006).
Input Resources			
Occupation, agriculture	1	ha yr^{-1}	The soil area used for durum wheat cultivation.
Wheat seed, Swiss integrated production, for sowing {CH}| production | Cut-off, U	210±32	kg ha^{-1}	The seed density varied 180 to 240 kg ha^{-1}, and was referred to 70 % of the area cultivated. The data was derived from Table 1.2, while the process was extracted from the Ecoinvent v. 3.5 database.
Poultry manure, dried {CH}| treatment of poultry manure, drying, pelleting | Cut-off, U	25±5.4	Mg ha^{-1}	The amount organic fertilizer with a nitrogen content of 1.3 % (w/w) varied from 20 to 30 Mg ha^{-1} and was referred to 30 % of the area cultivated. The data was derived from Table 1.2. Such a process was extracted from the Ecoinvent v.3.5 database.
Energy, from diesel burned in machinery/RER Mass	1264.38±270	kWh ha^{-1}	The overall volume of diesel oil needed for all the agricultural treatments (i.e., ploughing, harrowing, fertilizing, sowing, weeding, and combined harvesting) varied from 100 to 150 L ha^{-1}. The thermal energy required to perform all the tractor operations was estimated by accounting for an average density of 0.85 kg L^{-1} and a lower heating value of 11.9 kWh kg^{-1}. Such a process was extracted from the Agri-Footprint 4.0 database.
Lubricating oil {RER}| production | Cut-off, U	5	kg ha^{-1}	The lubricating oil used was derived from Table 1.2. Such a process was extracted from the Ecoinvent v.3.5 database.
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}|	1.47	Mg km ha^{-1}	The transportation of durum wheat seeds to the field by a small-size truck travelling for about 10 km. Such a process was extracted from the Ecoinvent v. 3.5 database.

transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U			
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U	1.06	Mg km ha^{-1}	The diesel oil was transported to the field by a small-size truck for a distance of 10 km. Such a process was extracted from the Ecoinvent v. 3.5 database.
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5 | Cut-off, U	375	Mg km ha^{-1}	The dried poultry manure was transported to the field by a medium-size truck for a distance of 50 km. Such a process was extracted from the Ecoinvent v. 3.5 database.
Emissions from fertilised soil			
Dinitrogen monoxide	1.81	kg N_2O ha^{-1}	N_2O direct emissions derived from the on-field application of residual crops and organic fertiliser and were estimated in accordance with the Tier I methodology (IPCC, 2006).
Dinitrogen monoxide	0.302	kg N_2O ha^{-1}	N_2O indirect emissions from atmospheric deposition of N volatilized from managed soil were estimated in accordance with the Tier I methodology (IPCC, 2006).
Dinitrogen monoxide	0.407	kg N_2O ha^{-1}	N_2O indirect emissions from nitrate leaching and runoff resulting from the on-field application of organic fertiliser and crop residues, and were estimated in accordance with the Tier I methodology (IPCC, 2006).
Nitrogen oxide	1.028	kg NO ha^{-1}	NO direct emissions derived from the on-field application of organic fertilizers, and were estimated in accordance with Bouwman et al. (2002) and EPD® (2013).
Phosphorous	0.64	kg P ha^{-1} yr^{-1}	The annual amount of P emissions to water as resulting from leaching of soluble phosphates to ground water, run-off and erosion to surface water was estimated in accordance with EPD® (2013).

Table A.2
Inventory associated with the milling phase.

Parameters	Value	Unit	Comment
Outputs			
Semolina (DWS) Wheat Feed Pelletting (By-products)	1 0.212	kg kg (kg DWS)$^{-1}$	The milling phase gave rise to durum wheat semolina, and a co-product including bran, fine bran and tritello (i.e., wheat feed pellets), that was used as cattle feed. Both yields were extracted from Table 1.3. The damage associated with this phase was allocated to the product and co-product according to an economic-based criterion (94.6 % durum wheat semolina and 5.4 % wheat feed pellets) in accordance with UNAFPA (2018).
Input Resources			
Grains	1.15	kg (kg DWS)$^{-1}$	This process was described in Table A.1.
Tap water {Europe without Switzerland}| tap water production, underground water without treatment | Cut-off, U	0.0792	kg (kg DWS)$^{-1}$	The specific consumption yields were derived directly from the factory, while the processes referred to the electricity country mix and tap water were extracted from the Ecoinvent v.3.5 database.
Electricity, medium voltage {IT}| electricity voltage transformation from high to medium voltage | Cut-off, U	0.0515	kWh (kg DWS)$^{-1}$	
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, U	0.173	Mg km (kg DWS)$^{-1}$	The grain were transported from field to the factory for a distance of 150 km by a large-size truck. Such a process was extracted from the Ecoinvent v. 3.5 database.

Table A.3
Inventory associated with the pasta production step.

Parameters	**Value**	**Unit**	**Comment**
Outputs			
Dry pasta (DP) Pasta making by-products	1 0.00552	kg kg (kg DP)$^{-1}$	The pasta production phase gave rise to dry pasta and several discarded by-products consisting of dough wastes before and after extrusion and dry pasta packaging wastes, these being used as cattle feed. Both yields were extracted from Table 1.4. The impact associated with this phase was allocated to the product and by-products according to an economic-based criterion (95 % dry pasta and 5 % by-products) in accordance with UNAFPA (2018).
Input Resources			
Semolina	1.03	kg (kg DP)$^{-1}$	This process was described in Table A.2.
Tap water {Europe without Switzerland}| tap water production, underground water without treatment | Cut-off, U	0.35	kg (kg DP)$^{-1}$	The specific consumption yields referred to the production of 1 kg of dry pasta were derived from Tables 1.4 and 1.7. All processes referred to the tap water distribution, electricity country mix, methane production, distribution and combustion and as aerobic wastewater treatment, were extracted from the Ecoinvent v.3.5 database.
Electricity, medium voltage {IT}| electricity voltage transformation from high to medium voltage | Cut-off, U	0.247	kWh (kg DP)$^{-1}$	
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler modulating <100kW | Cut-off, U	0.304	kWh (kg DP)$^{-1}$	
Wastes to be treated			
Wastewater, average {CH}| treatment of, capacity 1.6E8l/year | Cut-off, U	0.167	L (kg DP)$^{-1}$	

Table A.4
Inventory associated with the PP bag production.

Parameters	Value	Unit	Comment
Outputs			
Polypropylene bag production	1	kg	This process allowed the manufacture of the primary packages for dry pasta. This is a unitary process.
Input Resources			
Polypropylene, granulate {RER}| production | Cut-off, U	1	kg	These processes were extracted from the Ecoinvent v.3.5 database.
Extrusion, plastic film {RER}| production | Cut-off, U	1	kg	
Printing ink, offset, without solvent, in 47.5% solution state {RER}| printing ink production, offset, product in 47.5% solution state | Cut-off, U	0.003	kg	

Table A.5
Assembly of the primary packaging.

Parameters	Value	Unit	Comment
Output			
Primary packaging Assembly	1	p (kg DP)$^{-1}$	One piece allows the primary packaging of 1 kg of dry pasta
Materials/Assemblages			
Polypropylene bag production	0.0144	kg (kg DP)$^{-1}$	The weight of each PP bag used was derived Table 1.5.
Processes			
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5 | Cut-off, U	0.316	kg km	The polypropylene bags were produced in another factory and transported to the pasta firm by medium-size trucks, the weighted average distance being 22 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.

Table A.6
Assembly of the secondary packaging.

Parameters	Value	Unit	Comment
Output			
Secondary packaging Assembly	1	p (kg DP)$^{-1}$	One piece allows the secondary packaging of 1 kg of dry pasta
Materials/Assemblages			
Corrugated board box {RER}| production | Cut-off, U	0.0298	kg (kg DP)$^{-1}$	The cardboard boxes used as secondary packages (Table 1.5) were made of such a raw material, this being extracted from the Ecoinvent v. 3.5 database.
Graphic paper, 100% recycled {RER}| production | Cut-off, U	0.0000617	kg (kg DP)$^{-1}$	The label applied to any cardboard box (Table 1.5) was made of such a raw material, this being extracted from the Ecoinvent v. 3.5 database.
Processes			
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5 | Cut-off, U	2.33	kg km	The cardboard boxes were produced in another factory and transported to the pasta firm by medium-size trucks, the weighted average distance being 78 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5 | Cut-off, U	0.00605	kg km	The labels were produced in another factory and transported to the pasta firm by medium-size trucks, the weighted average distance being 98 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.

Table A.7
Assembly of the tertiary packaging.

Parameters	Value	Unit	Comment
Output			
Tertiary packaging Assembly	1	p (kg DP)$^{-1}$	One piece allows the tertiary packaging of 1 kg of dry pasta.
Materials/Assemblages			
EUR-flat pallet {RER}| production | Cut-off, U	0.00125	p (kg DP)$^{-1}$	This material was extracted from the Ecoinvent v.3.5 database.
Graphic paper, 100% recycled {RER}| production | Cut-off, U	0.00000769	kg (kg DP)$^{-1}$	The pallet labels (Table 1.5) were made of such a raw material, this being extracted from the Ecoinvent v. 3.5 database.
Packaging film, low density polyethylene {RER}| production | Cut-off, U	0.000501	kg (kg DP)$^{-1}$	The polyethylene film (Table 1.5) was made of such a raw material, this being extracted from the Ecoinvent v.3.5 database.
Processes			
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, U	0.125	kg km	The pallets were transported to the pasta firm by large-size trucks, the weighted average distance being 100 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5 | Cut-off, U	0.000769	kg km	The labels were transported from to the pasta firm by medium-size trucks, the weighted average distance being 100 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5 | Cut-off, U	0.0501	kg km	The polyethylene film was transported to the pasta firm by medium-size trucks, the weighted average distance being 100 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.

Table A.8
Assembly of primary and secondary packaging materials.

Parameters	**Value**	**Unit**	**Comment**
Output			
Primary + secondary packaging	1	p (kg DP)$^{-1}$	One piece referred to the primary and secondary packaging of 1 kg of dry pasta.
Materials/Assemblages			
Primary packaging Assembly	1	p (kg DP)$^{-1}$	This assembly was needed to define the end of life of both packages.
Secondary packaging Assembly	1	p (kg DP)$^{-1}$	

Table A.9
Assembly of dry pasta.

Parameters	Value	Unit	Comment
Output			
Pasta Assembly	1	p (kg DP)$^{-1}$	One piece referred to 1 kg of packed dry pasta.
Materials/Assemblages			
Pasta of Semolina of Durum Wheat production	1	kg DP	This process was described in Table S3.
Lubricating oil {RER}| production | Cut-off, U	0.000037	kg (kg DP)$^{-1}$	The specific consumption yields referred to the production of 1 kg of dry pasta and were derived from Table 1.4. The process concerning detergent production was extracted from the Ecoinvent v. 3.5 database.
Chlorine, liquid {GLO}| production | Cut-off, U	0.00002	kg (kg DP)$^{-1}$	
Processes			
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U	0.0111	kg km	The lubricating oil were transported to the pasta firm by medium-size trucks, the weighted average distance being 300 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U	0.01	kg km	The chlorine liquid was transported to the pasta firm by medium-size trucks, the weighted average distance being 500 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.

Table A.10
Inventory associated with the consumer use phase.

Parameters	**Value**	**Unit**	**Comment**
Output			
Cooked pasta	1	kg	It referred to the consumer use of 1 kg of dry pasta.
Scraps of cooked pasta	0.0198	kg	Pasta loss at the consumer phase was assumed of the order of 2% of the quantity cooked (UNAFPA, 2018).
Inputs			
Tap water {Europe without Switzerland}| tap water production, conventional treatment | Cut-off, U	10	kg	It referred to the amount of tap water used to cook 1 kg of dry pasta (UNAFPA, 2018).
Sodium chloride, powder {RER}| production | Cut-off, U	0.07	kg	It referred to the amount of table salt used to cook 1 kg of dry pasta (UNAFPA, 2018).
Electricity, low voltage {IT}| electricity voltage transformation from medium to low voltage | Cut-off, U	0.391	kWh	It referred to the energy consumed (17 % by electric hob) to boil 10 L of water and cook 1 kg of dry pasta for 10 min (UNAFPA, 2018).
Heat, from resid. heating systems from NG, consumption mix, at consumer, temperature of 55°C EU-27 S	1.91	kWh	It referred to the energy consumed (83 % by gas-fired hob) to boil 10 L of water and cook 1 kg of dry pasta for 10 min (UNAFPA, 2018).

Table A.11
Disposal scenario for plastic packaging wastes content in primary packaging.

Parameters	Value	Unit	Comment
Output			
Waste Scenarios Plastic (PR+SE)	1	kg	This was a unitary process allowing plastic packaging wastes to be disposed of after pasta consumption.
Disposal scenarios			
Waste polypropylene {CH}| treatment of, sanitary landfill | Cut-off, U	14	%	The Italian scenario for the disposal of plastic packaging wastes was derived from Hera Group (2018). The disposal processes were extracted from the Ecoinvent v.3.5 database.
Waste polypropylene {CH}| treatment of, municipal incineration | Cut-off, U	45	%	
PP (waste treatment) {GLO}| recycling of PP | APOS, U	41	%	

Table A.12
Disposal scenario for plastic packaging wastes (Plastic Waste - 100% Recycling).

Parameters	**Value**	**Unit**	**Comment**
Output			
Plastic Waste - 100% Recycling (PR+SE)	1	kg	This was a unitary process allowing the plastic packaging wastes arising from the pasta packaging in the factory.
Disposal scenarios			
PP (waste treatment) {GLO}| recycling of PP | APOS, U	100	%	The plastic packaging wastes were 100 % recycled, as derived from Table 1.9. The disposal processes were extracted from the Ecoinvent v. 3.5 database.

Table A.13
Disposal scenario for cardboard and paper content in secondary packaging.

Parameters	Value	Unit	Comment
Output			
Waste Scenario for Carboard (PR+SE)	1	kg	This was a unitary process allowing the cardboard packaging wastes after pasta consumption to be disposed of.
Disposal scenarios			
Waste paperboard {CH}| treatment of, sanitary landfill | Cut-off, U	11.8	%	The Italian scenario for the disposal of cardboard wastes was derived from Hera Group (2018). The disposal processes were extracted from the Ecoinvent v.3.5 database.
Waste paperboard {CH}| treatment of, municipal incineration | Cut-off, U	8.5	%	
Paper (waste treatment) {GLO}| recycling of paper | APOS, U	79.7	%	

Table A.14
Disposal scenario for cardboard packaging wastes (Cardboard Waste - 100% Recycling).

Parameters	Value	Unit	Comment
Output			
Cardboard Waste - 100% Recycling (PR+SE)	1	kg	This was a unitary process allowing the recycle of the cardboard packaging wastes formed during pasta packaging in the factory.
Disposal scenarios			
Paper (waste treatment) {GLO}| recycling of paper | APOS, U	100	%	The cardboard packaging wastes were 100 % recycled, as derived from Table 1.9. The disposal process was extracted from the Ecoinvent v.3.5 database.

Table A.15
End of life scenario for the primary and secondary packaging material wastes (End of Life (Primary+Secondary) Packaging).

Parameters	Value	Unit	Comment
Output			
End of Life (Primary+Secondary) Packaging	1	p (kg DP)$^{-1}$	It referred to the life cycle of dry pasta.
Reference Assembly			
Primary + secondary packaging	1	p	See Table A.8.
Processes			
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U	0.708	kg km	The plastic packaging wastes to be disposed of were transported from distribution centers or retailers to specific disposal centers, the weighted average distance being 50 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U	1.48	kg km	The paper and cardboard packaging wastes to be disposed of were transported from distribution centers or retailers to specific disposal centers, the weighted average distance being 50 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U	0.0216	kg km	The plastic packaging wastes were transported to be disposed of from the factory gate to specific disposal centers, the weighted average distance being 100 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U	0.0299	kg km	The cardboard packaging wastes were transported to be disposed of from the factory gate to specific disposal centers, the weighted average distance being 100 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.
Disposal scenarios			
Plastic Waste Scenarios (PR+SE)	31.991	%	The allocation percentages were calculated on the mass-based criterion (kg of waste per kg of dry pasta) (Table 1.9), while the disposal scenarios were described in Tables A.11-A.14, respectively.
Carboard Waste Scenarios (PR+SE)	66.846	%	
Plastic Waste - 100% Recycling (PR+SE)	0.488	%	
Cardboard Waste - 100% Recycling (PR+SE)	0.675	%	

Table A.16
Disposal scenario of wooden pallet wastes.

Parameters	**Value**	**Unit**	**Comment**
Output			
Waste Scenarios for Wood (Tertiary)	1	kg	This was a unitary process allowing damaged pallets at the distribution centers to be landfilled.
Disposal scenarios			
Waste wood, untreated {CH}| treatment of, sanitary landfill | Cut-off, U	100	%	The Italian scenario for the disposal of wood packaging wastes was derived from Table 1.9. The disposal process was extracted from the Ecoinvent v.3.5 database.

Table A.17
Disposal scenario for cardboard and paper content in tertiary packaging.

Parameters	Value	Unit	Comment
Output			
Waste Scenarios for Pallet Labels (Tertiary)	1	kg	This is a unitary process allowing the pallet label wastes to be disposed of.
Disposal scenarios			
Waste graphical paper {CH}| treatment of, sanitary landfill | Cut-off, U	11.8	%	The Italian scenario for the disposal of paper label wastes was derived from Hera Group (2018). The disposal processes were extracted from the Ecoinvent v. 3.5 database.
Waste graphical paper {CH}| treatment of, municipal incineration | Cut-off, U	8.5	%	
Paper (waste treatment) {GLO}| recycling of paper | APOS, U	79.7	%	

Table A.18
Disposal scenario for polyethylene film wastes from tertiary packaging.

Parameters	Value	Unit	Comment
Output			
Waste Scenarios Plastic (Tertiary)	1	kg	This was a unitary process allowing the polyethylene film packaging wastes to be disposed of.
Disposal scenarios			
Waste polyethylene {CH}| treatment of, sanitary landfill | Cut-off, U	14	%	The Italian scenario for the disposal of polyethylene film wastes was derived from Hera Group (2018). The disposal processes were extracted from the Ecoinvent v.3.5 database.
Waste polyethylene {CH}| treatment of, municipal incineration | Cut-off, U	45	%	
PE (waste treatment) {GLO}| recycling of PE | APOS, U	41	%	

Table A.19
End of life scenario for the tertiary packaging material wastes (End of Life (Tertiary) Packaging).

Parameters	Value	Unit	Comment
Output			
End of Life (Tertiary) Packaging	1	p (kg DP)$^{-1}$	It referred to the life cycle of dry pasta.
Reference Assembly			
Tertiary packaging Assembly	1	p	See Table A.7.
Processes			
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U	0.000774	kg km	The pallet paper label wastes to be disposal of were transported from the factory gate to specific waste disposal centers, the weighted average distance being 100 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U	0.0501	kg km	The polyethylene film wastes to be disposal of were transported from the factory gate to specific waste disposal centers, the weighted average distance being 100 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U	0.00133	kg km	The wooden pallet wastes to be disposal of were transported from the factory gate to Euro pallet managing centers, the weighted average distance being 105 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.
Disposal scenarios			
Waste Scenarios Plastic (Tertiary)	28.6367	%	The allocation percentages were calculated on the mass-based criterion (kg of waste per kg of dry pasta) (Table 1.9), while the disposal scenarios were described in Tables A.18, A.17 and A.16, respectively.
Waste Scenarios Paper Label (Tertiary)	0.4419		
Waste Scenarios for Wood (Tertiary)	0.0072	%	
Reuse			
Reuse pallet_Baronia	70.9142	%	See Table A.20.

Table A.20
Reuse phase of the wooden pallet (Pallet reuse).

Parameters	Value	Unit	Comment
Output			
Reuse pallet	1	p (kg DP)$^{-1}$	It referred to the reuse of the wooden pallet piece associated with 1 kg of packed dry pasta.
Reference Assembly			
Tertiary packaging Assembly	1	p	See Table A.7.
Processes			
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, U	0.993	kg km	The wooden pallets were sent from the Euro pallet managing centers to the factory gate, the weighted average distance being 800 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.

Table A.21
Life cycle of dry pasta.

Parameters	**Value**	**Unit**	**Comment**
Output			
LC Pasta	1	p	It referred to the life cycle of dry pasta.
Assembly			
Pasta Assembly	1	p (kg DP)$^{-1}$	See Table A.9.
Processes			
Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, U	958	kg km	The palletized pasta was transported from the factory gate to the distribution centers, this distance being 895 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U	104	kg km	The pasta cartoons were transported from the distribution centers to the retailers, the weighted average distance being 100 km (Table 1.8). Such a process was extracted from the Ecoinvent v. 3.5 database.
Cooking Phase_Baronia	1	kg	See Table A.10.
Disposal scenarios			
Supplementary life cycles			
LC Packaging	1		See Table A.22.

Table A.22.
Life cycle of the primary, secondary, and tertiary packaging materials.

Parameters	Value	Unit	Comment
Output			
LC Packaging	1	p	It referred to the life cycle of all the packaging materials used.
Assembly			
Primary + secondary packaging	1	p (kg DP)$^{-1}$	See Table A.8.
Processes			
Electricity, medium voltage {IT}| electricity voltage transformation from high to medium voltage | Cut-off, U	0.0698	kWh (kg DP)$^{-1}$	The energy needs to pack 1 kg of dry pasta were derived from Table 1.7, and the process was extracted from the Ecoinvent v. 3.5 database.
Disposal scenarios			
End of Life (Primary+Secondary) Packaging			See Table A.15.
Supplementary life cycles			
LC Packaging Tertiary	1		See Table A.23.

Table A.23
Life cycle tertiary packaging.

Parameters	**Value**	**Unit**	**Comment**
Output			
LC Tertiary packaging	1	p	It referred to the life cycle of the wooden pallet.
Assembly			
Tertiary packaging Assembly	1	p (kg DP)$^{-1}$	See Table A.7.
Disposal scenarios			
End of Life (Tertiary) Packaging			See Table A.19.

CONCLUSIONS

AND

FUTURE PERSPECTIVES

By referring to fully transparent primary and secondary data, the estimated business-to-business carbon footprint (CF_{CDC}) of dry short pasta made of decorticated organic durum wheat semolina as 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. 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, such life cycle phases resulted to be the primary hotspot. Depending on the short or long pasta type and packing formats used (namely, 0.5-kg PP bags or PB boxes, and 3-kg PE bags), 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}), the latter corresponding to long goods packed in 3-kg PE bags for catering service.

Three promising strategies might in principle be applied to reduce CF_{CG} by lowering the GHG emissions associated firstly with the pasta cooking phase, secondly with the field phase, and thirdly with the generation of the thermal and electric energy needed to manufacture dry pasta. In this way, the cradle-to-grave carbon footprint of dry organic pasta was reduced to as much as 0.675 kg CO_{2e} kg^{-1}. Changing of the final product transport modality from road to rail and shortening the supply logistics of dry pasta and grains resulted in further reduction of 5 % in $CF_{CG.}$ This explained why the delocalization of the Italian pasta production sites is not of prime importance yet.

To limit the high demand for water and energy of the home pasta cooking process, several tests were carried out to elucidate the effect of the cooking water-to-pasta ratio (WPR) on the instrumental and sensory characteristics of cooked pasta. The main chemico-physical (i.e., specific water uptake, starch gelatinization degree, and hardness) and sensory (e.g., Firmness, Stickiness, and Bulkiness) properties of cooked pasta were practically independent of WPR in the range of 3-10 L kg^{-1}, even if in the case of spaghetti WPR might be lowered to as low as 2 L kg^{-1}. An empirical relationship was thus established to estimate the minimum WPR as a function of the surface-to-volume ratio and specific water uptake of the pasta type undergoing cooking. Based on the eco-sustainable pasta cooking procedure so validated, it was possible to develop an Arduino®-based eco-sustainable pasta cooker (EPC), capable of cooking dry pasta with far smaller amounts of water and energy than those used in the most common kitchen appliances and, thus, mitigating the carbon footprint of pasta cooking.

By using the SimaPro software, it was possible to develop a business-to-consumer model of the life cycle of dry organic pasta and evaluate its environmental profile in compliance with the IMPACT 2002$^+$ methodology. The overall weighted damage score (OWDS) of dry pasta, amounting to 832±23 μpt kg^{-1}, was mainly affected by the damage category of “Ecosystem quality” (45.2 %), followed by that of “Climate change” (20.9 %), “Resource depletion” (20.0 %), and “Human health” (13.9 %). Use of the eco-sustainable pasta cooker allowed the cradle-to grave carbon footprint of dry organic pasta to be reduced to 1.61±0.17 kg CO_{2e} kg^{-1}, and its OWDS to 764±22 μpt.

Since the characterization of the environmental profile of a single product is quite expensive, and the climate change impact category is by far more reliable than all the other ones accounted for in this PhD thesis, the carbon footprint assessment seems to be the cheaper tool to identify the major hotspots of the product life cycle stages. Thus, it is probably the best method to start improving the sustainability of the EU small- and medium-sized enterprises, equaling to 99 % of the EU food and beverage companies.

To reduce the energy consumption and improve the environmental performance of dry pasta, future research activities should firstly explore the organic farming potentials to increase organic durum wheat yields, and secondly drive the pasta manufacturers to evaluate if novel pre-gelatinized pasta products might be a feasible option. Finally, it is high time for the pasta makers to start selling not only pasta products, but also their specialized pasta cookers in order to allow even unskilled pasta cooks to prepare high quality cooked pasta in a very reproducible and quick way with as small as possible environmental impact.

Finally, the scope of this LCA entailed a number of limitations that might be improved by further studies, namely a systematic description of waste packaging recycling in accordance with the allocation at the point of substitution system model, an improved data quality assessment, a systematic uncertainty analysis, and a detailed modeling of the direct impacts of poultry manure on field direct and indirect N_2O emissions, durum wheat and fodder legume yields per hectare and, consequently, on climate change, eutrophication, human toxicity, ecotoxicity and especially land use that had a prevailing impact on the damage to the ecosystem quality.

NOMENCLATURE

1PEoL	Primary packaging end of life.
2-3PEoL	Secondary and tertiary packaging end of life
A	Acidification
AA	Aquatic acidification
A_A	Energy to pull the compressing probe away from the spaghetti strands after a 30% compression [J]
A_{Clp}	Downstroke energy to compress the spaghetti strands by 30% of their initial diameter [J]
A_{Csp}	Downstroke energy to compress the pasta pieces by 40% of their initial thickness [J]
A_{Dlp}	Upstroke energy to decompress the 30%-compressed spaghetti strands [J]
A_{Dsp}	Upstroke energy to decompress the 40%-compressed cooked pasta pieces [J]
AE	Aquatic eco-toxicity
AG_{DM}	Above ground residues [kg ha^{-1}]
AN	Ammonium nitrate
ANP	Aquatic eutrophication
AT	Articulated truck
B2B	Business-to-business
BC	Byproduct credit
BG_{DM}	Below ground residues [kg ha^{-1}]
b_R	Rib base [mm]
C	Carcinogens
CA	Cartons [kg]
CAL	Carton labels [kg]
CALW	Carton label waste [kg]
CAW	Carton waste [kg]
CC	Climate Change
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_{CG}	Cradle-to-grave carbon footprint of dry pasta [kg CO_{2e} kg^{-1}]
CF_{CG}	Cradle-to-grave carbon footprint of a functional unit [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}]
CF_{PC}	Carbon footprint of pasta cooking [kg CO_{2e} kg^{-1}]
CHP	Combined heat and power system
CL	Cooking loss [g g^{-1}]
COD	Chemical Oxygen Demand
COD_S	Chemical Oxygen Demand of starch [g O_2 g^{-1}]
CP	Consumer phase
c_{pi}	Specific heat of the i-th component [kJ kg^{-1} K^{-1}]
CQ	Overall cooking quality [dimensionless]
c_S	Starch content in pasta water [g L^{-1}]
CV	Coefficient of variation [%]
CW	Cooking water
D	Pasta dough [kg]
DALY	Disability-adjusted life years
DC	Distribution center
DCE	Distribution center
d_{CP}	Cooked spaghetti diameter [mm]
DCz	Generic z-th damage category
DDWK	Decorticated durum wheat kernels [kg]
df	Degree of freedom
d_i	Internal diameter of each pasta piece [mm]
DIW	Water used to prepare the dough [kg]
DKC	Cleaning Dockage [kg]
DKPC	Pre-cleaning Dockage [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]

d_{Rb}	Tube diameter at the base of each rib [mm]
d_{RP}	Raw spaghetti diameter [mm]
d_{Ru}	External diameter of each pasta piece [mm]
D_W	Water diffusivity [m^2 s^{-1}]
DW	Durum wheat [kg]
DWLS	Local supply of durum wheat [km]
DWS	DW semolina [kg]
DWSD	DW supply distance [km]
$e_{C,nom}$	Nominal power supplied per unit mass of the water-pasta suspension undergoing cooking [W kg^{-1}]
e_{CE}	Effective power supplied per unit mass of the water-pasta suspension undergoing cooking [W kg^{-1}]
E_{cons}	Energy effectively consumed to cook pasta [kJ]
E_e	Electric energy
EE	Electric energy
EF_1	N_2O-N emissions per N fertilizer mass [kg N_2O-N (kg N)$^{-1}$]
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 NH_3-N+kg NO_x-N-emitted)$^{-1}$]
EF_5	N_2O-N emissions per unit mass of N leached off [kg N_2O-N (kg N leaching off)$^{-1}$]
EF_{EE}	Emission factor for the electric energy distributed at the Italian grid, inclusive of non-renewable and renewable sources [g CO_{2e} kWh^{-1}]
EF_i	Emission factor for the generic i-th activity, expressed in [kg CO_{2e} kg^{-1}], [kg CO_{2e} kWh^{-1}] or [kg CO_{2e} Mg-1 km^{-1}]
EF_{TW}	Emission factor for tap water utilization [g CO_{2e} L^{-1}]
EF_{WD}	Emission factor for wastewater disposal [g CO_{2e} L^{-1}]
EoL	End-of-life
EoLPM	End of life of packaging material wastes.
e_{PA}	Specific energy consumed per unit mass of dry pasta [Wh g^{-1}]
$e_{PA,\ eff}$	Specific energy effectively consumed per unit mass of dry pasta [Wh g^{-1}]
E_{PC}	Effective energy consumed to cook pasta, as defined by Eq. (2.11) [kWh]
EPC	Eco-sustainable pasta cooker

EPD	Environmental Product Declaration
EPMC	Euro pallet managing center
EQ	Ecosystem Quality damage category
E_{RC}	Energy dissipated by radiation, convection and conduction from the pan and heating source [kJ]
E_S	Energy supplied by the induction hob to cook pasta [kJ]
ESCP	Eco-sustainable cooking procedure
ET	Thermal energy
ETBG	Thermal energy from biogas
E_{th}	Energy theoretically consumed to cook pasta [kJ]
EV	Water evaporated during dough extrusion [kg]
F_{30}	Cooked pasta hardness at 30% deformation (first bite) [N]
F_{40}	Cooked pasta hardness at 40% compression (first bite) [N]
F_{90}	Cooked pasta hardness at 90% deformation (second bite) [N]
F_{98}	Cooked pasta hardness at 98% compression (second bite) [N]
FCR	Specific N content of crop residues [kg N ha-1 yr-1]
FDF	First debranning fraction [kg]
FDF	First decortication fraction [kg]
FI	Field phase
Fi,j	Generic i-th characterization factor of the j-th impact category
Fo_h	Heat Fourier number of cooked pasta (=α t/sCP2) [dimensionless]
Fo_m	Mass Fourier number of cooked pasta (=D_W t/sCP2) [dimensionless]
FP	Field phase
$Frac_{GASF}$	NH_3- and NO_x-emissions per unit N fertilizer mass [kg NH_3-N+NO_x-N (kg N)$^{-1}$]
$Frac_{LEACH}$	N leaching off per unit N fertilizer mass [kg N (kg N)$^{-1}$]
F_{SN}	Specific N content of organic fertilizer [kg N ha-1 yr^{-1}]
FW	Field management
GB	Grinding bran particles [kg]
GHG	Greenhouse gas
GW	Global warming
GWP	Global Warming Potential

GWP_{EE}	Emission factor referred to the average Italian thermo-electric production from non-renewable and renewable sources [kg CO_{2e} kWh^{-1}]
GWPj	Global warming potential of the j-th GHG [kg CO_{2e} kg^{-1}]
H_{CPb}	Enthalpy of cooked pasta at T_b [kJ]
HERS	High-extraction rate semolina [kg]
HH	Human Health damage category
H_{PA}	Enthalpy of raw pasta at T_0 [kJ]
H_{PLS}	Enthalpy of the pan, lid and stirrer at T_0 [kJ]
$H_{PLSb,}$	Enthalpy of the pan, lid and stirrer at T_b [kJ]
h_R	Rib height [mm]
HRT	Heavy rigid truck
H_{W0}	Enthalpy of cooking water at T_0 [kJ]
H_{WEb}	Enthalpy of water evaporated at T_b [kJ]
H_{WFb}	Enthalpy of pasta water at T_b [kJ]
ICj	Generic j-th impact category
IPCC	Intergovernmental Panel on Climate Change
i_R	Rib hypotenuse [mm]
IR	Ionizing radiation
ISS	Impurities, stones, and straw [kg]
KW	Pasta dough discarded during kneading [kg]
LCA	Life-cycle assessment
LCP	Life cycle phase
LO	Land occupation
L_p	Length of each pasta piece [mm]
LP	Long extruded pasta
m	Mean value
MAL	Multiple axle lorry
m_{CPA}	Mass of cooked pasta [kg]
ME	Mineral extraction
m_i	Amount of the i-th component used to cook pasta [kg]
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 Eq. (1.2) [dimensionless]
MLBF	Milling light branny fraction [kg]
m_p	Mass of each pasta piece [kg]
m_{PA}	Mass of dried pasta [kg]
m_{PLS}	Mass of the pan, lid and stirrer [kg]
m_{T0}	Overall mass of the pasta-water mixture (= m_{PA}+m_{W0}) [kg]
m_{W0}	Initial mass of cooking water [kg]
m_{WAF1}	Mass of cooking water adiabatically flashed before dried pasta addition [kg]
m_{WAF12}	Mass of cooking water adiabatically flashed anytime the pan was unlidded [kg]
m_{WAF2}	Mass of cooking water adiabatically flashed as the lid was removed at the end of pasta cooking [kg]
m_{WBP}	Mass of cooking water at its boiling point [kg]
m_{WE}	Mass of water evaporated, as defined by Eq. (2.6) [kg]
m_{Wf}	Mass of pasta water [kg]
m_{WLO}	Cooking water mass as soon as the pan has been unlidded [kg]
m_{WPA}	Mass of water adsorbed by dry pasta [kg]
n	Number of cooking tests performed [dimensionless]
NC	Non-carcinogens
n_p	Overall number of pasta pieces in a given amount of raw pasta [dimensionless]
NP	Eutrophication
NP_{PC}	Nutrification effect score of pasta cooking [g PO_4^{3-} kg^{-1}]
NP_{WD}	Nutrification potential associated to the disposal of wastewaters having a given COD [g PO_4^{3-} kg^{-1} O_2]
n_R	Number of ribs per each pasta piece [dimensionless]
NMVOC	Non-methane volatile organic compound
NRE	Non-renewable energy
OLD	Ozone layer depletion

On-FE	On-field emissions
ORCS	Organic rotation cropping system
OWDS	Overall weighted damage score [μpt]
P	Pesticides
p	Piece of a pallet associated with the functional unit of choice
PaM	Packaging materials
P_C	Power supplied by the induction hob during pasta cooking [kW]
P_S	Power supplied by the induction hob [kW]
PAS	Publicly Available Specification
PB	Paperboard box [kg]
PC	Pasta cooking (consumer phase)
PCDW	Precleaned DW [kg]
PCF	Product Carbon Footprint
PDF	Potentially disappeared fraction of biological species
PDISTR	Final product distribution
PE	Polyethylene
PEE	Photovoltaic electric energy
PEF	Product Environmental Footprint
P_H	Power supplied by the induction hob during cooking water heating [kW]
PM	Packaging manufacture
PMP	Packaging material production
POCP	Photochemical ozone creation potential
PP	Polypropylene
PPACK	Pasta packaging
PPB	Paperboard box.
PPB	PP bag or paperboard box [kg]
PPDD	Palletized pasta delivery distance [km]
PPP	Pasta production and packaging
PPR	Pasta production
PPTM	Palletized pasta transport modality
PPW	PP bag or paperboard box wastes [kg]
pr	Probability level

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]
PW	Process water
PWM	Processing waste management
Q	Thermal energy
Q_{COD}	Specific COD load of pasta water [g O_2 kg^{-1}]
Q_e	Specific electric energy consumption [kWh Mg^{-1}]
Q_T	Specific thermal energy consumption [kWh Mg^{-1}]
r^2	Coefficient of determination
R_{BG-BIO}	Below ground-to above-ground biomass ratio [dimensionless]
RC	Reference case
R_{CP}	Cooked pasta resilience (=A_D/A_C) [dimensionless]
RD	Resource Depletion damage category
RI	Respiratory inorganics
RICPM	Relative increase in cooked pasta mass [g g^{-1}]
RO	Respiratory organics
RT	Light-medium rigid truck
RWDWS	Recombined whole durum wheat semolina [kg]
SC	Carton scotch tape [kg]
s_{CP}	Cooked pasta thickness [mm]
SCW	Carton scotch tape waste [kg]
sd	Standard deviation
SDF	Secondary decorticatin fraction [kg]
s_F	Water layer thickness [dm]
SGD	Degree of starch gelatinisation [%]
S_p	External surface of each pasta piece [dm^2]
SP	Short-cut extruded pasta
SSP	Single superphosphate

SSz	Single damage score of the z-th damage category
t	Cooking time [s]
T_0	Initial temperature [° C]
TA	Texture analysis
TANP	Terrestrial acidification/nutrification
T_b	Boiling point of water [° C]
t_C	Cooking time [s]
TE	Terrestrial eco-toxicity
TEG	Triethylene glycol
TOM	Total organic matter [g kg^{-1}]
TR	Transportation
t_{Rb}	Below rib thickness [mm]
TRf_p	Transport of final product
TR_{paw}	Transport of packaging and auxiliary materials, and wastes
t_{Ru}	Above rib thickness [mm]
TS	Table salt [kg]
TW	Tempering Water [kg]
T_{WM}	Temperature of cooking water at mid-height [°C]
U	Urea
V_c	Overall volume of all the internal cavities of each pasta piece [L]
V_W	Minimum volume of water needed to cook homogeneously cooked pasta [L]
WCC	Waste collection center
WCDW	Wet cleaned durum wheat [kg]
WDP	Wet extruded product [kg]
WDSz	Weighted damage score of the z-th damage category [μpt]
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-to-pasta ratio [L kg-^{1}]
WPR^{*}	Effective minimum cooking water-to-pasta ratio [L kg^{-1}]
WPR_{min}	Minimum cooking water-to-pasta ratio [L kg^{-1}]
WPW	Wooden pallet waste [kg]
WU	Relative increase in cooked pasta mass [g g^{-1}]
X_i	Generic i-th independent variable
X_{iR}	Reference value for any generic i-th variable X_i
x_{PR}	Raw spaghetti protein content [g/100 g]
x_S	Mass fraction of starch in raw pasta [g g^{-1}]

Greek Symbols

α	Empiric coefficient [kW]
α	Thermal diffusivity of cooked pasta [m^2 s^{-1}]
β	Empiric constant [kW]
ΔCF_{CG}	Relative variation of CFCG with respect to the reference value (=CF_{CG}-CF_{CGR}) [kg CO_{2e} kg^{-1}]
ΔH_{gel}	Gelatinisation enthalpy of wheat starch [kJ kg^{-1}]
ΔX_i	Relative variation of each independent parameter Xi with respect to the corresponding reference value (X_{iR})
η_C	Energy efficiency of the cooking system [%]
η_{IG}	Electric energy loss of the Italian grid [%]
η_{WAF1}	Fraction of water adiabatically flashed as the lid is firstly removed to add dried pasta (=m_{WAF1}/m_{W0}) [dimensionless]
η_{WAF12}	Fraction of water adiabatically flashed when the pan is unlidded (=$m_{WAF1}+m_{WAF2}$) [dimensionless]
η_{WAF2}	Fraction of water adiabatically flashed as the lid is newly removed to recover cooked pasta (=m_{WAF2}/m_{W0}) [dimensionless]
η_{WE}	Fraction of water evaporated (=m_{WE}/m_{W0}) [dimensionless]
η_{Wf}	Fraction of pasta water (=m_{Wf}/m_{W0}) [dimensionless]

η_{WPA}	Fraction of water adsorbed by cooked pasta ($=m_{WPA}/m_{W0}$) [dimensionless]
ρ_W	Water density [kg L^{-1}]
Ψ_i	Entity of the i-th activity [kg, J or Mg km]

Subscripts

C	Referred to the pasta cooking phase
E	Referred to water evaporated
H	Referred to the heating phase of the cooking water
L	Referred to lid
P	Referred to pan
PA	Referred to dried pasta
W	Referred to cooking water
0	Initial

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