PRODUCT CARBON FOOTPRINT: STILL A PROPER METHOD TO START IMPROVING THE SUSTAINABILITY OF FOOD AND BEVERAGE ENTERPRISES

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ABSTRACT

Given the complexity of food production, supply chains and distribution, this paper sustains that the mere assessment of the product carbon footprint might still be regarded as a first trial in the field of improving the sustainability of the food and drink industry.
After having reviewed the greenhouse gas (GHG) emissions associated with the agro-food system in industrialized countries, and summarized the main direct environmental impacts of the food industry, the pros and cons of the Life Cycle assessment (LCA) methodology were briefly examined together with the current standard methods used to assess the environmental impact of food and drink products. Once a cradle-to-grave product carbon footprint modelling had been developed, some mitigating actions might be tested with the final goal of reducing the GHG emissions associated with the most impacting product life cycle stages. As an example, such a procedure was applied to approximately halve the cradle-to-grave carbon footprint of two cereal-based products (i.e., dry pasta and malt beer). A cost/benefit analysis is required to relate the marginal increase in the product processing costs to each reduction in the product environmental load.

Keywords: beer, carbon footprint, dry pasta, environmental impact, GHG emissions

1. INTRODUCTION

The current food system is regarded as ecologically unsustainable (CHURCH, 2005; FOODDRINKEUROPE, 2012; WRI, 2013), since fossil fuels are essential requirements for running crop production, animal husbandry, food production and distribution, as well for the construction and maintenance of machinery and processing equipment, transportation vehicles, and infrastructures.

The greenhouse gas (GHG) emissions associated with food production and consumption were evaluated to constitute 19-29% of the global GHG emissions (VERMEULEN *et al*., 2012). By referring to the major environmental impact categories, such as climate change (CC), ozone depletion (OD), photochemical ozone creation (POC), acidification (A), eutrophication (NP), resource depletion, human toxicity, and eco-toxicity, the food, drink, tobacco and narcotics area of consumption in the EU-25 was estimated to generate up to 20-30% of the main impact categories (including 22-31% for CC), with the exception of 59% for NP (TUKKER *et al*., 2006).

An increasing number of studies has dealt with the long-term sustainability of the current trends in the production and consumption of food. In particular, the EU Standing Committee on Agriculture Research (SCAR) observed that food production is near to exceed environmental limits; land use change and land degradation, as well as the dependence on non-renewable fossil energy sources, contribute about one-fourth of the GHG emissions; agriculture, including fisheries, is the single largest driver of biodiversity loss (EUROPEAN COMMISSION, 2011). The average USA and EU diet, being rich in meat, fat and sugar, is a risk for individual health, social systems and the environment. Since the world population is expected to grow from about 7 billion to 9.6 billion people in 2050, as well as the global meat and milk consumption, especially in China and India, the promotion of healthy diets can reduce the environmental footprint of food consumption (EUROPEAN COMMISSION, 2011; FAO, 2018; MORESI and VALENTINI, 2010; WRI, 2013). In addition, food processing and retail industries are asked to stimulate the necessary changes in production and consumption patterns (WRI, 2013).

The food and beverage industry is a major contributor to the EU economy (FOODDRINKEUROPE, 2018), followed by the automotive, machinery and equipment, and chemical industries. As of 2015, it was the major driver of the economy, with turnover of € 1.109 trillion, employment of 4.57 million employees with 294,000 total number of companies. Actually, 99.1% (i.e., 280,000) of the companies are small and medium-sized enterprises (SMEs), these generating 48.1% (i.e., €538 billion) of the overall turnover, 48.4% (i.e., €107 billion) of the value added and 61.3% (i.e., 2.8 million employees) of employments. Owing to its environmental and economic importance, an intergovernmental set of 17 Sustainable Development Goals has already been identified in the food sector (FOODDRINKEUROPE, 2019), this being a core part of the 2030 Agenda for Sustainable Development (UN, 2015). Beyond the general statement of decreasing environmental burdens, such as GHG emissions, waste generation, as well as water and energy consumption, Goal 9 aims at building resilient infrastructures, promoting inclusive and sustainable industrialization and fostering innovations. The complex relation between innovation and agro-food sustainability was deeply analyzed by EL BILALI (2018) in order to identify what type of innovation should be promoted to foster transition towards a more sustainable food system.

Given the complexity of food production, supply chains and distribution, this paper aimed to present how the mere assessment of the product carbon footprint might effectively help food and drink industries to improve their sustainability. Section 2 focused on the GHG emissions associated with the agro-food system in industrialized countries, and especially in Italy. Section 3 summarized the main direct environmental impacts of the food industry. Section 4 briefly reviewed the basic of the Life Cycle Analysis (LCA) methodology with the pros and cons of the main standard methods used to assess the food and drink environmental impact. Section 5 further discussed if the key elements for sustainable food processing are a priori identifiable or should be considered on a case-by-case basis. Finally, the importance of prioritizing the life cycle stages with the highest environmental impact as derived from business-to-consumer LCA studies was addressed in Section 6. More specifically, by resorting to the cradle-to-grave carbon footprint (CF_{CG}) modelling for two typical cereal-based food and drink products (i.e., dried pasta and malt lager beer), several mitigation options were selected in order to reduce their climate change impact. In spite of assessing the effect of such options on other environmental impact categories, the only estimation of the CF_{CG} was regarded as intrinsically sufficient to promote a first improvement in the sustainability of the great majority of the food and drink enterprises.

2. GHG EMISSIONS FOR THE AGRO-FOOD SYSTEM IN INDUSTRIALIZED COUNTRIES

Although from the millenary climate observations the warming since the middle of the 20th century might be primarily attributed to natural causes, such as solar activity and random variations (DE LARMINAT, 2016), the human contribution cannot be considered negligible (IPCC, 2013). The human population has grown from about 3.0 to 7.7 billion people since 1960 (ANONIMOUS, n.d.), and in all probability has exerted a primary impact on the environment. It is, indeed, responsible for the huge release of the so-called greenhouse gases (GHG), namely CO_2, CH_4, N_2O, hydrochlorofluorocarbons (HFCs), perfluorinated chemicals (PFCs) and SF_6, in the atmosphere. Since 1980 the volumetric concentrations of CO_2, CH_4 and N_2O in the atmosphere over marine surface sites have definitely increased from about 380 to 405 ppm (NOAA, n.d.), 1566 to 1835 ppb and 301 to 328 ppb (EEA, 2017), respectively.

To allow any person now living on the Earth and those expected to live until 2100 the same rights to emit GHGs, the GHG emission space per capita and in a year should be limited to 2400 kg of CO_2, 59 kg of CH_4, and 0.67 kg of N_2O, provided the atmospheric concentration of CO_2 is less than 450 ppm with CH_4 and N_2O emissions kept at the same levels measured in 1995 (CARLSSON-KANYAMA, 1998; IPCC, 1996). Thus, the per capita GHG emissions permitted each year within a 20-yr time perspective, as estimated by summing the mass of each GHG times its corresponding global warming potential (IPCC, 2013), would amount to (1x2400+84x59+264x0.67=) 7533 kg CO_{2e} yr^{-1}.

By referring to the national inventory reports (NIR) published by UNCC (2018), it is possible to assess whether such permitted GHG emissions are congruent with the ones currently in several countries. In 2007, the direct per capita emissions ranged from 24.0 to 1.6 Mg CO_{2e} yr^{-1} for the USA and India, respectively (BERNERS-LEE, 2010).

As shown in Table 1, in 2016 the Italian GHG emissions (including those adsorbed by land use, land use change and forestry, LULUCF) amounted to circa 398 Tg CO_{2e} (ISPRA, 2018), equivalent to the Italian per capita CF of about 6.7 Mg CO_{2e} yr^{-1}. Altogether, these emissions were mainly composed of CO_2, followed by CH_4 and N_2O, while the contribution of the halogenated compounds (i.e., HFCs, PFCs, NF_3, and SF_6) was negligible. The main GHG emissions were from the energy sector (347.1 Tg CO_{2e}), this was followed by the industrial

(32.1 Tg CO_{2e}), agricultural (30.4 Tg CO_{2e}), and waste (18.3 Tg CO_{2e}) sectors, while the category LULUCF was the main GHG sink (-29.9 Tg CO_{2e}). More specifically, the agriculture sector mainly emitted CH_4 from animal husbandry [i.e., enteric fermentation (14.0 Tg CO_{2e}) and manure management (3.1 Tg CO_{2e})] and rice cultivation (1.7 Tg CO_{2e}), and N_2O from agricultural soils (8.9 Tg CO_{2e}) and manure management (2.1 Tg CO_{2e}). The industrial processing ones were mainly due to the iron and steel industry, followed by the chemical, and pulp, paper and print ones. The food processing, beverages and tobacco sector emitted ~3.7 Tg CO_{2e} (ISPRA (2018).
The contribution of the agro-food sector to the overall direct GHG emissions cannot be directly extracted from any NIR. In fact, most of its subsectors (namely, agro-food product transportation; production and transportation of packaging materials; food transport from retailer to consumer's house; electric energy consumed to preserve foods in the home freezer, fridge, etc.; gas and/or electric energy consumed to cook foods; disposal of food losses or wastes) are aggregated in other sectors. The Italian contribution without the consumer and post-consumer phases was found to be about 19% of the overall GHG emissions (MORESI, 2014), this falls within the range estimated by TUKKER *et al*. (2006).
The main direct impacts of food processing are derived from waste generation, water use, and energy use (DIEU, 2009). Food waste is intense in farms due to spoilage (~21% of supply), but limited to ~7% throughout food processing. Food waste may be the loss of inedible materials or rejected products from sorting, grading, peeling, trimming, and squeezing. It may amount to the 50-70% of fresh citrus fruits or crab and shrimp processed (DIEU, 2009). Packaging materials (i.e., paper- and card-board, plastics, glass, metals, and wood) are largely used to protect processed foods not only from deterioration and/or contamination (primary packaging), but also from mechanical damage through the distribution and retailing operations (secondary and tertiary packaging).
In food processing large volumes of water are used as the main ingredient, particularly in drink production, as the initial and intermediate cleaning source, transportation conveyor of raw materials, and principal agent used in sanitizing plant areas and machinery (DIEU, 2009). The water consumption in fruit and vegetable processing ranges from 4 to 32 m^3 per Mg of product treated, of which approximately 50% is used just for washing and rinsing. The water used to make beer or milk products may vary from 9 to 18 m^3 Mg^{-1}. The resulting wastewaters are generally rich in organic matter, and sometimes are contaminated with pesticide residues from raw material treatments. Up to 50-60% of the water might be reclaimed and reused after screening, filtering or dilution with fresh water.
Air emissions during food processing may contain fine particles, combustion products (CO, CO_2, NO_x), volatile organic compounds, and in the case of fish by-products may contain unpleasant odorous contaminants, such as H_2S, and $(CH_3)_3N$ (DIEU, 2009).
The energy needs of food industry are of low or medium intensity. Some sectors (e.g., wet corn milling, beet sugar, soybean oil mills, malt beverages, meat packaging, canned and frozen fruits and vegetables, bread, and baked products) are however high-energy users (DIEU, 2009). The 38% of all the energy consumed by the Italian agro-food industry is electric, while the remainder is thermal (MISE, n.d.). The total impact of energy use might be lessened by minimizing the energy needs of production, producing energy from waste, and using renewable energy sources.

Table 1. Summary report for the overall Italian direct CO_2 equivalent emissions, including or excluding the net GHG emissions adsorbed from Land Use, Land-Use Change and Forestry (LULUCF), as referred to the main GHG sources (i.e., CO_2, CH_4, N_2O, and halogenated compounds, HC, as HFCs, PFCs, NF_3, and SF_6) and sink categories in the year 2016, as extracted from ISPRA (2018).

GHG Source	CO_2	CH_4	N_2O	HC	Subtotal 1	Subtotal 2	Total
Sink Categories				Tg CO_{2e}			
1. Energy	334.93	7.66	4.49	0			347.08
A. Fuel combustion	332.44	2.93	4.48	0		339.86	
1. Energy industries	103.79	0.13	0.44	0	104.36		
2. Manufacturing industries and construction	46.96	0.28	0.71	0	47.94		
3. Transport	103.38	0.22	0.91	0	104.51		
4. Other sectors	77.81	2.30	2.41	0	82.52		
5. Other	0.52	0.00	0.02	0	0.53		
B. Fugitive emissions from fuels	2.48	4.73	0.01	0		7.22	
1. Solid fuels	0.00	0.04	0.00	0	0.04		
2. Oil and natural gas	2.48	4.69	0.01	0	7.18		
2. Industrial processes and product use	14.76	0.05	0.57	16.72		32.10	32.10
A. Mineral industry	10.61	0.00	0.00	0.00	10.61		
B. Chemical industry	1.46	0.00	0.12	1.49	3.08		
C. Metal industry	1.71	0.04	0.00	0.01	1.76		
D. Non-energy products from fuels and solvent use	0.98	0.00	0.00	0.00	0.98		
E. Electronic Industry	0.00	0.00	0.00	0.22	0.22		
F. Products used as substitutes for Ozone-depleting substances	0.00	0.00	0.00	14.66	14.66		
G. Other product manufacture and use	0.00	0.00	0.46	0.33	0.79		
3. Agriculture	0.54	18.87	10.98	0.00		30.39	30.39
A. Enteric fermentation	-	14.04	-	0.00	14.04		
B. Manure management	-	3.11	2.12	0.00	5.23		
C. Rice cultivation	-	1.71	-	0.00	1.71		
D. Agricultural soils	-	-	8.86	0.00	8.86		
E. Prescribed burning of savannas	-	-	-	0.00	0.00		
F. Field burning of agricultural residues	-	0.017	0.004	0.00	0.02		
G. Liming	0.01	-	-	0.00	0.01		
H. Urea application	0.53	-	-	0.00	0.53		
4. LULUCF	-31.08	0.40	0.76	0.00		-29.93	-29.93
A. Forest land	-36.08	0.28	0.001	0.00	-35.80		
B. Cropland	2.46	0.002	0.03	0.00	2.49		
C. Grassland	-6.64	0.12	0.04	0.00	-6.48		
D. Wetlands	-	-	-	-	-		
E. Settlements	9.01	-	0.68	0.00	9.69		
F. Harvested wood products	0.17	-	-	0.00	0.17		
5. Waste	0.09	16.29	1.90	0.00		18.29	18.29
A. Solid waste disposal	-	13.62	-	0.00	13.62		
B. Biological treatment of solid waste	-	0.12	0.53	0.00	0.65		
C. Incineration and open burning of waste	0.09	0.06	0.02	0.00	0.18		
D. Waste water treatment and discharge		2.49	1.35	0.00	3.84		
Total CO_2 equivalent emissions without LULUCF							427.86
Total CO_2 equivalent emissions with LULUCF							397.94

3. THE ENVIRONMENTAL IMPACT OF FOOD PROCESSING

The complete supply chain of the food industry from the production of raw materials via food processing to the consumption and disposal by the consumer is quite complex and is schematically sketched in Fig. 1.

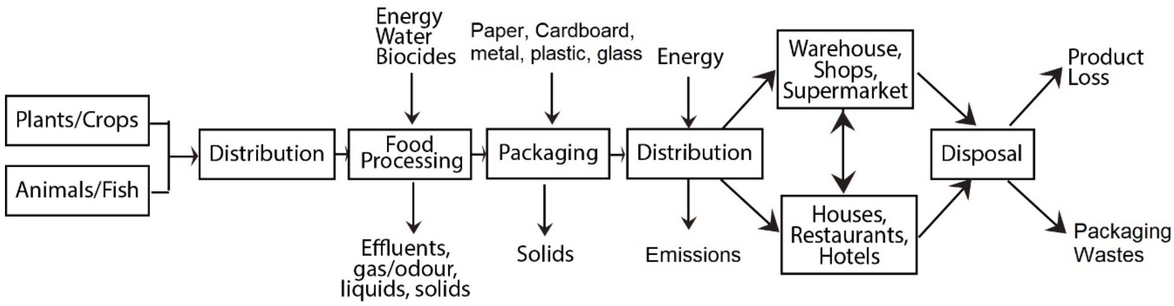

Figure 1. Simplified flow sheet of the supply chain of the food industry, as adapted from MORESI (2014).

4. LIFE-CYCLE ASSESSMENT: PROS AND CONS

Life-cycle assessment (LCA) is a technique capable of assessing the environmental impact associated with a product, process or activity during its life cycle from raw material extraction via material processing, packaging, distribution, use, repair and maintenance to the final disposal, that is from cradle to grave (MINKOV *et al*., 2016). Its procedure is standardized by the International Organization for Standardization (ISO, 2006ab) and is performed in four different phases:

i) *Goal and scope* of the study to set the functional unit (i.e., the reference unit), system boundaries, allocation methods and impact categories of choice, as well as the assumptions and limitations used.
ii) *Inventory analysis* by constructing a flow chart including all the activities involved in the system boundaries and a flow model to relate all input and output data to and from the environment in order to account for 99% of the mass and energy used in the system under study.
iii) *Impact assessment* to convert the inventory analysis results into specific environmental impact categories. These may be also categorized under the development, manufacture, use, and disposal phases of the product examined.
iv) *Interpretation* to discuss the outcomes of the above stages, identify the data elements contributing most significantly to each impact category and measure their sensitivity, assess the completeness and consistency of the study, and provide a basis for conclusions and recommendations.

Several impact categories are used to measure the potential impacts to the natural environment, human health or depletion of natural resources. Table 2 lists the main ones together with their characterization models, as derived from MANFREDI *et al*. (2012) and MORAWICKI (2012). Thus, by summing up any release to air, water or soil Y_i (expressed in mass, energy, mass-km basis) associated to the system boundaries times its corresponding science-based conversion factor, called characterization factor ($F_{i,j}$), it is possible to estimate the score of the generic impact category (IC_j) as:

$$IC_j = \sum_i (\Psi_i \, F_{i,j}) \qquad (1)$$

In particular, the environmental impact of climate change can be directly calculated by using the 100-year time horizon Global Warming Potentials (GWP) relative to the CO_2 of the GHGs, which were recently reassessed by IPCC (2013).

Table 2. Main impact categories used in several LCA standard methods, as extracted from MANFREDI *et al*. (2012) and MORAWICKI (2012).

Impact category	Category definition	Indicator Unit	Ref.s
Climate Change (CC)	The potential change on the Earth climate is due to human activity and GHG release.	kg CO_{2e}	IPCC(2007)
Ozone Depletion (OD)	The industrial gas concentrations accelerating O_3 decomposition in the Earth's stratosphere affect living organisms	kg CFC-11_e	WMO (1999)
Acidification (A)	The release of NO_X and SO_2 which combine with water in the atmosphere forms HNO_3 and H_2SO_3.	mol H^+_e	SEPPÄLÄ *et al.* (2006)
Eutrophication- aquatic (NPA)	The release of N- and P-rich nutrients in surface waters results in excessive plant growth.	Fresh water: kg P_e; Marine water: kg N_e	STRUIJS *et al.* (2009)
Eutrophication- terrestrial (NPT)	The deposition of N from the emissions released by N-rich nutrients affects terrestrial ecosystems too.	mol N_e	SEPPÄLÄ *et al.* (2006)
Photochemical Ozone Creation (POC)	The formation of ground-level O_3, as due to the reaction of NO_X and volatile organic compounds, causes irritation for humans and damage for plants.	kg $NMVOC_e$	VAN ZELM *et al.* (2008)
Ecotoxicity-aquatic, freshwater (ET)	Interaction among chemical compounds and organisms in the environment.	CTU_e	ROSENBAUM *et al.* (2008)
Human Toxicity- *cancer effects* (HTC)	Chemical compounds may cause several types of cancer in humans or	CTU_h	ROSENBAUM *et al.* (2008)
non-cancer effects (HTNC)	chronic non-cancer effects including mutagenicity, toxicity, etc.	CTU_h	ROSENBAUM *et al.* (2008)
Particulate Matter (PM)	Particulate matter causes respiratory problems.	kg $PM_{2.5e}$	HUMBERT *et al.*(2011)
Ionizing Radiation- human health effects (IR)	Ionizing radiation affects the risk for human cancer incidence and mortality increase.	kg U_{235e}	DREICER *et al.* (1995)
Resource Depletion- *water* (RDW)	Use and depletion of fresh water, minerals and fossil resources impact ecosystems and many species survival.	m^3 of water related to local water scarcity	FRISCHKNECHT *et al.* (2008)
mineral/fossil (RDMF)		kg Sb_e	VAN OERS *et al.* (2002)
Land Transformation (LT)	The extent of changes in land properties and effects on the area affected.	kg Soil Organic Matter	MILÀ I CANALS *et al.* (2007)

The environmental performance of food and drink production may be currently assessed by various standard methods, such as those listed in Table 3. Some of them (i.e., Product Carbon Footprint; PAS2050; Bilan Carbone®, BC; GHG Protocol) make use of only the impact category of climate change and give no hint about the overall environmental impact of the products, even if the emissions from direct land-use changes over the previous 20 years are generally included (Table 3). Other standard methods evaluate from seven (i.e., LCA, and Environmental Product Declaration, EPD®) to 14 (Product Environmental Footprint, PEF) impact categories. Their scores are estimated using a series of LCA data sources and characterization factors, which obviously are strongly dependent on the LCA databases used. There is thus a strong need for reliable databases to achieve a trustworthy assessment of a product life cycle environmental performance, as observed by the food and drink companies involved in several PEF pilot tests (FOODDRINKEUROPE, 2017).

Table 3. Brief description of some international standard methods for product and service environmental assessment together with the impact categories (IC) accounted for (same labels as in Table 2).

Standard method	Description	Impact categories chosen	Ref.s
Life Cycle Assessment (LCA)	Specifies requirements and provides guidelines for LCA studies.	CC; OD; A; NP; POC; RD; LU.	ISO (2006ab)
Carbon Footprint of Product	Allows the calculation of PCF, based on LCA specified in ISO (2006ab).	CC; LUC.	ISO/TS (2013)
PAS 2050	Provides a standardized guidance for calculating the PCF of goods and services.	CC; LUC.	BSI (2008)
Bilan Carbone®	Tool developed by the French Environment & Energy Management Agency GHG to assess GHG emissions.	CC; LUC.	ADEME (2010)
Environmental Product Declaration (EPD®)	Tool supported by the Swedish government.	CC; OD; A; NP; POC; RD; LU.	ISO (2006c)
GHG Protocol	Defines how measuring, and reporting GHG emissions in the USA.	CC	BHATIA *et al.* (2011)
Product Environmental Footprint (PEF)	Novel European Community methodology under development.	CC; OD; A; NPA; NPT; POC; ET; HTC; HTNC; PM; IR; RDW; RDMF; LT.	MANFREDI *et al.* (2012)

The greater the number of impact categories accounted for, the more precise the environmental profile of the product under study will be. Nevertheless, the estimation with as many as 14 impact categories (Table 3) was harshly criticized by numerous stakeholders, such as academia (CIMINI and MORESI, 2018a; FINKBEINER, 2014; LEHMANN *et al.*, 2016), industry (ACEA, 2013; BDI, 2015), policy-makers (BMUB/UBA/TUB, 2014), and consumer associations (ANEC, 2012), for being uselessly complex and very expensive. In fact, the Federation of German Industry (BDI, 2015) estimated an average cost of about 100 k€ for assessing the PEF profile of a single product. Furthermore, some critical issues were identified to ensure that the LCA delivered robust results (NOTARNICOLA *et al.*, 2017). In particular, the intrinsic variability of the agricultural system affected the inventory analysis, impact assessment, and interpretation phases. The higher the output per hectare the higher will be the eco-efficiency of the final product. However, long-term sustainability of food production in a given production area is not considered in the current LCA method. Many LCA studies give no details about the soil, climate and weather conditions, timescale adopted, transport distances and modes used to deliver raw materials and final products, as well as the use phase and related wastes. A more meaningful functional unit for food products was also proposed by SONESSON *et al.* (2017) in order to relate the nutritional function of foods to their LCA results and account for the sustainable food consumption and food security. How to represent such variability in LCA studies without having to collect an enormous number of extra data that would make such studies disproportionately expensive is a primary challenge for LCA researchers and practitioners. Thus, to allow small- and medium-sized food and drink enterprises to improve their sustainability in the most direct and economical method, the assessment of the Product Carbon Footprint (PCF) appeared to be more useful. In fact, not only was the climate change impact category with the lowest levels of uncertainty (CIMINI and MORESI, 2018a), but also was the major contributor to acidification (r^2=0.82), eutrophication (r^2=0.66), and photochemical ozone formation (r^2=0.86) categories **(**HUIJBREGTS *et al*., 2006).

5. IDENTIFICATION OF THE KEY ELEMENTS FOR SUSTAINABLE FOOD PROCESSING

The food and beverage industry is seeking to improve its environmental performance and identify which actions are suitable for a more sustainable production (MORESI, 2014).
No food processing nowadays is 100% sustainable owing to the lack of energy, ingredients and packaging materials derived from renewable resources; excessive water use; the inherent CH_4 and N_2O emissions associated with crop production and animal husbandry; and lack of biodegradable packaging materials (MORAWICKI, 2012). Nevertheless, by accounting for only the impact category of climate change, MORAWICKI (2012) suggested a simple and progressive approach to relieve the environmental impact of a food company. First, food processing plant efficiencies for energy, water, and raw and packaging material consumption should be improved and fossil energy usage replaced with renewable one by purchase or self-generation. Second, the GHG emissions associated with the transportation of raw materials and final products should be reduced. Third, the GHG emissions resulting from the field phase should be minimized. Fourth, the impact of the post-consumer disposal of packaging materials, as well as food loss, is to be reduced.
Despite being firm-oriented, such an approach might result in mitigation actions exerting a minimum reduction in the product carbon footprint. Thus, the mitigation opportunities should be prioritized starting from the life cycle stages with the highest contribution to PCF, as previously assessed (CIMINI and MORESI, 2018b). This procedure was specifically applied to improve the sustainability of two typical cereal-based food and drink products, as detailed in the following cases studies.

6. CASE STUDY NO. 1: LAGER BEER PRODUCTION

The cradle-to-grave carbon footprint (CF_{CG}) of a malt lager beer was previously estimated (CIMINI and MORESI, 2016, 2018c) by applying the PAS 2050 standard method (BSI, 2008). All the aforementioned four LCA canonical stages were referred to a functional unit consisting of 1 hL of malt beer, as produced in a large-sized brewery with an annual beer capacity of $3x10^6$ hL and packed in 66-cL glass bottles. The system boundaries for this case study are shown in Fig. 2. According to PAS 2050 (Section 7.2), the geographical and time scopes of this LCA study are the Western Europe and from the years 2006-2016. Main process data were of the primary type (CIMINI and MORESI, 2016).
By using all the essential data previously given (CIMINI and MORESI, 2018b), the LCA model was able to estimate the CF_{CG} as 127 kg CO_{2e} per hL of beer. The contribution of the different life cycle stages are shown in Fig. 3.

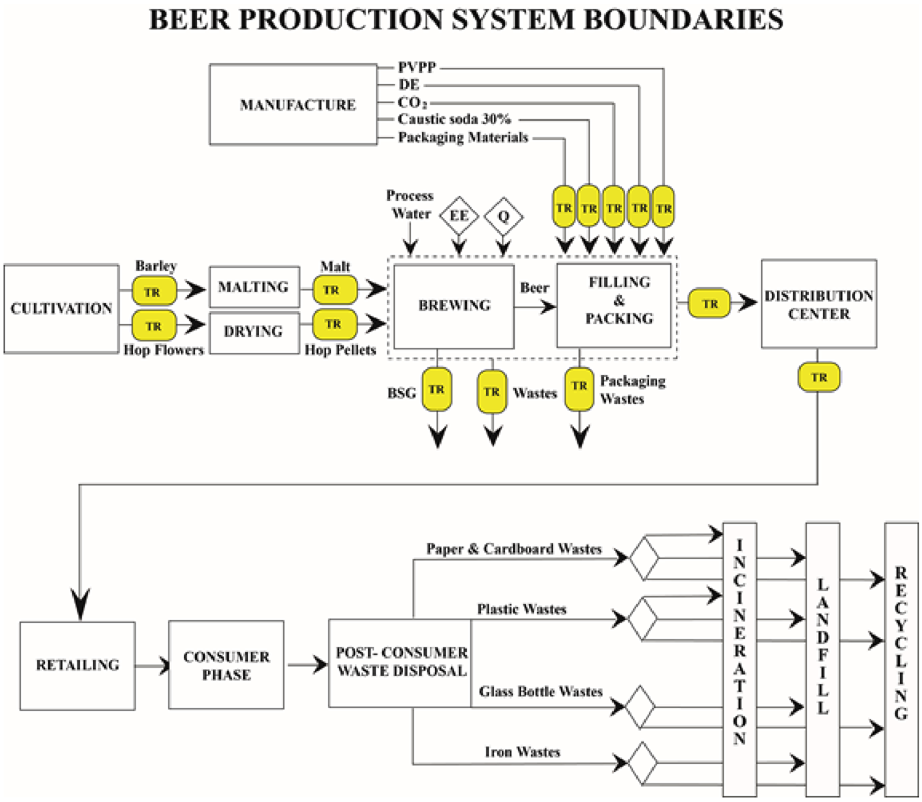

Figure 2. Beer system boundaries, as adapted from CIMINI and MORESI (2018c). The main identification items are listed in the *Abbreviations and Nomenclature* section.

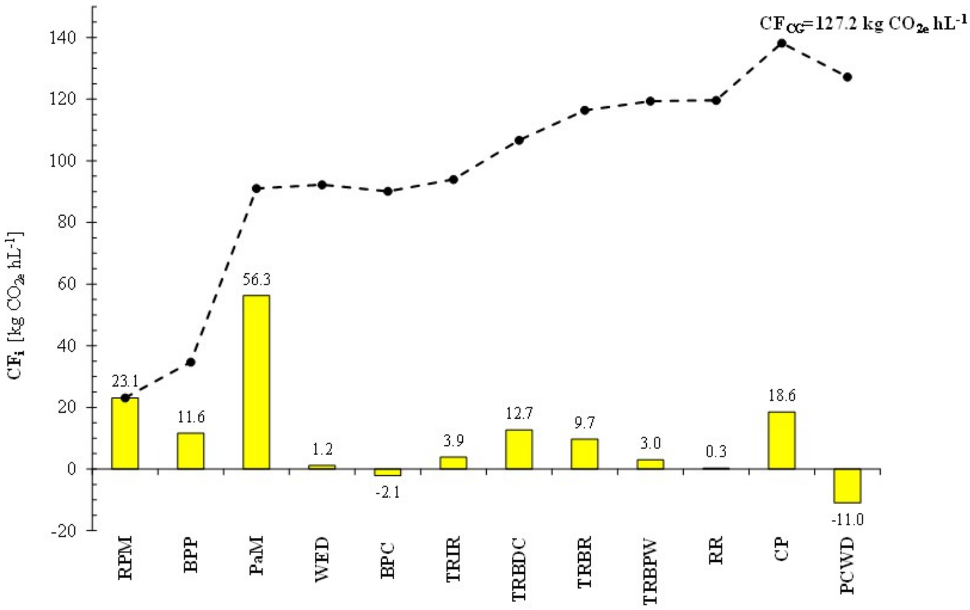

Figure 3. Contribution of the different life cycle phases to the cradle-to-grave carbon footprint (CF_{CG}) of 1 hL of beer packed in 66-cL glass bottles in a large-sized brewery, as estimated from the LCA model previously developed (CIMINI and MORESI, 2018b), and its cumulative score (see broken line). For the identification items refer to the *Abbreviations and Nomenclature* section.

The life cycle phases contributing mostly to the CF_{CG}, in descending order, were associated with packaging material manufacture (~56 kg CO_{2e} hL^{-1}), overall transportation (~29 kg CO_{2e} hL^{-1}), production of malted barley and processing aids (~23 kg CO_{2e} hL^{-1}), consumer use (~19 kg CO_{2e} hL^{-1}), beer production and packaging (~12 kg CO_{2e} hL^{-1}), and waste disposal (1.2 kg CO_{2e} hL^{-1}). CO_{2e} credits derived from the use of spent grains and surplus yeast as animal feed (2.1 kg CO_{2e} hL^{-1}) and from recycling of glass bottles, paper and cardboard wastes (11 kg CO_{2e} hL^{-1}).

Instead of adopting the aforementioned MORAWICKI's approach to sustainability, a series of improvement opportunities was scheduled to sequentially reduce the contribution of the most impacting life cycle phases of the above reference case.

Firstly, the replacement of 10% recycled glass bottles with 100% recycled ones reduced the CF_{CG} by about 21 % with respect to the reference case. By shifting the transportation mode from 100% of road freight to 100% of rail freight to manage logistics flows, an additional 10% decrease in CF_{CG} was achieved. The use of organic instead of conventional barley grown locally had the effect of decreasing the CF_{CG} by another 9%. A quasi zero-carbon alternative for electricity generation is solar-photovoltaic electricity. Such a shift further lessened the CF_{CG} by 13%. On the contrary, by reducing the delivery distance of malted barley from 500 to 250 km, no significant change was observed in the CF_{CG};hence, reducing distance had a negligible effect.

Table 4 shows all the emission factors (EF_i) that were varied and how the above sequential series of mitigation options practically halved the beer carbon footprint from about 127 to 60 kg CO_{2e} hL^{-1}.

Since the per capita consumption of beer in Italy is about 31.8 L yr^{-1} (ASSOBIRRA, 2018) and the current Italian population is 59,228,336 (WORLDOMETERS, 2019), the GHG emissions associated with the Italian consumption of beer would be reduced from 2.39 to 1.13 Tg CO_2 yr^{-1}. The application of the aforementioned mitigating actions had the effect of limiting the contribution from beer to 0.28% of the overall Italian GHG emissions (Table 1).

Table 4. Effect of the sequential mitigation strategies used to minimize the cradle-to-grave beer carbon footprint (CF_{CG}) and its cumulative percentage variation with respect to that pertaining to the reference case ($\sum \frac{\Delta CF_{CGj}}{CF^*_{CG}}$). The sequential stepwise procedure started from the most impacting life cycle phase as resulting from Fig. 3.

Mitigation strategy	Parameter varied		Unit	CF_{CG} [kg CO_{2e} hL^{-1}]	$\sum \frac{\Delta CF_{CGj}}{CF^*_{CG}}$ [%]
Beer reference case (*)				127.2	0
100% recycled glass bottles	EF_{RB}	1.08→0.48	kg CO_{2e} kg^{-1}	100.3	-21
Malt & beer rail transport	EF_{RT}	0.168→0.039	kg CO_{2e} $(Mg\ km)^{-1}$	88.2	-31
Organic malt	EF_{OC}	1.143→0.546	kg CO_{2e} kg^{-1}	76.6	-40
Local malt	d_{RM}	500→250	km	76.5	-40
Photovoltaic electric energy	EF_{PEE}	0.324→0.055	kg CO_{2e} kWh^{-1}	60.2	-53

7. CASE STUDY NO. 2: DRY PASTA PRODUCTION

The cradle-to-grave CF_{CG} of an organic durum wheat semolina pasta was previously estimated (CIBELLI *et al.*, 2017; CIMINI *et al.*, 2019c) using the PAS 2050 standard method (BSI, 2008). All the LCA canonical stages were referred to a functional unit consisting of 1

kg of dry pasta, produced in a medium-sized pasta factory with a capacity of approximately 125 Gg yr^{-1} and packed in 0.5-kg polypropylene (PP) bags. The system boundaries for this case study are shown in Fig. 4. According to the PAS 2050 (Section 7.2), the geographical and time scopes of this LCA study were the Western Europe and from the years 2006-2016. Finally, the process data were of the primary type, as reported by CIMINI *et al*. (2019c).
The estimated dry pasta CF_{CG} was about 1.8 kg CO_{2e} kg^{-1}, the contribution of all the life cycle phases being plotted in Fig. 5. Their impacts were therefore ranked as follows: field phase (~0.67 kg CO_{2e} kg^{-1}), home pasta cooking (0.65 kg CO_{2e} kg^{-1}), pasta production and packaging (~0.20 kg CO_{2e} kg^{-1}), transportation (~0.15 kg CO_{2e} kg^{-1}), packaging material manufacture (~0.11 kg CO_{2e} kg^{-1}), durum wheat milling (~0.05 kg CO_{2e} kg^{-1}), end of life of packaging materials (~0.03 kg CO_{2e} kg^{-1}) and pasta losses (~0.02 kg CO_{2e} kg^{-1}). CO_{2e} credits resulted from using wheat milling by-products, and pasta making and packaging wastes for animal feed (~0.07 kg CO_{2e} kg^{-1}) as an alternative to soybean meal fodder (CIMINI *et al*., 2019c).

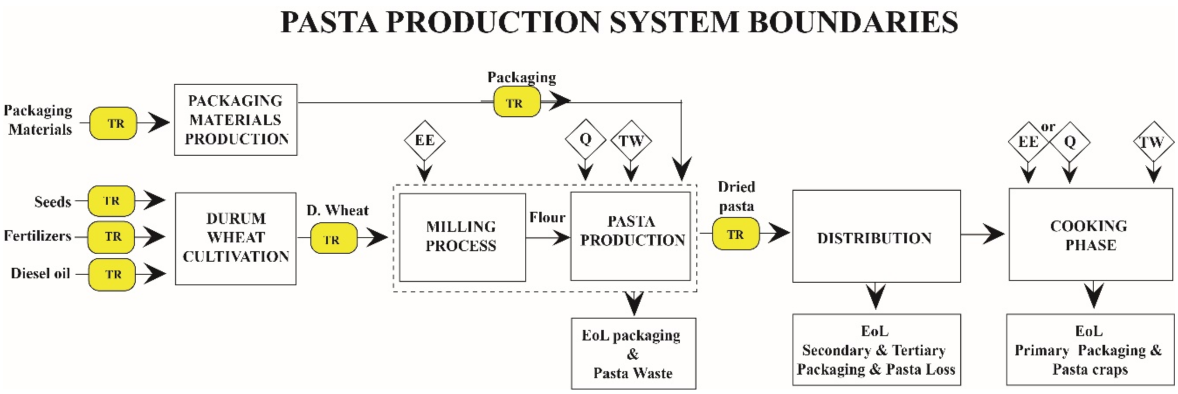

Figure 4. Dry pasta system boundaries, as adapted from CIMINI *et al.* (2019c). The main identification items are listed in the *Abbreviations and Nomenclature* section.

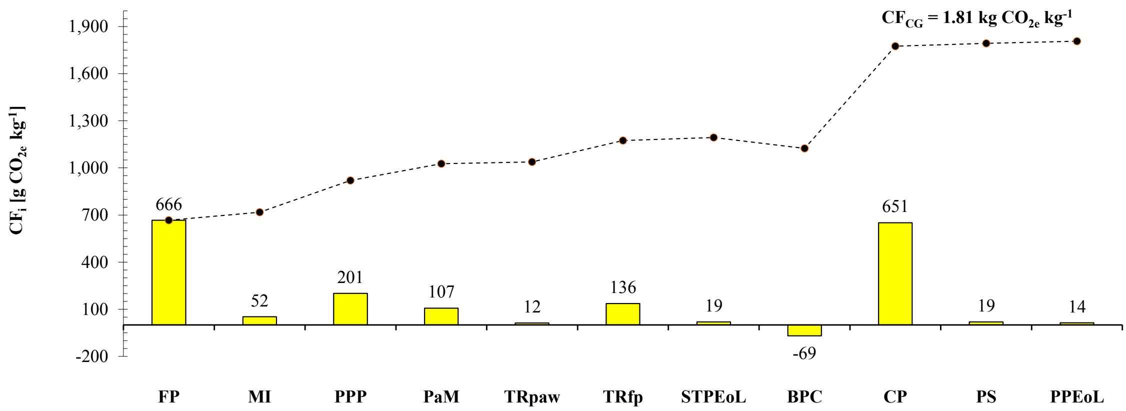

Figure 5. Contribution of the different life cycle stages to the cradle-to-grave carbon footprint (CF_{CG}) of 1 kg of dried organic pasta packed in 0.5-kg PP bags in a medium-sized pasta factory, as estimated from the LCA model previously developed (CIMINI *et al.*, 2019c), and its cumulative score (see broken line). The main identification items are listed in the *Abbreviations and Nomenclature* section.

To improve the sustainability of such product, a series of mitigating actions were programmed to reduce the contribution of the most impacting life cycle phases of the above reference case. In particular, to limit the impact of the primary hotspot (i.e., the consumer and post-consumer ones), the eco-sustainable pasta cooking procedure suggested by CIMINI *et al*. (2019ab) was applied by setting the cooking water-to-dry pasta ratio at 2 L kg^{-1} and the nominal cooking power at 0.4 kW. In this way, the CF_{CG} was cut by 29% with respect to the reference case. Use of organic crop rotation enabled the CF_{CG} to be decreased by another 13%. By replacing the methane needed for the steam generating boilers with biogas, the CF_{CG} was further reduced by 7%. Use of solar-photovoltaic electricity also lessened the CF_{CG} by an extra 9%. Similarly, by shifting from road to rail freight transport, a supplementary 2% reduction in the CF_{CG} was obtained. Finally, when the final product or grain delivery distance was shortened from 900 or 150 km to as low as 250 or 50 km, respectively, the CF_{CG} still reduced by 2 or 1%. In total, such a sequential series of mitigating options allowed the dry pasta carbon footprint to be reduced from 1.81 to 0.68 kg CO_{2e} kg^{-1} (Table 5).

Table 5. Effect of the sequential mitigation strategies used to minimize the cradle-to-grave dry pasta carbon footprint (CF_{CG}) and its cumulative percentage variation with respect to that pertaining to the reference case ($\sum \frac{\Delta CF_{CGj}}{CF^*_{CG}}$). The sequential stepwise procedure started from the most impacting life cycle phase as shown in Fig. 5.

Mitigation strategy	Parameter varied		Unit	CF_{CG} [kg CO_{2e} kg^{-1}]	$\sum \frac{\Delta CF_{CGj}}{CF^*_{CG}}$ [%]
Dry pasta reference case (*)				1.81	0
Eco-sustainable cooking	P_C	2.3→0.4	kWh kg^{-1}	1.28	-29
Organic rotation cropping	EF_{OC}	0.534→0.36	kg CO_{2e} kg^{-1}	1.06	-42
Thermal energy from biogas	EF_{BG}	0.231→0.029	kg CO_{2e} kWh^{-1}	0.92	-49
Photovoltaic electric energy	EF_{PEE}	0.513→0.055	kg CO_{2e} kWh^{-1}	0.77	-58
Pasta rail transport	EF_{RT}	0.168→0.047	kg CO_{2e} $(Mg\ km)^{-1}$	0.72	-60
Pasta regional distribution	d_P	900→250	km	0.70	-62
Durum wheat local supply	d_{RM}	150→50	km	0.68	-63

Since the per capita consumption of pasta in Italy is about 23.5 kg yr^{-1} (UNAFPA, 2015), the GHG emissions associated with the Italian consumption of dry pasta would reduce from 2.52 to 0.95 Tg CO_2 yr^{-1}. The aforementioned mitigating actions had the effect of reducing the impact of the dry pasta sector to the 0.24% of the overall Italian GHG emissions (Table 1).

8. CONCLUSIONS

In this work, the main direct environmental impacts of the food industry and GHG emissions for the agro-food system in industrialized countries were analyzed together with the main advantages and disadvantages of the standard methods currently used to assess the food and drink environmental impact.

Owing to the great deal of money needed to characterize the whole environmental profile of a single product, and the fact that the climate change impact category was by far more reliable than all the other ones used in the EPD® and PEF standard methods made the assessment of the product carbon footprint a cheaper tool to identify the major hotspots of the food supply chain. Thus, it is probably the best method to start improving the sustainability of the 99% of the food and beverage SMEs. It was used here to select a sequential series of mitigating actions in order to reduce the cradle-to-grave product carbon footprint (CF_{CG}) of 1 hL of beer packed in 66-cL glass bottles from about 127 to 60 kg CO_{2e} hL^{-1}, and that of 1 kg of dry organic pasta packed in 0.5-kg PP bags from 1.81 to 0.68 kg CO_{2e} kg^{-1}. A cost/benefit analysis might help SMEs to relate the marginal increase in the overall final product costs to each reduction in the product environmental load.
Since only the assessment of GHG emissions might result in burden shifting, a further step should investigate the effect of the selected mitigating actions on other environmental impact categories.

ABBREVIATIONS AND NOMENCLATURE

A	Acidification
BC	Bilan Carbone®
BPC	CO_{2e} credits from by-product use as cattle feed;
BPP	Brewing and packaging processing
BSG	Brewer's spent grain
CC	Climate Change
CF_{CG}	Cradle-to-grave product carbon footprint [kg CO_{2e} hL^{-1} or kg^{-1}]
CFC	Trichlorofluoromethane or Freon-11
CO_{2e}	Carbon dioxide equivalent
CP	Consumer phase
CTU_e	Comparative Toxic Unit for ecosystems
CTU_h	Comparative Toxic Unit for humans
DE	Diatomaceous earth
DC	distribution centers
d_P	Distribution distance of packed dry pasta [km]
d_{RM}	Supply distance of raw materials [km]
EE	Electric energy
EF_{BG}	Emission factor for biogas [kg CO_{2e} kWh^{-1}]
EF_{OC}	Emission factor for organic crop [kg CO_{2e} kg^{-1}]
EF_{PEE}	Emission factor for photovoltaic electric energy [kg CO_{2e} kWh^{-1}]
EF_{RB}	Emission factor for 100% recycled glass bottles [kg CO_{2e} kg^{-1}]
EF_{RT}	Emission factor for rail freight transport [kg CO_{2e} $(Mg\ km)^{-1}$]
EoL	End of life
EPD	Environmental Product Declaration
ET	Ecotoxicity – aquatic, freshwater
EU	European Union
F_{ij}	Generic i-th characterization factor of the j-th impact category
FP	Field phase
GHG	Greenhouse gas
HC	Halogenated compound
HFC	Hydrochlorofluorocarbon
HTC	Human toxicity - cancer effects
HTNC	Human toxicity - non-cancer effects
IC	Impact category
IR	Ionizing radiation – human health effects
LCA	Life cycle assessment
LT	Land transformation
LULUCF	Land use, land use change and forestry
MI	Milling
NIR	National Inventory Report
NMVOC	Non-methane volatile organic compound

NP Eutrophication
NPA Eutrophication- aquatic
NPT Eutrophication- terrestrial
OD Ozone depletion
PaM Packaging materials
PAS Publicly available specification
P_c Specific food cooking power [kWh kg^{-1}]
PCF Product carbon footprint
PCWD Post-consumer waste disposal
PEF Product environmental footprint
PFC Perfluorinated chemical
PM Particulate matter/respiratory inorganics
POC Photochemical ozone creation
PP Polypropylene
PPEoL Primary packaging end of life.
PPP Pasta production and packaging
PS Pasta scraps
PVPP Polyvinylpolypyrrolidone
Q Thermal energy
RD Resource depletion
RDMF Resource depletion – mineral/fossil
RDW Resource depletion – water
RPM Raw and processing materials
RR Retailer refrigeration
r^2 Coefficient of determination
SME Small- and medium-sized enterprise
STPEoL Secondary and tertiary packaging end of life
TR Transportation
TRBPW Transportation of byproducts and wastes
TRBR Transportation of beer in cartons from DCs to retailers
TRBDC Transportation of palletized beer to distribution centers
TRfp Transport of final product
TRIR Transportation of input resources to the brewery gate
TRpaw Transport of packaging and auxiliary materials, and wastes
TW Process water
WED Waste and effluent disposal
$\Delta CF_{CG}/CF_{CG^*}$ Relative percentage variation of CF_{CG} with respect to that pertaining to the reference case [%]
Ψ_i Generic i-th activity, expressed in mass, energy or mass-km basis.

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