LCA FOR FOOD PRODUCTS

Life cycle assessment of the average Spanish diet including human excretion

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Abstract

Background, aim and scope The aim of this work is to find out to what extent human excretion is relevant in the context of a Spaniard's overall food intake. A case study dealing with the average Spanish diet is carried out, including the whole life cycle of food: agricultural and animal production, industrial processing, distribution and retail, home storage and cooking, solid waste management and human excretion.

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Methods An extensive literature review was carried out to obtain life cycle assessment (LCA) data for Spanish food products. Also, the Danish LCA Food database and other European literature sources were used, along with ecoinvent background data. Human excretion and wastewater treatment were accounted for with a specific model recently developed, which required calculating the average nutritional composition of the Spanish diet. Concerning life cycle impact assessment, only three impact categories, namely global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP), were assessed, along with primary energy use (PEU) as environmental indicator.

Results Food production clearly appears as the main hotspot in the Spanish diet. Human excretion, along with further wastewater treatment, is not a negligible process in EP and GWP, where it is the second most important source of emissions, with 17% of the overall emissions. However, if biogenic CO_2 emissions are not taken into account, the contribution of human excretion to GWP becomes very small (3%). The contributions to AP (2%) and PEU (3%) are also very small.

Discussion The main limitation of this study is the lack of representative data to cover food production in Spain. Nevertheless, our total estimates for GWP and PEU per person per year are in accordance with previous studies, as well as the identification of animal food as a main source of environmental impacts. These studies achieve similar results without including human excretion, but concerning EP, there are no previous studies focusing on this impact category at the diet level.

Conclusions Food production is the most important life cycle stage in the Spanish diet, especially meat and dairy products. Nevertheless, human excretion as a life cycle stage has been found to be important in EP due to the emissions of nutrients in treated sewage.

Recommendations and perspectives These results show that excretion should not be overlooked in LCA studies dealing with diet shifts and studies aimed at identifying the life cycle hotspots of food products.

Keywords Carbon cycle · Food · Human excretion · Life cycle assessment · Nutrient cycle · Wastewater treatment

1 Introduction

When a life cycle perspective is taken into account, food consumption appears as one of our most resource-demanding and polluting daily activities. Several studies at both the national and international levels have identified food supply as one of the main contributors to the environmental impacts caused by private consumers (Nijdam et al. 2005; Tukker et al. 2006). This explains why food has been in the focus of life cycle assessment (LCA) since the early 1990s (Weidema 1993), as a suitable tool to find ways to make food production and consumption patterns sustainable.

Although research has been mostly addressed to individual food products or particular stages of their life cycle (farming, processing, packaging, transports, home processing and storage, and waste management), some authors have also studied the environmental impacts of food supply from a diet perspective, either for identification of the most polluting food items or for comparison of dietary choices (Davis et al. 2010; Carlsson-Kanyama 1998; Kramer et al. 1999; Jungbluth et al. 2000; Carlsson-Kanyama et al. 2003; Heller and Keoleian 2003).

Human excretion remains the least studied life cycle stage at both the product and diet levels. So far, only the fate of nutrients has been modelled in some LCA studies. Sonesson et al. (2004) proposed a systematic procedure to include emissions of chemical oxygen demand, nitrogen and phosphorus as a result of food composition, but human excretion as a whole was not addressed. These processes are usually excluded from the system boundaries, although the biochemical transformations of food in the human body lead to pollutants released to air and water, which should be quantified and assessed in a similar way as it is done when organic matter is treated in a landfill or a composting plant.

Recently, a simple model to include human excretion in LCA of food products has been developed (Muñoz et al. 2008). This model uses basic nutritional composition of food items to calculate the emissions of several pollutants to air and the composition of wastewater, as well as consumption of auxiliary materials and energy related to toilet use. The contents in wastewater, when used as the input to a wastewater treatment model like the one by Doka (2003), allow the LCA practitioner to completely close the

balance of materials and energy of food supply. This integral view is provided in Muñoz et al. (2008), in a case study on a single product, namely broccoli, where the importance of the human excretion stage is compared to that of production, distribution and home processing. The aim of this work is to carry out a similar assessment, but at the diet level. This is done by taking into account all food consumed by a person in 1 year, exemplified by the Spanish average diet.

2 Method

2.1 The average Spanish diet

Detailed data on food purchases by the Spanish population are available through official statistics (Ministerio de Agricultura, Pesca y Alimentación 2006a). Table 1 shows the composition of food purchases by weight in 2005, including purchases by households, restaurants, catering and institutions (schools, hospitals, prisons, retirement homes, company canteens, etc.). The data refer to final consumption, thus excluding industrial purchases for processing. Tap water consumption is also excluded, but bottled water is included.

2.2 Scope of the study

From the product groups in Table 1, we only excluded those for which inventory data related to production was not been possible to obtain. This applies to some items included in the 'other' category, namely honey, soups, nuts and unspecified products in weight, which altogether account for 2% of the total purchases in Table 1. Thus,

Table 1 Per capita food purchases (net weight) in Spain in 2005

Product group	kg	%
Eggs	14	1.6
Meat products	66	7.5
Fish and seafood	37	4.2
Dairy products	143	16.2
Bakery products	70	8.0
Vegetable oils and fats	22	2.5
Vegetables	108	12.2
Fruit	103	11.7
Beverages	174	19.8
Bottled water	68	7.7
Other	77	8.7
Total	881	100

Source: Ministerio de Agricultura, Pesca y Alimentación 2006a

the present study assessed the life cycle impacts of 864 kg food person^{-1} year^{-1} (98% of total purchases by weight).

The study included all the upstream and downstream operations required for the consumer to have ready-to-eat food: farming, industrial processing, distribution and retail, home storage and cooking, human excretion and wastewater treatment. Where data were available, packaging production was included. This was the case for 62% by weight of the assessed food products. The functional unit chosen is the supply of food for a Spanish citizen in the year 2005.

Life cycle impact assessment (LCIA) focused on a limited set of indicators. The following impact categories were included: global warming potential (GWP), eutrophication potential (EP) and acidification potential (AP), applied at the characterisation level using the characterisation models by the CML 2001 method (Guinée et al. 2002). Primary Energy use (PEU) has also been used as an environmental indicator, measured in MJ. The choice of GWP, EP and AP was based on the fact that they can be very sensitive to carbon and nitrogen flows, which are important in food LCA studies, and in particular in the human excretion stage, since all the carbon and nitrogen ingested is released to air and water (Muñoz et al. 2008). With regard to PEU, it is used as a simple and easily understandable indicator of process efficiency, which has traditionally been used in environmental assessment of processes and products, including food (Pimentel 1973).

2.3 Food production

A literature review was carried out in order to find previous LCA studies on Spanish food products. Published studies include beef, pork and ostrich (Núñez et al. 2005), fresh and canned tuna (Hospido and Tyedmers 2005; Hospido et al. 2006); mussels (Iribarren et al. 2010); milk (Hospido et al. 2003), ready meals (Zufia and Arana 2008); wheat, peas and sunflower (Nemecek et al. 2007); olive oil (Molero 2006); tomatoes (Williams et al. 2008; Antón et al. 2005); strawberries (Williams et al. (2008); lettuce (Hospido et al. 2009); fresh and frozen broccoli and beans (Milà i Canals L et al. 2008); oranges (Sanjuán et al. 2005); wine (Aranda et al. 2005; Gazulla et al. 2010); beer (Hospido et al. 2005); coffee roasting (Humbert et al. 2009); and mineral water (Davis and Sonesson 2008). Nevertheless, these studies did not cover all the required products; thus, data from production in other European countries were used (Table 2). Two important additional data sources were the Danish LCA Food database (Nielsen et al. 2003) and the study on energy use in the food sector by Carlsson-Kanyama and Faist (2000). In LCA Food data sets, the default electricity production profile was changed by the Spanish one, as included in the ecoinvent database (Dones et al. 2007). The

study by Carlsson-Kanyama and Faist (2000) includes mainly inputs from technosphere associated to agriculture and industrial processing, such as fuels and electricity, fertilizers, pesticides, etc. In order to obtain product data sets from these data, background inventory data from ecoinvent were used to model these inputs. Fertilizer-derived emissions in agriculture (ammonia, dinitrogen monoxide, N and P leaching to groundwater) were estimated in these data sets following the recommendations by Milà i Canals et al. (2007).

Concerning carbon accounting, it was taken into account that agricultural production leads to carbon fixation in biomass and that part of this carbon is also retained in animals biomass. Carbon fixation is included as a negative emission of CO_2, calculated from the elemental composition of food. This elemental composition is obtained from nutritional composition (dry mass, carbohydrates, protein, etc.) with the human excretion model by Muñoz et al. (2008).

2.4 Wholesale and retail

The storage scenario for this life cycle stage can be summarized as follows:

- Cooling storage was considered for meat, fish, seafood and dairy.
- Frozen storage was only considered for those products recorded in the statistics as traded frozen.
- All the remaining products were assumed to be stored at room temperature at both the wholesale and retail stores.

Energy consumption for storage in distribution centres and retail stores was modelled using data from the LCA Food database, replacing the Danish electricity production profile by the Spanish one. Another aspect taken into account is a rough estimation of greenhouse-gas emissions in retail stores, due to leakage of refrigerants in cooled display cabinets. These emissions have been recently estimated in the UK (DEFRA 2008) for different products, ranging from 20 to 532 g CO_2-eq. kg^{-1} product. Applying these figures to the chilled and frozen products in the present study leads to an emission of 33 kg CO_2-eq. person^{-1} year^{-1}.

The transport distance to regional distribution centres was defined based on previous Spanish studies including this transport step (Hospido et al. 2006; Davis and Sonesson 2008; Zufia and Arana 2008). In these studies, distances range from 230 to 650 km, the latter including transport to retail. We assumed a distance of 500 km. Concerning the transport to retail, the default distance in the LCA Food database was assumed (70 km). No food losses have been taken into account in these stages since they are assumed to be small when compared to those in the

Table 2 Data sources used for food production modeling

Products	Kg	Modelled as
Eggs	14	Eggs at farm gate from LCA Food database
Fresh meat of chicken, ovine and goat, rabbit, and unspecified fresh meat	25	Fresh chicken at slaughterhouse gate, from LCA Food database. Packaging is estimated with average data for meat in Denmark (Weidema et al. 2008)
Fresh pork meat, salted meat, lard, cured ham	22	Spanish pork production data from Nuñez et al. (2005). Emissions of CH_4 and N_2O from manure management were added following the Intergovernmental Panel on Climate Change (IPCC) methodology for national greenhouse-gas inventories (IPCC 2006). Packaging is estimated with average data for meat in Denmark (Weidema et al. 2008)
Fresh bovine meat	10.2	Spanish beef production data from Nuñez et al. (2005). Emissions of CH_4 from enteric fermentation and CH_4 and N_2O from manure management were added following the Intergovernmental Panel on Climate Change (IPCC) methodology for national greenhouse-gas inventories (IPCC 2006). Packaging is estimated with average data for meat in Denmark (Weidema et al. 2008)
Frozen meat	1.8	Frozen chicken meat at slaughterhouse gate, from LCA Food database. Packaging is estimated with average data for meat in Denmark (Weidema et al. 2008)
Knackwurst sausages, other processed meat	6.2	Composition and manufacture data from Davis and Sonesson (2008), including packaging production. Spanish pork meat used as main raw material
Fresh cod	0.62	Fresh cod fillet from LCA Food database. Packaging is estimated with average data for meat in Denmark (Weidema et al. 2008)
Fresh tuna	0.78	Data from Hospido and Tyedmers (2005) for Spanish tuna fisheries. The data in this study refer to carcass weight. A factor of 0.46 kg fillet per kilogram of carcass was taken into account to include processing losses (Hospido et al. 2006). Packaging is estimated with average data for meat from Denmark (Weidema et al. 2008)
Sole	1.2	Fresh flatfish fillet from LCA Food database. Packaging is estimated with average data for meat from Denmark (Weidema et al. 2008)
Hake, sardine and unspecified fresh fish	12	Fresh mackerel fillet, from LCA Food database. Packaging is estimated with average data for meat from Denmark (Weidema et al. 2008)
Salmon	0.79	Data from Ayer and Tyedmers (2009) for marine net-pen aquaculture in Canada. The data in this study refer to live weight. A factor of 0.46 kg fillet per kilogram of carcass was taken into account to include processing losses (Hospido et al. 2006). Packaging is estimated with average data for meat from Denmark (Weidema et al. 2008)
Trout	0.53	Fresh trout at farm gate, from LCA Food database. Packaging is estimated with average data for meat from Denmark (Weidema et al. 2008)
Frozen sole	0.43	Frozen flatfish fillet from LCA Food database. Packaging is estimated with average data for meat from Denmark (Weidema et al. 2008)
Frozen cod	0.37	Frozen cod fillet from LCA Food Database. Packaging is estimated with average data for meat from Denmark (Weidema et al. 2008)
Frozen hake and unspecified fish	3.5	Frozen mackerel fillet from LCA Food Database. Packaging is estimated with average data for meat from Denmark (Weidema et al. 2008)
Frozen salmon	0.1	Data used for fresh salmon, plus energy use in the processing plant according to the LCA Food database. Packaging is estimated with average data for meat from Denmark (Weidema et al. 2008)
Fresh and frozen seafood	11	Data for fresh, cooked and frozen mussels cultivated in Spain according to Iribarren et al. (2010), includes packaging production
Canned fish	4.9	Data from Hospido and Tyedmers (2005) and Hospido et al. (2006) for canned tuna, including fisheries, processing and packaging
Full milk, semi-skimmed milk, skimmed milk and milk shakes	108	Data from Hospido et al. (2003) for Spanish milk production, including packaging
Yoghurt	16	Milk production data from Hospido et al. (2003) plus energy use in yoghurt production from Carlsson-Kanyama and Faist (2000). Packaging is estimated with average data for dairy products in Denmark (Weidema et al. 2008)
Cheese and unspecified dairy products	19.3	Cheese from LCA Food database, using Spanish milk (Hospido et al. 2003) as raw material. Packaging is estimated with average data for dairy products in Denmark (Weidema et al. 2008)
Bread	56	Bread from LCA Food database, using Spanish wheat (Nemecek et al. 2007) as raw material
Cookies and cakes	14	Ingredients, processing and packaging data for Jaffa Cakes production in the UK (DEFRA 2009)

Table 2 (continued)

Products	Kg	Modelled as
Chocolate	3.22	Data for Cocoa cultivation and processing in Ghana (Ntiamoah and Afrane 2008)
Coffee	4.0	Data for coffee beans cultivation in Brazil (Coltro et al. 2006) plus roasting and packaging data from a Spanish plant (Humbert et al. 2009)
Spaghetti	4.3	Spaghetti data from Carlsson-Kanyama and Boström-Carlsson (2001) using Spanish wheat (Nemecek et al. 2007) as raw material
Sugar	7.1	Sugar production from sugar beet in Switzerland, from ecoinvent (Jungbluth et al. (2007)
Rice	5.8	Rice cultivation, processing and packaging in Italy, according to Blengini and Busto (2009)
Legumes	4.5	Protein peas production in Spain, from ecoinvent (Nemecek et al. 2007)
Olive oil	13	Olive oil production in Spain (Molero 2006)
Sunflower oil and other vegetable oils	8.5	Sunflower cultivation in Spain, according to ecoinvent (Nemecek et al. 2007). Oil production was approximated using data for rapeseed oil production in Europe, according to ecoinvent (Jungbluth et al. 2007)
Margarine	0.9	Margarine produced in Germany from palm oil, palm kernel oil, rapeseed oil, sunflower oil and maize oil (Nilsson et al. 2010) including packaging
Tomato and pepper	23	Data for tomato production in Spain from Williams et al. (2008), including packaging
Onion and garlic	11	Onion from LCA Food database
Cucumber	2.2	Cucumber cultivation data from Carlsson-Kanyama and Faist (2000)
Cabbage	2.0	Broccoli cultivation in Spain, including packaging, from Milà i Canals et al. (2008)
Green beans	2.6	Green beans cultivation in Spain from Milà i Canals et al. (2008)
Lettuce and leafy vegetables	9.5	Lettuce cultivation in Spain according to Hospido et al. (2009)
Mushrooms, asparagus and unspecified vegetables	18	Carrots from LCA Food database
Potatoes	36	Integrated potatoes production in Switzerland according to ecoinvent (Nemecek et al. 2007)
Frozen potatoes, processed potatoes	3.4	Integrated potatoes production in Switzerland according to ecoinvent (Nemecek et al. 2007). Processing data from Milà i Canals (2008) for frozen vegetables
Orange, mandarin orange, lemon	33	Orange cultivation in Spain, according to Sanjuán et al. (2005)
Bananas	9.2	Banana cultivation data from Carlsson-Kanyama and Faist (2000)
Apple, peach, pear, apricot, melon, watermelon, plum, kiwi and unspecified fresh fruit	55	Apple cultivation data from Carlsson-Kanyama and Faist (2000)
Strawberry	2.4	Strawberry cultivation in Spain according to Williams et al. (2008)
Grapes	2.4	Grapes cultivation data from Carlsson-Kanyama and Faist (2000)
Cherries	1.3	Cherries cultivation data from Carlsson-Kanyama and Faist (2000)
Canned fruit and vegetables	14	Tomato cultivation in Spain according to Williams et al. (2008) plus processing (material losses and energy use) data from Carlsson-Kanyama and Faist (2000)
Frozen fruit and vegetables	4.3	Frozen green beans produced in Spain according to Milà i Canals et al. (2008), including packaging
Canned ready meals and frozen ready meals	11	Cooked tuna with tomato dish produced in Spain, according to Zufía and Arana (2008), including packaging
Olives	3.6	Olive cultivation in Spain according to Molero (2006)
Sauces	2.9	Ketchup production in Sweden according to Andersson et al. (1998), including packaging
Wine and cider	28	Wine production in Spain according to Gazulla et al. (2010), including packaging
Beer	58	Beer production in Spain according to Hospido et al. (2005), including packaging
Juice	18	Orange cultivation in Spain, according to Sanjuán et al. (2005) plus juice production data from Carlsson-Kanyama and Faist (2000)
Soft drinks	65	Generic carbonated soft drink production according to Ercin et al. (2009), including packaging production
Mineral water	68	Mineral water production in Spain according to Davis and Sonesson (2008), including packaging production

household. Several studies in Europe and the USA suggest that retail losses are in the 1–5% range (Garnett 2006; DEFRA 2008; Kantor et al. 1997; Livsmedelsverket 1985).

2.5 Transport home

According to Spanish statistics (Ministerio de Agricultura, Pesca y Alimentación 2006a), 71% of the population goes shopping on foot, 20% by car and 7.2% using public transportation. The car and bus trips have been attributed the environmental burdens of fuel consumption, as described in Milà i Canals et al. (2007).

2.6 Home storage

Instead of allocating refrigerator and freezer energy demand on a product basis, the total electricity consumption per person per year has been calculated, as this approach requires less data and is considered to be less uncertain. A combined refrigerator and freezer per household, with a capacity of 255 and 94 L, respectively, has been considered, with a power consumption of 2.7 and 8.2 Wh L^{-1} day^{-1}, respectively, as included in the LCA Food database. This appliance is assumed to work all year, and the average number of persons per household is 2.81 (Instituto Nacional de Estadística 2007a). This leads to an average electricity consumption of 190 kWh $person^{-1}$ $year^{-1}$. This can be considered as a conservative figure since efficient appliances currently in the Spanish market consume 50% or less than our estimate (IDAE 2010).

2.7 Cooking

The environmental burdens of cooking are related to the energy used to prepare food. This has been quantified on a product basis, by defining a cooking scenario for each product category, and an energy use factor for each cooking mode. The LCA Food database does not provide enough data on cooking energy, and a model like the one developed by Sonesson et al. (2003) is too sophisticated for our assessment. We used generic energy use factors from Foster et al. (2006): 3.5 MJ kg^{-1} for boiling, 7.5 MJ kg^{-1} for frying, 0.8 MJ kg^{-1} for microwaving and 9.0 MJ kg^{-1} for roasting. These values refer to total energy delivered—either with electricity or gas—including heat losses. Due to the lack of statistics on the share of electric and gas cooking appliances in Spain, the energy used for cooking is assumed to be 50% originated by gas appliances, and the remaining 50% by electric appliances, with the exception of microwave ovens, which are only powered by electricity. The cooking scenario (Table 3) is based on the authors' judgement; therefore, it is subject to an important degree of uncertainty.

2.8 Solid waste

The percentage of non-edible portion for each product ranges from 0% for beverages to 32% for fish and seafood (Ministerio de Agricultura, Pesca y Alimentación 2006b). The weighed non-edible portion for the Spanish food waste is 9% or 71 kg $person^{-1}$ $year^{-1}$. However, using this figure as an approximation of organic waste production was judged to be underestimating the actual amounts produced since consumers not only discard what is not edible but also food past its use-by date, food gone off, plate leftovers, etc. Instead of this bottom–up approach, a top–down approach was taken: the total amount of urban waste in 2005 was 507 kg $person^{-1}$ (Instituto Nacional de Estadística 2005, 2007b), of which 44% is organic (Ministerio de Medio Ambiente 2008a). Detailed waste characterisation studies carried out in Catalonia (Agència de Residus de Catalunya 2007) and Gipuzkoa (Diputación Foral de Gipuzkoa 2002) found that kitchen waste constitutes 89% and 93%, respectively, of organic household waste. If 90% is assumed for Spain, then the overall amount of kitchen waste is 200 kg $person^{-1}$ $year^{-1}$. According to this estimate, 23% of bought food is wasted in Spain. According to the same study in Gipuzkoa, 71% of kitchen waste corresponds to raw food; therefore, no energy consumption related to cooking must be allocated to these discards.

Specific statistics on food waste treatment are not available in Spain. However, based on the production and composition of household waste mentioned above, and the amounts sent to different treatments in 2005 (Ministerio de Medio Ambiente 2008b), we estimated that 36% of organic material was composted, the remaining being landfilled (56%) or incinerated (8%). All these treatments have been modelled with ecoinvent data (Nemecek et al. 2007; Doka 2003).

2.9 Human excretion and wastewater treatment

The main input to the human excretion model by Muñoz et al. (2008) is the nutritional composition of food, as shown in Table 4. This composition constitutes the average for the 99 individual food items included in the study, weighed according to the amount ingested. Individual food compositions have been obtained from nutritional data tables (Martín-Peña 1997).

Concerning wastewater treatment, according to official statistics (Instituto Nacional de Estadística 2008), 92% of the population was connected to a wastewater treatment plant (WWTP) in 2005. Currently, there are 1,714 operating WWTPs in Spain, 35% of which apply some kind of advanced treatment, including enhanced nutrient removal (OSE 2009), whereas the remaining 65% applies secondary treatment. Finally, 65% of excess sludge is sent to

Table 3 Cooking scenario

100% Raw or no cooking	Salted meat, lard, cured meat, other processed meat, all canned fish, milk shake, yoghurt, cheese, other dairy products, bread, cookies and cakes, chocolate and cacao powder, sugar, margarine, cucumber, lettuce, all fresh fruits, canned fruits and vegetables, frozen fruits and vegetables, sauces, olives, all nuts, all beverages
100% Microwaving	All milk, ready meals
100% Frying	Knackwurst sausages, frozen potatoes.
100% Boiling	Rice, pasta, coffee and infusions.
75% Frying, 25% roasting	All fresh and frozen meat, all fresh and frozen fish, pulses
50% Boiling, 50% frying	Eggs, all seafood, cabbage, green beans, asparagus
50% Frying, 50% raw	Tomato, leafy vegetables, processed potatoes, all vegetable oils
33% Boiling, 33% frying, 33% roasting	Garlic, mushrooms, fresh potatoes
25% Boiling, 25% frying, 25% roasting, 25% Raw	Onion, pepper, other fresh vegetables

agricultural application (Ministerio de Medio Ambiente 2008a), while the remaining 35% is mostly sent to landfill. The wastewater treatment model used is described in detail in Muñoz et al. (2007). It includes sewer infrastructure, WWTP construction and operation, as well as sludge application to soil. The human excretion model was used to quantify emissions to air from human metabolism, auxiliary materials and energy from toilet use, wastewater composition and the composition of excess sludge from the WWTP. Eight percent wastewater was considered as emitted to the environment without treatment, whereas for the remaining 95%, WWTP treatment was considered, 65% of which with enhanced nutrient removal. Sludge land-filling was included with the model by Doka (2003). Figure 1 summarizes the overall balance of mass and energy of the food consumption stage, with special focus on human excretion and wastewater treatment.

3 Results

Figure 2 shows the LCIA results per functional unit, i.e. feeding an average Spaniard during 1 year. The figure shows the absolute contribution of six life cycle stages. In

Table 4 Nutritional composition of the Spanish diet (ingested food)

Constituents	% in weight
Water	75
Protein	3.6
Fat	5.8
Carbohydrate	13
Fibre	0.78
Alcohol	0.99
P	0.061

addition, the contribution of several food items and processes described in the previous sections can be seen.

The net GWP related to feeding an average Spanish citizen during a year (Fig. 2a) is 2.1 tons CO_2-eq. This figure is dominated by the food production stage. High-lighted contributions are those by meat products and dairy (54% of the total GWP for food production). Nevertheless, human excretion and WWTP is the second most important life cycle stage (17% of total CO_2-eq. emissions), due to carbon releases in respiration, wastewater treatment, sludge disposal, and although not seen in the figure, to auxiliary materials like toilet paper, soap and tap water. Home processes are also responsible for a relevant contribution in the life cycle, while wholesale and retail, waste management and home transport have low contributions, especially the latter. Another interesting aspect to observe in Fig. 2a is how the carbon balance is closed in human excretion since carbon fixed in biomass is mostly released in that stage. In particular, 75% of the carbon in bought food is released by human respiration, wastewater treatment and sludge disposal, whereas the remaining 25% is released through kitchen waste treatment, resulting in closed carbon cycle.

EP (Fig. 2b) is also dominated by the food production stage, where meat, dairy and beverages (mainly wine and beer) are responsible for 60% of the total emissions in this life cycle stage. Again, human excretion and WWTP is the second most important stage (17% of total EP). This importance is mainly related to the release of nitrogen and phosphorus compounds in the treated sewage. The con-tributions of wholesale and retail, transport to home, storage and cooking are negligible, whereas solid waste management is responsible for 4% of the total EP score.

The overall PEU per citizen and year is 20 GJ, with the most important contribution (Fig. 2c) taking place during food production, with several food groups being important
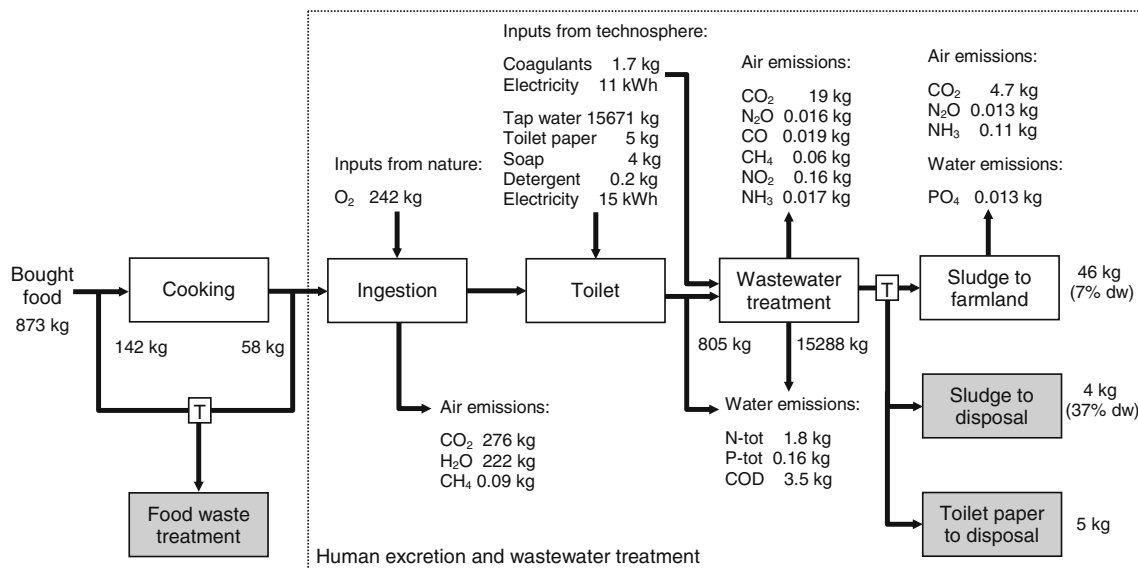
Fig. 1 Balance of the food consumption and excretion stage. Infrastructure inputs not shown. *Grey boxes* are modelled with ecoinvent data sets

contributors. Home processes, i.e. storage and cooking, are relevant from an energy perspective (22% of total PEU). Human excretion and WWTP are of very low importance, with only 3.5% of the total PEU; however, this percentage is higher than that of transport home and kitchen waste management.

Finally, in AP (Fig. 2d), again food production is the most important stage, with meat and dairy appearing as the most polluting food groups. Besides food production, only home storage and cooking have a relevant contribution (12% of total AP). Human excretion and WWTP are negligible in this impact category (2% of total AP).

4 Discussion

The results obtained can be compared to those from previous studies. Santacana et al. (2008) carried out an analysis of Spain's carbon footprint for the year 2000, using an input–output approach. They found a contribution for food of 1,650 kg CO_2-eq. person^{-1} year^{-1}, a figure 20% lower than our result of 2,100 kg CO_2-eq. person^{-1} year^{-1}. Given the level of uncertainty in these kinds of studies, these values can be considered to fit rather well. In fact, in a previous version of the present study (Muñoz et al. 2009), relying to a greater extent on the LCA Food database, the total emissions of greenhouse gases were 1,560 kg CO_2-eq person^{-1} year^{-1}. Greenhouse-gas emissions were also studied by Carlsson-Kanyama (1998) for different diet models, leading to greenhouse-gas emissions in the range of 420–3800 kg CO_2-eq. person^{-1} year^{-1}. Kramer et al. (1999) calculated the GWP of food supply in the Netherlands with an input–output approach, leading to emissions

of 2800 kg CO_2-eq. household^{-1} year^{-1}, but the number of persons per household is not stated. With our results, a Spanish household would be responsible for 5,900 kg CO_2-eq. year^{-1}, a figure substantially higher; the different approaches used (input–output/process LCA) could explain the differences in these two studies. Carlsson-Kanyama et al. (2003) found that PEU of Swedish food consumption may be in the 6.9–21 GJ person^{-1} year^{-1} range, while the figure obtained in our study is 20 GJ person^{-1} year^{-1}. Concerning contributions of food items, many studies highlight animal food as a critical issue (Kramer et al. 1999; Carlsson-Kanyama 1998; Jungbluth et al. 2000; Weidema et al. 2008), something in accordance with our study, especially in GWP, EP and AP.

It looks like these previous studies achieve similar results without including human excretion in their system boundaries. In GWP, this is due to the fact that most carbon emissions in the excretion stage are offset by carbon fixation in photosynthesis, resulting in an almost neutral carbon balance. This is shown in Fig. 3, where alternative results for GWP are shown, in which biogenic CO_2 emissions are not taken into account. The contribution from the human excretion stage falls from 17% in the original results to 3%, while the total emissions per person per year remain the same, 2.1 tons CO_2-eq. In the case of PEU, human excretion has a rather low contribution to the overall life cycle; therefore, omitting this stage does not change much the overall picture. However, this does not hold true for EP, an impact category not assessed in the cited studies, where human excretion is an important life cycle stage, as pointed out by Sonesson et al. (2004) and Muñoz et al. (2008). In Sonesson et al. (2004), the contribution of nutrients and chemical oxygen demand
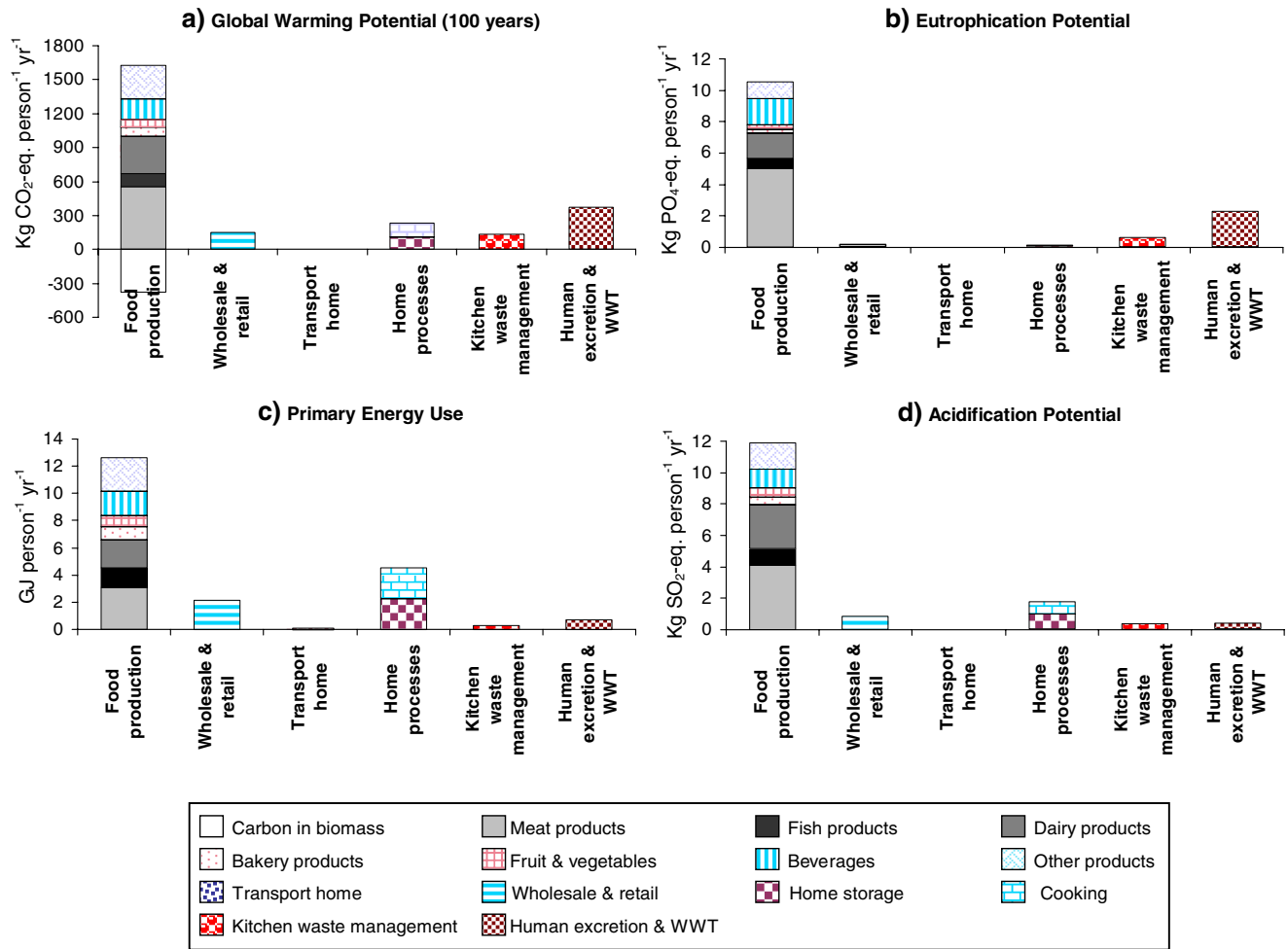
Fig. 2 Life cycle impact assessment results per functional unit

was assessed for different food items, resulting in total life cycle contributions to EP as high as 70% for apples and 55% for bread. In Muñoz et al. (2008), a contribution of 45% is found for broccoli. In our case study, the integrated contribution from the whole Spanish diet is 17%. We can think of two reasons explaining this lower contribution: one of them is that the production phase in the present study involves higher nutrient emissions due to inclusion of more resource-intensive products, especially meat. This makes the relative contribution of the excretion stage appear lower. Furthermore, in Muñoz et al. (2008), 89% of the WWTPs were assumed not to apply enhanced nutrient removal; therefore, the emissions of N and P were higher than in the present study.

We admit the fact that our study has many limitations: first of all, the data gaps on the production stage, since there are limited background data for food production in Spain. Furthermore, for some products, no data at all were found. For many products, we relied on the LCA Food database, which—besides not being representative of the Spanish

food sector—it has been built following a consequential approach to system boundaries, allocation and data selection, whereas our study can be labelled as attributional. Although we dealt with this problem by adapting some data sets (dairy production without milk quotas, average mix for electricity production instead of the marginal production
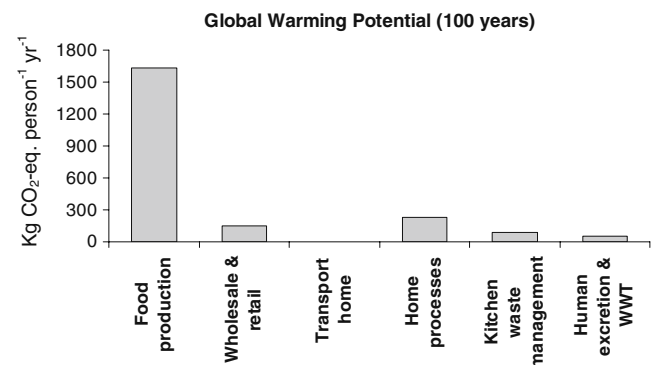

Fig. 3 Global warming potential per functional unit, excluding biogenic CO_2 emissions

technology), the use of this database could lead to biased results. In addition, environmental burdens of packaging have not been taken into account to their full potential due to lack of data. Thirty-eight percent of the food weight assessed did not include packaging production, whereas packaging disposal has not been included at all. The importance of packaging production in the life cycle of food varies between products: Jungbluth et al. (2000) found this aspect of minor importance for meat and vegetables, but it is very important for other products like beverages (Gleick and Cooley 2009; Hospido et al. 2005). Packaging disposal, on the other hand, usually has a very low contribution in food studies, regardless of the type of product (Iribarren et al. 2010; Humbert et al. 2009; Zufia and Arana 2008). Data for the cooking process, namely the share of cooking modes and the share of electric/gas cooking appliances, are very uncertain in this case study, but no alternative data were found. Nevertheless, a sensitivity analysis dealing with the share of frying, boiling and roasting showed only little changes when as far as the overall results are concerned.

5 Conclusions

Human excretion as a life cycle stage has been found to be important in the average Spanish diet, especially in EP, due to the emissions of nutrients in treated sewage. After food production, human excretion appears as the most important source of emissions in EP and GWP. However, if biogenic CO_2 emissions are not taken into account, the contribution of human excretion to GWP becomes very small. In PEU and AP, human excretion is not an important stage. In all these impact categories, food production is the main hotspot, highlighting meat and dairy products.

6 Recommendations and perspectives

Human excretion has been found to be important at both the product and diet levels. This life cycle stage should not be overlooked in LCA studies dealing with diet shifts since the emissions related to this life cycle phase are different when different food items are considered. Neither should it be omitted in attributional studies aimed at identifying the life cycle hotspots of a given food product or diet.

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