Environmental Life Cycle Assessment for improved management of agri-food companies: the case of organic whole-grain durum wheat pasta in Sicily

Silvia Zingale[1], Paolo Guarnaccia[1], Giuseppe Timpanaro[1], Alessandro Scuderi[1], Agata Matarazzo[2], Jacopo Bacenetti[3], and Carlo Ingrao[4]*

[1] Department of Agriculture, Food and Environment (Di3A), University of Catania. Via S. Sofia, 100 - 95123 Catania, Italy
[2] Department of Economics and Business, University of Catania. Corso Italia, 55 – 95129 Catania, Italy
[3] Department of Environmental Science and Policy, State University of Milan. Via Celoria, 2 - 20133 Milan, Italy
[4] Department of Economics, University of Foggia. Via Romolo Caggese, 1 – 71121 Foggia, Italy
* Corresponding author. E-mail address: carlo.ingrao@unifg.it (C. Ingrao).

Abstract

Purpose

This study was developed to address the environmental issues associated with a high-quality pasta production process, as the essential starting point to identify the related hotspots and the feasible improvement potentials.

Methods

To this end, a Life Cycle Assessment (LCA) at the food producer's gate was performed. Primary data were collected in a small-size Sicilian pasta factory located in Fiumefreddo (Sicily), where organic '*Senatore Cappelli'* durum wheat landrace is cultivated and later is processed into whole-meal semolina and pasta, whilst secondary data were extrapolated from Ecoinvent v. 3.5 database, as available in the SimaPro 9.1.0.11 software. The environmental profile of pasta was assessed by adopting the EPD (2018) (v 1.01) impact assessment method, which is required for use in case of Environmental Product Declarations (EPDs). The environmental profile of pasta was analysed in terms of four different impact categories, namely global warming, eutrophication, acidification, and photochemical oxidation, as recommended by the *PCR 2010:01 Uncooked pasta*, developed in the framework of the International EPD System.

Results

The obtained results, expressed in the form of equivalent indicators, suggest that cultivation is the phase contributing the largest impacts for all the midpoint categories considered by the LCIA method. In addition, it was observed that the contributions assessed in this study are highly comparable and aligned with those contained in the EPDs published in the pasta sector, specifically for the cultivation phase, which performs similarly to the only case of organic pasta EPD amongst those developed.

Conclusions

At the end, the study suggested that the cultivation of ancient varieties and landraces in organic and low-input farming systems have a large potential for reducing the environmental impact of pasta. Finally, although specific, the results of the study may be of interest to researchers, LCA practitioners, farmers and producers, policymakers, and other stakeholders, and could support the implementation of environmental labels.

Keywords

Sustainability; Agriculture; Food production; Organic dry pasta; Life cycle assessment; Durum wheat cultivation.

1. Introduction

Food systems are complex entities that affect diets, human health, and a range of other outcomes including economic growth, natural resource, and environmental resilience, and sociocultural factors (Fanzo et al., 2021). Although they have the potential to nurture human health and support environmental sustainability, food systems are currently threatening both (Willett et al., 2019). According to a line of thinking widely discussed in the scientific literature, food systems negatively affect:

- the environment, by contributing to climate change, biodiversity loss, freshwater use, chemical pollution, and land use change (Willett et al., 2019);
- the health of people, due to food and nutrition insecurity (Organization, 2018); and
- the economies and societies, because of market distortions and failures in food access and distribution (Campi et al., 2021).

Regarding environmental degradation, food systems are the main drivers of biodiversity loss (Dudley and Alexander, 2017) and generate approximately one-third of global greenhouse emissions (Niles et al., 2018). Moreover, food production is responsible for 70% of freshwater use (Rufí-Salís et al., 2020), and more than 60% of world fish stocks (FAO, 2016). In this regard, farming is often one of the most impacting stages in the life cycle of food products, mainly due to:

- the increasing use of agricultural lands (Fanzo et al., 2020);
- the intensive use of fertilisers and pesticides (Failla et al., 2020);
- the high resources consumption and pollutant emissions connected with animal feed production and supply (Costantini et al., 2021); and
- the inappropriate management of agro-losses (Ingrao et al., 2021).

Besides, food systems are affected by environmental changes: for instance, climate change is expected to substantially reduce agricultural productivity, decreasing the availability of food and causing about 500 thousand climate-related deaths in 2050 (Willett et al., 2019).

Hence, the current food production and consumption paterns do not guarantee food security for all people, indefinitely. Indeed, one-third of people on our planet is still malnourished - either hungry, micronutrient-deficient, overweight, or obese - (HPLE, 2017) and unhealthy diets are the main causes of the current rise in global ill health and chronic non-infectious diseases (Afshin et al., 2019).

Critical issues lie also in the socio-economic impacts of production concentration, which decreases food supply, food security, and sustainability levels of countries (Campi et al., 2021). Actors along agri-food supply chains have dissimilar powers, with highly vulnerable actors, such as small-scale agricultural producers whose medium- and long-term prospects for survival are threatened by the dominance of industrial agriculture and competitive global markets (Loboguerrero et al., 2020; Rivera et al., 2020).

Therefore, there is increasing emphasis upon the interactions between food systems and sustainable development, as the latter is possible only when:

- people are food secure and well-nourished;
- ecosystems are healthy and balanced;
- societies are resilient towards climate change; and
- the governance is fair and just (Caron et al., 2018).

To achieve those objectives, following authors like Dinesh et al. (2018), Herrero et al. (2021), and Loboguerrero et al. (2020), a real effort to be made should be that of turning challenges into opportunities, by:

- using innovation to achieve multiple Sustainable Development Goals (SDGs) in food system implementations, including eliminating poverty, hunger, and malnutrition, achieving good health and well-being, whilst promoting sustainability in all sectors including agriculture and food production;

- implementing special actions (e.g. agro-ecological systems) to reconfigure food production under climate change; and
- promoting a systemic behavioural change on the part of all stakeholders (decision-makers, implementers, scientists, farmers, processors, civil society organizations, businesses, and consumers).

So, the broad scope of the SDGs requires holistic approaches, such as the integrated assessment of the three dimensions of sustainability of foods' life cycles (Chaudhary, A. et al., 2018; Lu, 2020), to make sure that each step of the way, from production to disposal, is designed and developed in sustainable manners. Food chains have, in fact, their own specific features such as:

- seasonality of supply and demand;
- customer issues of traceability and risk management related to health, nutrition, and safety; and
- the environmental impact of food production, mainly due to extensive resource use, including water and land use, and to greenhouse gas (GHG) emission and waste generation from agricultural production (Boye and Arcand, 2013).

In this context, an important role within the agri-food industry is surely played by pasta production, with approximately 16.5 million tonnes of pasta produced annually worldwide, of which 21.2 and 12.12% are produced in Italy and the United States of America (USA), respectively (UNAFPA, 2020). According to the Regulation (EU) No 1333/2008 (European Commission, 2008), "pasta" is defined as any kind of shaped product obtained by extruding or forming a dough prepared with (unrefined or not) Durum Wheat (DW) semolina, water and (optionally) eggs and other flours or ingredients. The Decree of the President of the Italian Republic n.187/2001 (DPR n. 187, 2001), instead, specifies that the word "pasta" stands for the product obtained by drawing, rolling, and drying a dough prepared only with DW semolina and water. Indeed, the use of DW semolina gives the Italian pasta specific physicochemical and sensory properties that characterise and differentiate it throughout the world (Padalino et al., 2014; Sicignano et al., 2015). In this respect, in the Mediterranean area, where DW represents a staple crop (Guzmán et al., 2016), much attention is paid upon varietal and genetic characteristics of this tetraploid species *(Triticum turgidum* L subsp. *durum* (Desf.) Husnot) as well as agronomic and processing practices and their effect on pasta production quality and sustainability (Cappelli and Cini, 2021; Cecchini et al., 2020).

In this context, the present work was aimed at assessing the relevant environmental issues associated with a high-quality pasta production process, as the essential starting point to identify the related hotspots and the improvement potentials. In particular, the object of this study is the organic DW semolina pasta produced by a small-size Sicilian pasta factory using the *'Senatore Cappelli'* DW landrace. Landraces and old varieties are commonly defined as those cultivars grown before 1950, which had never undergone modern plant breeding programs. *Senatore Cappelli* is one of those ancient varieties and is the result of a genealogical selection from a North African landrace. It is characterised by a wide adaptability to organic farming in marginal areas and by an excellent content of proteins, dietary fibre, and antioxidants (Acquistucci et al., 2020; Dinelli et al., 2013)

Therefore, attention was focussed on such a type of pasta, in the light of:

- its consumption being recommended by Mediterranean dietary guidelines (Bach-Faig et al., 2011);
- its cultural significance for – and the representativeness of - the Italian and Sicilian traditional cuisine (Altamore et al., 2020);

- the importance of the organic DW *(Triticum turgidum* L subsp. *durum* (Desf.) Husnot) sector in Sicily, with special reference to ancient varieties and landraces (Ruisi et al., 2021);
- the existence of both Product Environmental Footprint Category Rules (PEFCR, 2018) and Product Category Rules (EPD, 2018) for pasta products.

Under this perspective, the Life Cycle Thinking (LCT) approach can be considered as the foundation for assessment of the environmental hotspots associated with food supply chains, and of the feasible improvements to make them of the highest quality and sustainability possible (Ingrao et al., 2018). Life Cycle Assessment (LCA) substantiates the LCT approach by means of a clearly structured methodology that is ruled by the International Standards 14040 and 14044 (ISO 2006 a, b), as stated by Ingrao et al. (2018). The present study wishes to make a relevant contribution in such a research content area, by highlighting the importance of using tools like LCA and, more widely, Life Cycle Sustainability Assessment (LCSA), to contribute to improving sustainability of agri-food systems. In this regard, the literature acknowledges both LCA and LCSA to be holistic multi-criteria methodologies for the assessment of the environmental, economic, and social dimensions of products' sustainability from a life cycle point-of-view (Traverso et al., 2012). LCSA represents, in fact, the combined application of Environmental LCA (ELCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA), and so allows for finding sustainable trade-offs amongst not only the product life cycle phases but, also, the three dimensions of sustainability (Ingrao et al., 2021; Traverso et al., 2012).

There exist two types of LCA, namely the attributional and consequential one. The former, which is usually the most applied approach, serves to evaluate the impacts of the processes used to produce a product within a chosen temporal window, whilst the latter considers how environmentally relevant physical flows may change in response to possible decisions (Ekvall et al., 2016). Consequentially, the attributional LCA is valuable for identifying opportunities for reducing emissions within the life cycle or supply chain, through improvements in processing efficiency or new technologies (Brander et al., 2009). The consequential LCA, instead, is of greater relevance for informing consumers and policymakers about the consequences of changes in the level of output, consumption and disposal of a product, including effects both inside and outside the life cycle of the product (Brander et al., 2009). In the light of this, an attributional LCA was applied for the purpose of this study development, in order to support the making of micro-level decision (Ingrao et al., 2017), that – to the authors' opinion – is the essential starting point for the planning and development of sustainability-oriented strategies in the food production field.

In recent years, agri-food companies are called to manage all the environmental impacts generated along their own agri-food chain by the adoption of integrated management approaches, encompassing system, product and process quality, such as the *Life Cycle Thinking* and *Life Cycle Management* approaches (Salomone et al., 2013). In particular, companies are increasingly searching for ways to reduce the environmental impacts of their products, whilst avoiding additional costs (Gallucci et al., 2021), thereby making their manufacturing systems both environmentally and economically sustainable. In this regard, the application of life cycle based tools has been documented over the years as useful to increase the competitiveness of the food industry through the establishment of a continual improvement process and the adoption of eco-innovation based solutions (Motta et al., 2018; Niero and Rivera, 2018). The study discussed in this paper could make a relevant contribution for such a purpose.

2. LCA in the pasta production sector: a literature review

This section comprehensively reviews some of the current pasta-based life cycle thinking literature, paying attention upon studies reporting findings from LCA applications. For this purpose, the authors conducted the bibliographical search in Scopus® using those they believed were the most representative keywords connected with the investigated system, namely "life cycle assessment" and "pasta ". Considering the centrality of the research, just studies that focussed upon DW pasta were considered, which means that studies exploring just the DW cultivation phase were excluded from the review. In such a way, seven studies were found to be published from 2007 to 2019 and were classified in **Table 1**. Results from those studies were found to be relevant and well on this study's target, and so were used as the essential backbone for this LCA development, as they provided the authors with the opportunity of building upon their knowledge on the key methodological aspects associated with LCA application in such a research field.

As illustrative, Bevilacqua et al. (2007) carried out an LCA of DW pasta marketed in Italy and found that the phase of DW cultivation along with that of semolina production were the largest contributors to the environmental burdens, overall associated with the DW pasta supply chain investigated by the authors. In another study, Lo Giudice et al. (2011) developed a simple, creative, and schematic Life Cycle Inventory (LCI) model for the environmental sustainability assessment of a pasta firm in Sicily, using illustrative tables and flowcharts. Specifically, the authors conducted an Input-Output Flow Material Analysis that allowed them to clearly quantify the input and output quantities involved in all the different phases of the industrial production of the dried pasta. As predictable, DW cultivation was determined to be the most contributing phase to the resource consumption and the material emissions associated with the investigated pasta supply chain. Another interesting work was developed by Röös et al. (2011), who quantifies the uncertainty in the Carbon Footprint (CF) of Swedish pasta and wheat cultivated in the region of Skåne on mineral soils, for different resolutions of the farm-level in-data. To investigate the confidence with which a producer could claim to have 'low-emitting wheat-based products', the authors designed several scenarios of wheat grain and pasta production using the Monte Carlo (MC) simulation. Doing so made it possible for them to highlight the necessity to develop more precise methods for assessing the soil N_2O emissions, as well as the persistence of many difficulties in calculating accurate values. Similarly, Heidari et al. (2017) quantified the damage of pasta production to terrestrial biodiversity in the Iranian territory based upon regionalised inventories and impacts. Through their study, and in line with previous literature like Bevilacqua et al. (2007), they demonstrated that the agricultural stage was the main contributor to terrestrial biodiversity loss caused by pasta production, with contributions ranging from 67% to 84%. Besides, to determine which production technology is responsible for differences amongst farms, variability in performance was assessed and, based upon the obtained results, CO_2 emissions from fossil fuel and water consumption for irrigation showed the largest impact and variability amongst the inventory list. Therefore, the authors recommended that pasta producers have DW sourced by farms that consume water efficiently and use modern agricultural machinery that consumes fuel efficiently.

Cimini et al. (2019) performed a CF on dry organic DW short-cut extruded pasta, following a business-to-consumer or cradle-to-grave approach (CFCG). Results showed that, differently than business-to-business CFs which are mostly conditioned by the greenhouse gases emitted throughout DW cultivation, a business-to-consumer CF mainly depends upon the phases of use and post-consumer waste disposal. Indeed, based upon the type of pasta produced (i.e., short and long goods) and the package format used (i.e., PP bags or PB boxes and PE bags), the CF was determined as varying from +0.3 to +14.8% with respect to the minimum score estimated corresponding to the CFCG of organic spaghetti packed in 3 kg PE bags for catering services. Another interesting study on the relevant environmental sustainability issues associated with pasta's life cycle was carried out by Fusi et al. (2016), who focussed upon the catering sector. The authors reported that pasta cooking is the major hotspot in both cook-warm and cook-chill systems, with particularly higher impacts from the cook-chill chain, because of the use of refrigerants and the consumption of energy.

Finally, an integrated methodology based on both an Environmental Impacts Analysis (EIAN) approach and the LCA was developed by Recchia et al. (2019), considering two different pasta production chains:

- a "high-quality pasta" chain (referred as "local or regional scenario"), which follows traditional procedures in a Tuscan farm that uses only ancient wheat varieties; and
- a "conventional pasta" chain (referred to as "global or industrial scenario"), in which pasta is produced using national and international grains, following industrial processes.

As a result, the high-quality pasta chain showed a better performance in terms of reducing the risk of soil degradation and agrobiodiversity loss, as well as the consumption of non-renewable resources, mainly due to the use of lower quantities of chemicals, a lower mechanisation level in the agricultural phase, and the use of ancient grains. Whilst, the conventional pasta chain presents more efficient exploitation of land and water resources, along with a reduced noise emitted by the processing equipment (Recchia et al., 2019).

Based upon the review performed, it can be concluded that a limited number of studies has been published thus far to address the environmental performance of DW pasta, and just one of those regarded the assessment of ancient-DW pasta. This can be read as a sign of the novelty of the study that, so, is expected by the authors to make a relevant contribution in terms of enhancing the scientific literature currently available on the subject. From **Table 1**, there is evidence that methodological choices are nearly similar amongst the studies reviewed, thus explaining the consistency between the results. In particular, it is possible to note that:

- the majority of the studies adopted a '*cradle-to-grave*' approach, excluding Röös et al. (2011), Fusi et al. (2016), and Heidari et al. (2017) who, instead, considered cradle-to-retail, cooking-to-transport, and cradle-to-gate boundaries;
- all the authors assessed the environmental impact of dry pasta made from modern DW varieties, with exception of Recchia et al. (2019) who, instead, investigated traditional pasta production systems on a Tuscan farm which processes only ancient DW varieties. According to Recchia et al. (2019), the LCA does not highlight significant differences between the conventional and high-quality pasta production chains, whilst the proposed integrated EIAN-LCA approach showed that the high-quality chain has a lower impact on soil degradation, agrobiodiversity losses, and on the consumption of non-renewable resources. Besides, authors suggested that CO_2 emissions from high-quality pasta production chain could be significantly reduced, obtaining significant improvements in LCA assessment, when compared with the conventional pasta production in a global scenario where margins for improvement are lower;
- 1 kg of packaged pasta was selected as functional unit (FU) of the system in the majority of the studies, with exception of Bevilacqua et al. (2007) and Fusi et al. (2016) who, instead, chose 0.5 of packaged pasta and 1 kg of cooked pasta as the FUs of their studies, respectively;
- all the studies used well-known and standardised assessment methods, except for Lo Giudice et al. (2011) who performed an LCI, and Recchia et al. (2019) who developed a new integrated methodology based upon both site-specific and global evaluations;
- the authors were provided the data by local stakeholders, and limited access to secondary sources just for collection of the data that they could not collect otherwise;
- sensitivity analyses were carried out only in Röös et al. (2011), Cimini et al. (2019), and Fusi et al. (2016). Röös et al. (2011), for instance, focussed on data variability and uncertainty and, to some extent, modelled uncertainty in the methods used to quantify the emissions at the farm level. According to them, the stages of pasta processing, packaging, and transporting were associated with less data uncertainty, as their greenhouse gas (GHG) emissions arise only from energy-related processes. Contrary, the wheat cultivation stage is associated with large uncertainties, as its emissions depend on numerous factors like yield, amount of N fertiliser, and soil N_2O emissions. Similarly, Cimini et al. (2019) carried out a sensitivity analysis of CFCG to assess the influence of

different parameters (such as the origin of DW 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, and cooking modes) on the overall dry pasta environmental impact. Fusi et al. (2016) conducted a sensitivity analysis to test the robustness of the results, and to investigate the effect of the key assumptions made in the study. Parameters considered within the sensitivity analysis were different: the size of the pasta cookers and range tops and, the emissions from fuel combustion in the case of pasta cooking; and size of blast chillers, refrigerant types for refrigerated storage and transport, the size of trucks and transport distances in the case of cook-chill and cook-warm chains.

Finally, for a comprehensive overview of the sector, the review was extended to EPD documents that have been developed and published over the years: for greater understanding, they were summarised in **Table 2**. Through the EPD system currently applicable for dry pasta, producers of the sector are stimulated to measure and improve their environmental performances and can use the certification to provide the product with environmental claims, also facilitating comparative assertions (Ruini et al., 2012). Moreover, EPDs are useful tools to meet the growing demand for documentation, traceability, and information along with the food industry, from field to dish (Del Borghi, 2013).

The characterisation values of the midpoint categories considered by the aforementioned PCR were extrapolated from the EPD documents for each dry-pasta life cycle phase and were recorded in an excel document, to calculate statistics, including number of studies, median, mean, standard deviation, minimum and maximum. The summary of those results is presented in **Table 3**, from which it can be concluded overall, that:

- Global Warming Potential (GWP) is the impact category to be most affected by all life cycle stages and to be characterised by the highest variability within the results; and
- DW cultivation is averagely the hotspot for almost all the impact categories investigated, namely acidification (9.8 g SO_2 eq), eutrophication (6.0 g PO_4^{3-}), and global warming potential (582.7 g CO_2 eq), excluding photochemical oxidation in which its contribution is approximately equal to that of pasta production.

In addition to this, by scanning through the EPD documents found, the authors observed that:

- DW cultivation impact is mainly linked to the use of fertilisers and pesticides that are responsible for the emission of GHGs and other polluting compounds: such explains why the lowest value of GWP was found for the only company cultivating DW under an organic farming regime;
- the best environmental profile based upon the ensemble of EPD impact categories was determined to be that of the organic pasta producer;
- the companies that expanded the system boundaries to the phases of pasta cooking and post-consumption package disposal found that the contribution of pasta cooking is highly relevant in terms of energy consumption, thus emphasising upon the need to adopt more eco-sustainable cooking methods.

In conclusion, the review was useful for this paper’s authors to understand the key environmental issues associated with pasta production systems, and highlighted a gap in the specialised literature, related to the fact that only one study amongst those reviewed above was found as focussing upon ancient-DW derived pasta. In addition to this, no EPD was found on ancient-DW derived pasta, which further remarks the novelty and scientific relevance of the study conducted. The gap found was, however, surprising to the authors’ opinion, considering the increasing attention that ancient DW varieties are gaining amongst farmers, food producers and scholars, and consumers, due to their recognised suitability for design and implementation of sustainable farming methods and healthy diets. Therefore, the cultivation of ancient DW varieties within a local pasta supply chain was analysed in this study, with the final aim of contributing to filling that gap, and to enhancing the scientific literature currently available in such a relevant research content area, thereby giving added-value and novelty to the study itself.

Table 1. Published studies about dry DW pasta LCA

Reference	Methodology	FU	System Boundaries	Impact Assessment method	Impact categories	Data Quality
Bevilacqua et al (2007)	LCA	0.5kg packed pasta	Cradle-to-grave	Eco-indicator 99 methodology	All the categories provided by the LCIA method	Primary data from local producers; Secondary data from literature and databases.
Lo Giudice et al (2011)	LCI	1kg packed pasta	Cradle-to-grave	–	–	Primary data from local producers; Secondary data from Ecoinvent database.
Roos et al (2011)	CF	1kg packed pasta	Cradle-to-retail	GHG emission calculation method	Climate change	Primary data from farmers; Secondary data from literature and databases.
Fusi et al (2015)	LCA; WF of cooking operation only;	1kg cooked pasta	From the cooking stage to the food regeneration or to the ambient transport	ReCiPe method; Pfister et al. methodology (2009)	All the categories provided by the LCIA method	Primary data from scientific literature, manufacturers' specifications, legislation, and the cooking centre; Secondary data from Ecoinvent database and ILCD.
Heidari et al (2017)	Regionalised LCA	1kg pasta produced	Cradle-to-gate	ReCiPe method	All the categories provided by the LCIA method	Primary data from Iranian wheat farms, truck drivers, and the pasta factory; Secondary data from Ecoinvent database.
Cimini et al (2019)	CF	1kg packed pasta	Cradle-to-grave	PAS 2050	Climate change and also other categories such as acidification, eutrophication, ozone layer depletion, eco-toxicity and abiotic depletion	Primary data from the pasta factory; Secondary data from the Italian Institute for Environmental Protection and Research, LCA software, several databases and other technical reports.
Recchia et al (2019)	Integrated methodology based on Environmental Impacts ANalysis (EIAN) approach and LCA;	1kg packed pasta	Cradle-to-grave	The developed integrated method	Soil, air, water, resources, and climate change compartments and ten expected environmental pressures	Primary data from local producers; Secondary data from databases.

Table 2. Environmental Product Declarations of Pasta factories considered as reference for the study development

Pasta companies	Publication date	Revision	Reference PCR for dry pasta considered in the EPD review sample
Barilla durum wheat semolina pasta in paperboard box;	10/03/2011	14/12/2018	PCR 2010:01 (CPC 2371): uncooked pasta, not stuffed or otherwise prepared, ver. 3.0 of 2016-10-31;
Barilla durum wheat semolina pasta 5-kg for food service;	26/09/2013	14/12/2018	
De Cecco durum wheat semolina pasta;	25/10/2017	-	
Dried durum wheat semolina pasta - Patrimoni d'Italia;	19/02/2015	16/11/2018	
Barilla dry semolina pasta Selezione Oro Chef;	22/09/2014	14/12/2018	
Filiz dry semolina pasta;	06/02/2017	-	
Food service Organic Sgambaro Pasta (5-kg package);	03/08/2016	18/05/2018	
Food service Sgambaro pasta (5-kg package);	03/08/2016	18/05/2018	
Granarolo durum wheat semolina pasta;	-	17/11/2017	
Misko dry semolina pasta;	06/02/2017	-	
Voiello durum wheat dried semolina pasta;	06/02/2017		
Yellow label Sgambaro pasta	21/05/2013	18/05/2018	

Table 3. Summary of EPD impact categories values across different pasta companies.

EPD Impact Categories	DW cultivation					Milling					Packaging production					Pasta Production					Distribution				
	Mean	Median	Min	Max	St. Dev	Mean	Median	Min	Max	St. Dev	Mean	Median	Min	Max	St. Dev	Mean	Median	Min	Max	St. Dev	Mean	Median	Min	Max	St. Dev
Acidification ($g\ SO_2$ eq)	9.8	9.6	5.0	22.7	4.4	0.6	0.6	0.0	4.1	1.0	0.2	0.2	0.0	0.4	0.1	0.7	0.4	0.0	2.6	0.7	0.6	0.3	0.0	2.6	0.8
Eutrophication ($g\ PO_4^{3-}$ eq)	6.0	6.6	2.4	9.0	2.0	0.1	0.1	0.0	0.6	0.2	0.1	0.0	0.0	0.2	0.1	0.1	0.1	0.0	0.3	0.1	0.1	0.1	0.0	0.2	0.1
100-year Global Warming Potential ($g\ CO_2$ eq)	582.7	565.2	259.0	1080.0	243.4	66.2	66.2	0.0	269.5	64.8	57.9	55.0	0.0	132.8	34.9	241.3	191.1	0.0	810.2	186.2	50.0	39.3	0.0	150.0	44.0
Photochemical Oxidation ($g\ C_2H_4$ eq)	0.1	0.1	0.0	0.4	0.1	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.1	0.0

4. Materials and method

LCA is an environmental management tool that allows for holistic, systematic, and multidisciplinary evaluation of both environmental impacts and damages of products' life cycles, as the starting point to identify the improvement potentials.

An attributional LCA was applied in this study, to address the relevant environmental issues associated with a local organic ancient-DW dry-pasta supply chain, thereby contributing to supporting the transition towards sustainable food systems (Notarnicola et al., 2017). It was developed according to the specialised International Standards 14040-44:2006 (ISO, 2006), so following the phases of:

- Goal and Scope Definition;
- Life Cycle Inventory (LCI);
- Life Cycle Impact Assessment (LCIA); and
- Life Cycle Interpretation.

Each of those phases was discussed in the sections following in terms of their application to the ends of this study development. The EPD (2018) method (v 1.01) intended for EPD development and available in Simapro 9.1.0.11 software was used in this study for the environmental impact assessment phase. Indeed, as Del Borghi et al. (2019) stated, the EPD is a communication vehicle of environmental results previously obtained through application of LCA in compliance with a set of rules defined by the programme operator, known as Product Environmental Rules (PCRs). In parallel, the Product Environmental Footprint (PEF) is also one method for calculation of the environmental footprint of products. Under this perspective, both the *Product Category Rules 2010:01 Uncooked pasta*[1] *(PCRs$_{EPD}$)* (EPD, 2019) and the *Product Environmental Footprint Category Rules for Dry Pasta v. April 2018 (PCRs$_{PEF}$) (*PEFCR, 2018*)* were used by the authors for this LCA development. Thus, their combined application was done consistently with the aim and function of the study, to contribute to obtaining exact, reliable, and reproducible results.

Those two types of rules were integrated in this study, because the *PCRs$_{EPD}$* were found by the authors as not detailing the method for calculation of the emissions of N- and P-compounds from fertiliser application, but as cross-referencing it with the appropriate *Product Category Rules 2013:05 for arable crops* (EPD, 2016). The latter were, however, not used in this study as, differently than the aforementioned *PCRs$_{PEF}$*, they are valid for multiple arable crops belonging to the categories of cereals (e.g., wheat), oilseeds and oleaginous fruits, pulses, sugar crops, and other crops including forages and fibres (EPD, 2016). By contrast, the *PCRs$_{PEF}$* for dry pasta report parameters that are specific and accurate for DW cultivation, which is why they were preferred by the authors for the agricultural modelling.

Moreover, authors strictly followed the *PCRs$_{EPD}$* as guiding reference, to make their LCA results comparable with those from the sample of collected EPDs as reviewed in the previous section, so contributing to making this paper a scientifically valid harmonised tool for results dissemination and knowledge increase. But mostly, they referred to that sample to extrapolate the average contribution of package production and end-of-life to the total impact of the pasta supply chain per single midpoint category, and so compensate for the absence of collectable primary data. Additionally, the *PCRs$_{EPD}$* were followed in the interests of the pasta-factory that supported the study, since they are expected to allow for a more efficient and clear communication to final consumers, by accounting for those having been recognised as the most relevant impact categories for pasta production systems.

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[1] These rules were developed in the framework of the International EPD System. EPD®, 2019. Uncooked pasta not stuffed or otherwise prepared. Product category classification: UN CPC 2371. Vers. 3.11

4.1 Description of the Sicilian pasta production process

In this study, DW dried pasta is produced in Sicily through the following main processes: cultivation of DW according to the organic rule, milling of DW grains, mixing of the obtained semolina with water, kneading and extrusion, drying and packaging. So, this section is focussed upon the main product and process features of the small-size pasta factory located in Sicily, which effectively supported this study development. The production flowchart was shown in **Fig. 1**. In particular, the factory:

- cultivates under organic regime *Senatore Cappelli* DW in its own fields, thus, closing part of the production chain independently;
- receives and processes organic DW grains and semolina from other local farmers and processors, that integrates with their productions;
- produces different formats of pasta (e.g., long and short goods) from old DW varieties and landraces, thereby contributing to enhancing the increasingly threatened local agrobiodiversity;
- is managed by staff interested in sustainability issues and research activities.

Those elements permitted the retracement of the company's production chain, which was essential for the collection of qualitative and quantitative data as the starting point for the development of the inventory and environmental impact analysis.

Regarding the cultivation sub-system, *Senatore Cappelli* DW is cultivated in two different Sicilian areas:

- in the territory of Fiumefreddo, in the fields that belong to pasta producer involved in this study (hereinafter referred to as '*Farmer 1*'); and
- in the territory of the Enna, in the fields of the largest company supplier of *Senatore Cappelli* durum wheat grains (hereinafter referred to as '*Farmer 2*').

The distances to be travelled for DW grains acquisition are 5.5 km and 38.6 km, respectively for Farmer 1 and Farmer 2. In both cases, the cultivation is carried out according to the organic regime (Council Regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products) and provided well-designed crop rotation with legumes (*Vicia Faba* L.), and soil preparation. Introducing legumes as wheat's previous crop was conceived to provide several agro-ecological services as well as economic benefits (Aschi et al., 2017; Kumar et al., 2020). Legume crops, in fact, symbiotically fix atmospheric N_2 through their association with *Rhizobium bacteria*, thus maintaining a continuous N supply chain for the subsequent crops (Lötjönen and Ollikainen, 2017) and leading to a potential decrease in the use of inorganic N amendments (Hardarson, 1993; López-Bellido et al., 2006). Soil tillage includes operations to prepare the seedbed, such as chiselling and harrowing. Then, harvesting is done on mature wheat ears using combine harvester, which, in line with Owens (2001), avoid potential production losses due to ginning, disruption of kernels, and harvesting grain with excessive humidity. No drying is carried out because, at the harvest the grains have a low moisture content (lower than 14%).

After the harvesting phase, the raw material (i.e. the DW grains) is received and processed at the milling plant of the pasta production factory into semolina, through the operations of cleaning, tempering with water, grinding, and sieving, in agreement with specialised literature articles like González (1995). These steps respectively consist in:

- the separation of grain from foreign seeds, seeds of irregular size, and other impurities through different dry cleaning machines;
- the addition of water (approximately in a percentage of 3-5%) to wheat, to enable the production of semolina and bran without endosperm, with minimal power consumption;
- the breaking up of the wheat kernels and the separation of the endosperm from the bran, using rollers, plansischters, and purifiers.

With this technology, the company chooses the particle size distribution of semolina according to the desired pasta characteristics and the production requirements (Sicignano et al., 2015). Therefore, the semolina is stocked or directly moved to the pasta production plant.

Pasta production consists of mixing and kneading DW semolina with water (normally in a range of 25–30 kg of water per 100 kg semolina), until a homogeneous dough is obtained, which then is extruded, dried, and finally packed. The stages of mixing and extruding are performed under vacuum to avoid the formation of air bubbles in the pasta, to inhibit enzymes action, and to minimise the loss of pasta colour. Moreover, the extrusion pressure is essential to give the product the desired level of texture as in this way, according to Sicignano et al. (2015), the shape of pasta during cooking can be preserved.

The pasta factory in question utilises 'bronze dies', so the final products have a rough surface with large pores, which, as explained by Carini et al. (2014), results in higher porosity and therefore in superior suitability to bind the sauce. Drying is done at low-temperature values (40-60 degrees Celsius) for long treatment times (24 h) and causes the decrease of humidity from 30% to 12.5% which, according to the Italian legislation (Italian Law July 4, 1967, No. 580), is the maximum water content to ensure a long shelf-life as well as the commercialisation of the product. This operation is carefully managed to attain a uniform rate of water removal and, consequentially, a high-quality pasta, able to satisfy the consumer preferences both in terms of texture and organoleptic features (Giannetti et al., 2021).

Finally, the dry pasta is moved to the packaging line where is packed with polypropylene bags and cardboard, which protect the product from cracks and contamination and provide it with the label together with all the mandatory information as referred to the Regulation (EU) No 1169/2011 (European Commission, 2011).

4.2 Life Cycle Assessment application

4.2.1 Goal and scope definition

This study was conducted to address the environmental hotspots and the improvement potentials associated with the production of a DW organic dry pasta, produced from a small-size factory located in Sicily: for this purpose, LCA was performed with a '*cradle-to-gate'* approach in the light of the influence that such a food product has on the agro-economy of the Region. In particular, the system investigated was that of the production of organic dry pasta from '*Senatore Cappelli'* whole DW semolina. As part of this phase, the Functional Unit (FU) and the system boundaries were defined in this LCA elaboration phase, in a way to:

- be consistent with the aim and scope of the study;
- best represent the system under investigation;
- facilitate data collection;
- empower the pasta factory with eco-literacy; and
- enable comparisons on environmental performances with other pasta products sold on the market.

In the light of the above, the FU was identified in 1 kg of pasta, packed with a polypropylene bag. Besides the FU, the authors dealt with the boundaries of the system investigated, by setting them at the pasta factory's gate and, according to the $PCRs_{EPD}$, by including the phases of DW cultivation and semolina production (upstream part of the system), followed by the processing of that semolina into dried pasta (core part of the system) (see **Fig. 1**). As shown in **Table 4**, along with those phases, the system included the production of the package utilised for the packing of pasta and the transportation of the produced grains to the pasta producer. From both **Table 4** and **Fig. 1**, there is evidence that the phases of the packed-pasta distribution, consumption, and disposal – all forming the downstream part of the system - were set as outside of the system boundaries and so were excluded from the assessment. This was done for reasons of best representing the function of the system investigated and the aim of the study conducted.

Table 4. Association between processes and phases

Processes	Part of the system
• DW cultivation from input material preparation and acquisition; • DW semolina production in the grain milling plant; • Production of the package utilised for the packing of pasta; • Transportation of the produced grains to the milling plant;	Upstream
• Pasta production and packaging;	Core

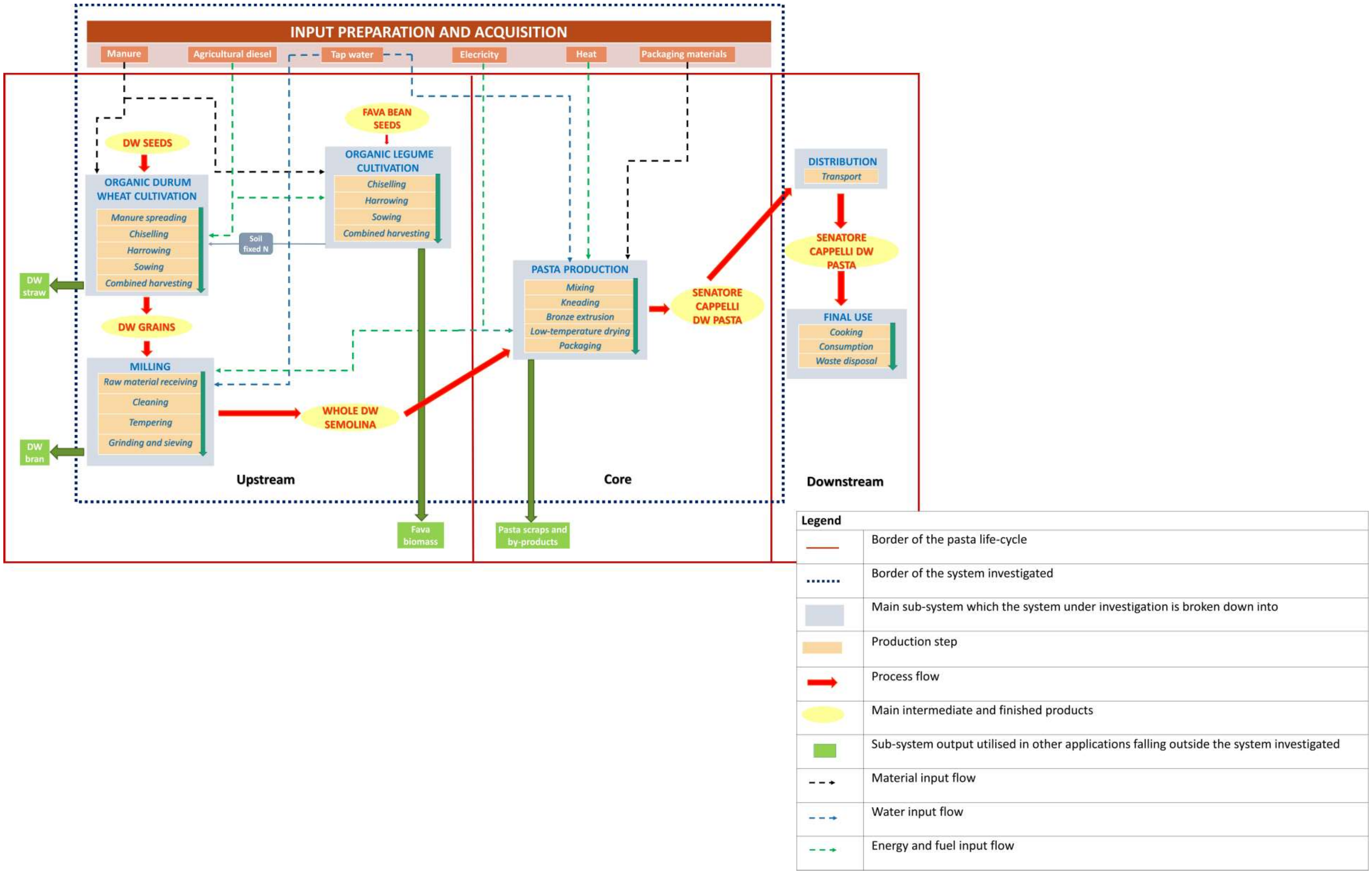

Figure 1. Boundaries of the investigated system

4.2.2 Life Cycle Inventory

The inventory analysis is the most time-consuming step of an LCA (Ingrao et al., 2019b). It is guided by the goal and scope definition, and its core activity is the collection and compilation of data on elementary flows from all processes in the studied product system drawing on a combination of different sources (Bjørn et al., 2018). Both primary and secondary data were used for that purpose. The former consists of site-specific data that were collected through the administration of questionnaires and face-to-face interviews with the farmers and the food technologist employees working for the pasta factory that supported the study development. In particular, the questionnaire was developed to collect management information on:

- main structural and economic features;
- stages of the production process;
- features of the obtained product; and
- amount and type of the residues and wastes to be treated (Valenti et al., 2016).

In particular, the questionnaire was designed to obtain information for 2017, 2018, and 2019 seasons and was organised into the following parts:

i) an introductory section containing general questions about pasta company e.g. name of the company, location, contact details, and so on; and

ii) a detailed section divided into as many subsections as there are the main stages of the production process (e.g. DW cultivation, milling, and pasta production), aimed at gathering information on agricultural inputs, farming and processing management practices, milling centres and pasta production plant structures, resource consumption, features and amounts of the obtained products.

Primary data were later combined with secondary data that were extrapolated from databases of acknowledged scientific value and relevance, such as the Ecoinvent v. 3.5, that is available in Simapro 9.1.0.11, namely the software that was used for this assessment development. This database was used for its suitability for the modelling of agriculture and food-industry systems, and for the large number of materials and processes it contains (Frischknecht and Rebitzer, 2005). In particular, secondary data essentially regarded the material preparation phase, including the production of all the material and energy inputs of all steps of the system investigated. Both primary and secondary data were detailed and reported in **Tables 5-9**.

Allocations were made according to the *PCRs$_{EPD}$* for uncooked dry pasta, which meant that an economic allocation was done for wheat cultivation and milling, whilst a mass-based one was adopted for pasta production. Results shown confirm that, in line with the previously published literature reviewed in this paper, the economic criterion is well suited for allocation of both inventories and impacts between products and by-products in some of the steps of pasta supply chains, such as farming and milling. In the former phase, economic allocation was used by the authors in that it allowed for modelling grains as the core product they are supposed to be, despite for ancient DW varieties they are produced in lesser quantities than straw. As a matter of fact, the total wheat biomass output from the cultivation phase, just before harvesting is composed: of grains, for 21 %; and, of straw, for the remaining 79 % (see **Table 9**). The content of straw in the gross biomass produced was estimated using a 0.21 Harvest Index (HI)[2] for '*Senatore Cappelli'* DW: that index clearly shows that, similarly to other landraces and ancient varieties, the Senatore Cappelli DW is characterised by lower yields compared with modern cultivars (Dinelli et al., 2013; Giunta et al., 2007). So, it is understood that a physical allocation would have mistakenly brought out straw as the main product, thereby questioning the key function of the cultivation system investigated that – it is remarked - is to produce grains rather than straw.

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[2] The HI is given by the ratio between the amount of grains and the amount of the gross biomass produced

Straw is an output biomass that fulfils the criteria and conditions provided by the Ministerial Decree n. 264/2016 (D.M. 13 ottobre 2016, n. 264), so that a by-product can be defined as such, namely:

- having clear, integral, and direct applications in other production processes;
- being utilised directly by the production company or by different previously defined users;
- complying with commodity and environmental quality requirements in a way to ensure that its utilisation does not cause environmental impacts different than those authorised for the plant it is intended for;
- adequate environmental quality requirements from the production stage on; and
- having a market value.

Concerning the market value, it should be noted that in the past, relatively-high straw productions, like those of the landrace from which the pasta object of this study is obtained, were a desirable wheat trait, because the straw was valuable for livestock feeding and bedding (Carranza-Gallego et al., 2018). Also currently, straw production became desirable again, since it provides the possibility to sequester C without compromising grain yields (Konvalina et al., 2014), and is increasingly used for a wide range of profitable, innovative applications out farm use (Ingrao et al., 2019a). In the light of this, and in line with the literature, straw was considered as a grain cultivation by-product, and so was modelled as a grain cultivation co-product for the LCA development.

To comply with the PCR_{EPD}, in the milling phase an economic allocation was preferred to a mass-based one. The latter, however, considering the amounts of products and by-products in stake, to the authors' opinion would have been effective in representing the milling's function of producing flour.

The following formulas were used for calculation of the allocation percentages:

- *mass-based allocation*

$$AP_P = \frac{Q_P}{(Q_P + Q_{CP})} \times 100$$

$$AP_{CP} = \frac{Q_{CP}}{(Q_P + Q_{CP})} \times 100$$

- *economic allocation*

$$AP_P = \frac{Q_P \times MP_P}{[(Q_P \times MP_P) + (Q_{CP} \times MP_{CP}]} \times 100$$

$$AP_{CP} = \frac{Q_{CP} \times MP_{CP}}{[(Q_P \times MP_P) + (Q_{CP} \times MP_{CP}]} \times 100$$

in which: AP is the allocation percentage calculated; Q is the quantity of product (P) or co-product (CP), already shown in **Tables 5-9**; and MP is the market price for both the P and CP.

The market prices used to perform allocation in the DW cultivation phase were extrapolated from the weekly wholesale price list published by A.G.E.R. Borsa Merci Bologna (Settimanale n. 38 del 8 Ottobre 2020 – Listino Borsa n. 37), whilst for milling they were provided by the local producers operating in the pasta supply chain investigated. **Table 10** shows the ensemble of the market prices considered for allocation in the phases of cultivation and milling. Allocation results were shown in **Table 11,** along with the production yields associated with each phase of the pasta supply chain.

Emissions due to the on-field application of cow manure were calculated and were found to be relatively low, mainly thanks to the adoption of an organic farming system. In particular, N_2O, NH_3, $N0_3$- and P-emissions were estimated following the PEFCR for dry pasta, whilst N emissions were computed according to the methodology proposed by Brentrup et al. (2004). The agricultural activities were implemented imputing models already contained in Ecoinvent to the cultivation phase using the values of 1.045E-4 ha (Farmer 1) and 7.779E-5 ha (Farmer 2) which, as a reminder, are referred to as 1 kg of wheat biomass production. Those two values were calculated clearly as a reverse of the production yields in kg per ha of cultivated fields.

In addition, the inclusion of legumes (*Vicia faba* L.) in rotations was considered for its relevant role within the organic farming practices carried out by Farmers 1 and Farmer 2 to lower N fertiliser inputs, whilst maintaining high yields. As shown in **Tables 5** and **7**, *Vicia faba* L. cultivation was modelled using the qualitative and quantitative data provided by the farmers involved. Furthermore, consistently with the legume rotation function, the Fixed-N was modelled as a co-product of legume cultivation and then, as an input product to the wheat cultivation phase. Such findings confirm the well-documented benefits associated with low-input grain farming (Ali et al., 2015).

Regarding the milling and pasta production phases, all the inputs and outputs, as well as the environmental impacts associated with the grain production phase were proportioned to the values 0.327 kg (Farmer 1) and 0.725 kg (Farmer 2), which are required for the production of respectively 1 kg whole-meal semolina and 1 kg of pasta. More specifically, it has been considered that, from the DW, the milling yield is whole-meal semolina for the 95%, whilst brans form the remaining 5%. The electricity required for the milling and the pasta production processes is low voltage electricity generated from photovoltaic panels and was modelled using background datasets available in Ecoinvent v. 3.5.

Since it was not possible for this team of authors to collect primary data about the production of packaging materials and end-processing of packaging waste, the impacts of primary and secondary packaging were extrapolated from the existing EPDs published for pasta and, therefore, were considered by adding them to the final results from the assessment. In particular, only the EPDs of the companies that used a package consisting of a polypropylene film and cardboard box were considered and, for each of those, the average contribution of the package's life cycle to the total impact was calculated and was added to the midpoint results of each impact category considered in this study.

About the transports involved, the latter are just in the phases of cultivation and milling; for contrast, there are no transports in the other phases included in the pasta production system because they are developed within the same plant.

Table *5*. Inventories associated with the DW cultivation phase, with the harvesting phase excluded

CULTIVATION DATA INVENTORY	**FARMER 1 (PASTA FACTORY FIELDS)**	**FARMER 2 (LOCAL FARMER FIELDS)**	
OUTPUTS	**AMOUNT**	**AMOUNT**	**UNIT OF MEASURE**
Output products			
Wheat Biomass, gross (grain + straw)	1	1	kg
Emissions from fertiliser application to air			
Dinitrogen monoxide	0.0988	0.0988	g
Ammonia	1.078	1.078	g
Nitrogen total	0.307	0.307	g
Emissions from fertiliser application to water			
Phosphorus	0.0858	0.0858	g
Nitrate	5.972	5.972	g
INPUTS	**AMOUNT**	**AMOUNT**	**UNIT OF MEASURE**
Resources			
Transformation, from annual crop, organic	1.045E-4	7.779E-5	ha
Transformation, to annual crop, non-irrigated, extensive	1.045E-4	7.779E-5	ha
Occupation, annual crop, non-irrigated, extensive	1.045E-4	7.779E-5	
Carbon dioxide, in air	0.648	0.648	kg
Carbon, organic, in soil or biomass stock	0.0366	0.0272	kg
Materials			
Organic wheat seed from Farmer 2	0.0188	0.0156	kg
Fixed N from legumes rotation	0.0209	0.0156	kg

Agricultural treatments			
Solid manure loading and spreading	1.32	1.32	kg
Seeds transportation	0.094	-	kgkm
Chiselling	1.045E-4	-	ha
Ploughing	-	7.779E-5	ha
Harrowing	1.045E-4	7.779E-5	ha
Sowing	1.045E-4	7.779E-5	ha

Table 6. Inventories associated with the combined harvesting phase

HARVESTING PHASE DATA INVENTORY	**FARMER 1**	**FARMER 2**	**UNIT OF MEASURE**
OUTPUTS	**AMOUNT**	**AMOUNT**	
Output products			
Grain	1	1	kg
Straw	3.76	3.76	kg
INPUTS	**AMOUNT**	**AMOUNT**	**UNIT OF MEASURE**
Resources			
Energy, gross calorific value, in biomass	35.817	35.817	MJ
Materials			
Wheat biomass cultivation	4.76	4.76	kg
Agricultural treatments			
Combine harvesting	4.974E-4	3.703E-4	ha
Baling processing	0.00537	0.00537	p

Table 7. Inventories associated with the legumes (rotational crop) cultivation

LEGUME CULTIVATION PHASE DATA INVENTORY		**UNIT OF MEASURE**
OUTPUTS	**AMOUNT**	
Output products		
Fava biomass	1	kg
Fixed N	0.1	kg
INPUTS	**AMOUNT**	**UNIT OF MEASURE**
Resources		
Carbon dioxide, in air	1.416	kg
Occupation, annual crop, non-irrigated, extensive	5.04E-4	ha a
Transformation, from annual crop, non-irrigated, extensive	5.04E-4	ha
Transformation, to annual crop, non-irrigated, extensive	5.04E-4	ha
Materials		
Fava bean seed, organic, for sowing	0.056148	kg
Agricultural treatments		
Sowing	5.04E-4	ha
Tillage, cultivation, chiselling	5.04E-4	ha
Tillage, harrowing	5.04E-4	ha
Transport, tractor and trailer, agricultural	0.01	ha
Emissions to air		
Carbon dioxide	-0.415	kg

Table 8. Inventories associated with the milling

MILLING PHASE DATA INVENTORY		
OUTPUTS	**AMOUNT**	**UNIT OF MEASURE**
Output products		
Wholemeal semolina	1	kg
Bran (crusca)	0.052	kg
INPUTS	**AMOUNT**	**UNIT OF MEASURE**
Materials		
Grain from Farmer 1	0.327	kg
Grain from Farmer 2	0.725	kg

Tap water	0.0627	kg
Electricity		
Elecricity, low voltage, IT, photovoltaic	0.211	kwh
Grain transportation, tractor and trailer, agricultural	2.013	kg km
Grain transportation, lorry 3.5-7.5 metric ton	105.3	kg km

Table 9. Inventories associated with the pasta production

PASTA PRODUCTION PHASE DATA INVENTORY		
OUTPUTS	**AMOUNT**	**UNIT OF MEASURE**
Output products		
Pasta	1	kg
Pasta scraps	0.0260	kg
Other pasta by-products	0.0080	kg
Emissions in air		
Water	0.119	kg
INPUTS	**AMOUNT**	**UNIT OF MEASURE**
Materials		
Wholemeal semolina	1.034	kg
Tap water	0.119	kg
Electricity		
Elecricity, low voltage, IT, photovoltaic	0.125	kWh
Heat, district or industrial, natural gas	0.467	MJ

Table 10. Market prices considered for the economic allocation of the cultivation and milling phases

Life-cycle stage	**Products/co-products**	**Market prices**	**Unit of measure**
DW cultivation	Grain	357.5	€/ t
	Straw	64.5	
Milling	Semolina	0.85	€/kg
	Bran	0.26	

Table 11. Allocation methods and percentages applied in the product system processes

Life-cycle stage	***Products/co-products***	***Production yields (%)***	***Allocation percentage***	***Allocation method***
DW cultivation	Grain	21	59.57	Economic
	Straw	79	40.43	
Grain milling	Whole semolina	95.06	98.43	Economic
	Bran	4.94	1.57	
Pasta production	Pasta	96.72	96.72	Physical
	Scraps	2.51	2.51	
	Other minor by-products (‘pastaccio’)	0.77	0.77	

For completeness, **Figure 2** shows the main reference flow throughout the entire system investigated in this study. Specifically, three sub-systems and the specific functional units chosen for each of them can be observed.

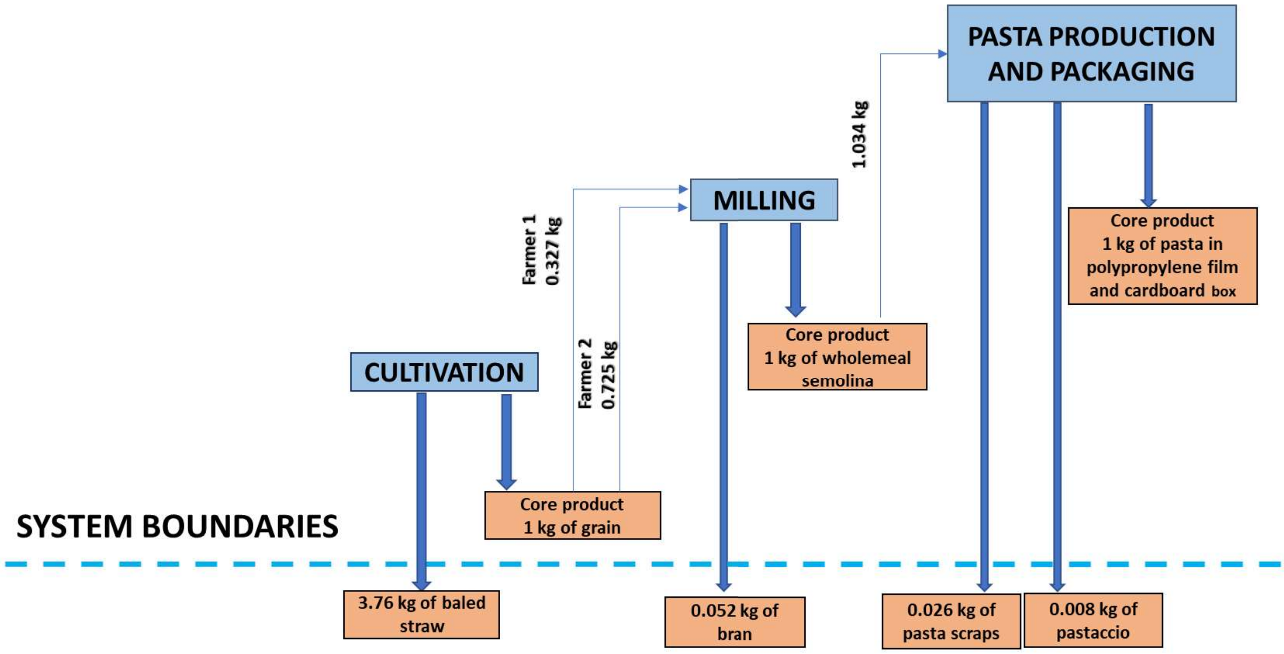

Figure 2. Reference flow throughout the entire system investigated

4.2.3 Life Cycle Impact Assessment (LCIA)

This phase was developed by aggregating the material and energy output inventories in a limited set of midpoint impact categories comprised by the EPD (2018) (v 1.01) method, which is the one included within the Simapro 9.1.0.11 software and is intended for use in case of EPDs.

LCA for EPD is an effective environmental management tool, aimed both at the communication of environmental information and analysis of different scenarios that might enhance the environmental performances of the food industry (Del Borghi, 2013). Four impact categories, namely global warming, eutrophication, acidification, and photochemical oxidation have been chosen amongst those comprised by the method. Their nomenclature, measurement units, and meaning are shown in **Table 12**.

Table 12. Impact categories extrapolated from the EPD (2018) method v. 1.01

Category	Unit of measure	Meaning
Global warming potential (GWP_{100})	kg CO_2 equivalents	Indicator of how much energy a greenhouse gas traps compared to an equivalent amount of CO_2 within a given period of time (100 years). It is used to measure the carbon footprint (CF) of products or processes.
Eutrophication (EP)	kg PO_4^{3-} equivalents	Indicator of the enrichment of the aquatic ecosystem with nutritional elements, due to the emission of nitrogen or phosphor-containing compounds.
Acidification potential (AP)	kg SO_2 equivalents	Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides.
Photochemical oxidant creation potential (POCP)	kg NMVOC equivalents	Indicator of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight.

Attention was focussed upon those categories because, in agreement with the specialised literature and the EPDs collected and reviewed in this paper, they were considered by this team of authors to be representative of the food supply chain investigated and consistent with the function of the study.

5. Results and Discussion

The contributions of the entire investigated system to global warming, acidification, photo-oxidant formation, and eutrophication were presented in **Figure 3** and **Figure 4**. Additionally, contributions coming from the different phases have been assessed and reported in **Table 13**, thus best highlighting the environmental criticalities of the system investigated. The analysis of the obtained results shows that, in line with the subject literature, cultivation is the phase contributing the largest impacts for all the categories considered by the method. As for Cimini et al. (2019), this can be attributed to the consumption of aged manure and of diesel fuel for soil management activities, together with the direct and indirect N_2O emissions. As illustrative, DW cultivation, milling, pasta production, and packaging contribute 58.98 %, 20.86 %, 12.70 %, and 7.44 % of the total CF associated to the system investigated. Milling exhibits the greatest impacts for all midpoint categories except eutrophication, whilst the contribution from pasta production is notable mainly for global warming. The incidence of the package's life cycle is relevant mainly for global warming and photochemical oxidation.

Moreover, from comparison of results from this study (Fig. 3 and 4) with background results from EPD review (Table 3), it was found that, overall, the environmental impacts of the system investigated is lower than the respective mean values. This is valid for all stages of the investigated system but for milling, as it generates slightly higher impacts in terms of global warming, and for DW cultivation that highly contributes to photochemical oxidation.

It should be underscored, however, that two different units of measure were used to express the photochemical oxidation impact, namely: g of ethylene equivalents (in the reviewed EPD sample); and g of NMVOC equivalents (in this study following the aforementioned EPD-based environmental assessment method). Therefore, the comparison performed was based upon the application of the conversion factor (0.59 kg-C_2H_4 eq/kg-NMVOC eq) proposed by Goedkoop et al. (2012) for the ReCiPe methodology (Laurent et al., 2014). This made it possible for this paper's authors to calculate the value of 0.89 kg C_2H_4 eq that so expresses the photochemical oxidation impact for the cultivation phase in a way to be comparable with the related mean contained in Table 3.

The cultivation phase performs, however, best compared with the EPD reference sample, showing:

- an eutrophication impact lower than the mean value; and
- environmental impacts for GWP and acidification that are lower than not only the related means calculated in Table 3 but, also, the related minimums that, specifically, correspond to the only organic farming case.

These findings confirmed the importance of the organic practices in lowering the environmental impacts associated with the agricultural phase, and remarked that ancient varieties can further contribute in that regard. In particular, according to this team of authors, the lowest impact associated with the cultivation phase should be attributed to the allocation criteria used for DW cultivation and related percentages obtained (**Table 11).** Indeed, the production of a relevant quantity of straw, which is typical of old and/or ancient varieties, makes the ancient DW grains responsible for a minor part of the total environmental impact. Therefore, the cultivation of old varieties and landraces in organic and low input systems seems to have a large potential for reducing the environmental footprint of wheat-based products like pasta through the production of high amounts of residue (i.e. straw). Following Kulak et al. (2015), it is not always true that product LCA supports intensive high input and high output systems but rather, at least at the agricultural stage, some low-yielding systems, such as the one investigated within this study, can be more eco-efficient than high-input agriculture.

It should be underscored, however, that the comparison between the reviewed-EPD sample and this study is clearly affected by differences in:

- agricultural management practices;
- soil and climate conditions;
- milling and pasta-making technologies;
- production yields; and,
- versions and updates of the adopted impact assessment methods.

Finally, being the DW cultivation the environmental hotspot of the system, as evident from both Fig. 3 and Fig. 4, the assessment dealt also with the calculation of the most impactful material emissions in air, water, and soil associated with that phase (**Table 14**). These emissions can be intended as resulting from the sum of those coming from the input material preparation (background emissions) and from the fertiliser application (primary emissions).

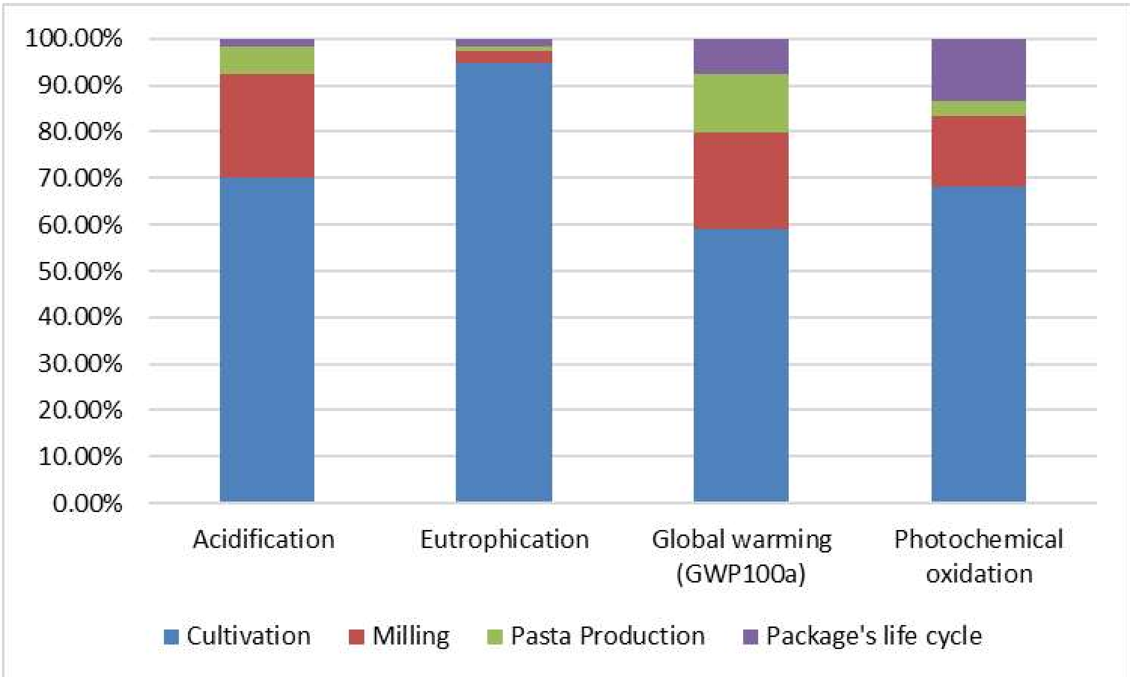

Figure 3. Percentage contributions of the pasta supply chain phases per each impact category using characterisation results from the EPD method used for the assessment.

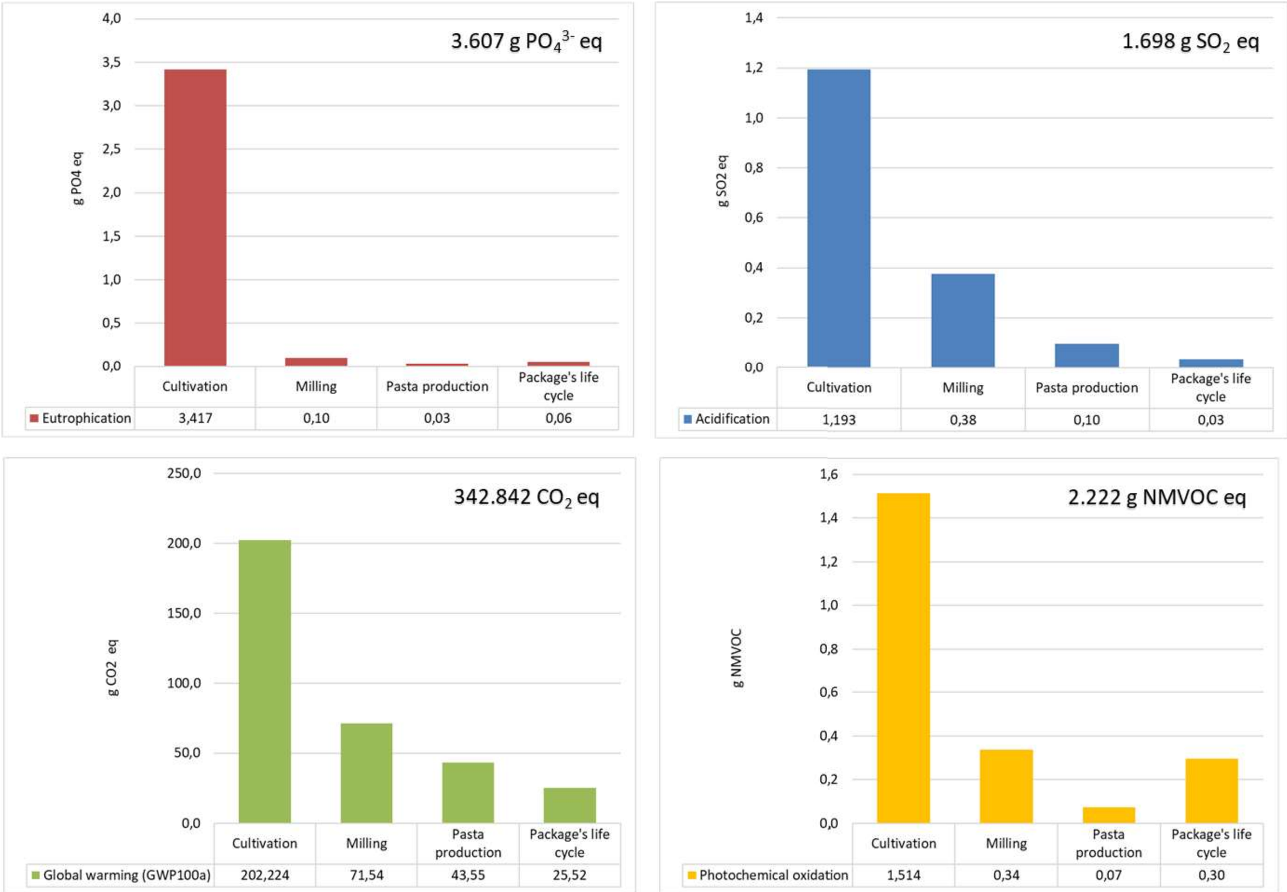

Figure 4. Total contributions of the impact categories per kg of packed pasta

Table 13. Contributions to the impact categories due to the DW supply chain per kg of packed pasta

Impact category	U.M	DW Cultivation	Milling	Pasta production	Package's life cycle
Acidification	g SO_2 eq	1.193	0.38	0.10	0.03
Eutrophication	g PO_4^{-3} eq	3.417	0.10	0.03	0.06
Global warming (GWP100a)	g CO_2 eq	202.22	71.54	43.55	25.52
Photochemical oxidation	g NMVOC eq	1.514	0.34	0.07	0.30

Table 14. Emissions associated with the cultivation phase for the impact categories of the study

Material emissions	Emission compartment	Output Inventory		Midpoint Assessment result	
		Amount	U.M.	Value	U.M.
Acidification (0.00119 kg SO_2 eq)					
Nitrogen oxides	Air	1.25	g	0.000872	kg SO_2 eq
Sulphur dioxide	Air	272	mg	0.000272	
Eutrophication (0.00342 kg PO_4 eq)					
Nitrate	Water	18.6	g	0.00186	kg PO_4 eq
Phosphorus		265	mg	0.00081	

Nitrogen, total	Air	946	mg	0.000397	
Nitrogen oxides		1.25	g	0.000162	
Global warming (0.202 kg CO_2 eq)					
Carbon dioxide, fossil	Air	133	g	0.133	kg CO_2 eq
Dinitrogen monoxides		313	mg	0.0831	
Methane fossil		199	mg	0.00556	
Photochemical oxidation (0.00151 kg NMVOC)					
Nitrogen oxides	Air	1.25	g	0.00125	kg NMVOC
NMVOC		195	mg	0.000195	
Carbon monoxide, fossil		947	mg	4.32E-5	
NMVOC		272	mg	2.21E-5	

6. Conclusions and future perspectives

The LCA study was conceived to assess the sustainability of organic DW cultivation and pasta production in a company located in Sicily, as essential for the identification of both environmental hotspots and improvement potentials. The application of the methodology allowed the assessment of the environmental impacts associated with the product life cycle, from DW cultivation to pasta packaging, following a cradle-to-gate approach. According to authors, the obtained results may be useful for the compilation of the EPD of the pasta product assessed in this study, may contribute to enriching the scientific literature currently available in the field of LCA of ancient DW varieties, for which a gap was observed by the authors. In addition to this, though they are site-specific, they could be used by practitioners, farmers and producers, policymakers, and other stakeholders worldwide to enhance their knowledge on such a research content area and, more generally, on LCA application to agro-food systems. Consistently with other recently published studies, from their study the authors found DW cultivation to be the hotspot of the entire pasta production chain. However, by comparison with recently published EPDs on the pasta sector, the environmental sustainability profile of the investigated system results highly positive, strengthening the evidence that the cultivation of ancient durum wheat varieties and landraces under organic regime represents a way to achieve multiple improvements and sustainable development goals. However, it is already possible from this analysis to outline the following potential strategies to improve the pasta-factory environmental profile:

- the application of minimal or no-tillage techniques;

- the return of crop straw to soils, throughout different methods like mulching and/or incorporation;
- the implementation of different crop rotations besides the leguminous based ones, including other species according to their nitrogen fixation potential and adaptability to soil and climatic conditions of the company's cultivation areas.

The feasibility and environmental advantages of these potential solutions will be verified with the experienced agronomists of the company, and will be evaluated by the authors in future investigations. In this regard, to contributing to making the whole research even more supportive of making micro-level decision and improving farm management, it is the authors' intention to expand the assessment to the weighing phase. Such will be done by the authors in the near future, along with expanding the assessment to the downstream processes of pasta distribution and consumption, and to the linkages between environmental and economic, social, cultural, and health issues. This will include the estimation of the nutritional quality of pasta products in LCA-based environmental assessments, following authors like Chaudhary, Abhishek et al. (2018) and McAuliffe et al. (2020). Finally, the authors believe that this study puts emphasis upon the importance of promoting and spreading LCA of local agri-food systems, to allow Sicilian products to boost their competitiveness and attractiveness in the market, throughout the achievement of environmental sustainability requirements.

CRediT authorship contribution statement

Carlo Ingrao, Silvia Zingale, Paolo Guarnaccia: Conceptualisation, Data Curation.
Carlo Ingrao, Silvia Zingale: Methodology, Software.
Carlo Ingrao: Validation, Supervision.
Silvia Zingale, Paolo Guarnaccia, Giuseppe Timpanaro, Alessandro Scuderi, **Agata Matarazzo**: Writing – original draft
Carlo Ingrao, Jacopo Bacenetti: Writing - Reviewing and editing

Data availability statement

All data collected and analysed during this study are included in this published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Acronym list

DW	durum wheat	EPD	environmental product declaration
SDGs	sustainable development goals	PAS2050	publicly available specification 2050:2008

PEFCR	product environmental footprint category rules	CML-IA	center of environmental science of Leiden university impact assessment
PCR	product category rules	HI	harvest index
LCA	life cycle assessment	GWP	global warming potential
LCI	life cycle inventory	EP	Eutrophication
LCIA	life cycle impact assessment	ODP	ozone depletion potential
ELCA	environmental life cycle assessment	AP	acidification potential
LCC	life cycle costing	POCP	photochemical oxidant creation potential
SLCA	social life cycle assessment	WF	water footprint
LCSA	life cycle sustainability assessment	DP-EPDCRs	dry pasta environmental product declarations category rules
CF	carbon footprint	DP-PEFCRs	dry pasta product environmental footprint category rules
MC	monte carlo	N_2O	nitrous oxide
CFCG	carbon footprint cradle to grave		
PP	polypropylene		
PB	paperboard		
PE	polyethylene		
EIAN	environmental impacts analysis		
FU	functional unit		
GHG	greenhouse gas		
N	nitrogen		

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