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Environmental Profile of Organic Dry Pasta

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In this work, the cradle-to-grave environmental profile of an organic pasta production chain was assessed and compared to that of a typical conventional one, by using a well-known life-cycle assessment software in compliance with a few single- or multiple-issue standard methods. Both products relied on national durum wheat grains, were made in Italian medium-sized pasta factories, and packed in 0.5-kg polypropylene bags. All these methods identified the durum wheat cultivation and pasta cooking phases as the main hotspots. The organic pasta production chain was characterized by 10-46% higher scores than conventional pasta, mainly because the smaller organic grain yield per hectare requesting larger land occupation resulted in a greater damage to the ecosystem quality.

1. Introduction

Dry pasta is a typical Italian food increasingly preferred worldwide. It is mainly produced in Italy, the USA, Turkey, and Russia with circa 3.37, 2.0, 1.67, and 1.08 million Mg yr^{-1}, respectively (IPO, 2018).

Owing to the increasing interest of the general consumer towards the environmental impact of the foods and beverages of daily use, major pasta makers have started to assess the environmental impact of their productions using the Environmental Product Declaration methodology (EPD®, 2018).The cradle-to-distribution scores of the main impact categories (i.e., climate change, acidification, eutrophication, and photochemical ozone creation potential) reported online at https://www.environdec.com/ are definitively quite different, probably because of the diverse databases, agricultural techniques, processing conditions, or distribution logistics accounted for. The main hotspots of such a production chain are usually associated with durum wheat cultivation and home pasta consumption. According to Bevilacqua et al. (2007), the environmental impact of the former might be reduced by reverting to organic agriculture, while that of the latter was regarded as difficult to be mitigated in the short term, being external to the production network. Recchia et al. (2019) compared the environmental sustainability of local and global pasta production chains and found that the conventional pasta chain prevailed in terms of a more efficient exploitation of land and water resources. In previous work (Cimini et al., 2020a), the cradle-to-grave environmental impact of 1 kg of dry pasta, made of conventional durum wheat (DW) semolina, produced from a medium-sized pasta factory located in the North of Italy and packed in 0.5-kg polypropylene (PP) bags, was investigated by using a well-known life-cycle assessment (LCA) software in compliance with a few single- or multiple-issue standard methods (Jungbluth, 2019). The aim of this work was to compare the above environmental profile to that of a different chain of organic pasta production by using the same LCA software and standard methods.

2. Methodology

The life-cycle analysis was ISO-compliant (ISO, 2006a, b). Its goal was to assess the environmental profile of 1 kg of dried pasta made of organic durum wheat semolina, packed in 0.5-kg polypropylene (PP) bags, and produced from a medium-sized pasta factory located in the Campania region of Italy, as well as to identify their life-cycle hotspots. Figure 1 shows the system boundary examined. The upstream processes involved the organic DW cultivation, production of seeds, organic fertilizers, and auxiliary and packaging materials, as well as the electricity and fuel used in the agricultural treatments. The core processes comprised the transportation of DW grains and packaging materials to the pasta factory, *in situ* DW milling, pasta manufacture and packaging, disposal of by-products, and transportation of packed pasta to distribution

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centers and sale points. Then, the downstream processes accounted for the pasta cooking, and disposal of all packaging wastes formed. As concerning the inventory analysis, the so-called primary data (e.g., input resources and outputs, transport modality and distances travelled) were collected or measured directly by company (Cimini et al., 2019), while the secondary data were extracted from the databases (i.e., Agri-footprint v. 4.0, Ecoinvent v. 3.5) embedded in the LCA software SimaPro 9.0.0.41 (PRé Consultants, Amersfoort, NL). About 70% of the nominal non-irrigated land was used to grow DW, while the remaining 30% to fodder legume, such soil area being managed with aged poultry manure compost. All the emissions from fertilized soils were calculated according to EPD® (2013) and IPCC (2006), while the allocation factors for DW grains, straw and below ground residues, semolina and milling byproducts, as well as dry pasta and pasta wastes, were estimated as suggested by UNAFPA (2018). Approximately 0.71 kg of semolina was recovered from conventional milling of 1 kg of organic DW. The primary, secondary, and tertiary packaging of dry pasta consisted of a PP bag, a carton with a paper label, and an EPAL wooden pallet wrapped by a polyethylene stretch film. The cooking energy and water requirements amounted to 2.3 kWh and 10 L per each kg of raw pasta (UNAFPA, 2018). All post-consumer packaging wastes were disposed of according to the Italian waste management scenarios (Cimini et al., 2019).

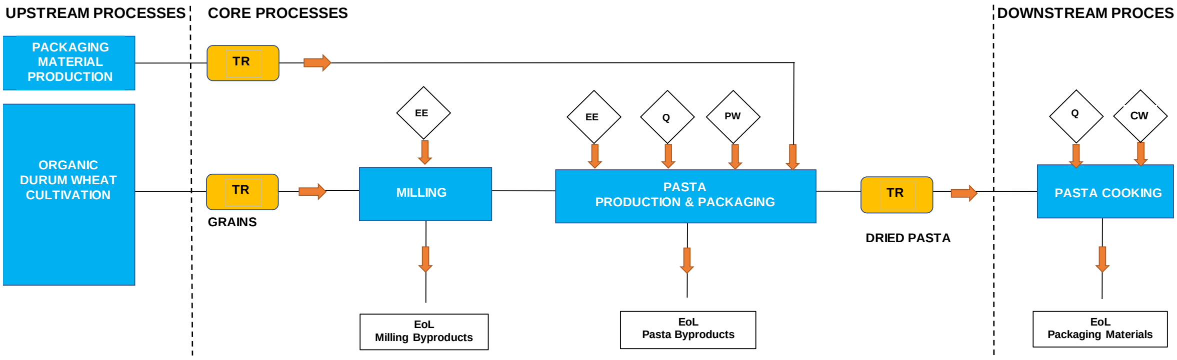

Figure 1: Dried pasta system boundary including the upstream, core and downstream processes: CW, cooking water; EE, electric energy; EoL, end of life; PW, process water; Q, thermal energy; TR, transport.

The environmental impact was assessed in compliance with the Cumulative Energy Demand (CED) (Frischknecht et al., 2007), Publicly Available Specification (PAS) 2050 or Carbon Footprint CF (BSI, 2011), IMPACT 2002+ (Jolliet et al., 2003), and Product Environmental Footprint (PEF: EC, 2018) standard methods. The CED or CF method accounts for just a single environmental impact category (IC), such as the renewable and non-renewable energy demand indicator, and climate change over a 100-yr time horizon, respectively. The IMPACT 2002+ method groups the 15 default ICs into four damage categories (DC_z), these measuring the damage to *human health* (HH), expressed in disability-adjusted life years (DALY) lost because of an exposure to toxic chemicals; to *ecosystem quality* (EQ), measured in potentially disappeared fraction (PDF) of biological species most likely not surviving in the geographical area examined; to *climate change* (CC) by referring to a 500-yr time-horizon; and to *depletion of non-renewable resources* (RD), quantified as the additional primary energy required to extract a unit of mineral and non-renewable primary energy. Such DCs are normalized with respect to the European population and then aggregated using a unitary weighting factor to yield an *overall weighted damage score* ($OWDS_I$). The PEF method accounts for 16 mid-point ICs, which may be normalized with respect to their global impacts and weighted (Sala et al., 2017, 2018) to obtain another overall weighted score (OWS_P), this not accounting for the human and eco-toxicity ICs for their low robustness (UNAFPA, 2018).

3. Results and Discussion

3.1 Cumulative energy demand and carbon footprint of dry pasta

By referring to Figure 1, the CED analysis pointed out that the non-renewable (fossil, nuclear, primary forest) and renewable (biomass, geothermal, solar, water, wind) energy sources amounted to 32.8 MJ_e per kg of organic dry pasta (Table 1), while those used for a conventional pasta was just 24.7 MJ_e kg^{-1} (Cimini et al., 2020a). The most impacting phase for organic pasta was DW cultivation, followed by home pasta consumption, and pasta making and packaging. The cooking phase of conventional pasta was, on the contrary, that most impacting. Since the organic DW crop yield was ~3.75 Mg ha^{-1} yr^{-1}, just 61% of the conventional one, the CED indicator and carbon footprint (CF) were 33% and 10% greater than those for conventional pasta, respectively (Table 1). The organic pasta production chain was characterized by more energy-efficient transformation processes, but burdened by a more impacting distribution logistics, exclusively based on road transport (Cimini et al., 2019).

Table 1: Contribution of the different life cycle phases to the cradle-to-grave Cumulative Energy Demand (CED) and Carbon Footprint (CF) of a functional unit (1 kg) of organic (this work) or conventional (Cimini et al., 2020a) pasta packed in 0.5-kg PP bags in medium-sized pasta factories.

Pasta type		**Organic Pasta**		**Conventional Pasta**	
	Single-issue environmental impact	**CED**	**CF**	**CED**	**CF**
Life Cycle Phase		$[MJ_e\ kg^{-1}]$	$[g\ CO_{2e}\ kg^{-1}]$	$[MJ_e\ kg^{-1}]$	$[g\ CO_{2e}\ kg^{-1}]$
Field phase	(FP)	12.83	845	5.38	585
Milling	(MI)	1.20	66	1.68	89
Packaging material manufacture	(PMP)	2.19	65	2.25	75
Pasta production	(PPR)	3.46	188	4.13	239
Pasta packaging	(PPACK)	0.60	30	0.32	16
Transport of final product	(PDISTR)	2.32	139	0.88	54
Pasta cooking phase	(CP)	11.81	649	12.32	759
End of life of packaging material wastes	(EoLPM)	-1.60	-1	-2.22	-12
Overall score		***32.82***	***1,980***	***24.74***	***1,806***

Table 2: Environmental profile of 1 kg of organic (this work) or conventional (Cimini et al., 2020a) pasta packed in 0.5-kg PP bags, as estimated using the IMPACT 2002$^+$ and PEF standard methods: Percentage contribution of the two most impacting life cycle phases (i.e., field, FP, and pasta cooking, CP, phases), and score of each mid-point impact category (IC_j).

Impact category IC_j	**Organic Pasta**			**Unit**	**Conventional**		
	FP (%)	**CP (%)**	**IC_j Score**		**IC_j Score**	**FP (%)**	**CP (%)**
			IMPACT 2002$^+$				
Carcinogens	18.4	10.3	$1.32x10^{-2}$	kg $C_2H_3Cl_e$	$5.23x10^{-2}$	4.7	71.8
Non-carcinogens	50.6	11.4	$1.61x10^{-2}$	kg $C_2H_3Cl_e$	$1.99x10^{-2}$	25.9	48.6
Respiratory inorganics	55.2	17.6	$1.20x10^{-3}$	kg $PM_{2.5e}$	$8.37x10^{-4}$	51.3	13.9
Respiratory organics	49.7	16.1	$5.03x10^{-4}$	kg C_2H_{4e}	$4.26x10^{-4}$	20.1	45.6
Ionizing radiation	66.5	14.1	25.5	Bq $^{14}C_e$	7.17	26.0	17.2
Ozone layer depletion	43.0	15.1	$1.46x10^{-7}$	kg CFC-11_e	$1.51x10^{-7}$	23.8	43.3
Aquatic ecotoxicity	28.2	11.8	125.1	kg TEG water	185.0	12.1	37.3
Terrestrial ecotoxicity	34.8	8.1	47.4	kg TEG soil	44.2	12.8	30.4
Terrestrial acidification/nutrification	57.5	18.3	$4.62x10^{-2}$	kg SO_{2e}	$2.82x10^{-2}$	50.3	9.8
Aquatic acidification	50.6	21.9	$7.78x10^{-3}$	kg SO_{2e}	$5.28x10^{-3}$	45.6	14.2
Aquatic eutrophication	92.8	3.6	$1.13x10^{-3}$	kg PO_4^{3-}	$5.34x10^{-4}$	85.0	8.9
Land occupation	99.7	0.05	5.32	m^2 org. arable	2.42	100.0	0.03
Global warming (GW_{500})	39.3	34.7	1.76	kg CO_{2e}	1.56	28.0	44.7
Non-renewable energy	34.1	37.2	27.6	MJ primary	23.8	17.1	51.3
Mineral extraction	52.9	27.8	$2.42x10^{-2}$	MJ surplus	$3.6x10^{-2}$	75.0	15.1
			PEF				
Climate change (GW_{100})	43.6	32.2	2.05	kg CO_{2e}	1.88	33.5	41.4
Ozone depletion	40.6	14.1	$1.58x10^{-7}$	kg CFC-11_e	$1.74x10^{-7}$	22.2	44.8
Ionising radiation, Human Health	66.5	14.1	$2.51x10^{-1}$	kBq $^{235}U_e$	$7.05x10^{-2}$	26.1	17.2
Photochemical ozone formation-HH	61.6	13.4	$5.26x10^{-3}$	kg $NMVOC_e$	$4.07\ x10^{-3}$	47.1	18.4
Particulate matter	59.6	14.5	$8.59x10^{-8}$	disease inc.	$5.00\ x10^{-8}$	62.2	8.3
Human toxicity, non-cancer	51.1	13.0	$1.27x10^{-7}$	CTU_h	$1.16x10^{-7}$	34.6	33.2
Human toxicity, cancer	61.1	16.0	$1.12x10^{-8}$	CTU_h	$1.08x10^{-8}$	48.8	31.5
Acidification	49.6	22.6	$1.02x10^{-2}$	mol H^+_e	$6.64x10^{-3}$	45.0	13.5
Eutrophication freshwater	72.5	12.2	$5.51x10^{-4}$	kg P_e	$3.01x10^{-4}$	61.7	12.4
Eutrophication marine	73.5	9.4	$2.62x10^{-3}$	kg N_e	$2.08x10^{-3}$	57.5	15.6
Eutrophication terrestrial	58.3	18.1	$3.68x10^{-2}$	mol N_e	$2.16x10^{-2}$	51.1	8.5
Ecotoxicity freshwater	40.5	5.7	1.04	CTU_e	$9.26x10^{-1}$	37.9	26.8
Land use	99.3	0.3	619	Pt	296	101.9	0.1
Water scarcity	14.0	66.6	$8.32x10^{-1}$	m^3 depriv.	$4.23x10^{-1}$	51.4	0.1
Resource use, fossils	34.4	37.9	26.7	MJ	21.9	17.8	50.5
Resource use, minerals and metals	57.2	21.3	$2.99\ x10^{-6}$	kg Sb_e	$2.16x10^{-6}$	71.5	13.0

3.2 Environmental profile of dry pasta

Table 2 compares the mid-point impact categories (IC) of one functional unit of organic pasta to those of a conventional pasta (Cimini et al., 2020a). By referring to the IMPACT 2002$^+$ method, the organic field phase exerted its prevailing effect on the ICs of land occupation, aquatic eutrophication, ionizing radiation, terrestrial acidification and nutrification, respiratory inorganics, mineral extraction, non-carcinogens, and aquatic acidification. These ICs prevalently affected the conventional pasta too, even if the contribution of mineral extraction was higher owing to the use of fossil-derived fertilizers. The impact category of non-renewable energy mainly influenced the cooking phase of both pasta types examined. The packaging material manufacture was the life cycle phase mainly contributing to the ICs of carcinogens and aquatic ecotoxicity in the case of organic pasta, or of terrestrial eco-toxicity and aquatic eco-toxicity for conventional pasta (data not shown for simplicity).

According to the PEF method, the organic field phase was that mostly affecting the impact categories of land use, marine and freshwater eutrophication, ionizing radiation, photochemical ozone formation, human toxicity-cancer, particulate matter, terrestrial eutrophication, and resource use-minerals and metals. The use phase of organic pasta considerably influenced the ICs of water scarcity, resource use-fossils, and climate change. The estimated water scarcity indicator, expressing the relative available water remaining per area in a watershed once the demand of humans and aquatic ecosystems had been met, was quite the double of that referred to conventional pasta, which on turn was chiefly controlled by the field phase (Table 2). The global warming scores (2.05 vs. 1.88 kg CO_{2e} kg^{-1}) differed from those (1.76 or 1.56 kg CO_{2e} kg^{-1}) estimated using the IMPACT 2002$^+$ method, since the latter makes use of 500-yr time horizon global warming potentials (Houghton et al., 2001), while the PEF method of the 100-yr time-horizon potentials updated by Myhre et al. (2013). Overall, the environmental profile of both pasta products by and large agreed with the PEF characterization benchmark values of dry pasta (UNAFPA, 2018).

The end-point characterization of the environmental profile of organic pasta in conformity with the IMPACT 2002$^+$ and PEF methods is shown in Table 3. The damage impact on HH and EQ mainly derived from the field phase, while that on CC and RD from the consumer phase. A similar damage impact originated from conventional pasta. Particularly, the impact on EQ, which accounts for the contribution of four normalized impact categories (i.e., aquatic and terrestrial ecotoxicity, terrestrial acidification and nutrification, and land occupation), was primarily dependent on the damage characterization factor for land occupation (Jolliet et al., 2003). Thus, the lower organic crop yield per hectare than the conventional one increased the damage to EQ from 3.02 to 6.23 PDF m^2 yr. The weighted damage score relative to EQ for organic pasta was about the double of that for conventional pasta, while those relative to HH, CC, RD were 13-16% greater than the corresponding ones for conventional pasta. Finally, the overall weighted damage score ($OWDS_I$) amounted to 946 micropoints (μPt) per kg of organic pasta or to ~647 μPt per kg of conventional pasta (Cimini et al., 2020a). $OWDS_I$ firstly stemmed from the damage to EQ (48%), and then from that to both CC and RD (38%), the organic field phase contributing up to 67% of its overall value. In the case of conventional pasta, the overall score originated from the damage to CC+RD (48.5%) and then to EQ (~34%) with 48.5% contribution of the field phase.

Table 3: End-point characterization of the environmental profile of 1 kg of organic (this work) or conventional (Cimini et al., 2020a) dried pasta packed in 0.5-kg PP bags according to the IMPACT 2002$^+$, and PEF standard methods: percentage contribution of the two most impacting life cycle stages (symbols as in Table 1), single (SS_Z) and weighted (WDS_Z) damage scores of each damage category (DC_Z), and overall weighted scores ($OWDS_I$, and OWS_P).

Damage category (DC_Z)	**Organic Pasta**				**Conventional Pasta**			
	FP (%)	**PC (%)**	**SS_Z**	**WDS_Z** (μPt)	**FP (%)**	**PC (%)**	**SS_Z**	**WDS_Z** (μPt)
				IMPACT 2002$^+$				
Human health (HH)	53.5	17.0	9.30×10^{-7} $^{\alpha}$	131	40.8	27.1	7.91×10^{-7} $^{\alpha}$	112
Ecosystem quality (EQ)	95.4	0.7	6.23 $^{\beta}$	455	89.2	3.8	3.02 $^{\beta}$	221
Climate change (CC)	39.3	34.7	1.76 $^{\gamma}$	178	28.0	44.7	1.56 $^{\gamma}$	157
Resource depletion (RD)	34.1	37.2	27.7 $^{\delta}$	182	17.2	51.3	23.9 $^{\delta}$	157
$OWDS_I$	*67.2*	*16.4*	-	*946*	*48.5*	*29.3*	-	*647*
				PEF				
OWS_P	*57.1*	*23.1*	-	*195*	*44.5*	*29.9*	-	*141*

$^{\alpha}$ DALY $^{\beta}$ PDF m^2 yr $^{\gamma}$ kg CO_{2e} $^{\delta}$ MJ primary

By referring to the aggregated single score (OWS_P) of the PEF method, that for organic pasta was equal to 195 μPt, this being 39% greater than that for conventional pasta (~141 μPt). Even with the PEF method, both scores were firstly affected by the agricultural phase (57% vs. 45%) and secondly by the pasta cooking one (23% vs. 30%). Despite the characterization factors used by the PEF method are representative for the global scale instead of the European scale as considered by the IMPACT 2002$^+$ one, both methods not only conveyed the same damage assessment, but also identified the same primary and secondary hotspots of the dry pasta life cycle. Some ICs were characterized by different scores deriving from the models used for their calculation (Cimini et al. 2020a).

3.3 Options to reduce the environmental profile of dry pasta

Any mitigation action should aim at reducing firstly the damage to EQ and secondly that to CC and RD.
Several studies have demonstrated that organic farming for durum wheat cultivation, avoiding the use of fossil-derived fertilizers and pesticides, is a low-carbon agriculture with smaller greenhouse gas (GHG) emissions per hectare than the conventional wheat cultivation. Unfortunately, its lower productivity asks for more cultivated land, and unfortunately this greatly enhances the damage to EQ.
The carbon footprint of durum grains is significantly influenced by the crop rotation system used (Gan et al., 2011), this being also validated by four-year rotation crop experiments conducted in selected areas by Ruini et al. (2013) with grain yields varying from ~7.5 Mg ha^{-1} in Northern Italy to 4.2-5.0 Mg ha^{-1} in Southern Italy. The lowest environmental impact involved the rotation of durum wheat with fodder and land occupation of one hectare every two years. In the organic farming examined here, ~70% of the nominal non-irrigated land was cultivated with DW, while the remaining 30% with alfalfa, its land occupation totaling 1.4 ha every two years. Thus, since such organic farming was more productive than the best one tested in Southern Italy by Ruini et al. (2013), the only option that might mitigate the environmental impact of the field phase would be to apply such an organic DW cultivation in the same cultivation areas of Northern Italy experimented by Ruini et al. (2013) in the hope of increasing the organic DW yield from ~3.75 to 7.5 Mg ha^{-1} yr^{-1}. In these conditions, the organic pasta chain mentioned above would be characterized by a CED indicator, a Carbon Footprint, and overall weighted scores $OWDS_I$ and OWS_P of 26.4 MJ_e, 1.58 kg CO_{2e}, and 629 μPt and 140 μPt per kg of organic pasta, respectively, with an environmental profile approaching to that of the typical conventional pasta chain. As concerning the other life cycle phases, the transformation and transportation ones in both chains appeared to have been already optimized, their associated impacts representing 20-25% of the overall CED indicator and carbon footprint (Table 1). Finally, the environmental impact of the home pasta cooking phase might be minimized by resorting to more energy-efficient appliances, such as the novel Arduino®-based eco-sustainable pasta cooker operating with a water-to-pasta ratio of 3±1 L kg^{-1} and an electricity consumption of 0.6±0.1 kWh kg^{-1} (Cimini et al. 2020b).

4. Conclusions

The cradle-to-grave environmental impact of organic dry pasta was investigated using an LCA approach and compared to that of a typical conventional pasta. The CED analysis, carbon footprint, and global environmental impact using the IMPACT 2002^+ and PEF standard methods allowed the same hotspots (i.e., durum wheat cultivation and pasta cooking) to be identified. Nevertheless, the general consumer should be conscious that organic pasta production is characterized by 10-46% higher scores than conventional pasta, mainly because the current smaller organic grain yield per hectare increases land occupation and, consequently, results in a greater damage to the ecosystem quality. By assuming to transfer the present organic farming to other cultivation areas where higher crop yields had been already experienced, it was possible to align the environmental impact of the organic pasta chain to that of the conventional pasta chain, this confirming the paramount impact of the agricultural phase on the damage to the ecosystem quality. Conversely, the replacement of the gas-fired hobs, mainly used in Italy, with novel eco-sustainable pasta cookers might relieve the damage to climate change and resource depletion. In conclusion, the business-to-business environmental impact of conventional or organic dry pasta might be reduced with the help of more sustainable DW cultivation and less energy- and water-consuming home appliances.

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