Nutritional data management of food losses and waste under a life cycle approach: the case study of the Spanish agri-food system[(1,2)]

Garcia-Herrero, I.[a,*], Margallo, M. [a], Laso, J. [a], Batlle-Bayer, L.[b], Bala, A.[b], Fullana, P.[b], Vazquez-Rowe, I.[c], Gonzalez, M.J.[a], Amo, F[a], Durá, M.J.[a], Sarabia, C.[a], Abajas, R.[a], Quiñones, A.[a], Irabien, A.[a], Aldaco, R[a]

[a] Universidad de Cantabria, Avda. de los Castros s/n 39005 Santander, Spain. E-mail: garciahmi@unican.es, Tel. + 34 942206749/ Fax + 34 942201591

[b] UNESCO Chair in Life Cycle and Climate Change, Escola Superior de Comerç International (ESCI), Universitat Pompeu Fabra (UPF), Passeig Pujades 1, 08003 Barcelona, Spain

[c] Pontificia Universidad Católica del Perú, Departamento de Ingeniería, Red Peruana Ciclo de Vida. Avenida Universitaria 1801, San Miguel L0032, Lima, Perú.

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Abstract

Food losses and waste (FLW) tend to be referred to in terms of mass, occasionally in economic terms, disregarding the nutritional-cost nexus of such losses. This work aims to estimate the nutritional food losses and waste (NFLW) of the Spanish agri-food system in terms of energy, macronutrients, fibre, and vitamins and minerals along the entire supply chain. Nutritional food losses (NFL) occurring prior to the distribution level, and nutritional food waste (NFW) at the retail and consumption stages, are distinguished, and 48 representative food commodities and 32 nutrients are characterised. To provide insight into the extent of these values, the results are compared to the equivalent recommended daily intake. Moreover, the NFLW for an average Spanish citizen is compared to that for other representative diets: Mediterranean, lacto-ovo-vegetarian, and vegan, in addition to the Spanish recommended guidelines. Finally, a Nutritional Cost Footprint (NCF) indicator combining nutritional and economic variables is proposed to define recovery strategies. The results suggest that 1016 kcal, 70.7 g proteins, 22 g dietary fibre, 975 mcg vitamin A, 117 mg vitamin C and 332 mg calcium daily per capita are embedded within Spanish FLW. Agricultural production accounts for 40% of NFLW, and fruits and vegetables are the categories with the largest potential for nutritional and economic food wastage mitigation. Results from this paper provide NFLW data and analysis to strengthen and simplify the decision-making process of FLW management strategies.

Keywords: food analysis; food composition; food losses and waste; nutritional losses and waste; economic losses and waste; supply chain; reference daily intake; nutrient rich food index; Spanish agri-food system; Mediterranean diet.

1. Introduction

The relationship between food security and sustainability appeared for the first time in the Bruntland report (WCED, 1987), which focused on the issue of ensuring the future global availability of food. Over the last thirty years, this concept has evolved to highlight the need consider the accessibility of food in addition to its availability (FAO, 2006). Food and nutrition security is a complex issue, associated with health through malnutrition, but also sustainable economic development, the environment, and trade (Scherhaufer et al., 2015). Nowadays, more than 800 million people still suffer from hunger, while paradoxically almost one third of the food produced for human consumption is lost or wasted, amounting to 1.3 billion tonnes a year (Gustavsson et al., 2011). According to the Food and Agriculture Organisation of the United Nations (FAO, 2013), this amount could equivalently feed 12% of the world's population currently estimated to be suffering from hunger. These figures highlight the imbalance existing between different regions and diets.

Food losses and waste (FLW) are the loss of important nutrients and micronutrients that are not ingested. Hence, FLW threaten food security and nutrition in a three-dimensional manner. Firstly, they lead to reduced food availability. Secondly, FLW present a negative impact on food access for those involved in harvest and post-harvest operations and who face FLW-related economic and income losses, and for consumers owing to the contribution of FLW to the tightening of the food market and rising food prices (Timmermans et al., 2014). Finally, FLW pose a threat to food security owing to the current unsustainable pattern of natural resource exploitation. Food systems contribute to around 30% of total energy consumption and 70-80% of human water withdrawals (Pimentel et al., 2008; Verma et al., 2015). Consequently, FLW comprise the wastage of embedded valuable resources that build up down the supply chain. In addition, the growing population and related increase in food demand are forecast to cause a 50% rise in natural resource consumption (Vora et al., 2016).

FLW have traditionally been referred to as a decrease in mass, at all stages of the food chain from harvest to consumption, of edible food that was originally intended for human consumption. Hence, numerous studies have focused on estimating the quantity of FLW in terms of mass. When studying the impact of FLW on nutrition, few studies have focused on calories. For example, Kummu et al., (2012) estimated FLW in mass using the FAO approach (Gustavsson et al., 2011), ultimately converting this into calorie values. They suggested that 24% of food production is lost or wasted, amounting to 720 kcal per capita per day in Europe. The same approach was followed by Lipinski et al. (2013), who gave a figure of 748 kcal lost per European citizen each day.

However, the use of the caloric content of foods for estimating FLW gives greater weight to energy-dense foods and loses sight of other wasted nutrients (Timmermans et al., 2014). Other nutritional dimensions, such as micronutrients (minerals and vitamins), are often disregarded. For example, fruits and vegetables are quantitatively the greatest FLW in terms of mass, in addition to being an important source of micronutrients, including organic acids and vitamin C, which promote iron absorption (Teucher et al., 2004). Fish and meat products are also nutrient-dense products, and these are being lost at an increasing rate. They are nutritionally important because of their iron content, especially considering that 23% of the population in Europe and up to 49% globally present iron deficiency anaemia (Lotfi et al., 2001; Benoist et al., 2008). Only two studies have been found in the literature that address a wider scope of nutritional FLW. One, conducted by the European Commission as part of the FUSIONS project, estimated the losses of vitamin A, beta-carotene, vitamin C, fibre, iron, zinc, n-3 fatty acids, lysine, and methionine for 9 indicator products, representing 65% of EU production (Scherhaufer et al., 2015). The other calculated the nutritional waste in the United States, at only retail and consumer level, of 213 commodities for 27 nutrients (Spiker et al., 2017). As far as the authors know, there are no studies that estimate nutrient and micronutrient losses for the entire supply chain.

Economic losses relating to FLW are also little studied. Buzby et al. (2014) determined that the total value of food lost at the retail and consumer level in the United States was $162 billion in 2010, with 70% of the economic losses being generated at consumer level (1US$=0.85€).

European level, economic losses were estimated to be €143 billion in 2012, with two thirds of the costs being related to household consumption (Stenmarck et al., 2016). Despite FLW-related costs having been properly defined at the consumer end of the supply chain, there is scant information on economic FLW at the front end of the food chain (i.e., agricultural production, post-harvest, and processing).

On the other hand, FLW policies currently focus on reducing the mass of FLW. This is the case of the Sustainability Development Goals (SDG), adopted in 2015 by the United Nations Member States. These include the aim of halving food waste at the retail and consumer level by 2030 and reducing food losses along production and supply chains, including post-harvest losses. As already suggested by the High Level Panel of Experts on Food Security and Nutrition (Timmermans et al., 2014), it is necessary for future FLW reduction strategies to consider, not only quantification in terms of mass, but also the decrease in the nutritional qualities attributed to food, at all stages of the supply chain. This work therefore assesses the nutritional losses and waste along the supply chain of the Spanish food system in terms of energy, macronutrients, fibre, vitamins and minerals. In order to make the results significant and help in the decision-making process, the study distinguishes between nutritional food losses (NFL), occurring prior to the distribution level, and nutritional food waste (NFW), occurring at the distribution and consumption stages. Moreover, nutritional losses and waste are compared to the recommended daily intake (RDI). To create awareness among producers and consumers, NFLW from an average Spanish citizen are compared to those from other representative diets: Mediterranean, lacto-ovo-vegetarian, and vegan, in addition to the Spanish recommended guidelines. Finally, the economic costs associated with FLW at the various stages of the supply chain are determined and an indicator for defining FLW management strategies is proposed, combining both nutritional and economic variables.

2. Materials and methods

A life cycle approach has been applied to estimate the nutrients and micronutrients embedded in FLW. This is a holistic approach that goes beyond the traditional focus on the processing stage to include the entire product pathway, from the extraction of raw materials to the return of waste to the ground (Azapagic, 2010). The life cycle approach was originally applied to environmental sustainability assessment, under the premise that to reduce the environmental impacts of an economic system, the whole life cycle of the activity must be considered. However, life cycle thinking is broadening its boundaries and is currently applied to other sustainability aspects, such as the economic (life cycle costing) or social (life cycle social assessment) dimensions.

Most studies in the literature focus on the nutritional characterisation of agri-food systems at the consumption stage, disregarding other steps in the supply chain. This work applies a life cycle approach to the Spanish agri-food system, taking into account every stage from agricultural production to consumer. The ultimate aim of the study is to go beyond the classical applications of life cycle assessment by exploring the nutritional and economic dimensions of food losses. The method followed in this work comprises 4 different steps, as shown in Fig. 1: i) definition of daily average consumption for the diet or diets under study; ii) estimation of food losses and waste in the different steps of the supply chain, as well as for the food categories under study; iii) calculation of nutritional food losses and waste (NFLW); and iv) assessment of the nutritional and economic impact of nutrient wastage. The various steps are described in the subsections below.

2.1 Diet design

The method used for designing diets is a key issue in consumption-oriented studies (Heller et al., 2013). Diets representative of national averages are often based on the apparent consumption (sold production + imports - exports) estimated from available statistics. However, this concept is flawed since it assumes that all food commodities sold and imported are consumed, and that the methods used for the two surveys produce comparable results. To overcome this problem, the data on Spanish average consumption was sourced from the food consumption database of the Spanish Department of Agriculture and Fisheries, Food and Environment (MAPAMA, 2017). The information for 2013 to 2016 was extracted for 48 representative food commodities grouped into 13 categories (fruits, vegetables, cereals, dairy, vegetable fats, nuts and seeds, fish, white meat, eggs, red meat, legumes and derivatives, potatoes, and sweets). These categories were defined based on the classification used in the MAPAMA database and the nutritional differences of the food groups (Table S1 of the supplementary material (SM)).

Table 1 shows the daily and weekly servings used to design the alternate diets considered. Spanish nutritional guidelines (SENC, 2016) recommend the consumption of more plant-based products and less meat. The Mediterranean diet was sourced from the study of Bach-Faig et al. (2011), and the lacto-ovo-vegetarian and vegan diets come from the recommendations of the Spanish Vegetarian Union (UVE, 2017). For comparative purposes, all the diets designed, including the average Spanish consumption, were adjusted to fit the 2,000 kcal daily intake recommended by the European Commission (EC, 2011). The daily consumption estimates for each diet studied are shown in Table S2 of the SM.

2.2. Calculation of food losses and waste

Material flow analysis was used to quantify the food losses and waste throughout the supply value chain. In this work, food losses and waste are defined as "a decrease, at all stages of the food chain from harvest to consumption, in mass, of food that was originally intended for human consumption, regardless of the cause" (Timmermans et al., 2014). The study makes the distinction between food losses occurring prior to the consumption level, regardless of the cause, and food waste occurring at consumption level, also regardless of the cause.

With regard to agricultural production, climatic conditions, diseases, and pests are the main reasons for FLW generation (MAPAMA, 2013a). On the other hand, inefficient manual and technical harvesting, unsatisfied quality standards, and mismatch between supply and demand cause losses at both harvest and post-harvest levels. Insufficiencies in infrastructure and logistics, lack of technology, lack of skills or knowledge, and unsatisfied quality standards are stated as reasons for FLW at the industrial level. According to HISPACOOP (2013), half of food wastage at consumer level could be avoided through adequate purchase and storage planning. Improper preparation, lack of awareness about the difference between expiration and preferential consumption dates, and portion size acquired in the supermarkets, are other reasons for food waste generation in households (Garcia-Herrero et al., 2018).

The FLW for each food category are determined as a function of the food quantity leaving the corresponding stage, as shown in Eqs. 1-2:

$$FLW_{i,j,k} = \left(\frac{\alpha_{i,j,k}}{1-\alpha_{i,j,k}}\right) \cdot F_{i,j-1,k} \quad (1)$$

$$F_{i,j,k} = F_{i,j-1,k} - FLW_{i,j,k} \quad (2)$$

Where $FLW_{i,j,k}$ are the food losses and waste of food commodity *k* belonging to food category *i* for each stage, *j*, of the supply chain (j=1, agricultural production, j=2, post-harvest handling and storage; j=3 processing and packaging; j=4 distribution; and j=5, household consumption). $\alpha_{i,j,k}$ is the percentage of food losses and waste generated in each *j* stage; $F_{i,j,k}$ is the food commodity *k* available for human consumption from category *i* and leaving the supply chain sector *j*.

The FLW weight percentages reported by the FAO for the European region (Gustavsson et al., 2013) were used to quantify FLW volumes, except post-harvest losses for which there is data available for Spain in the FAOSTAT Balance sheets. These percentages were adapted to the Spanish region whenever possible (MAPAMA, 2013a, 2013b), and are described in Table S4 of the SM.

For processed products comprising either a single ingredient (such as cheese and sunflower oil), or more than one ingredient (such as margarine and biscuits), conversion factors were considered to estimate the corresponding FLW in agricultural and post-harvest stages in terms of unprocessed products (Table S5 of the SM). Total conversion yields were assumed for food commodities included in the meat, fish, and seafood categories. More information on the estimation of food losses and waste is provided in Garcia-Herrero et al., (2018).

2.3. Calculation of nutritional food losses and waste

Estimating nutrient loss from FLW may be helpful for people trying to prevent FLW by engaging the public and companies and increasing awareness on this subject (Scherhaufer et al., 2015). Figure 1 shows the conceptual scheme for the steps followed to assess the nutritional food losses and waste (NFLW). As shown in Fig. 1, once the FLW have been determined, the nutritional food losses and waste (NFLW) can be estimated. A set of 32 nutrients was selected for this purpose, including macronutrients, vitamins, and minerals. The macronutrients selected were energy (kcal), total proteins (g), vegetable proteins (g), animal proteins (g), total fat (g), saturated fat (g), monounsaturated fat (g), polyunsaturated fat (g), cholesterol (mg), carbohydrates (g), sugars (g), starch (g) and dietary fibre (g). The minerals included sodium (mg), potassium (mg), calcium (mg), magnesium (mg), phosphorous (mg), iron (mg), and zinc (mg). The vitamins included vitamin A (mcg), retinoids (mcg), carotenoids (mcg), vitamin D (mcg), vitamin E (mcg), thiamin (mg), riboflavin (mg), niacin (mg), vitamin B-6 (mg), vitamin B-9 (mcg), vitamin B-12 (mcg), and vitamin C (mg). These components were selected based on the availability of data in the Institute for Education in Nutrition and Dietetics from Spain (CESNID) database and their significance in the formulation of dietary guidelines (EC, 2011).

Nutritional data was obtained from the CESNID (2003) food composition tables. These tables, which are registered in the FAO International Network of Food Data Systems (FAO/INFOODS), were selected owing to the wide range data contained and the Spanish origin of the food products assessed. Food products or ingredients not appearing in this database (cacao seeds, palm oil, and linseed oil), were sourced from the National Nutrient Database for Standard Reference of the United States Department of Agriculture (USDA). Although this database is not European, it was selected because it provides composition data for more than 8,000 food products, comprising the most elaborate food composition database as indicated by the European Fusions project (Scherhaufer, 2015). Further discussion on food composition tables and nutritional data for the food commodities studied can be found in Section S5 of the the SM.

For each food commodity, a representative item was matched from the described databases. For example, an average of flank steaks and briskets was assumed to represent fresh beef meat, while breast and loin were considered for chicken meat and pork meat, respectively. Whenever feasible, the selections were based on the most representative products according to the Spanish consumption database (MAPAMA, 2017).

Once the nutritional data had been compiled, the NFLW could then be calculated using Eq. 3:

$$NFLW_{i,j} = \sum_{k} FLW_{i,j,k} \cdot NC_{i,j,k} \quad (3)$$

Where $NC_{i,j,k}$ is the nutritional content of FLW for food commodity k within category i and supply stage j. Since the nutritional data available in food databases is at product level, nutritional content cannot be distinguished for unprocessed food along the supply chain. This may lead to an overestimation of the nutritional content of FLW, especially for fruit and vegetable commodities, because it does not consider the degradation of nutrients over time. Moreover, food composition databases contain information about edible food, which may differ from the nutritional features of FLW. For this reason, this work follows the approach of Scherhaufer et al. (2015), assuming that data from food composition databases are an estimate for the nutritional composition of waste and the inedible parts of food commodities.

The assessment of nutrient losses and waste in terms of human nutritional requirements can be conducted by comparing NFLW values to the dietary reference intakes (RDI) set by the European Regulation (EU) No 1169/2011 of the European Commission (EC, 2011) and the European Food Safety Authority (EFSA, 2010). To estimate NFLW at population scale, the total per capita losses were multiplied by the average Spanish population size for the period 2013-2016 (46.77 million).

2.4 Nutritional and economic impact of nutrient wastage

To assess the overall nutritional quality of a diet, diet quality indices are often used. The Nutrient Rich Foods (NRF) Index is a formal scoring system that ranks food on the basis of its nutrient content; it can be applied to individual foods, meals, or a total diet (Drewnowski, 2010). In this work, we have applied the nutrient profile model developed by Drewnowski et al. (2009) and Fulgoni et al. (2009) to the FLW related to the diets under study, in order to determine the nutritional impact of food losses and waste.

The most widely used NRF algorithm is NRF9.3, which is based on 9 nutrients (protein, fibre, minerals calcium, iron, magnesium and potassium, and vitamins A, C and E) that should be encouraged, and 3 nutrients (saturated fat, added sugar and sodium) that should be limited, as described in Eq. 4:

$$NRF9.3 = \sum_{i} w_i \left(\sum_{l=9} \frac{NR_l}{DV_l} \cdot 100 - \sum_{m=3} \frac{LIM_m}{MRV_m} \cdot 100 \right) \quad (4)$$

Where *NR* is the intake of nutrient *l* (to encourage), *DV* is the daily recommended value of nutrient *l*, *LIM* is the intake of nutrient *m* (to limit), and *MRV* is the maximum daily recommended value for the nutrient *l*. W_i is the weighting factor of food category *i* and can be estimated using kcal or weight basis. In this work, the weight basis has been selected to avoid the overrepresentation of calorie-dense foods.

The daily recommended value of nutrients was sourced from EU Regulation No. 1169/2011 of the European Commission (EC, 2011) and the EFSA (2010) as proposed by Sluik et al. (2015) in their assessment of different NRF indices based on European data. The reported values are similar to those from the US Food and Drug Administration (FDA) used in Drewnowski (2010), with the exception of potassium and vitamins A and E, for which American values duplicate European values. The maximum daily recommended values were sourced from EFSA (2009), and agree with FDA values.

Added sugar is not included in either the CESNID or USDA database. However, as studied in the work of Fulgoni et al. (2009), since added sugar data is not very readily available, using total sugars as a nutrient to limit may be a reasonable option (Fulgoni, 2009). Moreover, these authors demonstrated that total and added sugar are highly correlated.

Economic variables can also be used to determine the impact of food losses and waste. Down the supply chain, from production to retail, value is generally accumulated, linked to successive phases of the elaboration of the final product. This occurs not only in processed foods, but also with shorter food chains, such as those of fresh commodities (Timmermans et al., 2014). To estimate the NFLWF, it is first necessary to determine the economic food losses and waste (EFLW), as described in Eq. (5).

$$EFLW_i = \sum_j EFLW_{i,j} = \sum_j FLW_{i,j} V_{i,j} \tag{5}$$

Where $EFLW_{i,j}$ represents the economic food losses and waste of food category i in supply stage j, and $V_{i,j}$ their corresponding economic value. Prices at origin, wholesale and consumer level were obtained from the Spanish Ministry of Economy and Competitiveness (MINECO, 2015) and the MAPAMA (2015b) (see Section S6 of the SM). The same costs were assumed for FL at agricultural production and post-harvest stages. For the processing stage, the economic production values reported by Eurostat were used when consistent data was available. In other cases, wholesale prices were used for the processing and distribution stages.

Finally, we propose the Nutritional Cost Footprint (NCF) to assess both the nutritional and economic impact of FLW. This index can be estimated by weighting the normalised previous two metrics (Eq. 6):

$$NCF_i = \alpha_i \frac{NRF9.3_i}{\overline{NRF9.3}} + \beta_i \frac{EFLW_i}{\overline{EFLW}} \tag{6}$$

Where α_i is the weighting factor for the nutritional impact and β_i is the weighting factor for the economic impact of FLW. In this work, equal weighting is assumed and thus, α_i =β_i=0.5.

3. Results and discussion

3.1 Nutritional food losses and waste in the Spanish supply system

The estimated losses and waste of nutrients embodied in FLW are shown in Table 2. The daily NFLW calculated for the Spanish agri-food system amount to 1016 kcal, 70.7 g proteins, 22 g dietary fibre, 975 mcg vitamin A, 117 mg vitamin C, and 332 mg calcium per capita, among others. Results suggest that most macronutrients and micronutrients are lost in the agricultural production step, with this stage representing more than 40% of the total NFLW. The consumption step is the second main source of NFLW, where more than 30% of the nutrients are wasted. The exceptions are animal proteins, starch, retinoids, and vitamins D and B-12, for which the nutritional loss embedded in household waste is larger than the estimated nutritional loss related to agricultural FLW. The remaining supply stages, processing, distribution, and post-harvest account for 13%, 8% and 7% of the NFLW, respectively.

Fig. 2-5 and Table 3 present the contribution of the food categories under study to the wastage of nutrients (more detailed information can be found in Section S7 of the SM). For macronutrients, the cereals category contributes the most to the loss of nutritional energy (36%), half of which is lost in the consumer step. Somewhat behind this, vegetable fats and fruits contribute to 16% and 11%, respectively, around 50% of the losses occurring at the agricultural level. Cereals also account for the majority of NFLW for vegetable proteins (42%), dietary fibre (23%), and starch (69%), again mainly due to waste at consumer level. The dairy category represents a third of the protein wastage, almost 80% occurring at the consumption stage. Finally, we can also highlight the losses of dietary fibre due to fruit and vegetable production, which together account for nearly 40% of fibre NFLW.

Similarly to macronutrients, most of the minerals are also embedded in NFLW of cereals, with the exception of potassium, where 28% is embedded in NFLW of vegetables.

The pattern is different when the NFLW of vitamins is assessed. Almost 90% of vitamin A is lost along the vegetable supply chain, 49% of which is due to agricultural production. Vegetables are also responsible for the losses of 51% of vitamin C and 36% of folate, half of which are wasted at consumer level. Fish and seafood products contribute the most to NFLW of vitamin D (82%) and vitamin B12 (76%). The contribution of fruit to NFLW of vitamins is less, but also significant, accounting for 16% of folate and 32% of vitamin C. Finally, almost 60% of vitamin E is embedded in FLW of vegetable fats, mainly due to sunflower oil.

Regarding nutrients to limit, the study focuses on saturated fat, sugar and sodium. The NFLW of saturated fat are mostly shared with cereals, due to the consumption of biscuits and vegetable fats, accounting for 38% and 21%, respectively. The pattern is slightly different for sugar, for which fruits (41%), cereals (19%), and sweets (17%) are the main contributors. Finally, vegetable fats comprise the major NFLW of sodium (54%), entirely due to losses in olive production for olive oil, and cereals (23%) owing to bread wasted at consumer level.

Some slight differences are seen when seasonal variability is considered. The consumption of dairy derivatives and fresh vegetables is observed to increase 3% in the spring-summer season, while the consumption of fresh fruits experiences a 6% rise (Table S3 of the SM). This involves larger losses of vitamins, particularly vitamins A and C, whose NFLW in the spring-summer season are 7.1% and 6.6% higher, respectively. Additionally, the NFLW of total proteins, sugar, and potassium, are each estimated to be 3% higher. In the autumn-winter season, greater losses of saturated fat (1.2%) and cholesterol (1.6%) are observed. More information can be found in Section S9 of the SM.

3.2 Nutritional food losses and waste compared with nutritional requirements

Table 3 compares the macronutrient and micronutrient values embedded in FLW to dietary reference intakes in order to estimate the equivalent number of adults that could be fed from

NFLW. Since food commodities are not ready for consumption or recoverable at every step of the supply chain, we have distinguished NFL and NFW; NFL refers to the daily nutritional losses per capita occurring from agricultural production to processing; while NFW refers to losses at the distribution and consumption levels. Nutrients to limit have been excluded from the comparison, due to the purpose of the assessment. Results suggest that, on average, 15.3 million people could meet their recommended daily intake from the nutrients present in food waste, in other words, a third of the Spanish population. This number triples for total proteins, for which the estimation of NFW equals the quantity required for 42 million people daily. This is, in particular, due to dairy products wasted in households. Slightly less, but also above average data levels, was the waste of vitamins A and C, amounting to 19 million equivalent people. The minimum NFW are observed for vitamin E, amounting to the equivalent recommended daily intake of 5.4 million people.

Larger values are estimated for NFL, for which losses at the beginning of the supply chain account for, on average, the daily requirements of 28 million equivalent adults. The pattern observed is quite different from that described previously, with the highest estimates for vitamins C (48 million equiv. people) and A (38.6 million equiv. people), while the lowest are for calcium (11.5 million equiv. people).

Our results suggest that around 80% of the Spanish population could meet their nutritional needs from food losses and waste. However, this is a first estimation, assuming a best-performance scenario —an approach that considers all FLW to be avoidable and the embedded nutrients recoverable, which is often not true.

3.3 Nutritional food losses and waste for average Spanish consumption compared with those from alternative diets

Table 5 shows the comparative assessment of daily NFLW for an average Spanish citizen, according to current consumption patterns, and the equivalent NFLW following 4 alternative diets based on: the Spanish Dietary Guidelines; the Mediterranean diet; the lacto-ovo-vegetarian diet; and the vegan diet (the full set of NFLW is available in Section S8 of the SM).

The results suggest that the daily nutritional loss of beneficial nutrients (i.e., protein, fibre, minerals calcium, iron, magnesium and potassium, and vitamins A, C, and E) is, on average, higher for the alternative diets than for the average Spanish diet (Table 5). This is mainly due to the fact that average patterns in Spain include cereal, fruit, and vegetable intakes that are 1.5-1.2 times below the recommended values (based on kcal). Moreover, these are the main categories contributing to FLW, because of their perishable character (fruits and vegetables) and their high waste at consumer level (cereals). The main exception is total proteins with regard to Mediterranean and vegan diets, owing to the overconsumption (2.3 times) of dairy products and, in particular, animal proteins because of red meat consumption. Other exceptions include: vitamins D, B-12, and niacin, because of a higher intake of fish; vitamin E, due to vegetable fats; and retinoids, once again because of dairy product consumption.

When comparing the alternative diets with each other, it can be seen that the majority of nutrients to encourage have a greater presence in FLW of vegan diets than the others, with the exception of protein (due to the absence of dairy and meat products in the diet), and vitamins A and C (Castañé et al., 2017). The reduced NFLW of vitamins A and C in the vegan diet are due to the lower consumption of vegetables with regard to the other diets, in contrast to a higher intake of fruits and legumes.

For nutrients to limit (saturated fat, sugars, and sodium), there is no clear pattern. The NFLW of saturated fat in the average Spanish diet were twice that estimated for the alternative diets. Conversely, the sugar and sodium content was greater for the Mediterranean diet, owing to the higher consumption of cereals, fruits, and vegetable fats. The lowest amount of sodium was observed in the lacto-ovo-vegetarian diet, owing to the decreased intake of vegetable fats, which generates the largest NFLW of sodium due to olive production, as described above.

Although the values shown in Table 5 serve to compare the nutrients embedded in food wastage for the different diets, this assessment fails to determine which diet generates the highest nutritional quality losses. For this, the nutrient-rich food index NRF9.3 was estimated according to Drewnowski (2009). Fig. 6 shows the NRF9.3 scores for the diets studied, distinguishing between NFL and NFW. The highest value was obtained for the Mediterranean diet, estimated to be 2.6 times greater than that of the average Spanish diet. This is explained by a generally higher consumption of nutrients to encourage, essentially contained in fruits and vegetables, and lower disqualifying nutrients, mostly embedded in cereal products, such as biscuits. This is closely followed by the Spanish guidelines, which recommend a lower intake of fruits but more dairy and legume products. The nutritional quality waste at retail and consumer level accounts for all the diets was between 34 and 41% for the entire supply chain (NRF9.3-NFW), which should create awareness among consumers. The vegetables category is responsible for the largest overall impact in both NFL and NFW, followed by fruits. Consequently, these are the categories for which greater effort should be invested in reducing nutritional wastage in the Spanish agri-food system, from the nutritional point of view. The results in Fig. 6 also demonstrate that the more nutrient-rich a diet is, the greater the quantity of nutrients lost and wasted. Obviously, the conclusion of these results is not to maintain current patterns of consumption, but raise awareness of which food categories are most vulnerable to NFLW.

3.4 Nutritional cost footprint

Figures 7-8 compare the nutritional quality of FLW of the different food categories with their economic cost. FL and FW are disaggregated to distinguish between producer and consumer decision-making. Performance terciles have been defined to sort the different food categories according to the intensity of the nutritional-economic wastage. The rating letter "A" is applied to food categories that exhibit the lowest nutritional and economic losses and waste, while "C" is the opposite. For example, the dairy category presents the worst rating in terms of waste at retail and consumer level (Fig. 8), but its rating improves to “B” for the producer level.

According to this analysis, the food categories that show the worst nutritional-economic efficiency from agricultural production to processing are vegetables, fruits, vegetable fats, potatoes, legumes, red meat, cereals, and nuts and seeds. From distribution to consumption, white meat is added to the list, while legumes improve their score to “B” and vegetable fats and nuts and seeds to “A”.

Although this rating method can illustrate which food commodities require greater effort with regard to preventing losses, it fails to rank items further within the same tercile and it provides no quantitative measure of FLW quality. In this sense, the scores in Fig. 7-8 have been normalised and weighted to calculate the Nutritional Cost Footprint (NCF), as shown in Fig. 9.

The proposed index identifies vegetables as the food category with the largest nutritional-economic losses at every stage of the supply chain, being 16% greater at the agricultural and processing stages. This category is closely followed by fruits, where similar scores are obtained for both losses and waste. In terms of FL, vegetable fats also exhibit low efficiency, although a higher efficiency is observed at the consumption stage. Finally, dairy and red meat may result in significant NCF scores, being 53% and 41% more efficient than vegetables.

3.4.1.1 Limitations for nutrient recovery

Antinutritional factors (ANFs) are biological compounds available in foods that reduce nutrient utilisation or food intake, thereby contributing to impaired gastrointestinal and metabolic performance (Arendt and Zannini, 2013). ANFs present in FLW may prevent the recovery and reuse of nutrients along the supply chain. Metal ion scavengers and antivitamins are the main groups of factors affecting protein utilisation and depressing digestion (Scherhaufer et al., 2015). Examples include mycotoxins, glycoalkaloids, flavonoids, oxalates, phytates, saponins, pesticide residues, and protease inhibitors. However, some ANFs, such as tannins, have anti-carcinogenic properties and their intake can be advisable, despite their anti-nutrient character (Smeriglio et al. 2017).

Phytic acid, or phytate, could be the main limitation for the reuse of the nutrients present in the categories of cereals, legumes, and nuts, due to their ability to form insoluble complexes with minerals such as Ca, Mg, Zn, and Fe, which are not absorbed by humans. Although monogastric animals, such as humans, poultry, fish, and pigs, have a very limited capacity for the degradation of phytic acid in the stomach, polygastric animals do possess the phytase enzymatic complex. This complex is able to degrade phytate, even releasing the phosphorus from which it is composed so this can be absorbed by the digestive tract (Vashishth et al., 2017; Reddy et al., 2017).

Proteinase inhibitors typically present in legumes can also behave as ANFs because they inhibit pancreatic serine proteases, limiting the use of certain proteins. As an example, fishmeals based on vegetable proteins are being studied to valorise agricultural by-products or losses, the main proteinase inhibitors in these being ANFs (Perez et al., 2006). On the other hand, anti-carcinogenic properties have also been attributed to proteinase inhibitor (Clemente et al., 2004, Duranti, 2006).

Other significant ANFs are flavonoids, mainly present in fruits and vegetables, the categories for which there are the largest NFLW of vitamins. Despite presenting antioxidant properties, flavonoids can also impair the absorption of minerals such as iron and zinc through chelation (Russo et al., 2000).

Notwithstanding these facts, different methods such as fermentation, germination, and thermal (only for heat-sensitive ANFs, such as proteinase inhibitors) or enzymatic treatments, can considerably reduce the ANF content (Gupta et al., 2015).

This study identifies a data gap with regard to the amounts of FLW unsuitable for human consumption or animal feed, as most of the literature focuses on qualitative aspects. Nonetheless, the presence of ANFs in FLW should not be considered a limitation for nutrient recovery or reuse, provided that careful monitoring and reduction of their content by the technologies described is applied.

3.5 Study limitations

This work assumes that nutritional data from food composition databases is an estimation for the nutrient and micronutrient content of both edible and inedible parts of food products. This overestimates the nutritional content of FLW because it does not consider the degradation of nutrients over time, nor the inedible fraction that is often present and of lower nutritional content than the edible part (Scherhaufer et al., 2015). For example, the nutrient density of fresh foods decreases after harvest and during storage, especially under inadequate handling conditions. This is more drastic for fruits and vegetables, where vitamin C degrades immediately after harvest, with losses of up to 100% after 4 days in fresh spinach (Timmermans et al., 2014).

The nutritional data found in food databases is at product level. To quantify the nutritional content of FLW at food category level, the most representative products from each category were selected. For this reason, there may be further products that are not represented in this study.

Additionally, total sugar instead of added sugar has been considered as a nutrient to limit the estimation of NRF9.3. This may lead to higher penalties for foods rich in total sugar, such as fruit, despite their lack of added sugar. Despite this, nutrient-rich foods obtained higher scores than foods rich in nutrients to limit.

Finally, the most significant source of uncertainty in this work derives from the loss and waste percentages used for the calculations. The data used from Gustavsson et al. (2013) is for the European region as a whole, and differences between countries are not considered. These percentages have been updated using Spanish studies whenever possible, although the majority have been considered of insufficient quality given the differences in method and definitions of FLW. Nevertheless, the data from Gustavsson et al. (2013) is the best currently available, and considered a good reference for this work.

4. Conclusions

This work assesses nutritional food losses and waste (NFLW) along the supply chain in the Spanish food system, in terms of energy, macronutrients, fibre, vitamins, and minerals. The study distinguishes between nutritional food losses (NFL), occurring prior to the distribution level, and nutritional food waste (NFW), occurring at the retail and consumption stages. 48 representative food commodities and 32 nutrients have been characterised.

A Nutritional Cost Footprint (NCF) index combining the nutritional and economic impact of FLW has been proposed. This index identifies vegetables as the food category with the largest nutritional-economic losses at every stage of the supply chain, closely followed by fruits.

Considering that only part of the food losses and waste (FLW) can realistically be recovered, our results suggest that NFW is the equivalent of the recommended daily intake of a third of the Spanish population, increasing to 80% when NFL are also included.

Current food wastage policies do not differentiate between supply stages, setting reduction targets only at consumer level. This work highlights the necessity of establishing specific strategies according to critical food categories and supply stages. Moreover, we have revealed the need to expand the scope of FLW beyond mass, to include the nutritional (and economic) variable as a measure of food quality lost and wasted.

Finally, this study demonstrates how food data composition and analysis provide an invaluable tool for the decision-making process, in this case supporting FLW management policies.

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