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Quantifying household waste of fresh fruit and vegetables in the EU

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ABSTRACT

According to national studies conducted in EU countries, fresh fruit and vegetables contribute to almost 50% of the food waste generated by households. This study presents an estimation of this waste flow, differentiating between unavoidable and avoidable waste. The calculation of these two flows serves different purposes. The first (21.1 kg per person per year) provides a measure of the amount of household waste intrinsically linked to the consumption of fresh fruit and vegetables, and which would still be generated even in a zero-avoidable waste future scenario. The second (14.2 kg per person per year) is a quantity that could be reduced/minimised by applying targeted prevention strategies. The unavoidable waste was assessed at product level, by considering the inedible fraction and the purchased amounts of the fifty-one most consumed fruits and vegetables in Europe. The avoidable waste was estimated at commodity group level, based on the results of national studies conducted in six EU member states. Significant differences in the amounts of avoidable and unavoidable waste generated were found across countries, due to different levels of wasteful behaviours (linked to cultural and economic factors) and different consumption patterns (influencing the amount of unavoidable waste generated). The results of this study have implications for policies both on the prevention and the management of household food waste.

1. Introduction

The Food and Agriculture Organization of the United Nations (FAO) has estimated that approximately one third of the food produced globally for human consumption is lost or wasted, representing a significant loss of the resources spent producing, processing and transporting that food, and a threat to food security (FAO, 2011). As the global population is growing rapidly and becoming wealthier, more resources will be needed in future decades to guarantee food security. The reduction of food waste is therefore a potential strategy for closing the gap between the supply and demand of food (Foley et al., 2011; Godfray and Garnett, 2014). For this reason the United Nations has adopted a specific target in the Sustainable Development Goals (SDG) to halve per capita global food waste at retail and consumer levels and reduce food losses along the production and supply chain by 2030 (Target 12.3) (United Nations, 2015). The European Commission has committed to the SDG 12.3 reduction target and regards food waste as a priority area within its Circular Economy Action Plan (European Commission, 2015).

A quantification of the amount of food wasted is fundamental to the development of effective prevention and reduction strategies and can be used to verify the efficacy of prevention campaigns over time (Caldeira et al., 2017; Thyberg and Tonjes, 2016). In response to this need, a growing body of literature has recently emerged on the quantification of food waste across the supply chain on a global, regional and national scale. However, due to the lack of a common definitional framework and different methodological approaches, these studies are not always comparable (Caldeira et al., 2017; Xue et al., 2017).

The study conducted by Monier et al. (2010) was the first attempt to quantify the amount of food waste generated at EU scale. This study, which considered food waste generated from the manufacturing stage up to consumption, estimated that approximately 180 kg per person per year (kg/p/y) of food are wasted annually in the EU. Of this amount, the authors quantified that 101 kg/p/y are generated at consumer level (76 kg for households and 25 kg for the food service sector). Therefore, according to this work, households are the highest contributor to food waste generation. In this study, food waste generation was considered as a whole without differentiating between commodity groups. A recent estimate by the European Commission provided a value of 161 kg/p/y of food waste generated in the EU in 2012 (European Commission, 2018). The project FUSIONS (Food Use for Social Innovation by Optimising Waste Prevention Strategies) (FUSIONS, 2016), funded by the European Commission, provided an estimation of food waste generated at European level considering the

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total food chain of 173 kg/p/y, 21 kg/p/y of which are generated at food service and 92 kg/p/y by households (Stenmarck et al., 2016). Within the same project, the contribution of each commodity group was roughly estimated, obtaining that 31% of the total consumption waste (including both households and food service) was linked to fruit and vegetables, equal to 35.3 kg/p/y (Scherhaufer et al., 2015). Kemna et al. (2017) made a detailed estimation of the overall food flows in Europe, based on a range of data sources (e.g. FAO, Eurostat, the European Food Safety Authority - EFSA, scientific literature and grey literature) and quantified the waste flows through the supply chain. They concluded that 290 kg per capita of food are wasted in total, of which 168 kg per capita at consumer level. A study on consumer food waste in the EU (Vanham et al., 2015), quantified food waste as 123 kg/p/y (considering households and food service together), providing a distinction between commodity groups. According to this work, the categories of fruit and vegetables (including potatoes) are together responsible for 63% of the food waste generated. Three studies conducted at national level in the UK (WRAP, 2012), Germany (Kranert et al., 2012) and Denmark (Edjabou et al., 2016), have quantified the waste generated by households, differentiating between commodity groups. The share of household food waste caused by the consumption of fresh fruit and vegetables (FFVs) was respectively 44% in the first study and 47% in the second and third study.

This large predominance of FFVs in the food waste generated by households is to be expected when considering that:

- FFVs contribute in weight to around one third of the total food purchases (a share of 30% was reported for the UK (DEFRA, 2010a) and Eberle and Fels (2016) reported a share of 29% for Germany).
- Unlike processed products, FFVs generally present an inedible component, which will be discarded in all cases.
- FFVs are highly perishable products (together with meat and fish); therefore, compared to more stable commodities (e.g. pasta, rice, sugar) it is more likely that they will not be consumed in time.
- FFVs are relatively cheap commodities (e.g. compared to meat and fish) and therefore it could be expected that consumers are more careless about letting them spoil.

In order to investigate further how the consumption of FFVs contributes to household food waste generation in the EU, a model was created to estimate household waste of FFVs by capitalising on existing knowledge (e.g. national statistics on food purchases, direct measurements of food waste generation, physical aspects of the products linked to waste production). To this purpose, two main objectives were defined:

1. To estimate the unavoidable waste intensity (UWI) and avoidable waste intensity (AWI) of FFVs purchased in the EU28 at product level and commodity group level respectively (Section 2).
2. To estimate the amount of avoidable and unavoidable FFVs waste generated by EU households (Section 3).

The quantification of the avoidable and unavoidable waste generated serve different purposes. The first is a measure of the amount of FFVs currently wasted in the EU28 that could be reduced by applying prevention strategies. The second, calculated as the inedible fraction of the FFVs purchased, is a measure of the amount of household waste that is intrinsically linked to the consumption of FFVs. Therefore, this amount of waste would still be produced even in a future scenario where avoidable waste is reduced to zero. All the flows presented in this work refer to the EU28 and the year 2010.

Unlike in previous studies that provided an estimation of the consumption waste of FFVs in the EU at commodity group level (Kemna et al., 2017; Scherhaufer et al., 2015; Vanham et al., 2015), the inedible component of FFVs is here assessed at product level in order to provide a more precise estimation of the unavoidable waste linked to the consumption of this group of commodities. Furthermore, the method presented in this study to estimate the unavoidable waste of FFVs at household level has wider potential applications.

Firstly, it can be used to estimate the amount of unavoidable waste generated during the industrial production of derived fruit and vegetable products (e.g. pre-cut or pre-peeled vegetables, canned fruit, tomato sauce). As the waste generated at this stage of the food supply chain often has the potential to be reused in other production systems (Mirabella et al., 2014), this would provide an estimation of the potential quantities of each product available for valorisation, which is of great interest from a circular economy perspective.

Secondly, such a method could help to investigate how the generation of food waste can be influenced by changing consumption patterns. As hectic modern lifestyles are causing a consumption shift to more processed food (Schmidt Rivera et al., 2014), the generation of unavoidable food waste is being transferred from households to food manufacturers. The combination of the method here presented with future scenario analysis would enable to predict where in the food supply chain and in what quantities this waste generation will occur, providing useful information for both waste management and valorisation purposes.

The paper is structured as follows. Section 2 presents the work conducted to estimate the coefficients of avoidable and unavoidable waste intensity for a range of FFV products, defined as the share of household purchases of fruit and vegetables that are wasted (concept defined in the next section). The flows of unavoidable and avoidable waste at EU level and at national level for three selected countries were then calculated based on these coefficients (Section 3). A comparison of the results with the existing literature and a discussion of the implications and limitations of this work are provided in Section 4 and conclusions are drawn in Section 5.

2. Evaluation of the waste intensity of fresh fruit and vegetables

In this paper, food waste is defined as food originally produced for human consumption that leaves the food supply chain. A distinction is made between unavoidable food waste (waste arising from food preparation or consumption that is not, and has never been, edible under normal circumstances), and avoidable food waste (food thrown away that was, at some point prior to disposal, edible) (WRAP, 2009). The unavoidable/avoidable waste intensity of a product is defined as the share in terms of mass of unavoidable/avoidable waste out of the total purchased amount of that product, as illustrated by Eqs. (1) and (2).

$$UWI\ [\%] = unavoidable\ waste\ [Mt]/total\ purchases\ [Mt] \tag{1}$$

$$AWI\ [\%] = avoidable\ waste\ [Mt]/total\ purchases\ [Mt] \tag{2}$$

The nominator of Eq. (1) is the total mass of that product which is wasted unavoidably (e.g. peeling, trimmings), the nominator of Eq. (2) is the total mass of that product which is wasted avoidably (e.g. an uneaten apple) and the denominator in both equations is the amount of that product purchased in a given period of time. According to the definition of unavoidable waste adopted in this work, the generation of unavoidable waste is directly linked to a physical property of the product, its inedible component (e.g. the peel of a banana), while the generation of avoidable waste is a consequence of the behavioural choices of the consumers. Therefore different approaches were adopted when estimating the UWI and the AWI, reflecting this conceptual difference.

This section presents the work conducted to define the UWI and AWI of different types of FFVs. The commodities selected were those included in the FAOSTAT crops production statistics (FAO, 2017) for the European Union (EU) under the headings: "vegetables & melons, total", "roots and tubers, total" and "fruit excluding melons, total", except for four commodities for which the fresh consumption in Europe is null or negligible according to the EFSA database (EFSA, 2015) (these were: carobs, fresh beans, taro and yams). In total 26 types of fruit and 25 types of vegetables (including roots and tubers) were selected.

2.1. Unavoidable waste intensity

In this work, the UWI of a FFV product, defined in Eq. (1) as the percentage of the purchased amount that is thrown away unavoidably, is considered equal to the inedible fraction of that product as provided by food composition databases. Three databases (Carnovale and Marletta, 2000; Public Health England, 2015; Rimestad et al., 2017) were used to extract the values of inedible fraction for the list of FFVs of interest, as presented in Tables 1 and 2. These databases provide extensive information on the nutrient content of foods commonly consumed in the countries where they were developed, including the edible fraction (from which the inedible fraction was calculated). As illustrated by Tables 1 and 2, for all the commodities that appeared in more than one nutritional database the average value of the inedible fraction was calculated; this value was then used as the UWI of that specific commodity. A number of outliers were identified and not included in the calculation of the average values. In some cases, the information provided in the nutritional database provides an explanation for this deviation from the other sources. For instance, in the case of asparagus, Public Health England (2015) states that before measuring the edible fraction, the base was removed (hence it is logical that the value of inedible fraction will be lower compared to the other studies). In addition, the value of inedible fraction for figs recorded in this database was significantly lower than that in Carnovale and Marletta (2000) (2% compared to 25%). This is probably a consequence of the first source considering the skin as edible, and the second source considering it as inedible; it was therefore decided to exclude the first value.

2.2. Avoidable waste intensity

The generation of avoidable waste is a consequence of the behavioural choices of the consumers (e.g. poor planning or storing products for too long). In turn, the behaviour of consumers is influenced by the characteristics of the product (e.g. package properties), personal factors (e.g. household size or cooking skills) and by the broader societal context (e.g. high availability of cheap food or hectic lifestyles) (Parfitt et al., 2010; Ponis et al., 2017; Roodhuyzen et al., 2017; Thyberg and Tonjes, 2016).

This section attempts shedding light on the connection between some product characteristics and the avoidable waste generated, in order to link the household consumption of FFVs in the EU28 to the quantity of avoidable waste that this consumption generates. To this purpose, we chose two product factors, which were expected to influence the amounts of avoidable waste generated: the perishability and the average price of the product (Hebrok and Boks, 2017; Jörissen et al., 2015; Thyberg and Tonjes, 2016).

2.2.1. Influence of perishability and price on avoidable waste intensity

Following the conceptual framework developed Roodhuyzen et al. (2017), the following causal pathways can be hypothesized:

- Hypothesis 1: Consumers might be more inclined to buy more than necessary and/or leave to spoil cheaper commodities compared to more expensive ones (negative correlation expected between price and AWI).
- Hypothesis 2: For highly perishable products, it is more likely that if consumers store them for too long or under suboptimal conditions, they will not be consumed in time (positive correlation expected between perishability and AWI).

Table 1
Inedible fraction of fresh fruits (%) based upon literature values (1: Carnovale and Marletta, 2000, 2: Rimestad et al., 2017, 3: Public Health England, 2015) and UWI (%) of fruit z (UWI_z).

Commodity	Inedible fraction (1)	Inedible fraction (2)	Inedible fraction (3)	UWI_z
Apples	15	9	13	12
Apricots	6	7	8	7
Avocados	24	26	29	26
Bananas	35	34	37	35
Blueberries	0	0	0	0
Cherries	14	14	17	15
Cranberries		2	0	1
Currants	2	0	3	1
Dates			14	14
Figs	25		*2**	25
Gooseberries		2	9	6
Grapefruit	30	*50**	32	31
Grapes	6	4	2	4
Kiwis	13	26	14	18
Lemons and limes	36	37	31	34
Oranges	20	22	29	24
Peaches and nectarines	9	7	11	9
Pears	16	10	15	14
Persimmons	3	16	7	9
Pineapples	43	49	47	46
Plums and sloes	10	6	6	7
Quinces	21		31	26
Raspberries	0	0	0	0
Sour cherries	15	14		15
Strawberries	6	2	6	5
Tangerines, mandarins, clementines, satsumas	17	23	22	21

* Outliers, excluded from the calculation of the average.

Table 2
Inedible fraction of fresh vegetables (%) based upon literature values (1: Carnovale and Marletta, 2000, 2: Rimestad et al., 2017, 3: Public Health England, 2015) and UWI (%) of vegetable z (UWIz).

	Inedible fraction (1)	Inedible fraction (2)	Inedible fraction (3)	UWI_z
Artichokes	66	57	57	60
Asparagus	43	47	*25**	45
Cabbages and other brassicas	16	22	20	20
Carrots and turnips	18	17	23	19
Cauliflowers and broccoli	42	*20**	46	43
Chillies and peppers, green	18	15	16	16
Cucumbers and gherkins	23	3	8	11
Eggplants (aubergines)	8	19	4	10
Garlic	25	21	21	22
Leeks, other alliaceous vegetables	23	17	*43**	20
Lettuce and chicory	8	5	12	8
Maize, green		44	41	43
Melons	53	46	40	45
Mushrooms and truffles	4	11	17	11
Okra**				5
Onions, dry***	17	7	10	11
Onions, shallots, green	7	4	31	14
Peas, green	69		63	66
Potatoes	17	17	15	16
Pumpkins, squash and gourds	16	21	23	20
Spinach	17	30	19	22
String beans	5	0	9	5
Sweet potatoes		28	16	22
Tomatoes	0	0	1	0
Watermelon	48	54	43	48

* Outliers, excluded from the calculation of the average.
** Value taken from string beans.
*** According to the FAOSTAT classification, these are onions at a mature stage (as opposed to spring onions).

In order to investigate these hypotheses, the existing literature was reviewed to identify studies that quantified the AWI of FFVs at product level at household stage. The most comprehensive data source available found was Muth et al. (2011). This report quantified coefficients of AWI for 54 types of FFVs. To obtain these values, first they calculated the waste percentage of each product as the difference between the amount purchased and the amount consumed (equal to the total waste), divided by the amount purchased. This is equal to the sum of the UWI and the AWI calculated by means of Eqs. (1) and (2) respectively. They then subtracted from the waste percentage thus obtained the inedible fraction (equal to the UWI), obtaining the AWI. The values of inedible fraction were taken from USDA (2007). In this current study, each of the 54 commodities analysed was associated with a measure of perishability and price, in order to study the influence of these properties on the AWI. The average price of the commodities analysed was extracted from Buzby et al. (2011).

A product's perishability is generally described by its shelf life. This is defined as "*the time until a perishable product becomes unacceptable to consumers under given storage conditions*" (Singh and Cadwallader, 2004). As FFVs are living tissues up to the point of consumption, their shelf life depends on a large number of factors (e.g. stage of ripening, growing conditions, harvesting time, storage conditions during transport, type of packaging, display on the supermarket shelves, and storage conditions at home (Muriana, 2017; WRAP, 2011). For this reason these products are described as items with a random lifetime (in contrast with processed products that have a fixed shelf life) (Muriana, 2017). Therefore attempting to assign a value of shelf life based only on the product name is particularly challenging. Nevertheless, the perishability of a product is directly linked with some of its intrinsic properties, one of which is the water activity (Van Boxstael et al., 2014). The water activity indicates the amount of freely available water in a food product, and is directly linked to the potential development of microbial growth. Therefore products presenting higher levels of water activity are more perishable than others (Kemna et al., 2017). For this reason, water activity was used in this work as a proxy of perishability. The values of water activity for the range of FFVs analysed were taken from Chirife and Fontan (1982).

The influence of price and water activity on the AWI was analysed by linear regression analysis. The underlying assumptions of normality of the residuals and homoscedasticity of the residuals were met for both models. The results of this analysis, presented in Table 3, show that no statistically significant relationship was obtained between the AWI and the independent variables, as the coefficients of both regressions had *p*-values higher than 0.1. This is supported by the visual representation of the relationship between these variables provided in Figs. S.1 and S.2 of the Supplementary Material.

According to this analysis, neither variations in price nor in water activity levels can explain the variation in the values of AWI observed across different types of FFVs (contradicting hypotheses 1 and 2) and therefore, based on the data available, no clear trend was found that made it possible to estimate coefficients of AWI at product level for FFVs. It was therefore decided to make an estimation of the AWI of FFVs at commodity group level (presented in the next section).

Table 3
Two linear regressions with AWI as dependent variable and standard error in brackets.

	Regression 1	Regression 2
Water activity	−5.7479 (3.5778)	
Price		−0.0118 (0.0083)
Intercept	5.9736* (3.5380)	0.3254*** (0.0309)
N	54	54
R^2	0.0473	0.0376
R^2 (adjusted)	0.0290	0.0191

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

A reason for this finding is that there are several other factors that might relate to the waste levels generated from the consumption of FFVs, such as the package properties (e.g. minimum package size) and the use of pre-cut of pre-peeled products (Roodhuyzen et al., 2017). These factors might be interacting with each other, for instance pre-cut or pre-peeled products are usually more perishable - intuitively causing higher waste - but also more expensive - intuitively causing lower waste. Therefore, the factors under analysis in this work are only a part of the complex landscape of conditions that can influence, positively or negatively, wasteful behaviour in consumers.

It is important to highlight that this work focused only on some of the food products available for consumption, namely FFVs, which all have similar levels of perishability, and relatively similar prices. If other types of food products had been included in the analysis, including those that have significantly longer shelf life (e.g. sugar) or that are significantly more expensive (e.g. meat), this might have led to a different result. For instance, DEFRA (2010b) conducted a similar analysis including all food types, and observed a negative correlation between product price and the percentage of purchases wasted.

2.2.2. Assessment of avoidable waste intensity (AWI_{fruit} and AWI_{veg})

The starting point in the estimation of the coefficients of AWI for FFVs was the analysis of six national studies (Edjabou et al., 2016; Kranert et al., 2012; Silvennoinen et al., 2014; van Westerhoven and Steenhuisen, 2013; WRAP, 2014; Zapata, 2017). These studies estimated the amount of avoidable waste generated in households for different commodity groups including FFVs.

Two of the studies provided directly a value of AWI for fruit and a value for vegetables (WRAP, 2014; Zapata, 2017), while the remaining ones provided values of avoidable waste (in terms of mass). In order to convert these values of avoidable waste into a measure of AWI, they were divided by the amounts of fruit/vegetables purchased in each country, according to Eq. (2). The total household purchases of FFVs for each country of the EU28 in 2010 were estimated from three main sources. The first is a dataset published by DEFRA (2010a) that provides the quantities of several food commodities purchased by UK households. The second is a dataset based on the household budget surveys (Household Budget Surveys, 2010) that compares the expenditures on FFVs in all EU countries, using a common fictitious currency (Purchasing Power Standard, PPS) that accounts for price differences and changes in currencies across the different European countries. By comparing these two sources, it was possible to extract the amounts purchased in the remaining countries of the EU28. For example, according to the household budget survey, the mean consumption expenditure (in PPS) of private households in Denmark was 1.22 times the one recorded in the UK. By combining this information with the per capita amount of fruit purchased by private households in the UK (equal to 39 kg/p/y, obtained from DEFRA 2010a), we estimated that the per capita amounts of fruit purchased in Denmark was 48 kg/p/y. The latest version of the household budget surveys (referring to the year 2010) did not provide a value for Germany. However, it was possible to extract from a third source (Eberle and Fels, 2016) the amounts of FFvs purchased by households in that country.

Tables 4 and 5 show the coefficients of AWI obtained respectively for fresh fruit and fresh vegetables. In the case of Spain and the UK, these coefficients were taken directly from the literature source used. For each of the remaining countries, the per capita avoidable waste generated from fruit consumption was divided by the per capita amount of fruit purchased, obtaining a value of AWI_{fruit}. The coefficients of AWI_{fruit} thus obtained ranged from 6.7% to 14.6%. To obtain an average EU value of AWI_{fruit} the geometric mean of the coefficients at country level was calculated. Then the quality of the data sources used was assessed using the

Table 4
Estimations of AWI_{fruit} (%) based upon literature values, average value and 95% confidence interval (CI).

Country	Source	Reference year	Avoidable waste [kg/p/y]	Amount purchased [kg/p/y]	AWI_{fruit} %
Germany	Kranert et al. (2012)	2010	6.9	57.3*	12.0**
Spain	Zapata (2017)	2016			7.7
Denmark	Edjabou et al. (2016)	2011	5.0	47.9***	10.4**
Netherlands	van Westerhoven and Steenhuisen (2013)	2013	5.6	38.5***	14.6**
Finland	Silvennoinen et al. (2014)	2010	3.0	44.8***	6.7**
United Kingdom	WRAP (2014)	2012			14.1
EU (geometric mean)					10.5
Uncertainty factor					1.14
95% CI					9.2–11.9

* Taken fromEberle and Fels (2016).
** Calculated as the ratio between “Avoidable waste” and “Amount purchased”.
*** Calculated from Defra (2010a) and Household Budget Surveys (2010).

Table 5
Estimations of AWI_{veg} (%) based upon literature values average value and 95% confidence interval (CI).

Country	Source	Reference year	Avoidable waste [kg/p/y]	Amount purchased [kg/p/y]	AWI_{veg} %
Germany	Kranert et al. (2012)	2010	9.6	75.2*	12.8**
Spain	Zapata (2017)	2016			4.1
Denmark	Edjabou et al. (2016)	2011	11.6	56.8***	20.5**
Netherlands	van Westerhoven and Steenhuisen (2013)	2013	10.3	55.3***	18.7**
Finland	Silvennoinen et al. (2014)	2010	4.4	53.4***	8.2**
United Kingdom	WRAP (2014)	2012			20.8
EU (geometric mean)					12.3
Uncertainty factor					1.14
95% CI					10.8–14.0

* Taken from Eberle and Fels (2016).
** Calculated as the ratio between “Avoidable waste” and “Amount purchased”.
*** Calculated from Defra (2010a) and Household Budget Surveys (2010).

pedigree matrix approach, based on six characteristics: *reliability*, *completeness*, *temporal correlation*, *geographic correlation*, *further technological correlation* and *sample size* (Beretta et al., 2013, Frischknecht et al., 2007). The underlying assumption of this method is that the parameter under study (in this case the AWI_{fruit}) follows a lognormal distribution (Ciroth et al., 2016). The pedigree matrix method enables to estimate the uncertainty that corresponds to the square of the geometric standard deviation of the distribution. Based on this parameter, a confidence interval of the mean was calculated (Table 4). Details on the application of this method are provided in the Supplementary Materials, Section 3. The same operation was performed with the vegetable category and the results are presented in Table 5.

3. Quantification of waste flows at EU scale

The values of UWI (calculated at product level) and AWI (calculated at commodity group level) obtained in Section 2 were then used to estimate the unavoidable and avoidable waste generated in EU households from the consumption of FFVs. Fig. 1 presents a visualization of the method followed for the fruit category (although the same applies to the vegetables category). A three-step method was followed:

1. The amount of each product purchased by households in the EU28 in 2010 ($Fruit_{z\_purchases}$) was estimated from the total amount of fresh fruit purchased ($Fruit_{purchases}$) and the distribution of consumption of different products (α_z), by means of Eq. (3) (Section 3.1).
2. The unavoidable waste associated with the consumption of fresh fruit in EU households (UW_{fruit}) was obtained by combining the UWI_z coefficients with the purchased amount of each product ($Fruit_{z\_purchases}$), by means of Eq. (4) (Section 3.2).
3. The avoidable waste associated with the consumption of fresh fruit in EU households (AW_{fruit}) was calculated from the average value of AWI for fruit (AWI_{fruit}) and the total amount of fruit purchased ($Fruit_{purchases}$) by means of Eq. (5) (Section 3.3).

3.1. Purchased amount of each product

The total amount of fresh fruit purchased by households in the EU28 in 2010 ($Fruit_{purchases}$) was calculated by adding up all the purchased quantities obtained for each country, calculated as explained in Section 2.2.2. The total purchased amount of fruit was equal to 26.3 Mt. Calculated in the same way, the corresponding value for vegetables was 35.5 Mt.

Then a factor to account for the distribution of the consumption of the different products (α_z) was calculated for each commodity, based on the EFSA database (EFSA, 2015). This database provides information recorded at national level on the average amounts of each commodity consumed in 16 countries. The weighted average was calculated (based on the country's population) to obtain the average values of consumption of each product in the EU28. This value was then divided by the total fruit consumption to obtain the α_z. The α_z factors for fruit and for vegetables are presented respectively in Tables S.1 and S.2 of the Supplementary material. For fruit, the main share of consumption is represented by apples (37%) followed by bananas (15%) and oranges (10%), while for vegetables the most consumed were potatoes (37%) followed by tomatoes (19%) and carrots (7%).

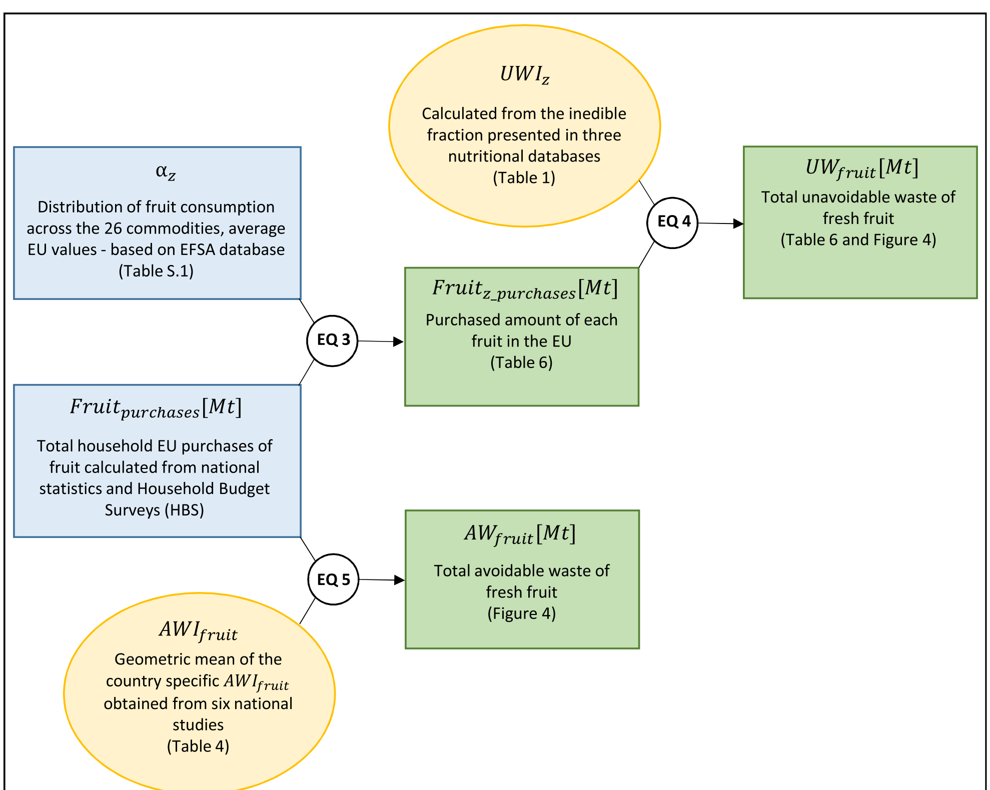

Fig. 1. Graphical representation of the method followed to calculate the unavoidable and avoidable waste generated from household consumption of fresh fruit in the EU28, the same sources and calculations apply to vegetables. z = 1:26, EQ3, EQ4 and EQ5 are provided in Sections 3.1,3.2 and 3.3 respectively.

Table 6
Amounts of fruit purchased by EU households in 2010 and related unavoidable waste (all quantities are in Mt).

	$Fruit_{z\_purchases}$	UW_z
Apples	9.76	1.20
Apricots	0.40	0.03
Avocados	0.16	0.04
Bananas	3.83	1.35
Blueberries	0.01	<0.01
Cherries	0.35	0.05
Cranberries	<0.01	<0.01
Currants	0.03	<0.01
Dates	<0.01	<0.01
Figs	0.03	0.01
Gooseberries	0.01	<0.01
Grapefruit	0.33	0.10
Grapes	0.61	0.02
Kiwis	0.87	0.15
Lemons and limes	0.10	0.03
Oranges	2.75	0.65
Peaches and nectarines	1.85	0.16
Pears	1.83	0.25
Persimmons	0.10	0.01
Pineapples	0.32	0.15
Plums and sloes	0.58	0.04
Quinces	0.01	<0.01
Raspberries	0.07	<0.01
Sour cherries	0.10	0.01
Strawberries	0.78	0.04
Tangerines, mandarins, clementines, satsumas	1.41	0.29
Total [Mt]	26.30	4.60 (3.85–5.34)

Table 7
Amounts of vegetables purchased by EU households in 2010 and related unavoidable waste (all quantities are in Mt).

	$Vegetable_{z\_purchases}$	UW_z
Artichokes	0.20	0.12
Asparagus	0.24	0.11
Cabbages and other brassicas	1.00	0.20
Carrots and turnips	2.34	0.45
Cauliflowers and broccoli	1.13	0.49
Chillies and peppers, green	1.00	0.16
Cucumbers and gherkins	1.01	0.11
Eggplants (aubergines)	0.50	0.05
Garlic	0.07	0.01
Leeks, other alliaceous vegetables	0.31	0.06
Lettuce and chicory	1.73	0.14
Maize, green	0.13	0.06
Melons	0.94	0.43
Mushrooms and truffles	0.55	0.06
Okra	<0.01	<0.01
Onions, dry*	0.93	0.10
Onions, shallots, green	0.02	<0.01
Peas, green	0.88	0.58
Potatoes	13.24	2.16
Pumpkins, squash and gourds	0.89	0.18
Spinach	0.39	0.08
String beans	0.55	0.03
Sweet potatoes	0.02	0.01
Tomatoes	6.65	0.02
Watermelon	0.82	0.40
Total [Mt]	35.53	6.03 (5.23–6.83)

* According to the FAOSTAT classification, these are onions at a mature stage (as opposed to spring onions).

The purchased amounts of each product ($Fruit_{z\_purchases}$) were then calculated by means of Eq. (3). The results are presented in Table 6 for fruit and Table 7 for vegetables.

$$Fruit_{z\_purchases} = Fruit_{purchases} \times \propto_z \quad (3)$$

where

z = 1:26.
$Fruit_{z\text{-}purchases}$ is the purchased amount of fruit z
$Fruit_{purchases}$ is the total amount of fruit purchased by EU households
α_z is the share of consumption of fruit z.

As an example, the amount of apples purchased was calculated by multiplying the total amount of fruit purchased (26.30 Mt) by the share of the consumption of apples out of the total fruit consumption (37%), resulting in 9.76 Mt.

3.2. Quantification of unavoidable waste

The unavoidable waste generated in EU households from the consumption of FFVs was calculated by means of Eq. (4) (reported below for fruit, although the same equation applies to the vegetable category), from the coefficients of UWI presented in Tables 1 and 2 and the purchased amount of FFV products calculated in the previous section. The resulting values are presented in Table 6 for fruit and Table 7 for vegetables.

$$UW_{fruit} = \sum_{z=1}^{26} Fruit_{z\_purchases} \times UWI_z \quad (4)$$

where

z = 1:26.
UW_{fruit} is the total unavoidable waste generated from the household consumption of fresh fruit.
$Fruit_{z\text{-}purchases}$ is the purchased amount of fruit z (obtained in Section 3.1).
UWI_z is the unavoidable waste intensity of fruit z (obtained in Section 2.1).

For instance, in the case of apples the UWI (12%) was multiplied by the amount purchased (9.76 Mt) resulting in 1.20 Mt of unavoidable waste. This was repeated for all the fruit products considered, and the single values of unavoidable waste thus obtained were added together, resulting in a total value of 4.6 Mt of unavoidable waste linked to fruit consumption. To provide a measure of the uncertainty of the values of unavoidable waste generated, the minimum and maximum coefficients of UWI were used for each product (in other words Eq. (4) was applied a second time, with the values of UWI_z replaced by the minimum of each row of Tables 1 and 2, and a third time using the maximum of each row).

The total amounts of unavoidable waste generated from the consumption of fresh fruit and fresh vegetables in EU households were respectively 4.6 (min 3.8–max 5.3) Mt and 6.0 (min 5.2–max 6.8) Mt. These quantities represent a minimum amount of waste, below which, according to current consumption patterns, it is not possible to go.

As the coefficients of UWI are highly variable across different products, the total amount of unavoidable waste generated from the consumption of FFVs in EU households depends on the distribution of purchases across different products, as illustrated by Fig. 2 for fruit and Fig. 3 for vegetables. Therefore, this waste flow is likely to change in the case of a shift in consumption patterns (e.g. a shift from apples to bananas would lead to an increase in the unavoidable waste generated).

3.3. Quantification of avoidable waste

The avoidable waste associated with the consumption of fresh fruit in EU households was calculated by means of Eq. (5), from the average value of AWI for fruit (AWI_{fruit}) presented in Table 4

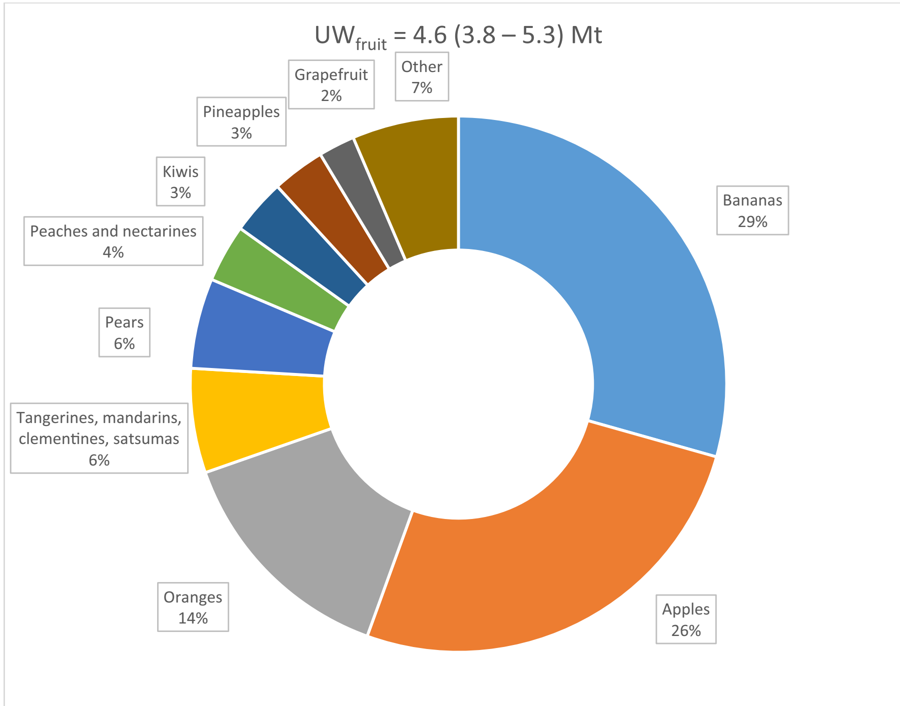

Fig. 2. Contribution of different types of fresh fruit to the total unavoidable waste caused by fruit consumption (UW_{fruit}).

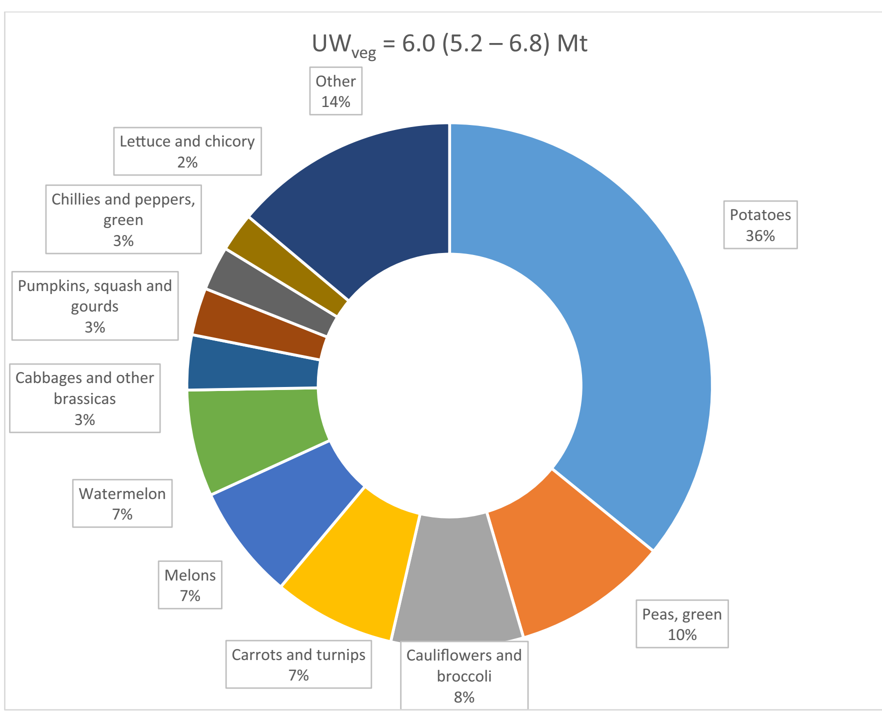

Fig. 3. Contribution of different types of fresh vegetables to the total unavoidable waste caused by vegetables consumption (UW_{vegs}).

and the total amount of fruit purchased ($Fruit_{purchases}$) calculated in Section 3.1. The same calculations apply to the vegetables category.

$$AW_{fruit} = Fruit_{purchases} \times AWI_{fruit} \quad (5)$$

where

AW_{fruit} is the total avoidable waste generated from the household consumption of fresh fruit.
$Fruit_{purchases}$ is the total amount of fruit purchased by EU households (obtained in Section 3.1 and equal to 26.3 Mt).
AWI_{fruit} is the avoidable waste intensity of fruit (obtained in Section 2.2 and equal to 10%).

To estimate the uncertainty of this result, this calculation was repeated by using instead of the average value of AWI_{fruit}/AWI_{veg}, the upper and lower limits of a 95% confidence interval (presented in Tables 4 and 5).

The total value of avoidable waste obtained for the fruit category was 2.8 (min 2.4–max 3.1) Mt. The correspondent value for vegetables was 4.4 (min 3.8–max 5.0) Mt. The range of values is wider in this case compared to unavoidable waste. This is due to the fact that large variations exist across the different national studies (as presented in Tables 4 and 5).

Fig. 4 illustrates the per capita flows of FFVs entering the household and leaving it as avoidable waste and unavoidable waste (the uncertainty is not reported for clarity of representation). These flows were calculated for the average EU citizen by dividing the total amounts of purchases and waste by the EU population in 2010. The differences (mass balance) are an estimation of the amounts consumed, in other words the intake. This is equal to 37.6 (min 35.4–max 39.8) kg/p/y of fruit and 50.0 (min 47.2–max 52.6) kg/p/y of vegetables.

3.4. Exploring the geographical variability of waste flows

In the previous sections the amounts of FFVs that are wasted, either as unavoidable waste or as avoidable waste, were estimated at EU level. Within Europe, it is expected that there will be significant geographical variability of the waste flows generated due to the following reasons.

- Different consumption patterns of FFVs (in terms of total amounts consumed and of which products are consumed the most) will cause different levels of unavoidable waste (as the inedible fraction varies significantly across products).
- The avoidable waste generated is a direct consequence of behavioural choices that are influenced by the socio-cultural context (Roodhuyzen et al., 2017).

Fig. 5 presents the per capita flows of FFVs entering the household and leaving it as avoidable and unavoidable waste, calculated for the UK, Germany and Denmark. As for Fig. 4, the difference between the amounts purchased and the amounts wasted represents an estimation of the intake. The reason for selecting these three countries was that in each of them the unavoidable waste linked to the consumption of FFVs had been measured in national studies (Edjabou et al., 2016; Kranert et al., 2012; WRAP, 2012). These studies were therefore used as a reference against which to check the values of unavoidable waste obtained in this work.

To calculate the waste flows for the selected countries the same procedure used in Sections 3.1–3.3 was followed. However, in this case, to calculate the avoidable waste generated, the country-specific values of AWI (Tables 4 and 5) were used. Furthermore, to evaluate the unavoidable waste generated, the country-specific values of α_z (representing the distribution of consumption across FFVs), taken from the EFSA database, were used. It is interesting to note that when comparing the UK and Germany, although the purchases of fresh vegetables are lower in the former country than in the latter:

- The related per capita amount of unavoidable waste generated is almost equal (due to a different consumption distribution).
- The related per capita amount of avoidable waste generated is higher in the UK (due to higher observed values of AWI).

As regards the geographical variability of the avoidable waste generated by households, Tables 4 and 5, which present the coefficients of AWI_{fruit} and AWI_{veg}, calculated in six national studies, show wide variability across countries. By comparing the country-specific values of AWI with the percentage of the income spent on food in each country (taken from Eurostat), a negative correlation was found in both cases (−0.68 for fruit and −0.83 for vegetables). In other words, countries where citizens spend a higher percentage of their income on food appear to be wasting less, which is aligned with previous findings (Parfitt et al., 2010; Thyberg and Tonjes, 2016; Vanham et al., 2015). As the six countries considered are amongst those where the percentage of income spent on food is the lowest (Fig. 6), the values of AWI_{fruit} and AWI_{veg} calculated in this work for the EU28 (as the geometric mean of the six values available) might be an overestimation of the real situation; the same might apply to the flows of avoidable waste obtained.

3.4.1. Testing the results at national scale

Of the six national studies used to evaluate the avoidable waste generation, three also calculated the amounts of unavoidable waste generated, reporting the following values:

- 8.8 kg/p/y for fruit and 12.4 kg/p/y for vegetables in the UK (WRAP, 2012).
- 7.5 kg/p/y for fruit and 11.7 kg/p/y for vegetables in Germany (Kranert et al., 2012).
- 9.1 kg/p/y for fruit and 13.3 kg/p/y for vegetables in Denmark (Edjabou et al., 2016)

A direct comparison between the per capita amounts of unavoidable waste reported above and those calculated in this study is illustrated in Fig. 7. The confidence intervals estimated in this work (Section 3.2) cannot be directly compared with those

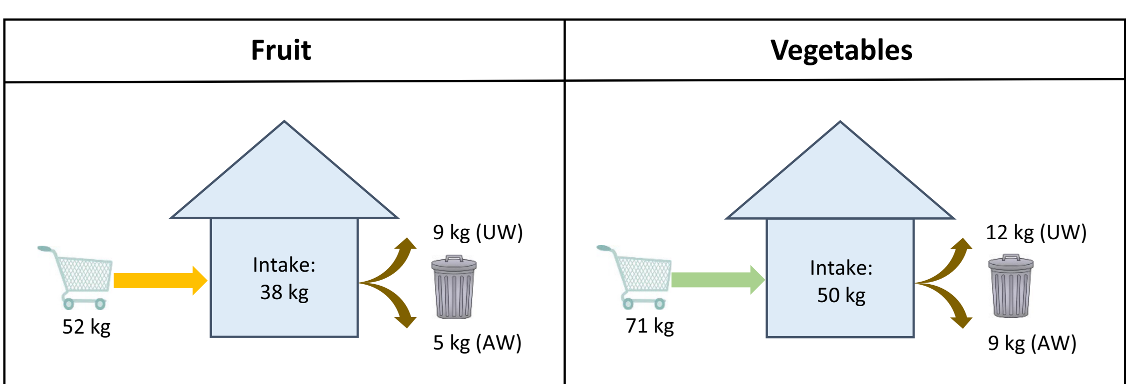

Fig. 4. Amounts of fresh fruit and fresh vegetables purchased, consumed, and wasted (avoidable & unavoidable waste) in the EU in 2010 (all quantities are in kg/p/y, numbers may not add up due to rounding).

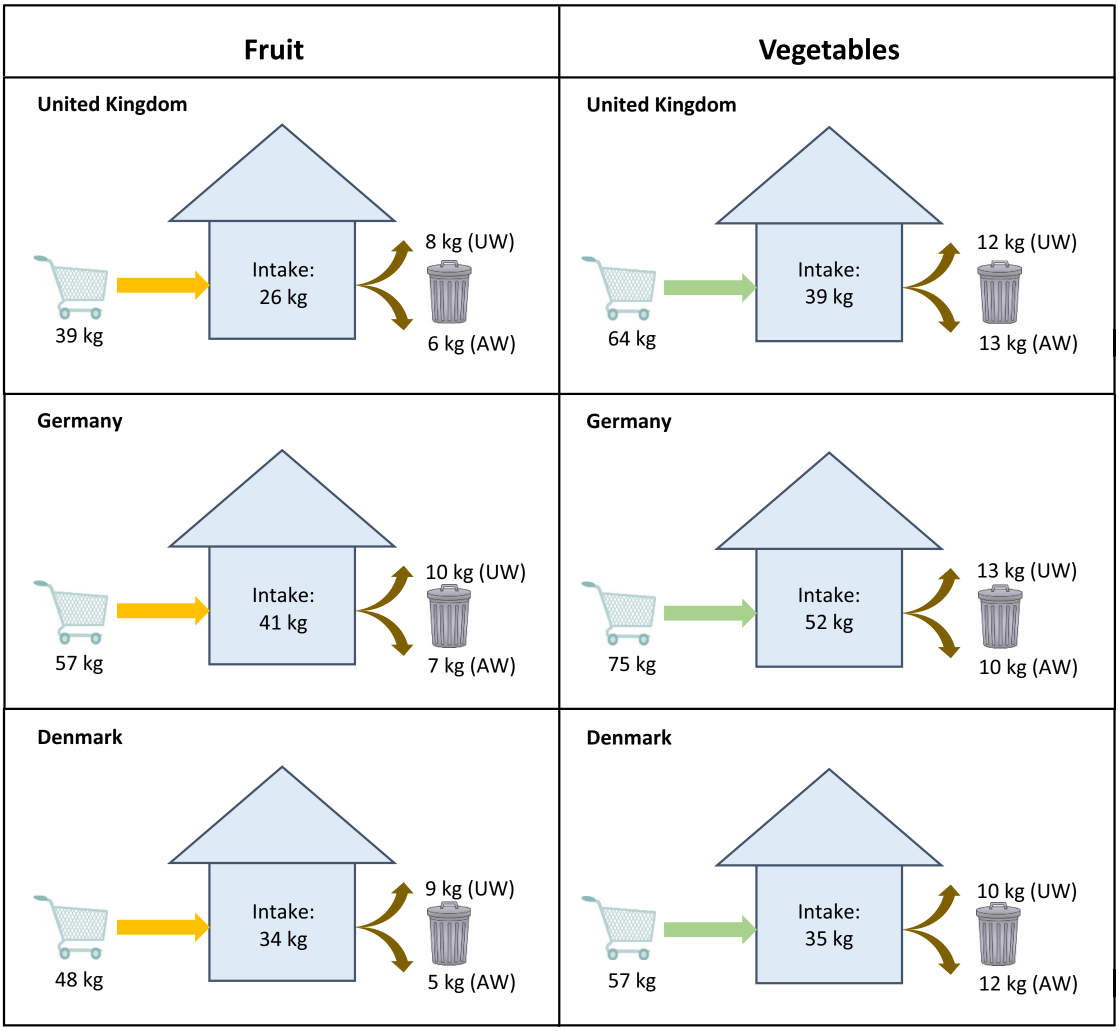

Fig. 5. Amounts of fresh fruit and fresh vegetables purchased, consumed, and wasted (avoidable & unavoidable waste) in the United Kingdom, Germany and Denmark in 2010 (all quantities are in kg/p/y, numbers may not add up due to rounding).

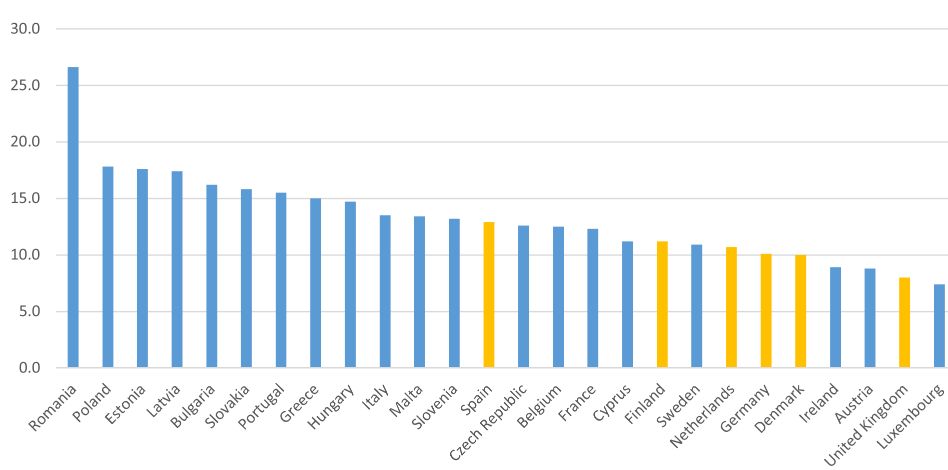

Fig. 6. Percentage of income spent on food in the EU28 in 2010 (data taken from Eurostat), the countries with yellow bars were used to calculate the average AWI for fruit and vegetables. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reported in these three studies, as each study assessed the uncertainty using a different method. For this reason confidence intervals are not reported in Fig. 7. It is possible to see that there is generally a good match between the results (the maximum gap between the amount estimated in this study and the amount observed was found for the vegetable category for Denmark, where the estimated amount is 25% lower). Fig. 7 shows that the waste estimation conducted in this study seems to underestimate the

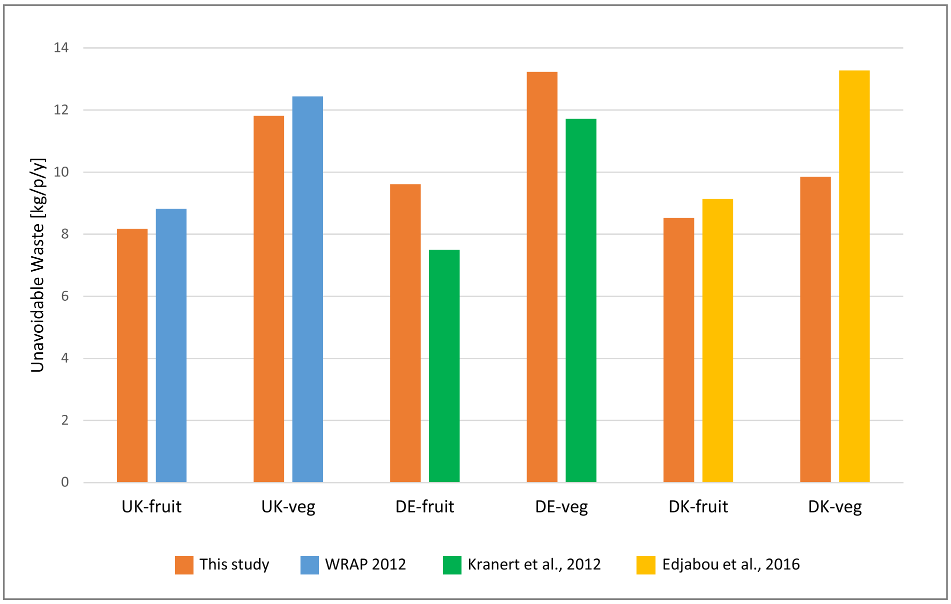

Fig. 7. Comparison between per capita values of unavoidable waste obtained in this study for the UK, Germany and Denmark and those calculated in the respective national study (all quantities are in kg/p/y).

unavoidable waste generated by households in the UK and Denmark, and overestimate it in the case of Germany. It is therefore not possible to identify a clear trend to explain this variation in the results. Nevertheless, it is important to highlight that the methods used to obtain these values are crucially different. In the national studies, the amounts of unavoidable FFV waste were measured either through waste compositional analysis or by asking participants to keep kitchen diaries (where they recorded the weight of all the food wasted). These analyses are very expensive, which represents a limitation both for the sample size and for the length of time for which they are conducted. Moreover, they might be affected by seasonal variation in consumption patterns (WRAP, 2012; Xue et al., 2017). This aspect was addressed in the study by WRAP (2012), in which a correction factor to account for seasonality was introduced. On the other hand, the values of unavoidable waste obtained in this work were calculated by combining data obtained from national statistics on household food purchases and food consumption surveys (as explained in Section 3.1), with data taken from food composition databases (as explained in Section 3.2). Notwithstanding these methodological differences, the similarity of the results obtained in this study with those observed adds reliability to the amount of unavoidable waste calculated at EU level.

4. Discussion

Three literature sources have quantified the EU consumers' food waste at commodity group level, including both the edible and inedible components (Kemna et al., 2017; Scherhaufer et al., 2015; Vanham et al., 2015).

Vanham and colleagues (2015) estimated that in the EU, 25 (min 5–max 44) kg/p/y of fruit, and 53 (min 10–max 91) kg/p/y of vegetables (including potatoes) were wasted at the consumption stage. Kemna et al. (2017) obtained similar values for the consumption waste of fresh fruit (20 kg per capita) and fresh vegetables and potatoes (55 kg per capita). These values are higher than those found in the current study: 14.6 (min 12.4–max 16.8) kg/p/y of fruit and 20.7 (min 18.0–max 23.5) kg/p/y of vegetables (Fig. 4). However, this is to be expected due to the inclusion of the food service sector in both studies. Furthermore, in the work by Vanham et al. (2015), processed fruit and vegetable products were also included, while in the study by Kemna et al. (2017), food waste at the consumption stage was calculated using the coefficients of waste intensity observed in the UK (which are the amongst the highest observed across Europe, see Tables 4 and 5). Finally, Scherhaufer et al. (2015) obtained an absolute value of fruit and vegetable waste at consumer level (including both households and food service) of 17.7 Mt. If this value is divided by the EU population in 2011, the resulting per capita amount is 35.3 kg/p/y, which corresponds to the value obtained in this work.

By comparing the total value of waste (avoidable and unavoidable) calculated for FFVs in this study, equal to 35.3 (min 30.4–max 40.3) kg/p/y (Fig. 4), with the values of household food waste obtained by Stenmarck et al. (2016) (92 kg/p/y) and Monier et al. (2010) (76 kg/p/y), we found that the total waste associated with the consumption of FFVs is:

- 38% of the household food waste calculated by Stenmarck et al. (2016).
- 46% of the household food waste calculated by Monier et al. (2010).

These values are aligned with the results of national studies (Eberle and Fels, 2016; Edjabou et al., 2016; WRAP, 2012), where FFVs accounted for between 44% and 47% of the total food waste generated at household level.

By repeating the same operation with only the unavoidable waste calculated for FFVs, equal to 21.1 (min 18.0–max 24.2) kg/p/y (Fig. 4), we found that the unavoidable waste associated with the consumption of FFVs is:

- 23% of the household food waste calculated by Stenmarck et al. (2016).
- 28% of the household food waste calculated by Monier et al. (2010).

In other words, the comparison between the results of this work with those of existing studies that estimated the total food waste generated by households, shows that a significant percentage of the waste generated by households (between 23 and 28%) is caused by the inedible parts of FFVs, (e.g. skin, peelings, trimmings).

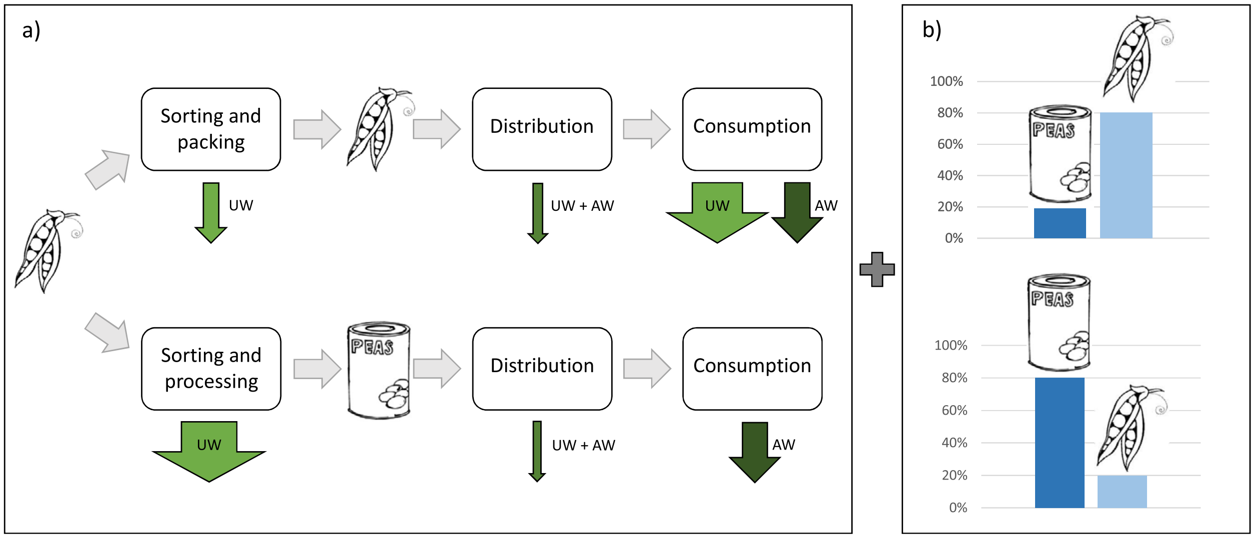

Fig. 8. Development of future scenarios of food waste generation by combining: (a) Estimations of unavoidable and avoidable waste generated from manufacturing to consumption of fresh and processed peas with (b) Future scenarios of consumption patterns.

Therefore, this represents a waste level (or a "waste floor", using a metaphor already used for greenhouse gas emissions) under which, no matter what prevention measure is put in place to reduce household food waste, it will not be possible to go unless consumption patterns change. In other words, the unavoidable waste linked to the consumption of FFVs could decrease if households purchased less FFVs, if they purchased a different selection of products (e.g. more berries and less bananas), or products with a higher level of processing (e.g. canned fruit or frozen vegetables). However, in this last case, the waste linked to the consumption of these products would simply be shifted to a different stage of the supply chain (manufacturing), and therefore such a consumption shift would likely cause a decrease in household waste but an increase in the waste generated at manufacturing level. This is illustrated with the example of fresh and canned peas presented in Fig. 8. By using future scenario analysis combined with the method here presented, the amounts of unavoidable waste of different FFV products generated at the manufacturing and household stages could be quantified under different predicted consumption patterns. Due to the different implications for waste management purposes of these two types of waste generation and the valorisation potential of food waste generated at the manufacturing stage, the results of such an analysis would be of great interest to decision makers.

Furthermore, the existence of a "waste floor" intrinsically linked to the consumption of FFVs should be kept in mind when monitoring the effects of prevention policies. In other words, as an absolute increase in the consumption of FFVs is bound to cause an increase in the amount of unavoidable waste generated, if avoidable and unavoidable waste are not accounted for separately, this increase in the recorded waste could hide the actual savings of avoidable waste obtained. Ultimately, this highlights the importance of accounting for avoidable and unavoidable waste separately when collecting empirical data on food waste generation.

In the assessment of the unavoidable waste generated by EU households, we assumed that consumers would always discard what food composition databases classify as inedible. Yet the very notion of what is edible is not universal, and might vary across and within countries (Caldeira et al., 2017). For instance, in the same household, some members may have the habit of eating apple peel and others may not, similarly, potato peel (considered inedible in the three sources consulted) might be eaten or not according to the recipe. It is for this reason that WRAP (2009) introduced the concept of "possibly avoidable" food, which is food that some people might eat and others might not. However, as one of the goals of this study was to estimate the total amount of unavoidable waste generated in the EU28 from the consumption of FFVs at household level, it was not possible to account for these specific cases, and therefore the values reported in the food composition databases consulted were taken as a reference point.

The calculation of the average values of AWI for fruit and vegetables was based on the levels of avoidable food waste observed in six national studies. However, as explained in Section 3.4, the average avoidable waste generated by the six countries considered might not be representative of the whole EU, due to the fact that these countries are amongst those in which a smaller percentage of income is spent on food (and are therefore likely to be wasting more). This highlights the need for more national studies measuring the food waste produced by households at commodity group level, especially in the less represented areas of Europe (eastern and southern European countries), to provide a more precise estimation of the avoidable waste generated.

Furthermore, the results of the existing national studies might not be fully comparable due to differences in: the data collection methods, the definition of food waste adopted, the destinations of food waste included (e.g. food waste disposed of through the sewer, fed to animals or home-composted is not accounted for in studies that are only based on waste compositional analysis, such as Edjabou et al. (2016). This was partly addressed by adopting the pedigree matrix approach, which enables to perform a qualitative assessment of the reliability and completeness of the data sources (e.g. considering the representativeness of the number of households under study). Nevertheless, this ultimately highlights the need for adopting a common definitional framework and a harmonised methodological approach in food waste accounting (Caldeira et al., 2017).

5. Conclusions and outlook

National studies (Eberle and Fels, 2016; Edjabou et al., 2016; WRAP, 2012) have estimated that between 44% and 47% of the total food waste generated by households is linked to the consumption of FFVs. This emphasises the importance of quantifying this waste flow both for waste management purposes and to design targeted prevention strategies to minimize its avoidable component.

This work has estimated the avoidable and unavoidable waste generated from the household consumption of FFVs in the EU28 in 2010 and provided an estimation of the uncertainty.

The unavoidable waste was assessed at product level, representing the first attempt to estimate the unavoidable waste of fresh fruit and vegetables generated by EU households at such a level of detail. The avoidable waste was instead estimated at commodity group level, as no clear trend was found to link different types of fruit and vegetable products to their observed levels of waste.

The main findings were:

– On average, 29% of the mass of FFVs purchased by households in the EU28 in 2010 was wasted, of which 17% was unavoidable waste and 12% was avoidable waste.
– In total EU households threw away 35.3 (min 30.4–max 40.3) kg/p/y of FFVs.
– The avoidable waste represented almost half of this quantity [14.2 (min 12.4–max 16.1) kg/p/y], showing a great potential for reduction achievable by implementing the right prevention strategies.
– The unavoidable waste estimated in this study [21.1 (18.0–24.2) kg/p/y] represented between 23% and 28% of the total household food waste calculated by Monier et al. (2010) and Stenmarck et al. (2016) respectively. This represents a waste level under which, if consumption patterns remain the same, it will not be possible to go, and which will need to be managed in the most environmentally beneficial way.
– Significant differences in the amounts of avoidable and unavoidable waste generated were found across countries: this is due to different levels of wasteful behaviours observed (due to cultural and economic factors) and different consumption patterns (e.g. countries consuming more bananas than apples, more FFVs compared to processed fruit and vegetable products, or simply more FFVs in absolute terms will generate more unavoidable waste).

This study may support decision making in the area of food waste in different ways, namely: i) the quantification of a ‘‘waste floor” in the food waste generated by households under current consumption patterns; ii) the identification of the main reasons for the variation in the waste levels found across countries (e.g. behavioural choices, type of products consumed and quantities); and iii) the possibility of using the proposed model in combination with future scenario analysis to investigate the influence of varying consumption patterns over the amounts of food waste generated, and the stage of the food supply chain where they are generated with implications for waste management and valorisation potential.

This research highlighted the potential for using a modelling approach to predict the amount of food waste generated by households, due to the scarcity of empirical data and the challenges connected with its collection (e.g. the expensiveness of waste surveys). To this purpose, a better understanding of the drivers of food waste would make it possible to create more refined models, especially for the accounting of the avoidable component of food waste. The correlation between the percentage of household income spent on food and avoidable waste generation, encountered in this work, represents an interesting starting point.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.wasman.2018.04.001.

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