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Fresh *versus* Dry Pasta: What is the Difference in their Environmental Impact?

Alessio Cimini, Mauro Moresi*

Department for Innovation in the Biological, Agrofood and Forestry Systems, University of Tuscia, Viterbo, Italy
mmoresi@unitus.it

In this work, the cradle-to-grave environmental profile of a not-stuffed, egg-free fresh pasta was assessed and compared to that of a conventional durum wheat semolina dry pasta by using a well-known life-cycle assessment software in compliance with the Product Environmental Footprint standard method. Both products made use of national common bread or durum wheat grains, were manufactured in Italian small- and medium-sized pasta factories and were packed in 0.5-kg plastic bags. Whereas dry pasta production was characterized by a cradle-to-grave carbon footprint (CF_{B2C}) of 1.88 kg CO_{2e}/kg and an overall weighted eco-indicator (EI) of 141 µPt/kg, fresh pasta manufacture was distinguished by a CF_{B2C} of 2.59 kg CO_{2e}/kg and an EI of 236 µPt/kg. Their different environmental impact mainly derives from the refrigerated transport of fresh pasta, its moisture content (24% w/w) being quite the double of that of dry pasta (12.5% w/w), and chilled preservation till final consumption. Even if the use of new smart energy-saving home appliances might mitigate the overall environmental impact of both products, the consumption of dry pasta instead of fresh pasta is more eco-sustainable, mainly because it is shelf-stable and needs no refrigerated supply chain.
KEYWORDS: Carbon footprint, fresh and dry pasta, LCA, Product Environmental Footprint, sensitivity analysis.

1. Introduction

In Italy, fresh pasta may be produced by mixing common bread flour or durum wheat semolina with water and/or eggs and may contain several stuffing ingredients. Its moisture content (x_W) should be greater than 24% (w/w), its water activity (a_W) range from 0.92 to 0.97. After having been pasteurized, it is packed in modified atmosphere, and stored at 4 ± 2 °C to assure a shelf-life of 60 days from the date of production (DPR, 2001). All-purpose bread wheat flour and eggs are its basic ingredients in Northern Italy, while standard semolina and water those mainly used in Southern Italy. In 2019, the total turnover of pasta production in Italy was near to 4.8 billion Euro (Italianfood.net, 2021). Dry pasta accounted for 86% of total pasta production compared to fresh pasta (11%) and frozen pasta (~3%) (Ruffo, 2017). In 2021, fresh pasta business in Italy was up to 890 million Euro owing to the increasing demand from restaurants, hotels, pubs, and households (Soressi, 2021).Whereas the environmental impact of dry pasta has been assessed by several authors, namely Bevilacqua et al. (2007), Cibelli et al. (2021), Cimini et al. (2019), Röös et al. (2011) and Zingale et al. (2022), that of any fresh pasta type is still to be evaluated, except for the cradle-to-grave environmental profile of a novel high-amylose bread wheat fresh pasta with low glycaemic index (Cimini et al., 2022a).The aim of this work was to compare the cradle-to-grave environmental profile of a not-stuffed, egg-free fresh pasta to that of a conventional durum wheat semolina dry pasta by using a well-known life-cycle assessment software and the Product Environmental Footprint standard method (EC, 2018).

2. Methodology

The life-cycle analysis was ISO-compliant (ISO, 2006ab). Its goal was to compare the environmental profile of 1 kg of fresh pasta made of common bread wheat (CBW) flour (as packed in 0.5-kg polyethylene, PE, bags under modified atmosphere, and produced from a small-sized pasta factory located in Central Italy) to that of 1 kg of dried pasta made of conventional durum wheat (DW) semolina (as packed in 0.5-kg polypropylene, PP, bags, and produced from a medium-sized pasta factory located in Northern Italy, as described previously by

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Cimini et al., 2021), as well as to identify their main life-cycle hotspots. Figure 1 shows the system boundaries examined. The upstream processes consisted of CBW or DW cultivation, production of seeds, fertilizers, pesticides, lubricants, and packaging materials, and accounted for the diesel fuel used in the agricultural treatments. The core processes included the bulk transportation of CBW or DW grains to the mill to obtain CBW flour or DW semolina. The milling step was carried out in the dried pasta factory, while it was external to the fresh pasta one. Thus, a further transportation step was needed. All packaging materials were transported to both pasta factories. As soon as extruded, fresh pasta was pasteurized, partially dried up to $x_W \geq 24\%$ (w/w), cooled at 4-6 °C, packed in 500-g PE bags under modified atmosphere using a mixture of food-grade N_2 and CO_2, and stored in refrigerated cells. Instead, dried pasta had a final moisture content lower than 12.5% (w/w). Palletized fresh or dried pasta was transported to distribution centers and retailers using refrigerated or conventional lorries, respectively. All processing wastes and by-products were disposed of as municipal solid waste (MSW). The downstream processes included the pasta cooking step and disposal of all post-consumption wastes (i.e., cooked pasta and packaging wastes) as MSW. As concerning the inventory analysis, the so-called primary data (e.g., input resources and outputs, transport modality and distances travelled) were respectively extracted from Cimini et al. (2022a) or Sgambaro (2014), whereas the secondary data derived from the Ecoinvent v. 3.8 or v. 3.5 database using the allocation, cut-off system model, which was incorporated into the LCA software Simapro (Prè Consultants, Amersfoort, NL), and other technical reports, as detailed below.

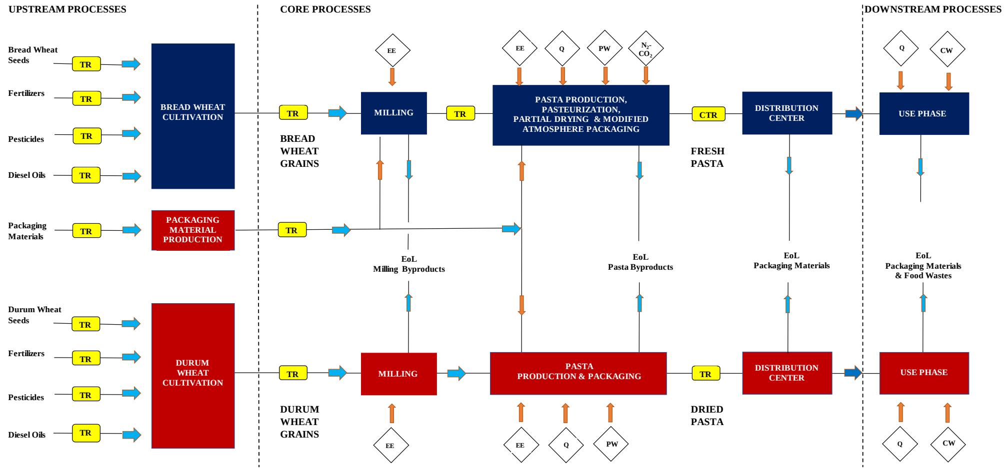

Figure 1: Fresh or dried pasta system boundary including the upstream, core and downstream processes: CTR, chilled transport; CW, cooking water; EE, electric energy; EoL, end of life; PW, process water; Q, thermal energy; TR, transport.

Table 1 summarized all agricultural practices and main processing parameters. All the emissions from fertilized soils were estimated using the recently updated IPCC Guidelines (Hergoualc'h et al., 2019), while the allocation factors for CBW or DW grains, straw and below ground residues, flour or semolina and milling byproducts, as well as fresh or dry pasta wastes, were estimated as suggested by UNAFPA (2018). Conventional milling of 1 kg of DW gave rise about 0.71 kg of semolina (Sgambaro, 2014), while that of common bread wheat yielded 73% of flour type 00 (Kanojia et al., 2018). The primary, secondary, and tertiary packaging of fresh or dry pasta consisted of 500-g PE or PP bags, paper-labelled cartons, and wooden pallets wrapped using PE stretch films. The energy and water requirements for cooking raw dried or fresh pasta were extracted from UNAFPA (2018) and EPD® (2022). All packaging wastes were disposed of according to the Italian waste management scenarios (Cimini et al., 2022a). The environmental impact was assessed using SimaPro 9.3.0.3 software (PRé Consultants, Amersfoort, NL) and the EF 3.0 method (adapted) v. 1.02, IPCC 2013 and IPCC 2021 characterization methods. Whereas the IPCC methods account for just the single environmental impact category (IC) of Climate Change using the Global Warming Potentials over a 100-yr time horizon, the EF 3.0 method is the Product Environmental Footprint (PEF) and accounts for the following 16 impact categories: Climate Change (expressed in kg CO_{2e}), Ozone Depletion (kg CFC-11_e), Ionizing Radiation-human health" (kBq $^{235}U_e$), Photochemical Ozone Formation (kg $NMVOC_e$), Particulate Matter (disease inc.), Human Toxicity, Non-Cancer (CTU_h), Human Toxicity, Cancer (CTU_h), Acidification (mol H^+_e), Freshwater Eutrophication (kg P_e), Marine Eutrophication (kg N_e); Terrestrial Eutrophication (mol N_e), Freshwater Eco-Toxicity (CTU_e), Land Use (Pt), Water Scarcity (m^3 depriv.), Resource Use-Fossils (MJ) and Resource Use-Mineral and Metals (kg Sb_e). These mid-point ICs may be normalized with respect to their global impacts (Sala et al., 2017) and weighted (Sala et al., 2018) to obtain an overall weighted eco-indicator (EI), the human and eco-toxicity ICs being discarded for their low robustness (UNAFPA, 2018).

Table 1: Input and output data of the main life cycle phases of durum wheat (DW) semolina dried pasta or common bread wheat (CBW) flour fresh pasta, as extracted from Sgambaro (2014) and Cimini et al. (2022), respectively: EP, end product.

Life Cycle Phase	*Input/Output Data*	DW	CBW	Unit
Field	NH_4NO_3 (N: 26%)	400	150	kg ha^{-1} yr^{-1}
	Urea (N: 46%)	100	150	kg ha^{-1} yr^{-1}
	$(NH_4)_2HPO_4$ (N: 18%, P_2O_5: 46%)	-	200	kg ha^{-1} yr^{-1}
	$Ca(H_2PO_4)_2$ (P_2O_5: 19%)	250	-	kg ha^{-1} yr^{-1}
	Wheat seed	200	250	kg ha^{-1} yr^{-1}
	Pesticides	3.25	1.8	kg ha^{-1} yr^{-1}
	Fuel diesel	130	70	L ha^{-1} yr^{-1}
	Grains	6100	7260	kg ha^{-1} yr^{-1}
	Straw	6038	12400	kg ha^{-1} yr^{-1}
Milling	Grains	6100	7260	kg ha^{-1} yr^{-1}
	Electricity energy	0.088	0.147	kWh/kg grains
	Thermal energy	0.0012	-	MJ/kg grains
	Water	0.435	0.033	kg/kg grains
	Kraft Paper bags	-	4.64	g/kg EP
	Durum wheat semolina	4442	-	kg ha^{-1} yr^{-1}
	Bread wheat flour	-	5300	kg ha^{-1} yr^{-1}
	Milling by-products	1658	2210	kg ha^{-1} yr^{-1}
Pasta production	Water	1.810	0.221	kg/kg EP
	Electric energy	0.179	0.221	kWh/kg EP
	Thermal energy	2.278	0.288	MJ/kg EP
	Sodium chloride	0.016	-	g/kg EP
	Lubricating oil	0.062	0.029	g/kg EP
	Chlorine liquid	0.105	0.016	g/kg EP
	Liquid nitrogen	-	10	g/kg EP
	Liquid carbon dioxide	-	5	g/kg EP
	Dry pasta	3558	-	kg ha^{-1} yr^{-1}
	Fresh pasta	-	5980	kg ha^{-1} yr^{-1}
	Pasta by-products	0.2482	19.6	g/kg EP
	Wastewaters	0.0026	0.00007	m^3/kg EP
	Municipal solid waste	0.0041	0.0062	kg/kg EP
Primary Packaging	Polypropylene bags	12.21	-	g/kg EP
	Polyethylene bags	-	31.4	g/kg EP
Secondary Packaging	Corrugated board box	42.98	93.3	g (kg FP)$^{-1}$
Tertiary Packaging	EUR-flat pallet	0.0083	0.0917	kg/kg EP
	Polyethylene film	1.66	2.85	g/kg EP
	Paper label	1.03	0.026	g/kg EP
Pasta assembly	Electric energy	0.03732	-	kWh/kg EP
Use	Pasta cooking time	10	3.5	min
	Water	10	10	L/kg EP
	Thermal energy	2.8	1.976	kWh/kg EP
	Table salt	-	100	g/kg EP
	Electric energy (Refrigerator)	-	2.46	kWh/kg EP
	Cooked pasta waste	-	0.02	kg/kg EP

3. Results and Discussion

3.1 Carbon footprint of common bread and durum wheat grains

Figure 2 shows the specific contribution of the emissions resulting from the use of seeds, fertilizers, pesticides, diesel fuel and lubricant oil, crop residues, and transportation to the overall carbon footprint of common bread wheat (CBW) production. In this case, the direct and indirect greenhouse gas (GHG) emissions (FE) represented the primary hotspot (50%), fertilizer production the secondary one (32%), seed cultivation the third one (8%), transportation the fourth one (7.0%), diesel fuel and lubricant oil consumption for management practices the fifth one (2%), and pesticide production the sixth one (1%). Thus, the overall GHG emissions allocated to CBW grains amounted to 299±44 g CO_{2e}/kg, while those pertaining to DW grains were near to 408 g CO_{2e}/kg (Cimini et al., 2021). Both these carbon footprint scores at the farm gate appeared to be in line with those estimated for conventional non-irrigated (319 g CO_{2e}/kg) or irrigated (264 g CO_{2e}/kg) wheat grain by the World Food LCA database, and for conventional durum wheat grain as averagely cultivated in France (405 g CO_{2e}/kg according to the Agribalyse v. 3.0.1 database), or in Italy (430 g CO_{2e}/kg according to the World Food LCA database). The crop rotation test performed in 13 farms located in the main Italian durum wheat cultivation areas resulted in carbon footprint scores increasing from 440 to 540 g CO_{2e}/kg as the crop yield reduced from 7.4 to 4.22 Mg/ha (Ruini et al., 2013).

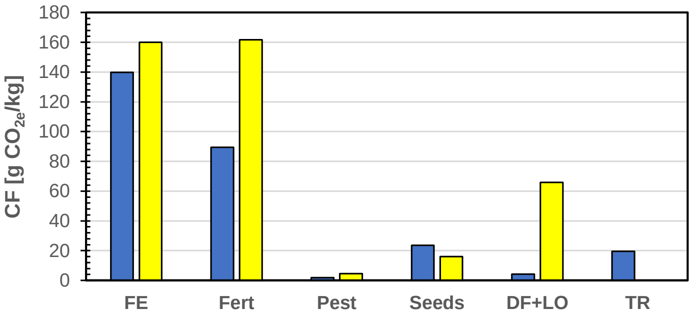

Figure 2: Contribution of the different life cycle stages to the overall carbon footprint of common bread (blue bars) and durum wheat (yellow bars): FE, field emissions; Fert, fertilizers; Pest, pesticides; Seeds, grain seeds; DF+LO, diesel fuel and lubricant oil; TR, transportation.

Table 2: Environmental profile of 1 kg of fresh pasta (this work) or conventional dried pasta (Cimini et al., 2021), as estimated using the PEF standard method: Percentage contribution of the three most impacting life cycle phases (i.e., field, FP; packaging material production, PMP; and pasta use, PU, phases), and score of each mid-point impact category (IC_j).

LC phase contribution **Impact category IC_j**	**FP** (%)	**PMP** (%)	**PU** (%)	**IC_j Score**	**Unit**	**IC_j Score**	**FP** (%)	**PMP** (%)	**PU** (%)
	Fresh Pasta					*Dried Pasta*			
Climate Change (GW_{100})	11	13	62	2.59	kg CO_{2e}	1.88	34	4	41
Ozone Depletion	9	9	68	2.97×10^{-7}	kg CFC-11_e	1.74×10^{-7}	22	3	45
Ionizing Radiation, Human Health	3	23	64	2.79×10^{-1}	kBq $^{235}U_e$	7.05×10^{-2}	21	10	17
Photochemical Ozone Formation-HH	17	20	51	6.00×10^{-3}	kg $NMVOC_e$	4.07×10^{-3}	47	7	18
Particulate Matter	15	38	35	8.14×10^{-8}	disease inc.	5.00×10^{-8}	62	10	8
Human Toxicity, Non-Cancer	12	19	59	2.36×10^{-8}	CTU_h	1.16×10^{-7}	35	11	33
Human Toxicity, Cancer	11	21	60	9.54×10^{-10}	CTU_h	1.08×10^{-8}	49	7	32
Acidification	26	14	51	1.21×10^{-2}	mol H^+_e	6.64×10^{-3}	45	5	14
Eutrophication Freshwater	36	19	40	8.18×10^{-4}	kg P_e	3.01×10^{-4}	62	9	12
Eutrophication Marine	47	12	27	4.17×10^{-3}	kg N_e	2.08×10^{-3}	58	5	16
Eutrophication Terrestrial	29	17	43	2.40×10^{-2}	mol N_e	2.16×10^{-2}	51	4	9
Ecotoxicity Freshwater	11	22	58	3.35×10^{1}	CTU_e	9.26×10^{-1}	38	8	27
Land Use	83	12	4	139	Pt	296	102	2	0.1
Water Scarcity	24	15	55	1.64	m^3 depriv.	4.23×10^{-1}	51	8	0.1
Resource Use, Fossils	6	18	66	37.3	MJ	21.9	18	8	51
Resource Use, Minerals And Metals	13	11	72	1.61×10^{-5}	kg Sb_e	2.16×10^{-6}	72	4	13

3.2 Environmental profile of fresh pasta

Table 2 compares the mid-point impact categories (IC) of one functional unit of fresh pasta to those of a conventional semolina dry pasta (Cimini et al., 2021). The field phase was found to affect mostly the impact categories of Land use and Marine Eutrophication, the packaging material manufacture mainly contributed to the IC of Particulate Matter. Then, the use phase considerably influenced the ICs of Resource Use - Minerals and Metals, Ozone Depletion, Resource Use-Fossils, Ionizing Radiation, Climate Change, Carcinogenic and Non-Carcinogenic Human Toxicity, and so on. In the case of dried pasta, the field phase greatly influenced not only the IC of Land Use and Marine Eutrophication, but also those of Resource Use - Mineral and Metals, Particulate Matter, Freshwater, Marine, and Terrestrial Eutrophication, and Water Scarcity. Like fresh pasta, the use phase of dried pasta had a prevailing impact on the ICs of Resource Use - Fossils, Ozone Layer Depletion, and Climate Change. Probably, because of the lower durum wheat grain yield per hectare (Table 1), the contribution of the field phase was higher than that of the use phase. On the contrary, the use phase of fresh pasta exerted a much greater impact than the field one owing to its compulsory refrigerated storage and transportation. Similarly, the packaging material manufacture was more impacting because fresh pasta was packed in thicker PE bags under modified atmosphere. By referring to global warming only, fresh pasta was characterized by a cradle-to-grave carbon footprint of 2.05 kg CO_{2e}/kg, while that of dried pasta was about 1.88

kg CO_{2e}/kg (Table 2).The end-point characterization of the environmental profile of fresh and dried pasta in conformity with the PEF method is shown in Table 3. The overall weighted single score (EI) amounted to about 236 micropoints (µPt) per kg of fresh pasta and to ~141 µPt per kg of conventional semolina dried pasta (Cimini et al., 2021). Whereas the former was firstly affected by the fresh pasta use phase (54.5%) and secondly by the agricultural one (19.4%), such hotspots for dried pasta reverted (Table 3) for the same reasons mentioned above.

Table 3: End-point characterization of the environmental profile of 1 kg of dried or fresh pasta according to the PEF standard method: percentage contribution of the different life cycle stages, and overall weighted score EI.

Product	**Life Cycle Phase Contribution (%)**									**EI**
	FP	MI	PMP	PPR	PPACK	PDISTR	PU	CPW	EoLPM	[μPt]
Fresh pasta	*19.35*	1.94	16.29	2.81		3.71	**54.46**	0.55	0.89	235.6
Dry pasta	**44.50**	6.36	5.50	11.81	1.06	4.17	*29.90*	*	-3.30	141.3

FP, field phase; MI, milling; PMP, packaging material production; PPR, pasta production; PPACK, pasta packaging; PDISTR, pasta distribution; PU, pasta use; CPW, cooked pasta waste; EoLPM, end of life of packaging waste. *, disregarded.

3.3 Options to reduce the environmental profile of fresh pasta and future perspectives

As shown in Table 3, any mitigation option should aim to reduce the contribution of the use phase firstly, followed by that of the CBW cultivation and packaging material manufacture.To relieve the use phase impact, two different actions might be adopted. Firstly, the gas-fired and electric cookstoves currently in use in the European countries should be substituted with smart cooking devices, such as for instance the novel eco-sustainable pasta cooker controlled using an Arduino® microprocessor, previously developed by Cimini et al. (2020). Such a cooker allows the cooking water and energy consumption requirements to be respectively reduced from 10 to 3 L and from ~1.3 to 0.6 kWh per each kg of fresh pasta with unchanged cooked pasta quality (Cimini et al., 2022b). Secondly, the energy consumed to preserve fresh pasta within the chill temperature range might be lowered by promoting, even with fiscal aids, the replacement of old refrigerators with new ones of higher energy class, especially if provided with new-generation refrigerants, such propane (R290), for its reduced global warming potential and near zero ozone depletion one. Special advertising campaign might help enhancing the consumer’s awareness to reduce the storage time of fresh pasta in home refrigerators from the default 30 days (EPD®, 2022) to no more than 10 days (Cimini et al., 2022a). Any action directed to mitigate the common bread wheat cultivation step would rely on lower nitrogen fertilization and soil conservation techniques, even if in the case examined here the grain crop yields were in line with the average ones in Central Italy and direct drilling was also used (Table 1). Finally, the impact of the packaging materials might be lessened by resorting to low gas permeable plastic bags to make their mass near to that of the PP bags used in dried pasta packaging (Table 1).Owing to the chilled truck transport of such a high-moisture product and its preservation in home fridges, the general consumer should be conscious that fresh pasta consumption is characterized by a greater eco-indicator than conventional (Table 3) or organic (Cibelli, et al., 2021) dry pasta.

4. Conclusions

The cradle-to-grave environmental profile of a conventional fresh pasta was assessed using an LCA approach and compared to that of a conventional semolina dry pasta. Its primary and secondary hotspots (i.e., pasta use and agricultural phases) were inverted in the case of dried pasta. Fresh pasta was characterized by an eco-indicator 1.67 or 1.21 times higher than that of conventional or organic dry pasta owing to the greater environmental impact of its chilled truck transportation and preservation in home refrigerators. New smart home appliances might help to relieve the environmental impact of both pasta products.

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