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The Italian meat production and consumption system assessed combining material flow analysis and life cycle assessment

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ABSTRACT

Meat production and consumption is associated with the generation of significant environmental pressure and impacts, and resource inefficiencies. This study combines Material Flow Analysis (MFA) and Life cycle Assessment (LCA) to analyse the meat supply chain in order to better comprehend the circularity of the system, considering the Italian meat supply chain as a case study. The system boundaries of both the MFA and LCA included all the life cycle stages starting from slaughter phase to meat consumption at household and food services level. The LCA study included also all the stages upstream of the slaughter phase. Consumed meat and animal by-products (ABPs) were quantified, and the potential benefits due to the re-use of rendered ABPs were assessed. Results showed an average meat consumption of 55 kg/per-capita/year with pig, poultry and cattle meat contributing respectively by 46%, 27% and 25%, followed by other meat categories, representing 2% of the total meat consumption. Daily meat consumption is responsible for the emission of 2.80 kg CO_{2eq} per capita with beef meat contributing to 65% of the emissions. Results showed the same relative importance among meat types for acidification, terrestrial and freshwater eutrophication, and land use impact categories. A sensitivity analysis showed that the approach to allocate environmental impacts between meat and rendered ABPs did not affect the ranking of meat categories. The system under study resulted to be efficient and to promote circularity, thanks to the re-use and valorisation of ABPs.

1. Introduction

The sustainability of the food system is at the core of EU environmental policies. In the context of the initiatives foreseen by the EU Green Deal (EC, 2019), in May 2020 the European Commission released its Farm to Fork Strategy (EC, 2020a), aiming to accelerate the transition to a sustainable food system. In addition, the European Commission has identified the food chain as key for the implementation of circular economy practices, highlighting the need to increase water re-use and improve nutrient management in agricultural activities (EC, 2020b).

In recent years, the scientific and public community have become increasingly aware of the environmental impacts of food production and several studies converged in indicating meat and meat-based products as one of the most impacting elements of diets, promoting a shift to diets with a reduced intake of animal products as a potential solution to reduce the environmental impacts of the food system (Clune et al., 2017; Notarnicola et al., 2017; Röös et al., 2013; Westhoek et al., 2014).

An improvement of the environmental performance of meat and meat-based products can be obtained by valorising the animal by-products (ABPs) generated along the meat supply chain (Toldrá et al., 2012; Van Zanten et al., 2014). Indeed, ABPs can be used to produce different kinds of products, such as biofuels, animal feed and petfood, biomedical and cosmetics, and fertilisers (Djekic and Tomasevic, 2016), reducing the amount of virgin raw materials that would be used for their manufacturing. So far, few studies have assessed the environmental implications of the re-use of ABPs. Xue et al. (2019), for example, assessed the sustainability of the German meat supply chain, and provided interesting points of reflection about system circularity and environmental impacts, considering rendering technological improvement as a mitigation strategy.

The agricultural sector, including livestock, plays an important role in the Italian economic system, and generates one fifth of the added

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value of the European agricultural system (Coluccia et al., 2020). Moreover, Italy is the leading European country in terms of the number of Protected Denomination of Origin (PDO), Protected Geographical Indication (PGI) and Traditional Specialities Guaranteed (TSG) acknowledgments (Coluccia et al., 2020). The European meat production trend in the period 2010–2014 showed an increase in pig production against a decrease in beef, poultry and sheep and goat meat production. In 2010, Italy was the fourth largest meat producer in the European Union (EU), after Germany, France and Spain; in 2020 it dropped to the sixth position behind Poland and the United Kingdom. The largest share of the Italian meat production is taken by pig meat, followed by poultry production, which has overtaken beef production since 2008 (FAOSTAT, 2000). Specifically, the Italian meat production system is characterized by a high slaughter weight for pig and poultry and by imports of live animals and carcasses from other countries for pig and beef to complement the domestic production. This distinctive scenario, specifically regarding the slaughter weight, could also influence the environmental impacts of the consumed meat, due to the higher input demand caused by a lower animal feed efficiency. These aspects influence also the amount of ABPs, and waste produced at slaughtering, processing, and consumption phases.

This study aims to analyse the Italian meat supply chain to better comprehend the circularity of the system, given its abovementioned specificities. It has three specific goals: i) to quantify mass flows along the Italian meat chain from slaughterhouse to consumption through material flow analysis (MFA), in order to evaluate the circularity of the meat supply chain and to estimate meat consumption expressed as real meat consumption, i.e. excluding bones; ii) to assess the potential environmental impacts generated along the meat chain using life cycle assessment (LCA); iii) to compare different allocation approaches and assess how they may influence considerations on the environmental impacts of meat consumption. This is particularly relevant given the considerable amount of ABPs generated by the Italian meat sector.

The adoption of a holistic approach based on the combination of MFA and LCA that takes into account the entire supply chain is useful to assess and quantify the flows of meat, to identify the main sources of losses and waste, leading to the proposal of ad hoc mitigation strategies (Caldeira et al., 2019), and to assess the sustainability of the Italian meat supply chain (Sgarbossa and Russo, 2017).

2. Materials and methods

2.1. Scope and system definition

This study analysed the meat production and consumption chain in Italy in 2013, focusing on quantities and environmental impacts. The year 2013 was chosen based on the availability of the underlying data used in the analysis. The quantities of meat, ABPs and waste in the Italian meat supply chain were calculated using MFA. Six main animal categories were considered: cattle (including buffalo), pig, poultry (including chicken, turkey, guinea fowl, duck and goose), sheep and goat, rabbit, and Equidae (including horse, mule, hinny and donkey). For the three most consumed species (cattle, pig and poultry) an additional analysis was performed to assess the environmental impacts of their consumption in Italy in 2013, by means of LCA.

2.2. Meat and ABPs definitions

This study is based on definitions reported in the EU legislation. The term “meat” is defined by Regulation (EC) No 853/2004 (European Parliament and the Council, 2004) as “edible parts of the animals including blood”. Carcass weight defines the weight of the slaughtered animal’s cold body, and is defined according to the animal categories as reported in Regulation (EC) No 1069/2009 of the European Parliament and of the Council.

ABPs are defined as materials of animal origin that people do not consume. Regulation (EC) No 1069/2009 (European Parliament and the Council, 2009) and European Commission Regulation (EU) No 142/2011 deal with the categorization, use and treatments of ABPs. ABPs are classified in three categories according the level of public and animal health risk and contamination. Category 1 (Cat 1) includes high risk level materials, Category 2 (Cat 2) medium level risk material and Category 3 (Cat 3) low level of risk. This categorization establishes the reutilization options.

The term “waste” is meant to refer to food waste and is used in accordance with the Waste Framework Directive (European Parliament and the Council, 2018) reporting that “food waste means all food […] that has become waste”. ABPs not used for the consumer market and disposed via incineration are also considered as waste according Directive (EC) 98/2008 (European Parliament and the Council, 2008).

2.3. Material flow accounting

Meat and meat products produced and consumed in Italy and related meat waste and ABPs were quantified using the MFA method. The approaches proposed by Caldeira et al. (2019) for food waste quantification and from Laraia et al. (2001) for the quantification of ABPs and waste at processing were followed and refined to be applied to the context of the meat chain in Italy. The quantification is based on a territorial-based perspective, i.e. it calculates the amount of meat and meat products consumed in Italy, as well as food waste and ABPs produced in Italy. Other disposed material flows, (e.g. plastic material, washing water) were not quantified.

The supply chain included the following stages: slaughtering, meat processing, retail, and consumption. Furthermore, imports and exports of meat and meat-based products were accounted for. Food stocks were not taken in account, due to the high perishability of the products considered. ABPs and waste were quantified at each step of the supply chain. Meat ABPs generated at slaughtering were quantified and associated to a specific re-use or disposal route according to their health level risk.

The first step of the MFA was the quantification of the number of animals slaughtered in Italy and the corresponding slaughtered live weight (LW). Data concerning the number of slaughtered animals and their LW at point of slaughter were collected from Italian statistical database (I.Stat, 2013) taking into consideration the animal categories and the their weight categories. Import and export of carcass and meat products, expressed as carcass weight (CW), were taken from FAOSTAT. Instead, trade of live animals was not considered because already accounted within the number of animals slaughtered nationwide. In a second step, the CW and the ratio between CW and LW were taken from I.Stat. These data, reported in supplementary materials (Tables S1, S2, S3, S4, S5, S6), were specific for each animal category and for the Italian case. The difference between LW and CW represented the total amount of ABPs generated at this stage. Following Regulation (EC) 1069/2009, the total amount of ABPs was distinguished between Categories 1, 2 and 3, and edible offals and hides by applying coefficients derived from the literature (Laraia et al., 2001) and reported in supplementary materials (Tables S7 and S8). ABPs are sent to rendering before being disposed or re-used, as reported by AssoGrassi (AssoGrassi, 2019). The amounts of rendered products were quantified based on the efficiency of the rendering process (65% for Cat 1, 63% for Cat 2, and 53% for Cat 3). The resulting quantities were categorized into fat or meal and then allocated to a specific use according to the information reported for Italy for different re-use options (pet food, feed, fertilizers, oleo-chemistry, biodiesel) and to their chemical composition and waste disposal (incineration), by applying the coefficients reported in Table 1, provided by AssoGrassi (2019). As this association involves 80% of the Italian rendering sector, data were considered representative for the Italian scenario. Water losses during rendering were quantified as the difference between the products sent to rendering and the rendered products.

The amount of CW produced for each species was allocated between

Table 1
Incineration and re-use of rendered products expressed as percentage of total amount of ABP reported for each category. Hides and edible offals are not included.

ABPs		%	Incineration	Biodiesel	Fertilizer	Oleo-chemistry	Feed	Pet food	Export Pet food
Cat 1	Fat	56.00%	18.00%	38.00%					
	Meal	44.00%	44.00%						
Cat 2	Fat	44.00%		44.00%					
	Meal	56.00%			56.00%				
Cat 3	Fat	46.00%	2.40%	2.96%		15.00%	20.23%	3.64%	0.98%
	Meal	54.00%			8.56%		0.43%	26.93%	18.55%

Reference: personal communication of AssoGrassi (2019).

industry processing and fresh distribution, including both retail and food services, using the shares reported by ISMEA (2013a) (Table S9). Trade of fresh and processed meat products was not considered at this stage as already included together with trade of carcasses, expressed in terms of CW equivalent. At processing phase, ABPs were calculated as cutting discard of carcass processing by applying species-specific coefficients (Table S10) (Laraia et al., 2001). Cutting discards ABPs were classified as Cat 3 ABPs destined to rendering process, and assigned the same destinations of Cat 3 ABPs generated at slaughtering. The amount of water evaporating at this stage was not estimated.

At retail phase, meat includes both processed meat and fresh meat. The split between the amount of meat entering retail and food services, respectively, was assumed equal to: 88% and 12% for cattle, 85% and 15% for poultry 80% and 20% for other meat categories. All these coefficients are taken from ISMEA (ISMEA, 2013b, 2013c; 2013d). Quantification of retail waste included carcass cutting discard at butcher shop and waste due to products reaching the end of their shelf-life before being sold. At retail, coefficients related to the generation of waste according to shelf-life were taken from Caldeira et al. (2019) while those due to cutting discards from Laraia et al. (2001). The remaining amount of meat (after subtracting retail waste) was considered available for consumption at household level.

Meat waste at consumption level in households and food services was calculated by using the coefficients reported in Table S10 (Caldeira et al., 2019). The amount of consumed meat was calculated by subtracting from the meat available for consumption at household and food services the amount of meat wasted. Retail and consumption wastes are expected to contribute to general waste and their destination was not further explored.

2.4. Life cycle assessment

The environmental impact of the Italian meat supply chain was assessed by applying LCA and using SimaPro software (version 9.0). The study follows the International Life Cycle Data system (ILCD) guidelines (JRC, 2010) and, for specific aspects listed below, is aligned to the Product Environmental Footprint (PEF) method (Zampori and Pant, 2019). An attributional approach was chosen. The functional unit of the study was the total amount of meat consumed in Italy, calculated through MFA. However, to compare the results of this study with other studies and allow a better interpretation of the results, the impact of 1 kg of each meat type was calculated as well. The analysis is focused on the consumption of cattle, pig, and poultry meat, as these were the mostly consumed meat types. The impacts were allocated between meat and ABPs by applying economic allocation (Zampori and Pant, 2019). System boundaries considered a cradle-to-grave approach. The life cycle was divided into six stages: agriculture/breeding, industrial processing, logistics, packaging, use, and end of life. Inventory data for each step of the supply chain were taken from Castellani et al. (2017) and Notarnicola et al. (2017), except for the end of life, where the rendering of ABPs was considered (Section 2.3).

Life cycle inventories were characterized using the EF 3.0 method (EC- JRC, 2019; EC, 2013; Fazio et al., 2018) including 16 impact categories (Table S14).

2.5. Sensitivity analysis

Allocation is used in LCA to solve the problem of multifunctionality of a system and it is suggested when virtual division or subdivision of inputs and outputs is not possible (JRC, 2010). The role of allocation is particularly relevant when assessing circular economy measures since it influences the environmental benefits and burdens associated with the production and use of by-products. The ISO 14040 and the ISO 14044 standards (ISO, 2006a, 2006b) recommend the following hierarchy for decisions on allocation: 1- system expansion, 2- allocation based on physical and biological causality 3- where such causality cannot be determined, allocation shall be based on other relationships between output and input, e.g. mass, volume or economic value. ILCD suggests choosing the allocation based on the decision context (EC- JRC, 2010). Zampori and Pant, 2019), instead, suggest allocating the environmental impacts of the slaughtering phase using economic allocation.

To assess the influence on the results of the allocation choices, a sensitivity analysis was performed. This was considered particularly relevant, as allocation is one of the main sources of uncertainty of LCA studies (Cellura et al., 2011). Four scenarios were defined with different approaches to allocate the impacts between meat and ABPs at slaughtering phase: 1) no allocation (NO); 2) mass allocation (MA); 3) economic allocation (EA); and 4) system expansion considering soybean produced in the EU (SE_EU) and 5) system expansion considering soybean produced in the US (SE_US). In the last two scenarios, avoided products were diesel, electricity, soybean meal and oil, and fertilizers. They were selected because they provided the same function as the substituted products. The substitution value was calculated considering the characteristic of rendered products reported in Table S11 and of the avoided products as reported in Table S12. Two types of mostly commonly used fertilizers were taken in account: calcium nitrate (NPK 15.5-0-0, Ca 26%) and di-ammonium phosphate (NPK 22-57-0).

3. Results

3.1. Material flow analysis

Fig. 1 shows the meat supply chain in Italy in 2013, from slaughtering to the consumer. The quantification and the destination of animal ABPs was also taken in account.

The Italian meat production corresponded to 6.53 Mt of meat expressed as LW, equal to 4.61 Mt of meat expressed as CW (Table 2). Pig meat represented the 49% of the share followed by poultry (25%), cattle (25%), sheep and goat, equidae and rabbit (each 1%). Imports of pig meat (CW) accounted for 68% of total meat imports, followed by bovine and poultry meat (25% and 4% respectively). The export of meat (CW) was mostly represented by pig meat (68%) and cattle meat (30%). The total meat available to be consumed corresponded to 3.29 Mt (expressed in CW). Pig meat contributed to 48% of the total, followed by poultry and bovine meat (contributing to 24% and 25% respectively). The remaining 3% of the consumption was shared between sheep and goat, equidae and rabbit.

Meat available after slaughterhouse was destined to industry processing or fresh distribution, including retail and food services. Meat allocated to processing industry was 1.89 Mt where pig meat

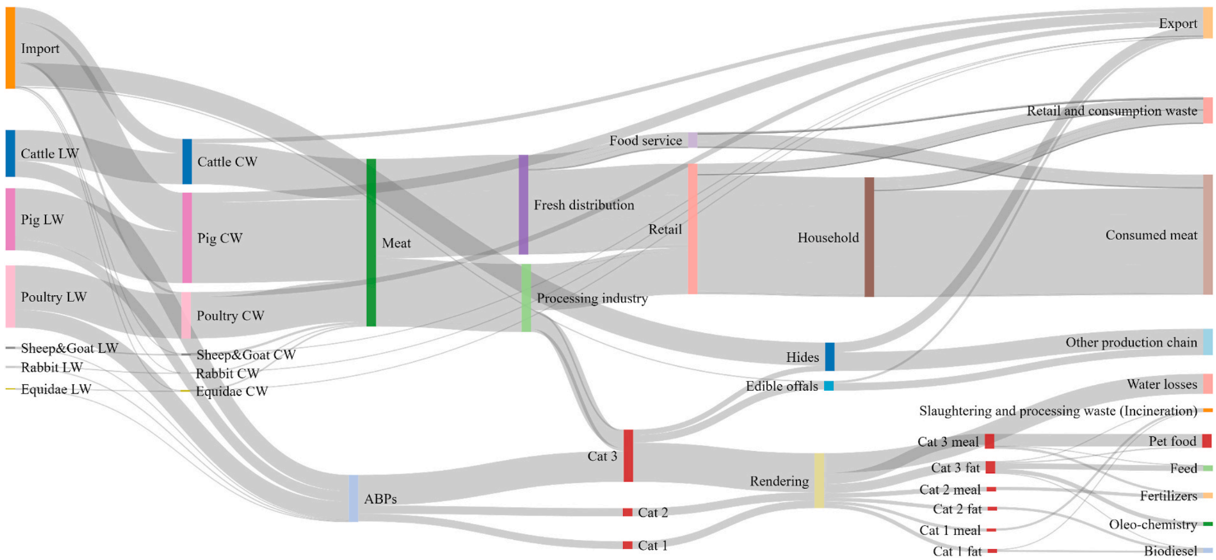

Fig. 1. Mass balance for the meat supply chain in Italy in 2013 (ABPs: animals by-products; Cat 1: Category 1; Cat 2: category 2; Cat 3: category 3; CW: carcass weight; LW: live weight).

Table 2
Meat flow in the supply chain. Meat balance expressed as Carcass Weight (CW), following phase expressed as megatons (Mt) of bone free meat.

Meat flow (Mt)	Meat balance	Processing	Fresh distribution	Retail	Food service	Consumed meat
Cattle	1.13	0.15	0.99	0.87	0.12	0.81
Pig	2.24	1.57	0.67	0.54	0.13	1.51
Poultry	1.15	0.17	0.97	0.83	0.15	0.89
Sheep&Goat	0.06	0.00	0.06	0.05	0.01	0.05
Rabbit	0.03	0.00	0.03	0.02	0.01	0.03
Equidae	0.03	0.00	0.04	0.03	0.01	0.03
Total	4.61	1.91	2.75	2.33	0.42	3.33

represented 83% of the total due to the large production of cured products form pig meat. Meat allocated to fresh distribution was 2.72 Mt (2.30 Mt to retail; 0.42 Mt to food service) with a share of 35%, 36% and 24% for poultry, cattle and pig meat. At household level pig meat represented 48% of the available meat, followed by cattle meat and poultry (24% and 26% respectively).

The MFA revealed that in 2013 3.33 Mt of meat were consumed in Italy, equal to 0.15 kg/day per capita and to 55.23 kg/year per capita. In percentage the total amount of consumed meat is represented by 46% of pig, 25% of cattle, 27% of poultry and 2% of other meat (rabbit, equidae and sheep and goat).

A total amount of 1.28 Mt of ABPs were estimated at slaughterhouse. ABPs were subdivided into three health risk level categories. Cattle meat is the main responsible for generation of ABPs (59%) and, in particular, Cat 1 ABPs (64% of the total Cat 1 ABPs generated). Edible offals were not considered into the total amount of ABPs destined to rendering process and were considered as a self-standing category, even though they are classified as Cat 3 ABPs by the EU legislation. Due to lack of information about their destination at national level, it was assumed that edible offals are destined to other production chains. Also hides, categorized as Cat 3 ABPs, were not considered part of ABPs destined to rendering process, as they are mainly used by the leather industry and other production chains.

The largest share of ABPs from the meat supply chain (equal to 68%), were generated at the slaughtering phase. ABPs were composed by 0.21 Mt of Cat 1, 0.23 Mt of Cat 2, and 0.84 Mt of Cat 3. At processing stage only Cat 3 material was generated (0.60 Mt) and contributed to 42% of the total Cat 3 material generated at slaughtering and processing stages.

Based on the assumption that the total amount of ABPs, except edible offals and hides, was destined to rendering process, the total amount of rendered products was quantified after considering losses due to water evaporation. Cat 1 material were converted into 0.14 Mt of rendered products, mainly fat (0.08 Mt). Cat 2 material were converted into 0.15 Mt of rendered products, mainly meal (0.09 Mt). Cat 3 material was converted in 0.76 Mt of rendered products, composed by 0.34 Mt of fats and 0.41 of meal.

The destinations of rendered material were mainly incineration for Cat 1 (0.084 Mt), biodiesel (0.068 Mt) and fertilizers (0.086 Mt) for Cat 2, fertilizers and feed, pet food and oleo-chemistry for Cat 3 (0.16, 0.38 and 0.11 Mt respectively) (Table 3).

Other sources of waste were retail phase (0.31 Mt) and consumer phase (0.36 Mt). Food services were instead a minor source of waste generation (0.04 Mt).

3.2. Life cycle assessment

Environmental impacts results were expressed per kg of consumed meat and referred to the overall meat consumption in Italy. The results were then analysed considering different allocation methods to assess the influence of allocation on ranking and contribution of the meat type.

3.2.1. Environmental impact assessment of consumption 1 kg of meat

The consumption of 1 kg of cattle meat presented the highest impact on all the impact categories, except for ionizing radiation. Poultry meat was more impacting than pig meat for the impact categories climate change, particulate matter, ionizing radiation, photochemical ozone formation, acidification, terrestrial eutrophication, freshwater eutrophication, land use, resource use both fossil and minerals and metals, and freshwater ecotoxicity (Table 4). Climate change, expressed as kg CO_{2eq} per kg of consumed meat, was equal to 7.90, 10.4 and 49.3 kg CO_2

Table 3
Incineration and re-use of renderedABPs expressed as Megatons (Mt). Hides and edible offals not included.

Total		Total	Incineration	Biodiesel	Fertilizer	Oleo-chemistry	Feed	Pet food	Export Pet food
Cat 1	Fat	0.076	0.024	0.051					
	Meal	0.060	0.060						
Cat 2	Fat	0.068		0.068					
	Meal	0.086			0.086				
Cat 3	Fat	0.343	0.018	0.023		0.114	0.154	0.028	0.007
	Meal	0.414			0.065		0.003	0.204	0.141
Total		1.047	0.143	0.102	0.151	0.114	0.157	0.232	0.148

Cat 3 does not include edible offals and hides and includes waste at processing stage. We assumed that offals were destinated to market and hides to leather industry.

Table 4
Environmental impact of the consumption of 1 kg of meat (economic allocation).

Impact category	Unit	Cattle meat	Pig meat	Poultry meat
Climate change, total	kg $CO_{2\ eq}$	4.93E+01	7.90E+00	1.04E+01
Ozone depletion	kg CF-C11 $_{eq}$	3.17E-05	2.95E-05	2.86E-05
Particulate Matter	Disease incidence	6.03E-06	9.16E-07	1.14E-06
Ionizing radiation	kBq $U^{235}{}_{eq}$	7.08E-02	9.32E-02	1.21E-01
Photochemical ozone formation	kg NMVOC $_{eq}$	5.48E-02	9.98E-03	1.19E-02
Acidification	molc $H^{+}{}_{eq}$	8.11E-01	1.26E-01	1.40E-01
Terrestrial eutrophication	molc N $_{eq}$	3.58E+00	5.50E-01	6.09E-01
Freshwater eutrophication	kg P $_{eq}$	8.02E-03	2.21E-03	2.63E-03
Marine eutrophication	kg N $_{eq}$	3.41E-01	6.09E-02	5.49E-02
Water use	m^3 world $_{eq}$	1.68E+01	3.16E+00	2.97E+00
Land use global	Pt	2.14E+03	3.07E+02	3.80E+02
Resource use, fossil	MJ	1.15E+02	3.13E+01	3.94E+01
Resource use, minerals and metals	kg Sb eq	2.86E-06	2.37E-06	2.45E-06
Human toxicity, cancer	CTUh	9.76E-09	1.99E-09	1.71E-09
Human toxicity, non cancer	CTUh	1.01E-06	4.52E-07	4.51E-07
Ecotoxicity, freshwater	CTUe	1.85E+02	8.60E+01	8.62E+01

$_{eq}$ per kg of meat for pig, poultry and cattle meat, respectively. Acidification, expressed as molc $H^{+}{}_{eq}$,per kg of consumed meat, ranged from 0.811 of cattle meat to 0.126 of pig meat. Terrestrial, freshwater and marine eutrophication were highest in cattle meat and equal to 3.58 molc N $_{eq}$, 0.008 kg P $_{eq}$, 0.341 kg N $_{eq}$; meanwhile the lowest values were 0.550 molc N $_{eq}$ and 0.002 kg P $_{eq}$ for pig meat and 0.055 kg N $_{eq}$ for poultry (see Table 4).

For all the meat types, agricultural and slaughter phases were the most contributing life cycle stages for climate change, acidification, eutrophication (terrestrial, freshwater, marine), water use and land use impact categories. In the case of climate change, the agricultural and slaughter phases were followed by the logistics phase. The end of life phase had the highest impact on freshwater ecotoxicity and contributed to a lesser extent to the impact on freshwater and marine eutrophication and water use (Tables S20, S21, S22).

3.2.2. *Environmental impact assessment of overall Italian meat consumption in 2013*

The environmental impact of meat consumption is influenced by the amount and the type of meat consumed. This study showed that the consumption of beef meat in Italy is lower than the one of poultry and pig meat. Results showed that beef, nevertheless, had the highest impact for most of the impact categories considered (Table 5) while pig meat, despite being consumed in higher quantity, contributed by 20% to total GHG emissions, because of a lower global warming potential per kg of meat. For each meat type the main contributor to the impact of meat consumption was the agricultural phase followed by the slaughtering stage.

The study revealed that the impact of climate change due to meat

Table 5
Environmental impact of the overall consumption of meat in Italy (economic allocation).

Impact category	Unit	Cattle meat	Pig meat	Poultry meat
Meat consumption	kg/year	8.10E+08	1.51E+09	8.80E+08
Climate change, total	kg $CO_{2\ eq}$	3.99E+10	1.19E+10	9.15E+09
Ozone depletion	kg CF-C11 $_{eq}$	2.57E+04	4.45E+04	2.52E+04
Particulate Matter	Disease incidence	4.88E+03	1.38E+03	1.00E+03
Ionizing radiation	kBq $U^{235}{}_{eq}$	5.73E+07	1.41E+08	1.06E+08
Photochemical ozone formation	kg NMVOC $_{eq}$	4.44E+07	1.51E+07	1.05E+07
Acidification	molc $H^{+}{}_{eq}$	6.57E+08	1.90E+08	1.23E+08
Terrestrial eutrophication	molc N $_{eq}$	2.90E+09	8.31E+08	5.36E+08
Freshwater eutrophication	kg P $_{eq}$	6.50E+06	3.34E+06	2.31E+06
Marine eutrophication	kg N $_{eq}$	2.76E+08	9.20E+07	4.83E+07
Water use	m^3 world $_{eq}$	1.36E+10	4.77E+09	2.61E+09
Land use global	Pt	1.73E+12	4.64E+11	3.34E+11
Resource use, fossil	MJ	9.32E+10	4.73E+10	3.47E+10
Resource use, minerals and metals	kg Sb eq	2.32E+03	3.58E+03	2.16E+03
Human toxicity, cancer	CTUh	7.91E+00	3.00E+00	1.50E+00
Human toxicity, non cancer	CTUh	8.18E+02	6.83E+02	3.97E+02
Ecotoxicity, freshwater	CTUe	1.50E+11	1.30E+11	7.59E+10

consumption in Italy in 2013 was 6.10E+10 kg $CO_{2\ eq}$ corresponding to 2.80 kg $CO_{2\ eq}$ per day per capita. The major contribution was due to cattle meat consumption (65%), followed by pig meat (20%) and poultry meat (17%). The impact on acidification was 9.70E+08 molc $H^{+}{}_{eq}$, terrestrial eutrophication was 4.27E+09 molc N $_{eq}$, freshwater eutrophication 1.21E+07 kg P $_{eq}$ and marine eutrophication 4.16 + 08 kg N $_{eq}$ (Table S27 and S29). These impacts, in terms of consumption grams per capita per day, were equal to values of 0.05 molc $H^{+}{}_{eq}$, 0.22 molc N $_{eq}$, 0.0006 kg P $_{eq}$, 0.2 kg N $_{eq}$, respectively (Table S34).

It should be highlighted that, although cattle meat consumption contributes to 25% of the total meat consumption it terms of mass, it is the largest contributor for 13 impact categories out of 16 (i.e. all excluded mineral and fossil resource use, ionizing radiation and ozone depletion, where instead pork meat was responsible for the largest share of the impacts). This is a crucial finding as it confirms how a partial or total replacement of beef with pork or poultry could significantly reduce the impacts caused by meat consumption in Italy.

3.2.3. *Sensitivity analysis*

The sensitivity analysis highlighted how different allocation approaches affect the results. Results are reported in Table 6. Fig. 2 reports the deviation of the impacts related to the consumption of 1 kg of cattle (Fig. 2a), pig (Fig. 2b) and poultry (Fig. 2c) obtained with each allocation approach from those obtained with the "no allocation" scenario, which always yielded the maximum impact values.

In the mass allocation scenario, cattle meat yielded values that were 40% or more lower than in the "no allocation" scenario for climate

Table 6
Overall impact assessment per 1 kg of meat consumed by meat typology, under the different allocation approaches (plus assumption on system expansion).

		Cattle meat					Pig meat					Poultry meat				
Impact category	Unit	NO[a]	MA[b]	EA[c]	SE EU[d]	SE US[e]	NO[a]	MA[b]	EA[c]	SE EU[d]	SE US[e]	NO[a]	MA[b]	EA[c]	SE EU[d]	SE US[e]
Climate change, total	kg $CO_{2\ eq}$	5.66E+01	3.26E+01	4.93E+01	5.63E+01	5.63E+01	8.42E+00	7.00E+00	7.90E+00	8.39E+00	8.40E+00	1.11E+01	8.32E+00	1.04E+01	1.09E+01	1.10E+01
Ozone depletion	kg CF-C11 $_{eq}$	3.17E-05	3.17E-05	3.17E-05	3.17E-05	3.17E-05	2.95E-05	2.95E-05	2.95E-05	2.95E-05	2.95E-05	2.86E-05	2.86E-05	2.86E-05	2.86E-05	2.86E-05
Particulate Matter	Disease incidence	6.95E-06	3.91E-06	6.03E-06	6.93E-06	6.94E-06	9.93E-07	7.85E-07	9.16E-07	9.90E-07	9.92E-07	1.23E-06	8.76E-07	1.14E-06	1.22E-06	1.23E-06
Ionizing radiation	kBq $U^{235}{}_{eq}$	7.60E-02	5.88E-02	7.08E-02	5.70E-02	5.76E-02	9.85E-02	8.41E-02	9.32E-02	9.51E-02	9.55E-02	1.28E-01	9.96E-02	1.21E-01	1.22E-01	1.23E-01
Photochemical ozone formation	kg NMVOC $_{eq}$	6.28E-02	3.64E-02	5.48E-02	6.20E-02	6.21E-02	1.06E-02	8.87E-03	9.98E-03	1.05E-02	1.05E-02	1.26E-02	9.62E-03	1.19E-02	1.22E-02	1.23E-02
Acidification	molc $H^{+}{}_{eq}$	9.34E-01	5.26E-01	8.11E-01	9.33E-01	9.33E-01	1.37E-01	1.08E-01	1.26E-01	1.37E-01	1.37E-01	1.52E-01	1.08E-01	1.40E-01	1.50E-01	1.51E-01
Terrestrial eutrophication	molc N $_{eq}$	4.13E+00	2.32E+00	3.58E+00	4.12E+00	4.12E+00	5.97E-01	4.70E-01	5.50E-01	5.96E-01	5.97E-01	6.60E-01	4.66E-01	6.09E-01	6.55E-01	6.58E-01
Freshwater eutrophication	kg P $_{eq}$	9.11E-03	5.51E-03	8.02E-03	9.09E-03	9.10E-03	2.32E-03	2.02E-03	2.21E-03	2.31E-03	2.32E-03	2.78E-03	2.21E-03	2.63E-03	2.75E-03	2.77E-03
Marine eutrophication	kg N $_{eq}$	3.89E-01	2.29E-01	3.41E-01	3.88E-01	3.89E-01	6.42E-02	5.53E-02	6.09E-02	6.37E-02	6.42E-02	5.79E-02	4.65E-02	5.49E-02	5.62E-02	5.78E-02
Water use	m^3 world $_{eq}$	1.91E+01	1.15E+01	1.68E+01	8.67E+00	8.61E+00	3.27E+00	2.96E+00	3.16E+00	1.75E+00	1.71E+00	3.06E+00	2.68E+00	2.97E+00	3.41E+00	3.28E+00
Land use global	Pt	2.47E+03	1.39E+03	2.14E+03	2.46E+03	2.46E+03	3.33E+02	2.62E+02	3.07E+02	3.26E+02	3.27E+02	4.11E+02	2.91E+02	3.80E+02	3.89E+02	3.92E+02
Resource use, fossil	MJ	1.31E+02	7.80E+01	1.15E+02	1.26E+02	1.26E+02	3.32E+01	2.80E+01	3.13E+01	3.26E+01	3.27E+01	4.18E+01	3.21E+01	3.94E+01	4.03E+01	4.07E+01
Resource use, minerals and metals	kg Sb eq	2.95E-06	2.65E-06	2.86E-06	2.27E-06	2.28E-06	2.39E-06	2.34E-06	2.37E-06	2.28E-06	2.29E-06	2.47E-06	2.37E-06	2.45E-06	2.10E-06	2.13E-06
Human toxicity, cancer	CTUh	1.12E-08	6.43E-09	9.76E-09	1.11E-08	1.12E-08	2.14E-09	1.74E-09	1.99E-09	2.07E-09	2.13E-09	1.83E-09	1.38E-09	1.71E-09	1.63E-09	1.81E-09
Human toxicity, non cancer	CTUh	1.10E-06	8.12E-07	1.01E-06	1.10E-06	1.10E-06	4.55E-07	4.46E-07	4.52E-07	4.52E-07	4.55E-07	4.54E-07	4.41E-07	4.51E-07	4.46E-07	4.54E-07
Ecotoxicity, freshwater	CTUe	2.05E+02	1.37E+02	1.85E+02	2.02E+02	2.03E+02	8.94E+01	8.03E+01	8.60E+01	8.81E+01	8.83E+01	8.94E+01	7.69E+01	8.62E+01	8.58E+01	8.65E+01

[a] No allocation.
[b] Mass allocation.
[c] Economic allocation.
[d] System expansion; European Union soybean origin.
[e] System expansion; United States soybean origin.

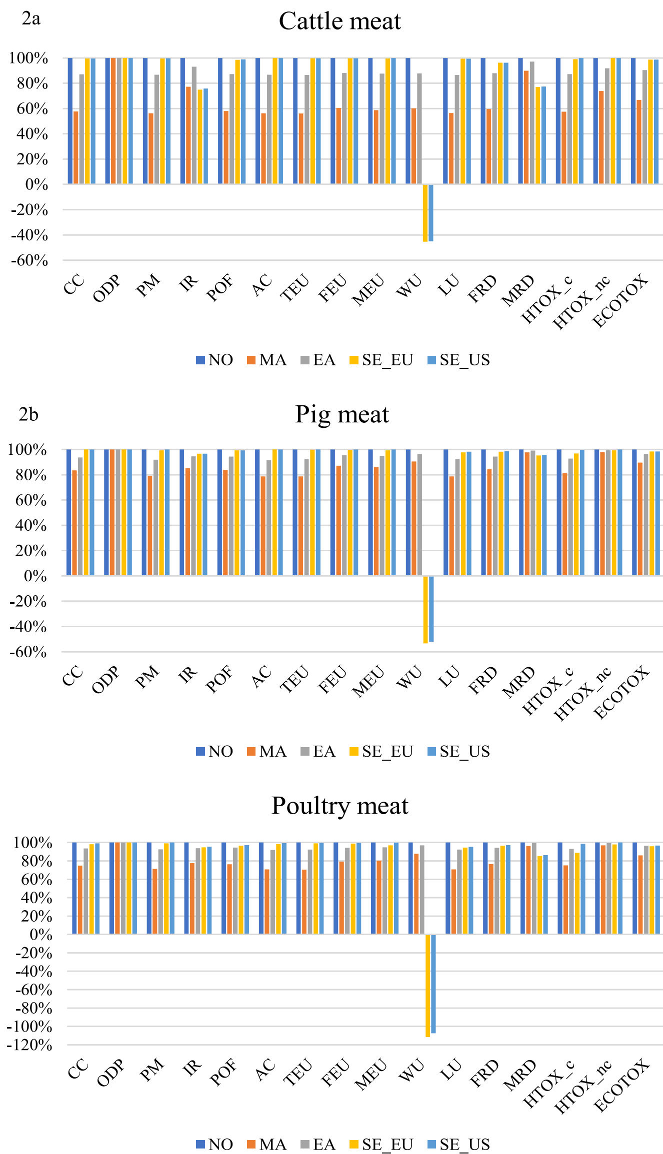

Fig. 2. Sensitivity analysis of allocation scenarios for the three considered meat categories (cattle, pig, poultry): deviation of impacts from the maximum value (no allocation, NO) taken as reference. MA: mass allocation; EA: economic allocation; SE_EU: system expansion with EU soybean; SE_US: system expansion with US soybean; CC: climate change, total; ODP: ozone depletion; PM: particulate matter; IR: ionizing radiation; POF: photochemical ozone formation; AC: acidification; TEU: terrestrial eutrophication; FEU: freshwater eutrophication; MEU: marine eutrophication; WU: water use; LU: land use global; FRD: resource use, fossil; MRD: resource use minerals and metals; HTOX_c: human toxicity, cancer: HTOX_nc: human toxicity, non cancer; ECOTOX: ecotoxicity, freshwater.

change, acidification, eutrophication (terrestrial, marine, freshwater), water use, land use and fossil resource use. When adopting economic allocation, the results were more than 11% lower than in the “no allocation” scenario for climate change, acidification, eutrophication (terrestrial, marine, freshwater), water use and land use, fossil resource use and freshwater ecotoxicity. For pig meat differences between no allocation and mass and economic allocation, respectively, were greater than 14% and 5% for climate change, acidification, eutrophication (terrestrial, marine, freshwater), land use and fossil resource use. For poultry meat differences higher than 19% and 5% were found between the “no allocation” scenario and the mass and economic allocation scenarios, respectively, for climate change, acidification, eutrophication (terrestrial, marine, freshwater), land use and fossil resource use. Larger differences between the results obtained in the mass allocation scenario and the no allocation scenario can be seen for cattle meat compared to pig or poultry meat, most likely due to the larger share of ABPs in cattle compared to the other species. Lower differences were noticed between the mass and economic allocation scenarios for all meat categories considered. The sensitivity analysis showed how the choice of allocation did not influence the results obtained for the ozone depletion impact category, instead the largest variations were found for the water use impact category, when comparing the results obtained with no allocation with those obtained with both system expansion allocation scenarios. The ranking of meat categories, in terms of their contribution to total impacts, remained the same in all allocation scenarios and the variation of the results obtained in the different scenarios presented a similar pattern across the three meat categories under study.

Considering both system expansion scenarios, cattle meat consumption was confirmed as major contributor to climate change, acidification, eutrophication, water use and land use, followed by pig meat and poultry meat consumption. For all the three meat categories the greatest reduction was found considering water use category while for cattle and pig meat also for mineral and metal resource use. No ranking differences were found considering different soybean origin in the system expansion scenario. The soybean origin however influenced the freshwater and marine eutrophication and the land use and the water use impact categories. In the scenario considering US soybean as avoided product, the reduction potential was lower compared to the use of EU soybean (Table S33).

The total impact of Italian meat consumption was calculated in the five scenarios considered and the contribution of the three meat categories was analysed. In all cases, the ranking of meat types was the same as identified in section 3.2.2 (Table S32). The global warming potential of per capita daily consumption of meat ranged between 2.03 kg $CO_{2\ eq}$ (calculated with mass allocation) and 3.12 kg $CO_{2\ eq}$ (calculated with system expansion); the results for the remaining impact categories are reported in Table S34.

4. Discussion

The results of MFA and LCA are discussed hereafter with the aim of highlighting open issues and challenges for further evaluations.

4.1. Material flow analysis

Several studies estimated meat consumption in Italy and in the EU, using different approaches, based either on agricultural supply (Food Balance Sheet) (Kelly et al., 1991), household budget surveys (HBSs) (EC, 2003) or on individual dietary surveys (IDSs) (Kennedy et al., 2010). All of these methods are affected by approximation and uncertainties (Hallström and Börjesson, 2013). Generally, given the broad scale of the assessment and the lack of data on meat consumption, ABPs and waste generation, the level of the accuracy of an estimation of meat consumption at the national scale might be quite limited and results show a large variability in the estimations. The meat consumption reported in this study is in accordance with other studies that report real meat consumption, i.e. meat consumption without bones and other losses. For example, at Italian national scale, ISMEA and FAOSTAT report a daily apparent consumption respectively equal to 0.21 and 0.23 kg CW/day per capita (Nathan and Scobell, 2012) and INRAN reports a consumption of real meat equal to 0.11 kg/day per capita (INRAN, 2013). According to Russo et al. (2017) the real meat consumption, based on the prior deduction of all meat losses, in 2013 was equal to 0.104 kg/day. GFK Eurisko and NIELSEN (GFK, 2013; NIELSEN, 2013), through an European scale level survey, reported a real meat consumption equal to 0.08 and 0.04 kg/day/per capita, respectively. Notarnicola et al. (2017) and Castellani et al. (2017) report per capita apparent consumption at European scale level of 0.21 kg CW/day (77.6

kg CW/year) composed by 0.11 kg CW/day (41.0 kg CW/year) of pig meat, 0.04 kg CW/day (13.7 kg CW/year) of cattle meat and 0.06 kg CW/day (22.9 kg CW/year) of poultry meat. These results are higher than the real consumption because they are expressed in terms of carcass weight (i.e. including bones, cartilages and extra fat). Despite the variability of results and unit of measurement, the ranking of meat types consumption is consistently led by pig meat, followed by poultry and cattle, and other meat.

This comparison highlights one of the sources of uncertainty in the quantification of meat consumption: the fact that the estimation of the quantity of meat consumed is affected by whether meat is expressed in carcass weight or real weight, the weight losses during cooking and transformation are considered, and the meat content in processed meat products and the food losses and waste at consumption level are accounted for.

Another element of uncertainty identified in relation to the MFA is the quantification of water losses caused by meat maturation and processing. Water content is highly correlated with the age and weight of slaughtered animal, fat content and body parts (Wierbicki and Deatherage, 1958; Zielbauer et al., 2016). Furthermore, during processing and seasoning, the loss of weight is largely influenced by the type of process and by the seasoning time for each specific product. In this study, due to the lack of data, the water losses along the meat chain were not quantified with the exception of ABPs rendering process

The quantification of food waste at retail and household phases was another point of uncertainty. Given the lack of national data (Bagherzadeh et al., 2014), European coefficients were used and no distinction could be made between edible and non-edible waste. This highlights how the lack of average national data on food waste generation at these stages can impair the identification and the development of focused mitigation strategies to reduce food waste and to propose ad hoc solutions for its re-use (i.e. pet food production from meat retail waste) (Castrica et al., 2018). Regarding this point, Corrado et al. (2019) also highlighted the need to harmonize the food waste measurements to reduce the discrepancy in the state of play on food waste quantification among different EU member states. This could be done by providing guidelines on food waste accounting.

The average slaughter weight of different species, used to estimate the amounts of ABPs generated, was specific for the Italian production system, where cattle is traditionally slaughtered both at light weight (i.e. white meat cattle) and pig at heavy weight. Italy is self-sufficient for the poultry meat supply and characterized by a medium-high slaughter weight (2.6 kg LW) (van Horne, P.L.M.; Bondt, 2013). The proportion of ABPs was comparable with data reported by Laraia et al. (2001) and personal communication of AssoGrassi. The latter reported an annual production of 1.34E+05, 1.21E+05 and 1.15E+06 tonnes of Cat 1, Cat 2 and Cat 3 materials, respectively, for the year 2013. These numbers were lower than the one of this study respectively by 36% (Cat 1), 47% (Cat 2) and 21% (Cat 3). Differences could be due to the fact that this association represents 80% of the Italian rendering plants. The greatest contribution is associated with cattle due to its lower conversion yield and higher slaughter weight. Cat 3 materials represent the majority of total ABPs, this is also the category presenting the greatest re-use options.

This study considered as possible re-use options only those suggested by AssoGrassi outlying circularity in the analysed system and valorisation of ABPs. Circularity means optimising a system (De Boer and Van Ittersum, 2018) and is considered as a reduction of input virgin materials and output of wastes bringing benefits from both an economic and environmental point of view (Haas et al., 2015). The implementation of rendering processes enables to reduce the environmental impacts caused by the meat production industry and by the final users of the derived products obtained (Mekonnen et al., 2016). For example, Cat 2 and Cat 3 materials were mainly destined to feed production or to the chemical industry highlighting the valorisation of the high protein and fat ABPs content. The production of biodiesel from fat of Cat 1 material is a relatively recent application, as it started after the spongiform encephalopathies (BSE) epidemic in alternative to the use of bovine fats to produce soaps and oleo-chemicals and feeds (Woodgate and Wilkinson, 2021). However, rendering process applied to Cat 1 ABPs is not enough to ensure their safe use, due to the fact that it does not allow to inactivate the prion protein responsible for the bovine BSE transmission (Meeker and Hamilton, 2006). Therefore Cat 1 material is mainly destinated to waste disposal (e.g. incineration with energy recovery) (Kim et al., 2005; Mekonnen et al., 2016; Santagata et al., 2017).

Further analyses to evaluate alternative rendered ABPs disposal options and different rendering scenarios, considering also wastewater treatment (Valta et al., 2015), transformation technologies, process efficiency and products yield (Arvanitoyannis and Ladas, 2008; Fritzson and Berntsson, 2006; Urlings et al., 1992) would be useful to identify the best choices according to both an environmental and economic perspective to enhance the valorisation of ABPs. In addition, an analysis of the geographical distribution of the actors of the meat chain in the Italian territory would serve as support in the strategic planning of efficient and sustainable synergies to improve the circularity of the system and avoid possible trade-offs, e.g. related to an inefficient logistics (Cristóbal et al., 2018). A deeper analysis of these elements would be important to support the implementation of national policies aiming at improving the circularity of the meat production system amongst producers.

Nevertheless, this study showed that the circularity of the meat supply chain, in terms of re-use of ABPs products, is quite advanced. ABPs, even if categorized with health risk, are used to produce energy or biofuels. The complete re-use of ABPs at slaughterhouse could be economically onerous for companies. Further investigations are needed and political strategies may be considered to support industries to follow best practices ensuring the circularity of resources. At household level, as re-use of this type of waste is not an option, the focus should be on food waste prevention. Here waste is the result of consumer habits that could be influenced by market communication and improvement of social responsibility (Tanner, 2016).

4.2. Life cycle assessment

4.2.1. Environmental impact assessment of meat consumption

The aim of this section is to provide a comparison of the impacts of meat production found in this study with similar studies from scientific literature. Due to the use of different characterization methods, the comparison with different studies is limited to this impact category. When assessing the findings of this study against the existing literature, it is important to keep in mind that meat production impacts are highly linked to the national context, the specific types of products, and the production systems. Some literature studies report values of global warming potential for Italian meat. However, comparability with the results of this study is limited as they often report impacts per unit of live weight or carcass weight and refer to specific breeding systems, characterized by inherently different environmental impacts (Bragaglio et al., 2018).

In the Italian context, cattle production comes from different types of farming systems (i.e. cow-calf intensive system, fattening system, specialized intensive system). Bragaglio et al. (2018) reported global warming potential values of Italian beef meat equal to 17.62 kg $CO_{2\ eq}$ and 26.30 kg $CO_{2\ eq}$ for 1 kg of LW for, respectively, a fattening system and a Podolian beef production system (traditional Italian enterprise). Buratti et al. (2017), instead, reported a value of 18.21 kg $CO_{2\ eq}$/kg LW in a conventional system and 24.62 kg $CO_{2\ eq}$/kg LW in an organic system. Nguyen et al. (2010a) assessed the environmental impact of beef production in the EU considering different production systems (i.e. intensively reared dairy calves at different slaughter age and suckler herds) obtaining values of global warming potential that ranged from 16.0 to 27.3 kg $CO_{2\ eq}$/kg CW. Other authors highlighted how the farming system, whether intensive or extensive, the origin of calves (dairy-based or suckler-based), the production method (organic or non-organic) and the diet (concentrate-based or roughage-based) affect the final value (de Vries et al., 2015). Asem-Hiablie et al. (2019) reported an impact on climate change of 48.40 kg $CO_{2\ eq}$/kg of consumed boneless edible meat in the USA, which is in line with the findings of our study.

Regarding pig meat, Bava et al. (2017) obtained a global warming potential equal to 4.25 ± 1.03 kg $CO_{2\ eq}$/kg LW in six farms located in the North of Italy. Unlike other pig production systems, the Italian one is characterized by a high slaughter weight, due to the presence of eight PDO labels of dry-cured ham. This negatively influences the environmental impacts of pig production, as fat deposition negatively affects the feed conversion ratio (Latorre et al., 2003). Within the national scenario, however, there is also a strong variability due to different management techniques and feeding strategies (Bava et al., 2017). Another study on pig production systems reported values varying between 4.81 and 9.75 kg $CO_{2\ eq}$/kg CW in the EU context (Nguyen et al., 2010). These values are highly affected by the weight at the slaughtering stage as a lower slaughter weight is associated with lower impacts caused by a shorter rearing time to reach that weight and therefore a reduced feed use per unit of live weight. Other examples of values of global warming potential results found in the literature for pig meat are: 3.77 kg $CO_{2\ eq}$/kg CW (Dalgaard et al., 2007); 3.34, 4.75 and 5.5 kg $CO_{2\ eq}$/kg CW (Lamnatou et al., 2016; Noya et al., 2017; Winkler et al., 2016); 2.32 and 3.22 kg $CO_{2\ eq}$/kg CW(Mackenzie et al., 2015; Reckmann et al., 2013) and 3.50 kg $CO_{2\ eq}$/kg LW (Djekic et al., 2021). These values are highly affected by the weight at the slaughtering stage. No study was found in the literature that reported impacts of pig meat per unit of boneless edible meat, hindering the comparison between the results of this current work with existing studies.

Focusing on poultry meat production, Cesari et al. (2017) reported global warming potential values of 3.03 kg $CO_{2\ eq}$/kg LW and 3.84 kg $CO_{2\ eq}$/kg LW respectively for light and heavy broilers, highlighting how the Italian poultry meat production system is more impactful than in other countries due to the worse Feed Conversion Ratio (FCR) of heavy broilers in comparison with light and medium ones, which is probably the main cause of the high GWP per kg of carcass weight of the Italian broiler. The values obtained in our study are in accordance with the range found in the literature: from 4.41 to 5.66 kg $CO_{2\ eq}$/kg CW (Leinonen et al., 2012), 2.77–2.79 kg $CO_{2\ eq}$/kg LW (López-Andrés et al., 2018) and 2.2 kg $CO_{2\ eq}$/kg LW (Wiedemann et al., 2017) but the paucity of studies reporting impacts for Italian poultry production are a limiting factor for a broad comparison of results.

4.2.2. Sensitivity analysis

As previously mentioned, allocation is used to solve the problem of multifunctionality of a system and economic allocation is generally preferred in multi-functional agricultural and agri-industrial processes. For example, Zampori and Pant (2019) reccomended to use economic allocation for meat products within slaughterhouse considering an economic value and only for meat and Cat 3 materials (i.e. assuming that Cat 1 and Cat 2 materials have no economic value). Although using a fixed economic value is a pragmatic approach, a drawback of this choice is that the price market changes through time and across different locations. Furthermore the relative importance of meat production can change (Roma et al., 2015).

The allocation approach affected mainly the processes involved in the agricultural phase as this is the stage where meat and ABPs are produced. Unlike economic allocation, the adoption of a system expansion approach enables to evaluate the avoided emission due the valorisation of ABPs products either as material or as energy carriers. In doing so, it is important to consider that ABPs are treated with a rendering process, essential to stabilize biological products by subtracting water to avoid decomposition, which requires the application of heat and electricity (Meeker and Hamilton, 2006). The study considered that the re-use of rendered animal ABPs avoided producing diesel, fertilizers and soybean meal and oil. In the specific case of soybean meal, only Cat 3 ABPs were considered, taking into account the EU legislation on the re-use of ABPs (European Parliament and the Council, 2009). However, as ABPs have a wide range of applications (except for Cat 1 material), other options could also have been considered (Mekonnen and Hoekstra, 2012).

With regard to the results calculated through the mass allocation approach, the results are always lower than with the other allocation methods because the percentage of allocation to meat is always higher than that to ABPs for all the meat categories. Generally, the system expansion approach yielded higher impacts than those obtained with mass and economic allocation, this is because this approach takes into account the inputs needed for rendering operation.

The opposite was noticed for the water use impact category. The large variations observed between the system expansion and the other allocation options for this impact category can be explained considering the water savings associated with the substitution of vegetable protein crops (i.e. soybean, canola), animal protein (i.e. meat), fertilisers and fuels for ABPs. Soybean is an important vegetable protein source for animal feeding purposes and in biodiesel production; however the cultivation of this crop requires large amounts of water (which vary according to the farming system and irrigation system) (Gerbens-Leenes et al., 2009; Mekonnen and Hoekstra, 2011; Miguel Ayala et al., 2016). As cattle resulted to be the highest impacting species, in water consumption terms, followed by pigs and poultry, confirming the findings of other studies (e.g. Gerbens-Leenes et al., 2013; Mekonnen and Hoekstra, 2012), considering ABPs as substitutes for beef-based pet food production, could further increase the resulting water savings.

On the other hand, the lack of variation in the results obtained in the sensitivity analysis for the ozone depletion impact category could be explained by the fact that at least 90% of impacts on ozone depletion are due to the meat logistic phase and refrigerants use (Bolaji and Huan, 2013). A sensitivity analysis focusing on the logistic phase or the consumption phase could show variations for this impact category (Notarnicola et al., 2017).

As shown by this study, the re-use of ABPs can reduce the environmental impact of meat production by avoiding the impacts caused by the use of other virgin materials and at the same time valorising what is considered a by-product (Bonou et al., 2020; Lamnatou et al., 2016). The system under study resulted to be efficient and promote circularity, thanks to the re-use and valorisation of ABPs (Toldrá et al., 2012; Woodgate and van der Veen, 2004). The availability of specific data about rendering technologies and other treatment options coupled with the market price variability could be a starting point to assess the environmental and economic sustainability of the meat production system (Golini et al., 2017). Overall, the results obtained showed that allocation choices do not affect the ranking of the most impactful meat categories and also the predominant role of the agricultural phase on the final results.

Improvements considering fat and protein content could be obtained with biophysical allocation methods, but this would need availability of accurate data per meat product (Mackenzie et al., 2017). Considering that the aim of this study is to provide an overview of the meat supply chain in the Italian context, biophysical allocation were taken into account.

5. Conclusions

This study presents an innovative approach to comprehensively evaluate a supply chain combining material flows analysis and related environmental impacts, thus providing the background for the development of ad hoc mitigation strategies.

The quantification of meat consumption in Italy was in line with the only previous study that performed the same estimation in terms of real meat consumption (Russo et al., 2017). The most consumed type of meat was pig meat, followed by poultry and cattle meat; this is explained also by the fact that pig meat is processed to produce cold cuts, twenty-one of them categorized as PDO products and twenty-two as Protected Geographical Indication (PGI). Nevertheless, cattle was the most impactful meat category mainly due to the enteric emissions, which are a physiologic characteristic of ruminant species, and due to the lower efficiency in the conversion from live weight to carcass weight for this meat category.

MFA highlighted sources of ABPs and waste. The quantification of the former and their disposal shows that the circularity of the system is already high even if optimization is possible as Cat 2 and Cat 3 re-use are characterized by low and zero health risk. Currently, Cat 2 material is mostly used for fertilizer production and Cat 3 material for feed production. Re-use of Cat 3 material, considering both fat and meal, could reduce the environmental impact related to the use of other protein sources (i.e. soybean) for feed production and, being fit for human consumption, the use of fat could substitute the use of other vegetable oils. Although this work estimated retail and household meat waste, further research is needed to detect its causes and the possibility of re-using it, leading to a reduction of this waste generation. This could help to understand and reduce the environmental burden caused by this supply chain.

The environmental impact liked to the consumption of 1 kg of cattle, pig and poultry meat and to the consumption of meat in Italy were assessed through LCA. A sensitivity analysis was performed to assess the influence of different allocation choices on the results and on the ranking of meat categories in terms of their environmental impact. The ranking of meat categories was the same in all the allocation scenarios explored. Guidelines suggest the type of allocation to prefer, considering that each allocation choice has its limitations and sources of uncertainty. Mass allocation is affected by the animal categories' conversion coefficient from LW to CW and economic allocation by the variability of the market price especially for ABPs. System expansion considered the avoided emission for some substitute products, chosen as representative, as no previous studies had been proposed at national level. The inclusion of additional substituted products in the analysis could provide new scenarios about material flow analysis (i.e. ABPs re-use options) and environmental impact. Further developments could comprehend also economic evaluation, especially for the disposal of ABPs and of waste at retail stage, and the analysis of the geographical localisation of the actors of the meat chain in order to investigate and identify the best strategies to improve the overall sustainability of the system.

CRediT authorship contribution statement

Giulia Ferronato: Writing – original draft, Formal analysis, Methodology, Visualization, Writing – review & editing. **Sara Corrado:** Conceptualization, Formal analysis, Methodology, Writing – review & editing. **Valeria De Laurentiis:** Investigation, Writing – review & editing, Formal analysis. **Serenella Sala:** Conceptualization, Methodology, Validation, Writing – review & editing.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128705.

References

Arvanitoyannis, I.S., Ladas, D., 2008. Meat waste treatment methods and potential uses. Int. J. Food Sci. Technol. https://doi.org/10.1111/j.1365-2621.2006.01492.x.
Asem-Hiablie, S., Battagliese, T., Stackhouse-Lawson, K.R., Alan Rotz, C., 2019. A life cycle assessment of the environmental impacts of a beef system in the USA. Int. J. Life Cycle Assess. 24, 441–455. https://doi.org/10.1007/s11367-018-1464-6.
AssoGrassi, 2019. Personal Communication.
Bagherzadeh, M., Inamura, M., Jeong, H., Publishing, O., 2014. Food waste along food value chains. OECD Food, Agric. Fish. Pap. https://doi.org/10.1787/5jxrcmftzj36-en.
Bava, L., Zucali, M., Sandrucci, A., Tamburini, A., 2017. Environmental impact of the typical heavy pig production in Italy. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2015.11.029.
Bolaji, B.O., Huan, Z., 2013. Ozone depletion and global warming: case for the use of natural refrigerant - a review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2012.10.008.
Bonou, A., Colley, T.A., Hauschild, M.Z., Olsen, S.I., Birkved, M., 2020. Life cycle assessment of Danish pork exports using different cooling technologies and comparison of upstream supply chain efficiencies between Denmark, China and Australia. J. Clean. Prod. 244, 118816. https://doi.org/10.1016/j.jclepro.2019.118816.
Bragaglio, A., Napolitano, F., Pacelli, C., Pirlo, G., Sabia, E., Serrapica, F., Serrapica, M., Braghieri, A., 2018. Environmental impacts of Italian beef production: a comparison between different systems. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.03.078.
Buratti, C., Fantozzi, F., Barbanera, M., Lascaro, E., Chiorri, M., Cecchini, L., 2017. Carbon footprint of conventional and organic beef production systems: an Italian case study. Sci. Total Environ. 576, 129–137. https://doi.org/10.1016/j.scitotenv.2016.10.075.
Caldeira, C., De Laurentiis, V., Corrado, S., van Holsteijn, F., Sala, S., 2019. Quantification of food waste per product group along the food supply chain in the European Union: a mass flow analysis. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2019.06.011.
Castellani, V., Fusi, A., Sala, S., 2017. Consumer footprint. Basket of Products indicator on Food. JRC technical report. https://doi.org/10.2760/668763.
Castrica, M., Tedesco, D.E.A., Panseri, S., Ferrazzi, G., Ventura, V., Frisio, D.G., Balzaretti, C.M., 2018. Pet food as the most concrete strategy for using food waste as feedstuffwithin the European context: a feasibility study. Sustain. Times. https://doi.org/10.3390/su10062035.
Cellura, M., Longo, S., Mistretta, M., 2011. Sensitivity analysis to quantify uncertainty in Life Cycle Assessment: the case study of an Italian tile. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2011.07.082.
Clune, S., Crossin, E., Verghese, K., 2017. Systematic review of greenhouse gas emissions for different fresh food categories. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.04.082.
Coluccia, B., Valente, D., Fusco, G., De Leo, F., Porrini, D., 2020. Assessing agricultural eco-efficiency in Italian Regions. Ecol. Indicat. 116, 106483. https://doi.org/10.1016/j.ecolind.2020.106483.
Commission Regulation (Eu), 2011. Commission Regulation (EU) No 142/2011 of 25 February 2011 Implementing Regulation (EC) No 1069/2009 of the European Parliament and of the Council Laying Down Health Rules as Regards Animal By-Products and Derived Products Not Intended for Human Consumpti.
Corrado, S., Caldeira, C., Eriksson, M., Hanssen, O.J., Hauser, H.E., van Holsteijn, F., Liu, G., Östergren, K., Parry, A., Secondi, L., Stenmarck, A., Sala, S., 2019. Food waste accounting methodologies: challenges, opportunities, and further advancements. Glob. Food Sec. https://doi.org/10.1016/j.gfs.2019.01.002.
Dalgaard, R., Halberg, N., Hermansen, J., 2007. Danish pork production: an environmental assessment. DJF Anim. Sci. 82.
De Boer, I.J.M., Van Ittersum, M.K., 2018. Circularity in Agricultural Production. Wageningen Univ, pp. 1–74.
de Vries, M., van Middelaar, C.E., de Boer, I.J.M., 2015. Comparing environmental impacts of beef production systems: a review of life cycle assessments. Livest. Sci. 178, 279–288. https://doi.org/10.1016/j.livsci.2015.06.020.
Djekic, I., Tomasevic, I., 2016. Environmental impacts of the meat chain - current status and future perspectives. Trends Food Sci. Technol. https://doi.org/10.1016/j.tifs.2016.06.001.
Djekic, I., Bozickovic, I., Djordjevic, V., Smetana, S., Terjung, N., Ilic, J., Doroski, A., Tomasevic, I., 2021. Can we associate environmental footprints with production and consumption using Monte Carlo simulation? Case study with pork meat. J. Sci. Food Agric. 101, 960–969. https://doi.org/10.1002/jsfa.10704.
EC, 2003. Household Budget Surveys in the EU, Methodology.
EC, 2013. Recommendation 2013/179/EU on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations.
EC, 2019. Communication from the commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. COM(2019) 640. Final.

EC, 2020a. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system. COM 381.
EC, 2020b. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A new Circular Economy Action Plan for a cleaner and more competitive Europe. COM 98.
EC- JRC, 2010. General guide for life cycle assessment - detailed guidance. In: International Reference Life Cycle Data System (ILCD) Handbook.
EC-JRC, 2019. Environmental Footprint reference package (EF 3.0). Available at: https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml.
European Parliament and the Council, 2004. Regulation (EC) No 853/2004 of the European Parliament and of the Council of 29 April 2004 Laying Down Specific Hygiene Rules for Food of Animal Origin.
European Parliament and the Council, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives.
European Parliament and the Council, 2009. Regulation (EC) No 1069/2009 of the European Parliament and Council of 21 October 2009 Laying Down Health Rules as Regards Animal By-Products and Derived Products Not Intended for Human Consumption and Repealing Regulation (EC) No 1774/2002 (Animal by-products Regulation).
European Parliament and the Council, 2018. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste.
FAOSTAT, 2000. Commodity Balances - Livestock and Fish Primary Equivalent. URL: http://www.fao.org/faostat/en/#data. accessed 5.12.21.
Fazio, S., Castellani, V., Sala, S., Schau, E.M., Secchi, M., Zampori, L., Diaconu, E., 2018. Supporting Information to the Characterisation Factors of Recommended EF Life Cycle Impact Assessment Methods. ILCD.
Fritzson, A., Berntsson, T., 2006. Efficient energy use in a slaughter and meat processing plant-opportunities for process integration. J. Food Eng. https://doi.org/10.1016/j.jfoodeng.2005.06.007.
Gerbens-Leenes, W., Hoekstra, A.Y., Van Der Meer, T.H., 2009. The water footprint of bioenergy. Proc. Natl. Acad. Sci. U.S.A. 106, 10219–10223. https://doi.org/10.1073/pnas.0812619106.
Gerbens-Leenes, P.W., Mekonnen, M.M., Hoekstra, A.Y., 2013. The water footprint of poultry, pork and beef: a comparative study in different countries and production systems. Water Resour. Ind. 1–2, 25–36. https://doi.org/10.1016/j.wri.2013.03.001.
GFK, 2013. Growth from knowledge. URL. https://www.panelconsumatorigfk.it (Accessed June 2021).
Golini, R., Moretto, A., Caniato, F., Caridi, M., Kalchschmidt, M., 2017. Developing sustainability in the Italian meat supply chain: an empirical investigation. Int. J. Prod. Res. https://doi.org/10.1080/00207543.2016.1234724.
Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How circular is the global economy?: an assessment of material flows, waste production, and recycling in the European Union and the world in 2005. J. Ind. Ecol. 19, 765–777. https://doi.org/10.1111/jiec.12244.
Hallström, E., Börjesson, P., 2013. Meat-consumption statistics: reliability and discrepancy. Sustain. Sci. Pract. Pol. https://doi.org/10.1080/15487733.2013.11908113.
INRAN, 2013. Istituto Nazionale di Ricerca per gli Alimenti e la Nutrizione.
ISMEA, 2013a. Istituto di Servizi per il mercato agricolo alimentare. URL. http://www.ismea.it/istituto-di-servizi-per-il-mercato-agricolo-alimentare. (Accessed June 2019).
ISMEA, 2013b. Settore suino- Scheda di settore.
ISMEA, 2013c. Allevamento Bovino Da Carne- Scheda di settore.
ISMEA, 2013d. Settore avicolo- Scheda di settore.
International Organization for Standardization (ISO), 2006a. ISO 14040:2006. Environmental management — Life cycle assessment — Principles and framework.
International Organization for Standardization (ISO), 2006b. ISO 14044:2006. Environmental management — Life cycle assessment — Requirements and guidelines. ISO 14044.
JRC, 2010. ILCD handbook - general guide on LCA - detailed guidance. https://doi.org/10.2788/38479.
Kelly, A., Becker, W., Helsing, E., 1991. Food balance sheets. World Heal. Organ. Reg. Publ. - Eur. Ser.
Kennedy, G., Ballard, T., Dop, M., 2010. Guidelines for Measuring Household and Individual Dietary Diversity. FAO.
Kim, Y.C., Shim, H.J., Lee, J.H., Kim, S.H., Kwon, J.W., Kim, W.B., Lee, M.G., 2005. Effects of enzyme inducers and inhibitors on the pharmacokinetics of intravenous DA-8159, a new erectogenic, in rats. Biopharm Drug Dispos. 26, 233–241. https://doi.org/10.1002/bdd.453.
Lamnatou, C., Ezcurra-Ciaurriz, X., Chemisana, D., Plà-Aragonés, L.M., 2016. Environmental assessment of a pork-production system in North-East of Spain focusing on life-cycle swine nutrition. J. Clean. Prod. 137, 105–115. https://doi.org/10.1016/j.jclepro.2016.07.051.
Laraia, R., Riva, G., Squitieri, G., 2001. I rifiuti del comparto agroalimentare. Stud. di settore. Rapp. ANPA 148.
Latorre, M.A., Medel, P., Fuentetaja, A., Lázaro, R., Mateos, G.G., 2003. Effect of gender, terminal sire line and age at slaughter on performance, carcass characteristics and meat quality of heavy pigs. Anim. Sci. https://doi.org/10.1017/s1357729800053625.
Leinonen, I., Williams, A.G., Wiseman, J., Guy, J., Kyriazakis, I., 2012. Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: broiler production systems. Poultry Sci. 91, 8–25. https://doi.org/10.3382/ps.2011-01634.
López-Andrés, J.J., Aguilar-Lasserre, A.A., Morales-Mendoza, L.F., Azzaro-Pantel, C., Pérez-Gallardo, J.R., Rico-Contreras, J.O., 2018. Environmental impact assessment of chicken meat production via an integrated methodology based on LCA, simulation and genetic algorithms. J. Clean. Prod. 174, 477–491. https://doi.org/10.1016/j.jclepro.2017.10.307.
Mackenzie, S.G., Leinonen, I., Ferguson, N., Kyriazakis, I., 2015. Accounting for uncertainty in the quantification of the environmental impacts of Canadian pig farming systems. J. Anim. Sci. https://doi.org/10.2527/jas.2014-8403.
Mackenzie, S.G., Leinonen, I., Kyriazakis, I., 2017. The need for co-product allocation in the life cycle assessment of agricultural systems—is "biophysical" allocation progress? Int. J. Life Cycle Assess. 22, 128–137. https://doi.org/10.1007/s11367-016-1161-2.
Meeker, D.L., Hamilton, C.R., 2006. An overview of the rendering industry. Essent. Render. All About Anim. By-Products Ind. 1–16.
Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15, 1577–1600. https://doi.org/10.5194/hess-15-1577-2011.
Mekonnen, M.M., Hoekstra, A.Y., 2012. A global assessment of the water footprint of farm animal products. Ecosystems 15, 401–415. https://doi.org/10.1007/s10021-011-9517-8.
Mekonnen, T., Mussone, P., Bressler, D., 2016. Valorization of rendering industry wastes and co-products for industrial chemicals, materials and energy: Review. Crit. Rev. Biotechnol. https://doi.org/10.3109/07388551.2014.928812.
Miguel Ayala, L., van Eupen, M., Zhang, G., Pérez-Soba, M., Martorano, L.G., Lisboa, L.S., Beltrao, N.E., 2016. Impact of agricultural expansion on water footprint in the Amazon under climate change scenarios. Sci. Total Environ. 569 (570), 1159–1173. https://doi.org/10.1016/j.scitotenv.2016.06.191.
Nathan, A.J., Scobell, A., 2012. How China sees America, foreign affairs. https://doi.org/10.1017/CBO9781107415324.004.
Nguyen, T.L.T., Hermansen, J.E., Mogensen, L., 2010. Fossil energy and GHG saving potentials of pig farming in the EU. Energy Pol. https://doi.org/10.1016/j.enpol.2009.12.051.
NIELSEN, 2013. Nielsen. URL. https://www.nielsen.com/. (Accessed June 2019).
Notarnicola, B., Tassielli, G., Renzulli, P.A., Castellani, V., Sala, S., 2017. Environmental impacts of food consumption in Europe. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.06.080.
Noya, I., Villanueva-Rey, P., González-García, S., Fernandez, M.D., Rodriguez, M.R., Moreira, M.T., 2017. Life Cycle Assessment of pig production: a case study in Galicia. J. Clean. Prod. 142, 4327–4338. https://doi.org/10.1016/j.jclepro.2016.11.160.
Reckmann, K., Traulsen, I., Krieter, J., 2013. Life Cycle Assessment of pork production: a data inventory for the case of Germany. Livest. Sci. 157, 586–596. https://doi.org/10.1016/j.livsci.2013.09.001.
Roma, R., Corrado, S., De Boni, A., Forleo, M.B., Fantin, V., Moretti, M., Palmieri, N., Vitali, A., Camillo, D.C., 2015. Life cycle assessment in the livestock and derived edible products sector. In: Life Cycle Assessment in the Agri-Food Sector. https://doi.org/10.1007/978-3-319-11940-3_5.
Röös, E., Sundberg, C., Tidåker, P., Strid, I., Hansson, P.A., 2013. Can carbon footprint serve as an indicator of the environmental impact of meat production? Ecol. Indicat. https://doi.org/10.1016/j.ecolind.2012.08.004.
Russo, V., De Angelis, A., Danieli, P.P., 2017. Consumo reale di carne e di pesce in Italia. Dal consumo apparente al consumo reale col metodo della detrazione preventiva delle perdite.
Santagata, R., Ripa, M., Ulgiati, S., 2017. An environmental assessment of electricity production from slaughterhouse residues. Linking urban, industrial and waste management systems. Appl. Energy. https://doi.org/10.1016/j.apenergy.2016.07.073.
Sgarbossa, F., Russo, I., 2017. A proactive model in sustainable food supply chain: insight from a case study. Int. J. Prod. Econ. https://doi.org/10.1016/j.ijpe.2016.07.022.
Stat, I., 2013. I.Stat. URL. http://dati.istat.it/ (Accessed June 2019).
Tanner, D., 2016. Food quality, storage, and transport. In: Reference Module in Food Science. https://doi.org/10.1016/b978-0-08-100596-5.03336-9.
Toldrá, F., Aristoy, M.C., Mora, L., Reig, M., 2012. Innovations in value-addition of edible meat by-products. Meat Sci. https://doi.org/10.1016/j.meatsci.2012.04.004.
Urlings, H.A., van Logtestijn, J.G., Bijker, P.G., 1992. Slaughter by-products: problems, preliminary research and possible solutions. Vet. Q. https://doi.org/10.1080/01652176.1992.9694323.
Valta, K., Damala, P., Orli, E., Papadaskalopoulou, C., Moustakas, K., Malamis, D., Loizidou, M., 2015. Valorisation opportunities related to wastewater and animal by-products exploitation by the Greek slaughtering industry: current status and future potentials. Waste and Biomass Valorization. https://doi.org/10.1007/s12649-015-9368-1.
van Horne, P.L.M., Bondt, N., 2013. Competitivness of the UE poultry meat sector. International comparison base year 2013.
Van Zanten, H.H.E., Mollenhorst, H., De Vries, J.W., Van Middelaar, C.E., Van Kernebeek, H.R.J., De Boer, I.J.M., 2014. Assessing environmental consequences of using co-products in animal feed. Int. J. Life Cycle Assess. 19, 79–88. https://doi.org/10.1007/s11367-013-0633-x.
Westhoek, H., Lesschen, J.P., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., Leip, A., van Grinsven, H., Sutton, M.A., Oenema, O., 2014. Food choices, health and environment: effects of cutting Europe's meat and dairy intake. Global Environ. Change 26, 196–205. https://doi.org/10.1016/j.gloenvcha.2014.02.004.

Wiedemann, S.G., McGahan, E.J., Murphy, C.M., 2017. Resource use and environmental impacts from Australian chicken meat production. J. Clean. Prod. 140, 675–684. https://doi.org/10.1016/j.jclepro.2016.06.086.

Wierbicki, E., Deatherage, F.E., 1958. Determination of water-holding capacity of fresh meats. J. Agric. Food Chem. 6, 387–392. https://doi.org/10.1021/jf60087a011.

Winkler, T., Schopf, K., Aschemann, R., Winiwarter, W., 2016. From farm to fork - a life cycle assessment of fresh Austrian pork. J. Clean. Prod. 116, 80–89. https://doi.org/10.1016/j.jclepro.2016.01.005.

Woodgate, S., van der Veen, J., 2004. The role of fat processing and rendering in the European Union animal production industry. Biotechnol. Agron. Soc. Environ.

Woodgate, S.L., Wilkinson, R.G., 2021. The role of rendering in relation to the bovine spongiform encephalopathy epidemic, the development of EU animal by-product legislation and the reintroduction of rendered products into animal feeds. Ann. Appl. Biol. https://doi.org/10.1111/aab.12676.

Xue, L., Prass, N., Gollnow, S., Davis, J., Scherhaufer, S., Östergren, K., Cheng, S., Liu, G., 2019. Efficiency and carbon footprint of the German meat supply chain. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.8b06079.

Zampori, L., Pant, R., 2019. Suggestions for updating the Product Environmental Footprint (PEF) method. JRC Technical Reports. https://doi.org/10.2760/424613, 2019.

Zielbauer, B.I., Franz, J., Viezens, B., Vilgis, T.A., 2016. Physical aspects of meat cooking: time dependent thermal protein denaturation and water loss. Food Biophys. 11, 34–42. https://doi.org/10.1007/s11483-015-9410-7.