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Hidden flows assessment in the agri-food sector: evidence from the Italian beef system

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Abstract

Purpose – The study proposes Material Flow Analysis (MFA) methodology as a tool to measure and qualify food waste in the Italian beef supply chain in each stage of the food supply chain, from farm to fork. In particular, the authors attempt to: (1) measure resources consumption and waste generation toward companies' and policymakers' sustainable evaluations; (2) enhance consumers' education in the field of agri-food resilience and sustainability.

Design/methodology/approach – MFA is applied to the entire Italian sector of beef consumed as packaged fresh product in 2020, during the Covid-19 pandemic. The analysis regards bovine, which represent roughly one-third of the national meat flow. To collect data, bottom-up and top-down mixed approach is applied. Subsequently, MFA results are used to calculate the wastage-related losses in terms of embedded natural resources (e.g. water, energy).

Findings – In 2020, it results that the Italian meat industry slaughtered more than 1.15 Mt of bovine to produce approximately 0.29 Mt of fresh meat, 0.69 Mt of by-products and over 0.015 Mt of food waste at households, while 0.15 Mt of beef meat is destined to catering services and food industry (out-of-boundaries). In terms of hidden natural resources, it emerged that, on average, more than 94bn m3 of water, approximately 101,000 TJ of energy and over 11,500 t of PET and PE trays are required to sustain the entire beef system.

Originality/value – This research is one of the few studies proposing MFA methodology as a tool to measure food waste and hidden associated flows in the agri-food sector. This analysis shows its utility in terms of natural resources (water, energy, materials) and waste quality/quantity evaluation, hidden flows accounting and development of new educational strategies toward food waste minimization and sustainability at household consumption.

Keywords Beef industry, Material flow analysis, Waste management, Agri-food sector

Paper type Research paper

1. Introduction

The Italian meat industry, which accounts for over 15% (20bn euro) of the domestic agri-food value (ISMEA, 2019a, b, c), represents a core business for the national economy, but requires huge amounts of natural resources and generates different typologies of waste, from food waste to packaging (Djekic and Tomasevic, 2016). On global scale, per capita meat

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consumption reaches its peak in North America (approximately 95 kg), followed by Oceania (70 kg) and Europe (65 kg), recording growth perspectives estimated at 2% by 2028 (Statista, 2021a). Therefore, meat industry shows either an increase in the overall consumption as a result of population growth or an increase in per capita meat consumption (Henchion *et al.*, 2014), affecting at the same time economy, society and environment in terms of resources and waste management (Allievi *et al.*, 2015). Worldwide, it is estimated that 987m heads of cattle have been bred in 2020 with a little decrease (−1.4%) compared to 2012 data (Statista, 2021b). In Europe, each year more than 77m bovine are bred, of which roughly 8.3% belongs solely to Italy, representing the fifth largest beef farmer in Europe (Eurostat, 2021). Statistics (Joint Research Center, 2010) estimate that over 29% (191 Mt of CO2e) of the entire greenhouse-gases (GHG) fluxes in the livestock production (661 Mt CO2e) derive from cattle breeding, of which approximately 20 kg of CO2e per kg of beef is generated in Italy.

On global scale, food commodities production and consumption represent an ever-growing challenge (Spiertz and Ewert, 2009; Béné *et al.*, 2019) – even more so, after the COVID-19 outbreak (Galanakis, 2020) – to which must be added the rising concern of food waste (Schanes *et al.*, 2018; Kim *et al.*, 2019). International reports (FAO, 2020; United Nations Environment Programme, 2021) and academic research (Caldeira *et al.*, 2019) have assessed that, each year, more than 1.3bn tons of food are generated either in developed or developing countries, of which approximately 85–88 Mt in Europe (FUSIONS, 2016). According to (Caldeira *et al.*, 2019), meat represents the fourth most wasted food category in Europe, accounting for over 14.2 Mt on an average production of 61.7 Mt (23%), and its largest quantity is discarded at final consumption (7.3 Mt), processing and manufacturing (2.9 Mt), food service and retail (1.7 Mt). Therefore, either national or international authorities have proposed several strategies toward sustainability and circularity in the agri-food sector, as confirmed by the *Sustainable Development Goals* (United Nations, 2021) or the *Closing the Loop* strategy (European Commission, 2018).

To this extent, considering the intense use of natural resources and the sharp production of GHG emissions, several authors have tried to address their research toward agri-food environmental, economic and social challenges. Indeed, as far as concerns resource consumption, Alexander *et al.* (2017) have demonstrated significant correlations between livestock production, food waste and mass, energy and protein losses, highlighting the urgent need for agribusiness efficiency. In addition, Cesari *et al.* (2018) have discussed possible suitable managing procedures to minimize agri-food ecological impacts, with livestock production being highly correlated to environmental issues such as deforestation, climate change, water pollution and biodiversity loss on global scale (Fiore *et al.*, 2018; Spada *et al.*, 2019). Then, Magalhães *et al.* (2020) and Mosna *et al.* (2021), focusing on the meat production, have estimated that the amount of wasted meat (3.5% of global food waste) corresponds to over 29% of the global food waste carbon footprint, suggesting the need for valorization either in the food and nonfood sectors. However, a concrete assessment of the hidden flows in the Italian beef supply chain is still missing, as well as limited in other realities.

In the light of these premises, the present research, through the application of the material flow analysis (MFA), investigates the beef supply chain metabolism and its related hidden and/or virtual material flows (i.e. energy, water, packaging) with a double purpose: (1) to measure resources consumption and waste generation toward companies' and policymakers' sustainable evaluations; and (2) to enhance consumers' education in the field of agri-food resilience and sustainability. Indeed, although academia and authorities have recognized the crucial importance of natural resources and waste management (e.g. Sustainable Development Goals, Farm to Fork Strategy), food-related energy, water and material streams remain underresearched. Therefore, the insights from the Italian beef system, replicable to different agricultural and industrial realities, contribute to the scarce empirical studies about hidden flows in the agribusiness, giving theoretical and managerial recommendations and highlighting, both at managerial and government level, the need for sustainability and circular assessments.

2. Materials and methods

2.1 Material flow analysis

The present research, in line with the EU Commission Delegated Decision 2019/1597 (OJEU, 2019a, b), applies the mass balance approach to assess beef meat flows, as well as hidden flows in terms of natural resources (e.g. water, energy). The MFA, defined as a "systematic assessment of the state and change of materials flow and stock in space and time" (Brunner and Rechberger, 2017), is an effective tool for assessing sustainability and circularity within entire national systems (Jacobi *et al.*, 2018), single industrial sectors (De Marco *et al.*, 2009) and single products (Lagioia *et al.*, 2012). In recent years, several studies have discussed the importance of MFA to better understand industrial sectors' metabolism and highlight hidden and/or virtual flow associated single products (Rahman and Kim, 2020; Rajkovic *et al.*, 2020), but only a few have been investigating the agri-food sector with reference to energy, water and food waste.

In accordance with Hendriks *et al.* (2000), the analysis followed systematic steps: (1) identification of material flows and definition of the "qualitative" model; (2) calculation of flows ("quantitative" model) and evaluation of results; and (3) interpretation of flows in order to identify opportunities and achieve social and environmental goals. To perform flows and calculations, the freeware STAN 2.6. (substance flow ANalysis) was used. This software, developed by the Institute for Water Quality, Resources and Waste Management at Vienna University of Technology, balances material and substance flows within a specific system ("beef meat production") and does not contain an internal database. Further, this study applies SankeyMATIC software to create Sankey diagrams, since it helps to compare the scale of resource flows and easily illustrates flows networks and related interconnections.

2.2 Literature background of material flow analysis in the agri-food sector research

In recent years, although a plethora of studies have applied the MFA to analyze raw material consumption and waste generation (Lederer *et al.*, 2021; Lombardi *et al.*, 2021; Westbroek *et al.*, 2021), only a few have explored its utility to assess sustainability and circularity in the agri-food sector. As highlighted by a review on Web of Science, one of the richest collections of citation indexes of academic research articles published in the most significant journals, books and proceedings worldwide, it emerged that scarce efforts have been conducted to investigate agricultural stage (Ghani *et al.*, 2015), industrial processing (Amicarelli *et al.*, 2020), food distribution and final consumption (Ju *et al.*, 2016; Leray *et al.*, 2016) with reference to food commodities. Among them, Tamura and Fujie (2014) have analyzed the material cycle of agriculture in Japan, with reference to sugar cane, pasturage and beef cattle, highlighting the importance of MFA studies to create economic and environmental value through industrial symbiosis. Further, Wyngaard and Kissinger (2019) proposed the analysis of desert food production systems, applied to bell peppers, identifying biophysical strengths and weaknesses of different technologies and suggesting greater investments in the role of public policies, while Amicarelli *et al.* (2021) defined the MFA as an essential tool in supporting waste managers toward food waste minimization. In addition, Leray *et al.* (2016) applied the MFA at final consumption to assess food provisioning, storage and management practices, emphasizing its utility in terms of socioeconomic evaluations under quantitative (how much) as well as qualitative (what, why) perspectives.

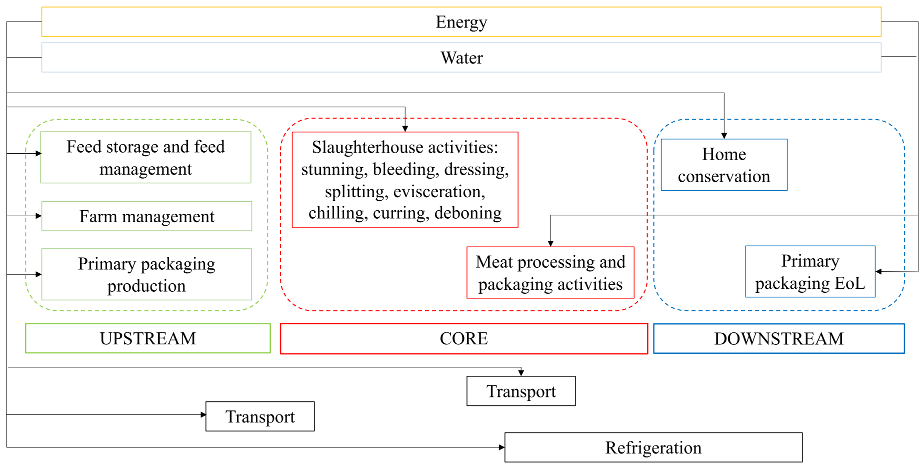
2.3 Boundaries, functional unit and general assumptions

The analysis respective to the entire Italian beef production in 2020 is so-called "beef production system." The functional unit is 1 ton (t) of fresh packaged meat for human nutrition consumed in Italy. The outputs considered within the analysis are: (1) "fresh meat," intending packaged beef cuts available for home consumption; (2) "by-products," meaning edible and inedible offal, skin, blood (category I-II) and other materials (category III); (3) "waste," intending hazardous, nonhazardous and food waste; (4) "wastewater," thus water from any combination of households, industrial, commercial and agricultural activities (OJEU, 2009; Tilley *et al.*, 2014; Galanakis, 2020). In accordance with Beretta *et al.* (2013), the authors intend "food waste" as food originally produced for human consumption but later employed for nonfood uses or energy recovery (e.g. animal feed, bioethanol production, incinerator).

The boundaries of the analysis cover all segments of the beef supply chain, from agricultural step to the final consumption stage (Figure 1). The boundaries include: (1) feed storage and management; (2) farm management; (3) primary packaging production (PET or PE trays); (4) slaughterhouse activities; (5) meat processing and packaging activities; (6) home conservation; (7) primary packaging end-of-life (EoL). Refrigeration (cold chain) has also been considered within the energy consumption calculations at slaughterhouse, at retail and at home. In regard to packaging, this work considers, in line with EDPCoop (2020), that approximately 16% of its composition comes from recycled PET (rPET), while over 84% from virgin PET. In terms of packaging EoL, it is assumed that more than 46% of the entire amount of PET circulating within the "beef production system" is collected and recycled. The remaining quota is addressed to energy recovery (47%) and landfill (less than 7%) (Corepla, 2019; ISPRA, 2016; Sustainable Development Foundation, 2020).

In terms of transport, three main steps have been considered: (1) from farm to slaughterhouse, in a range from 175 to 350 km; (2) from slaughterhouse to meat processing, between 125 and 250 km; (3) from meat processing to retail stores, between 100 and 200 km. Moreover, the authors have hypnotized the use of two typologies of trucks: 16 t (from farm to slaughterhouse) and 26 t (from slaughterhouse to retail stores) (LCAfood.dk, 2007; mit.gov.it, 2021). Transport from retail to households has not been included, as well as transport related to packaging, which is the trip from manufacturing to the logistic platform.

Figure 1 illustrates the flow diagram for the Italian beef industry. Bred live cattle are received and washed from manure and other pollutants. Slaughtering consists of essential operations: (1) stunning with mechanical, electrical or gas methods; (2) bleeding; (3) dressing,



Source(s): Personal elaboration by the authors

Figure 1.
Flow diagram for the Italian beef industry

to remove the skin, head, hoof and hide; (4) splitting and evisceration, to obtain edible and inedible parts, casings and paunch manure; (5) chilling; and (6) cutting and deboning (Heinz and Hautzinger, 2007).

2.4 Data collection

Although data acquisition is difficult for MFA (Rahman and Kim, 2020), it was conducted according to a top-down approach, based upon national and international reports, scientific articles and national databases. Moreover, to fill in data gaps, the authors contacted one of the first Italian companies in the field of sustainable meat chains and used the research triangulation to improve and increase the overall validity and credibility of the data sets and information. By means of merging primary data and secondary data (analysis of previous research and firms' reports and documents on website), the research triangulation allows to exploit the synergistic effects of joining investigative techniques to decrease the bias of a single observation in comparison of multiple data (Eisenhardt, 1989, 2002; Stake, 2006).

Table 1 illustrates an overview of the Italian livestock and slaughterhouse consistency in 2018 and 2020, before and during Covid-19 pandemic. It is important to highlight that, in the first half of 2020 (due to the lock down), the number of slaughtered cattle decreased by 17.8%. However, it has increased from June to December, approaching the 2018 levels. At first glance, a significant decrease in the average weight of cattle occurs (−14%), but also a slight decrease in the number of slaughtered animals (less than 3%), followed by an obvious decrease in the weight of the Italian cattle entering the slaughterhouse (−16%).

In order to investigate the Italian beef industry, the authors have collected companies' data according to Inalca (2018) and EDPCoop (2020). Data have been collected from Northern (Mantova), Central (Reggio Emilia, Modena, Faenza) and Southern (Avellino, Messina) farms and slaughterhouses, for an amount of more than 200 farms, 19 slaughterhouses and 3 distribution centers. These units contribute to the production, slaughtering and distribution of approximately one-third of Italian slaughtered cattle (over 700,000 heads per year).

Since the majority of data derived from national and international reports, as well as from Italian official statistics, the present research did not carry out an uncertainty data analysis. Only a few values, which differ from one report to another (e.g. food waste at households, transport from upstream stages to core and downstream ones), have been expressed with a range of diverse values. Therefore, both because the analysis led to low uncertainty level and because certain values would not have added further value to the paper, the authors did not conduct an uncertainty analysis (Lombardi *et al.*, 2021). Last, presenting the present research a static MFA focused on a single year, theoretical and managerial implications are only qualitatively discussed (Geng *et al.*, 2021).

Table 2 illustrates the inventory for water, energy and waste (input-output table) for 1 ton of fresh meat.

Table 1. Livestock and slaughterhouse consistency in Italy (2018–2020)

	Unit		2018	2020	Var. (2020/2018)
Italian reared cattle	Heads	a	5,949,393	5,993,015	0.73%
Average weight	t	b	0.52	0.45	−14.04%
Italian live weight	t	a × b	3,098,683	2,678,878	−13.55%
Slaughtered animals	Heads	c	2,658,875	2,582,535	−2.87%
Italian slaughtered live weight	t	b × c	1,382,814	1,154,393	−16.52%
Slaughter yield	%		56.90	54.90	

Source(s): Personal elaboration by the authors on Istat, 2020a, b

Table 2. Inventory for water, energy and waste (input-output table) for 1 t of fresh meat

Functional unit: 1 t of fresh packaged meat for human consumption	Feed	Downstream Farm management	Packaging production	Slaughterhouse activities	Core Meat processing and packaging activities	Downstream Home conservation	Packaging EoL
Input							
Renewable energy (MJ)	0	0	1,000	2,800	250	130	0.38
Nonrenewable energy (MJ)	32,000	11,000	2,400	29,000	9,200	4,700	10
Net use of fresh water (liters)	830,000	27,000	1,700	44,000	29,000	1,100	51
Output							
Hazardous waste disposed (g)	5.3	0	0.063	0	0	0	0
Nonhazardous waste disposed (kg)	67	6	19	0	100	0	25
Slaughterhouse by-products (I - II category) (kg)	0	0	0	754	80	0	0
Slaughterhouse by-products (III category) (kg)	0	0	0	158	0	0	0
of which							
Material for recycling (kg)	0	13	0	245	47	0	11.5
Materials for energy recovery (kg)	0	0	0	0	0	0	12
Exported energy (MJ)	0	0	0	0	0	0	410

Source(s): Frischknecht *et al.*, 2005, LCAfood.dk, 2007, GURI, 2013, Inalca, 2018, EDPCoop, 2020

3. Results

3.1 The Italian beef meat flow

Figure 2 illustrates the beef meat flow along the whole food supply chain, from upstream stages, including farm management activities (e.g. breeding activities) to downstream ones (e.g. home consumption, home conservation and disposal).

At the beginning, of the global number of animals bred on national land (5,993,015 heads for more than 2,678,878 t of live weight), only 43% are sent to slaughterhouse (2,582,535 heads for more than 1,154,393 t of live weight). Core activities are essentially distinguished within: (1) slaughterhouse operations; (2) meat processing; (3) logistic platform activities to retail. First, animals are subjected to stunning with mechanical, electrical or gas methods, then to bleeding to obtain blood and to dressing to remove the skin, head, hoof and hide. Subsequently, dead animals are split and eviscerated, to obtain edible and inedible parts, casings and paunch manure. Later, at meat processing, half-carcasses are moved to processing/logistic platforms for further deboning and packaging activities. Beef cuts (of different weight) are portioned and packaged in PET or PE trays and sent to retail stores for final consumption, for catering services and food industry (out of boundaries).

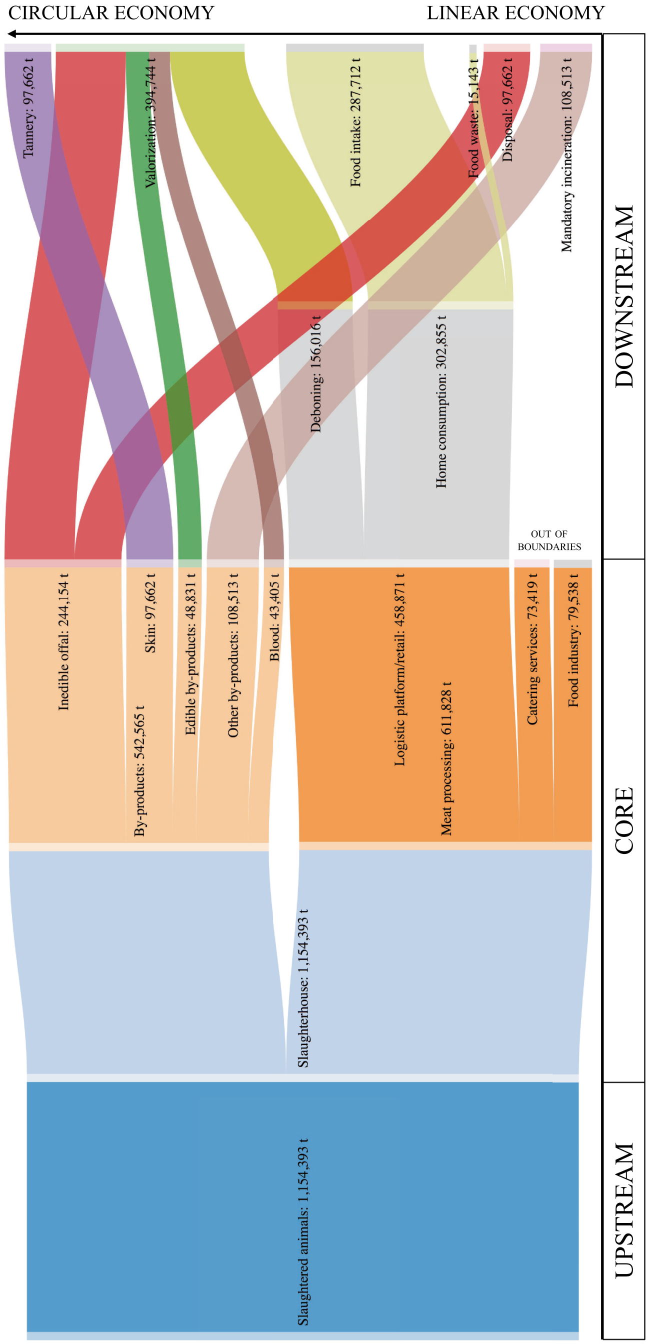
According to Figure 1, two main materials are obtained at slaughterhouse: (1) half-carcasses (611,828 t); and (2) by-products (542,565 t). If the half-carcasses are considered as homogeneous material, then the by-products can be divided into different subcategories, with different opportunities for valorization or disposal, as follows: (1) inedible offal (244,154 t); (2) skin (97,662 t); (3) edible products (48,831 t); blood (43,405 t); other by-products belong to category III and are intended for mandatory incineration (108,513 t). On the logistic platform, half-carcasses destined to home consumption (458,871 t) are further deboned, thus beef cuts arriving to households' have been estimated in 308,855 t (approximately 27% of slaughtered weight). At home, as stated by literature on food consumption behavior and food waste issue (Hamerschlag and Venkat, 2011), an additional 4–5% of food waste occurs, meaning that beef available for nutritional intake is assessed in only 287,712 (25% of slaughtered weight).

As stated by results, several by-products are destined to circular economy activities (e.g. skin to tanneries, edible by-products to food uses, inedible offal to recycling), but others are intended for disposal (more than 40% of inedible offal). It is clear that, despite the positive picture, there is still room for the industrial sector circularization (i.e. 221,318 t of by-products and food waste intended for disposal and/or incineration).

3.2 The food-related hidden flows: water, energy and packaging

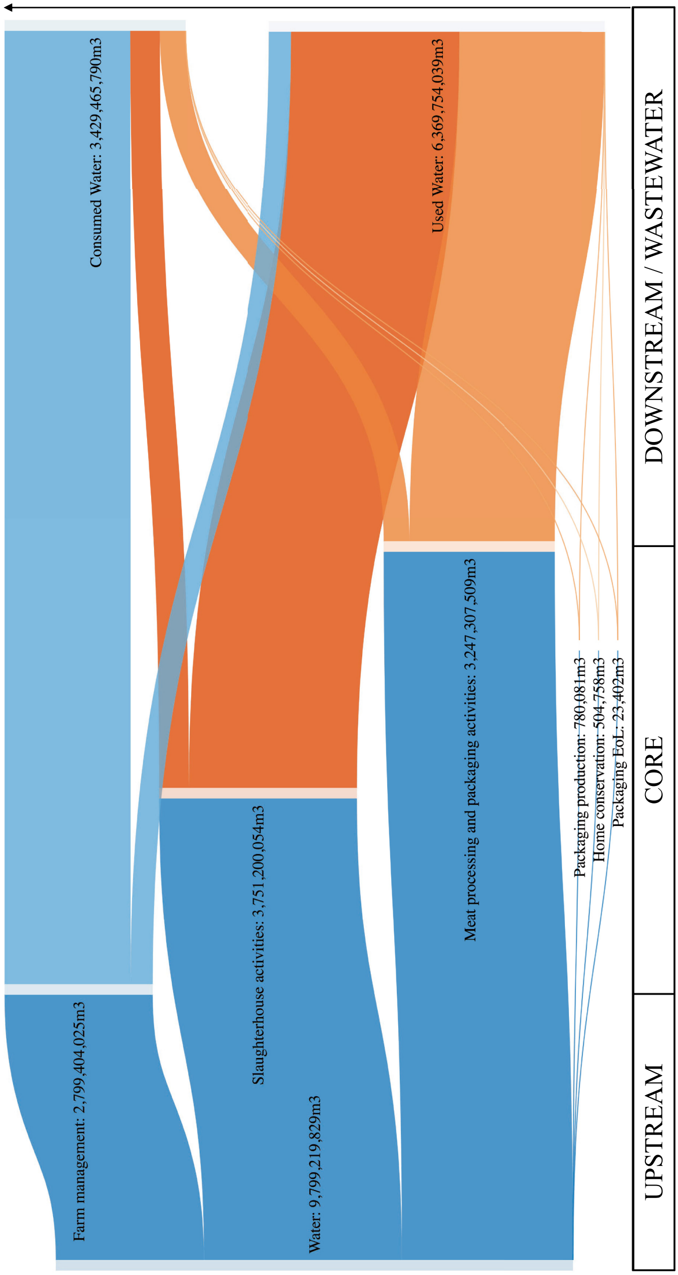
The beef supply chain hides some significant material and energy flows that are crucial in all environmental accounting investigations. These flows regard: (1) water along the whole food chain, from feed storage to farm management, as well as from slaughterhouse activities to home conservation; (2) energy (electricity) either for farm management, core operations or transport activities; and (3) water and energy involved in the primary packaging (PET or PE trays) production and EoL.

As illustrated by Figure 3, the beef supply chain could be considered as a water intensive production. At a first glance, it is clear that the majority of water supply is consumed at watering (approximately 76,143,762,280–92,940,180,430 m^3) and farm management operations (among 2,239,522,420–3,359,283,630 m^3), with the major amount of water embedded at upstream stages. Later, a significant amount of water is required at the slaughterhouse, where more than 2,575,450,783–4,926,949,324 m^3 is required, as well as during meat processing and packaging activities (approximately 3,247,307,510 m^3). Only a few shares of water are embedded at home conservation, where globally more than 504,750 m^3 is required.



Source(s): Personal elaboration by the authors

Figure 2.
Sankey diagram for the Italian beef meat flow (t/2020)



Source(s): Personal elaboration by the authors

Figure 3.
Sankey diagram for water consumption and water use (m^3/2020)

As for the water streams leaving the system, the authors have conveniently distinguished between "consumed waster" and "used water," according to Hashimoto and Moriguchi (2004) and Hashimoto *et al.* (2004). Indeed, "consumed" products are "products that changed from one shape to another along the supply chain, yet not losing their hidden usefulness" (e.g. water used for cattle watering), while "used" products are those "used for their intended purposes, but later are discarded with degraded commodity characteristics" (e.g. water for animals or plants washing). Therefore, the "consumed water" could be further used and recycled after purification processes.

It has been estimated that farm management and feed operations require more than 49,600 TJ of energy, of which quite anything comes from renewable sources (Figure 4).

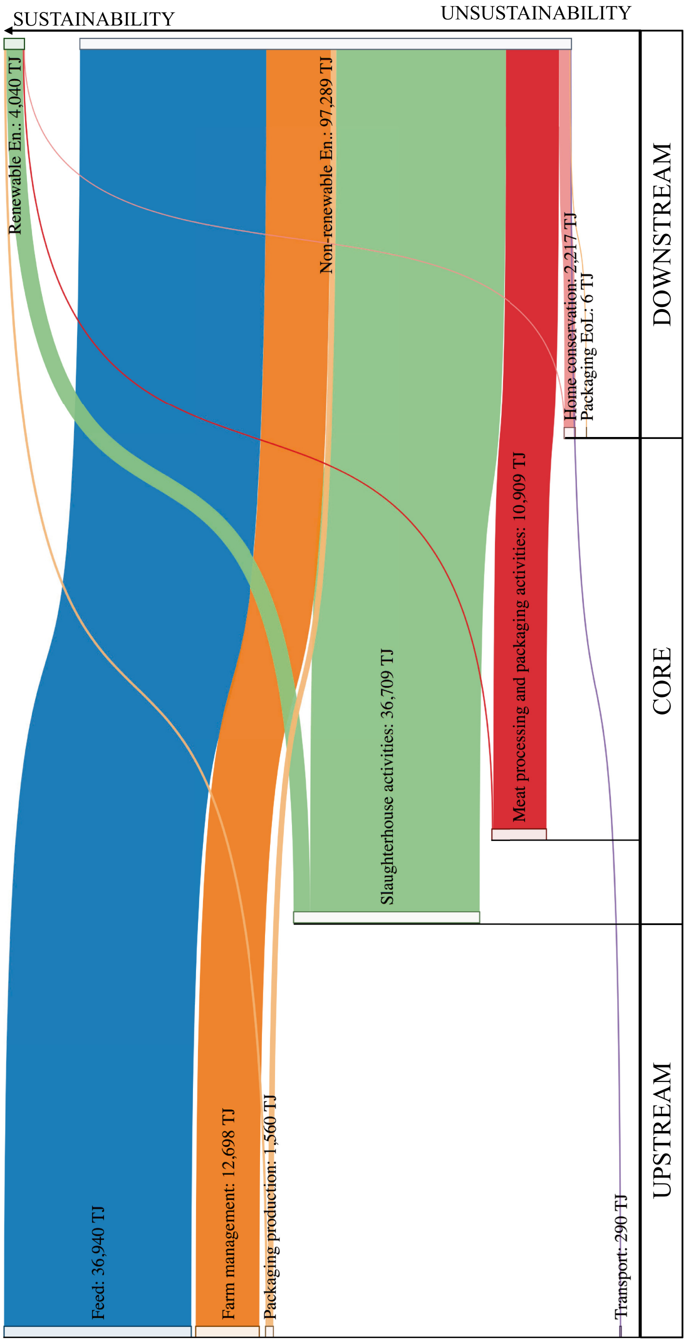
Slaughterhouse activities consume more than 36,700 TJ, of which approximately 9% are obtained through renewable sources while more than 91% from nonrenewable ones. The same goes for meat processing and slaughterhouse activities, where more than 10,900 TJ of energy is required (3% comes from renewable sources, 97% from not renewable ones). During the downstream stages, home conservation and packaging EoL require respectively 2,200 TJ and approximately 6 TJ of energy, of which only 3% derives from renewable sources. In terms of transport, based on an average diesel consumption of 2.8 km/l (26 t trucks) and 4 km/l (16 t trucks) (mit.gov.it, 2021), the national energy consumption equals approximately 195–386 TJ (average value: 290 TJ) and is divided in following stages: (1) from farm to slaughterhouse, 125–250 TJ; (2) from slaughterhouse to meat processing, 42–84 TJ; (3) from meat processing to retail stores, 25–50 TJ. Concisely, more than 77% of energy is used during upstream stages, while approximately 22% at core phase and less than 1% has been estimated at downstream stages.

According to Figure 5, the shares in energy sources are divided as follows: (1) at farm management, the majority of energy comes from oil (56%), natural gas (26%) and coal (12%), with a small percentage of energy that stems from other sources; (2) at slaughterhouse, more than 68% of energy derives from natural gas, approximately 16% from oil and 15% from coal. On average, it is estimated that along the whole beef production only a small percentage of energy comes from renewable sources (4% for hydroelectric, while <1% for solar, wind and biomass power).

It is estimated that each kg of meat requires approximately 25 grams (g) of primary packaging distinguished as follows: (1) 20 g of PET tray; and (2) 5 g of PE film. Therefore, the entire Italian beef production requires less than 11,500 t of packaging, with an energy hidden flow of 1,500 TJ and more than 780,000 liters of water. In terms of energy, more than 30% of energy comes from renewable sources, while the other quota from nonrenewable ones. Furthermore, at packaging EoL stage, it has been estimated that approximately 46% of the entire packaging entering system (5,290 t) is recycled, of which more than 845 t within the Italian beef system (with an energy feedback of approximately. In addition, more than 47% (5,400 t) is destined to energy recovery, while less than 7% (810 t) addressed to landfill. Theoretically, considering the average solid recovered fuel (SDR) calorific value in approximately 14 MJ/kg (GURI, 2013), it is possible to estimate the virtual waste-to-energy power embedded within the Italian beef system in approximately 161 TJ.

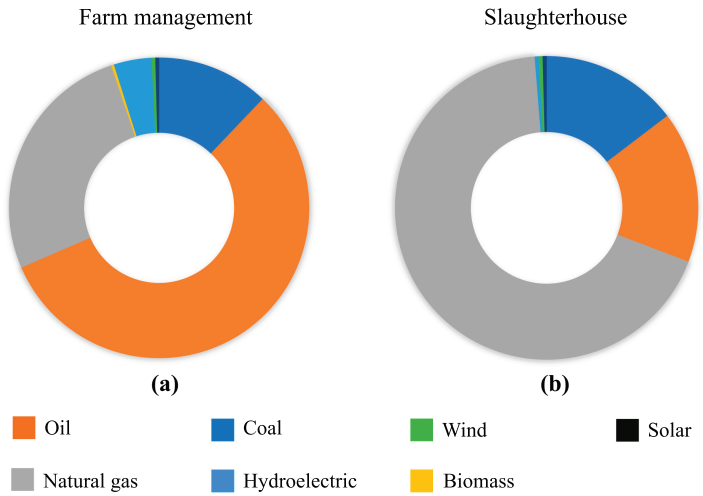
4. Discussion

The application of the mass balance approach, essential to better understand the Italian beef supply chain metabolism and to highlight hidden and/or virtual material flows associated to foods, helps: (1) to measure resources consumption and waste generation toward companies' and policymakers' sustainable evaluations; and (2) to enhance consumers' education in the field of agri-food resilience and sustainability. Indeed, the MFA allows the presentation of results in a focused, comprehensive and logical way, while simultaneously facilitates



Source(s): Personal elaboration by the authors

Figure 4.
Sankey diagram for energy (TJ/2020)



Source(s): Personal elaboration by the authors

Figure 5. Share in energy sources at farm management (a) and slaughterhouse (b)

transparency, understanding and communication within and without system boundaries (e.g. among companies, consumers and decision-makers). Moreover, its results offer an appropriate visualization of procedures, facts and features, which are universally understandable for wider age groups and transversal purposes.

4.1 Hidden flows measurement

As far as concerns the measurement of hidden and/or virtual material (i.e. fresh meat, water, PET), energy (e.g. fossil fuels) and waste (e.g. packaging, by-products) streams, the mass balance approach represents an essential instrument to comprehend industrial sectors metabolism. At first glance, it is estimated that more than 542,565 t of by-products have been generated in 2020, of which 45% are composed by inedible offal, 18% by skin, 9% by edible by-products, 8% by blood and over 20% by other by-products. The immediate and comparable snapshot helps to identify the addressed by-products and helps create background to implement industrial symbiosis at a local level. It also helps execute industrial networks at regional or country level. For instance, mass-balance results allow understanding of the allocation of secondary raw materials in different food and nonfood sectors, under a detailed perspective (what, where and how much), with specific reference to the production of food ingredients, per foot and animal feed, high-added value products and bio-energy production. Indeed, considering the circular economy perspective and the "production of goods by nature" definition (Nebbia, 1998), secondary raw materials have been assessed in more than: (1) 97,662 t of skin for tanneries; (2) 394,744 t of inedible and edible by-products, blood and bones for feed and nonfood valorization (e.g. bioenergy or bioethanol production). However, the mass-balance approach has also highlighted the significant existence of material waste (e.g. inedible offal for disposal), as well as by-products addressed to mandatory incineration (OJEU, 2009) and food waste at retail and households, toward which national and international strategies have been implemented in the field of education and minimization (United Nations, 2015). However, as stated by these results, to pursue circular and sustainable approaches, it is fundamental to obtain the detailed knowledge of the industrial metabolism of each sector, from the agricultural to the consumption stage.

According to Brunner and Rechberger (2017), under a theoretical perspective, it is essential to take care of a few aspects: (1) widespread datasets are essential to assess dynamic material flow models, comparable either in space or in time (e.g. between different industrial sectors; among the same industrial sectors but in different years); (2) uncertainty and sensitive analyses are significant to achieve robustness, reliability and comparability; (3) the mix of top-down and bottom-up approaches is essential to assess and calibrate models; (4) material qualities and opportunities for recyclability are crucial to "close the loop." Furthermore, static MFA is still considered attractive and significant, providing suitable snapshots for a system in space and time, as well as offering valuable patterns of material use and losses within a system (Binder *et al.*, 2009). Indeed, the static approach provides insights into systems at a specific time, allowing the holistic assessment of their current state (Allesch and Brunner, 2017), offering the chance to precisely establish the annual stocks and flows of natural resources and final products, as well as to monitor quantities in and between the processes in the system (Deshpande *et al.*, 2020).

4.2 Managerial and public authorities' implications

In the field of companies' and policymakers' sustainable evaluations, the mass-balance approach provides useful results either for environmental or resource management at private and public level (Wyngaard and Kissinger, 2019). Indeed, the mass-balance approach could be considered as a valuable and cost-efficient tool that provides a significant background for the choice of best-suited recycling and/or treatment technology. Its utility, among others, regards the precise identification of the hotspots of the supply chain, from cradle to crave, and the related opportunities. As highlighted within the beef system, MFA results have demonstrated the precise amount of water required per each stage of the production, clarifying unequivocally the more water-intensive and less water-intensive stages of the supply chain. Further, it has undoubtedly illustrated the energy load per stage of the supply chain, offering interesting perspective for sustainability and circular economy research. Although the Italian beef sector seems particularly virtuous in terms of resources and materials circularization (over 90% of by-products are intended for food and nonfood uses), there is still room for the energy renewal and for the enhancement of the energy systems sustainability through public call for tenders, considering that approximately 4% of total energy requirement comes from renewable sources (i.e. wind, solar, biomass and hydroelectric). These results, however, are not surprising. As stated by Carni Sostenibili (2015), the census of the Italian companies still shows a fragmented picture, mainly small-size family businesses and their low interest in aggregation phenomena (De Boni and Forleo, 2019). Therefore, circular approaches are still difficult to achieve and further efforts to enhance meat companies and avoid business fragmentation are required.

To this extent, the adoption of mass balance approaches to investigate either explicit or hidden flows in the meat industry (at single industrial plant and at country level) could help agri-food actors and public authorities to create actor bonds, resource ties and activity links, with the development and the connection among stakeholders being the key to renew still fragmented business networks (Havenid *et al.*, 2016). Indeed, smallholder farmers and fragmented businesses, which often deal with lack of information and knowledge, as well as weak financial capacity and limited collaboration and network orientation (Dicecca *et al.*, 2016; Tell *et al.*, 2016), could adopt mass-balance approaches and participate in value chain knowledge exchange to improve sustainability and circularity of their businesses. Further, the introduction of circular and sustainability assessments could help food suppliers, farmers, processors and retailers to increase their productivity by reducing resource consumption and waste production, improving at the same time customer relations and reputation through environmental protection strategies (Chauhan *et al.*, 2018; Esposito *et al.*, 2020). Small businesses should consider the multiple economic (e.g. value creation, local business opportunities), environmental (e.g. reduction of resource consumption) and social (e.g. creation of job opportunities) prospects arising from the implementation of industrial symbiosis at local and global level.

4.3 Promotion of consumers' education

The mass-balance approach could represent an essential tool to promote consumers' education in the field of agri-food resilience and sustainability through the adoption of simple, transparent and easily interpretable diagrams. To this extent, the static MFA provides a clear snapshot of all activities taking place in the system life cycle, representing a highly simplified but detailed educational tool (Deshpande *et al.*, 2020). Considering the need for explicit educational toolkits containing exercises to explain the concept of sustainability and circular economy (Favuzzi *et al.*, 2020; Feijoo *et al.*, 2020), useable by an average user (e.g. pupils, university students, rural and urban citizens), the chance of developing a static tool, which frames a certain phenomenon contextualizing it in a specific space and time, could help in reaching the aims of education *for* sustainable development, intending *for* as a purpose.

Although food waste generation occurs along the entire food supply chain, upstream stages (i.e. final consumption at home and at food services) represent the most critical steps in terms of thrown away food. Unsustainable and uneducated food consumption behaviors are the results of multiple variables such as bad purchases planning, incorrect labels' interpretation, unsuitable leftovers recovery into tasty and nutritious recipes and incorrect storage activities (Mondéjar-Jiménez *et al.*, 2016; Roe *et al.*, 2018; Secondi, 2019). However, among others, one of the main drivers of food waste behavior, either in developed or developing countries, is due to the unawareness of the wastage-related losses of natural resources required to produce raw ingredients and transform them into meals, as well as the ignorance of the food waste associated environmental impacts (estimated in over 3.3 Gigatons of CO2e each year) and the related financial losses (estimated in over US$1 trillion) (FAO, 2013; Poore and Nemecek, 2018; Our World in Data, 2020; Adamashvili *et al.*, 2019; Fiore *et al.*, 2015). Therefore, the MFA results can be useful for representing such set of variables (e.g. natural resources, energy flows, water requirement) through easily interpretable graphics (e.g. Sankey diagrams, flowcharts, input-output tables), giving direct and clear qualitative and quantitative information (Leray *et al.*, 2016). For instance, the opportunity to comprehend and track water and energy flows associated to wasted fresh beef could represent the background toward effective communication strategies, as well as a chance to learn new food consumption and wastage behaviors among consumers. Instructions and teachings focused on food management, cooking and storage skills could be better received and retained if illustrated in simple and immediate ways, above all among young generations, which are considered to be "healthy carriers" of inspiration, hope and culture toward sustainable development. In addition, innovative awareness campaigns, based, for example, on educational games, could apply the MFA results in an absolutely effective way, showing in a noncoercive but ludic way (Floricel, 2020) the hidden side of food waste, orienting consumers toward sustainable behaviors and inspiring best practices in the field of food waste minimization.

4.4 Theoretical implications, limitations and future research

Under a theoretical perspective, the MFA provides transparent and comparable snapshots of the investigated agri-food or industrial sector. Indeed, being a useful tool for environment, management and waste managers, it: (1) offers an early recognition of potentially harmful or beneficial stocks; (2) sets priorities according to environmental protection measures, resource preservation and waste management; and (3) allows the design of products, processes and systems toward environmental sustainability. In addition, the mass-balance approach could be applied at various stages of the supply chain, as well as across different agri-food sectors, pursuing sustainable targets at local and global level. Then, in the field of consumers' education, the presentation of MFA results through Sankey diagrams makes the understanding of the different issues, in space and time, particularly clear. Specifically, the application of the software STAN 2.6. to perform flows and calculation offers a graphical modeling with an automatic conversion into a mathematical model, considers data uncertainty and helps in reconciliating contradicting data, allowing the simplest and most precise analyses.

However, although the MFA allows the investigation (and comprehension) of quantitative features of flows, processes and stock within the system, tracking at the same time inputs, outputs, waste and emissions over time, data availability is one of the main challenges to its full effectiveness. Indeed, in addition to the intrinsic degree of uncertainty within MFA calculations, robustness and reliability of statistics are crucial to guarantee a strong interpretation of results, as well as an adequate interpretation of the agri-food systems metabolism. However, one possible direction for improvement could concern the application of the methodology right from the smallest entity of the supply chain, which would be a single industrial plant. Indeed, the drafting of mass and energy balances, associated to the construction of intersectoral tables, could make the calculation of aggregate values more reliable and robust at industrial or country level. It is not to be underestimated the application of the methodology – not too expensive and not too demanding from the workforce side – at the level of the single plant for the achievement of the sustainability objectives and for the achievement of important environmental certifications (e.g. ISO, EMAS).

5. Conclusions

The present research, through the application of the MFA to the entire Italian beef system, assessed that, in 2020, more than 1.15 Mt of bovine have been slaughtered to produce approximately 0.29 Mt of fresh meat, 0.69 Mt of by-products and over 0.015 Mt of food waste at households, while 0.15 Mt of beef meat has been allocated to catering services and food industry. Further, considering the utility of the methodology to evaluate natural resources and energy hidden flows, it has been estimated that, on average, more than 94bn m^3 of water, approximately 101,000 TJ of energy and over 11,500 t of PET and PE trays have been consumed to sustain the entire beef system. Then, it is possible to conclude that the MFA represents not only a material and energy inventory, but a useful tool toward resources and waste management research, providing well-grounded records to calculate environmental indicators (e.g. carbon and water footprint), as well as to assess environmental impacts (e.g. life cycle assessment) in the agribusiness. Indeed, it offers a better understanding of metabolism of various agri-food industries, highlighting hidden and/or virtual material flows associated to the entire beef supply system. In addition, it helps policymakers and companies' management to enhance resource consumption and waste production evaluations. Lastly, it could represent the ground to promote consumers' education toward agri-food resilience and sustainability.

References

Adamashvili, N., Chiara, F. and Fiore, M. (2019), "Food loss and waste, a global responsibility?!", *Economia Agro-Alimentare*, Vol. 21 No. 3, pp. 825-846. doi: 10.3280/ECAG2019-003014.

Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D. and Rounsevell, M.D.A. (2017), "Losses, inefficiencies and waste in the global food system", *Agricultural Systems*, Vol. 153, pp. 190-200.

Allesch, A. and Brunner, P.H. (2017), "Material flow analysis as a tool to improve waste management systems: the case of Austria", *Environmental Science and Technology*, Vol. 51 No. 2017, pp. 540-551.

Allievi, F., Vinnari, M. and Luukkanen, J. (2015), "Meat consumption and production – analysis of efficiency, sufficiency and consistency of global trends", *Journal of Cleaner Production*, Vol. 92 No. 2015, pp. 142-151.

Amicarelli, V., Bux, C. and Lagioia, G. (2020), "How to measure food loss and waste? A material flow analysis application", *British Food Journal*, Vol. 123 No. 1, pp. 67-85.

Amicarelli, V., Rana, R., Lombardi, M. and Bux, C. (2021), "Material flow analysis and sustainability of the Italian meat industry", *Journal of Cleaner Production*, Vol. 299, 126902.

Béné, C., Oosterveer, P., Lamotte, L., Brouwer, I.D., de Haan, S., Prager, S.D., Talsma, E.F. and Khoury, C.K. (2019), "When food systems meet sustainability – current narratives and implications for action", *World Development*, Vol. 113, pp. 116-130.

Beretta, C., Stoessel, F., Baier, U. and Hellweg, S. (2013), "Quantifying food losses and the potential for reduction in Switzerland", *Waste Management*, Vol. 33, pp. 764-773.

Binder, C.R., Van Der Voet, E. and Rosselot, K.S. (2009), "Implementing the results of material flow analysis", *Journal of Industrial Ecology*, Vol. 13, pp. 643-649.

Brunner, P.H. and Rechberger, H. (2017), *Handbook of Material Flow Analysis. For Environmental, Resource and Waste Engineers*, 2nd ed., CRC Press, Taylor & Francis Group, LLC, Boca Raton, London, New York, NY.

Caldeira, C., De Laurentiis, V., Corrado, S., van Holsteijn, F. and Sala, S. (2019), "Quantification of food waste per product group along the food supply chain in the European Union: a mass flow analysis", *Resources, Conservation and Recycling*, Vol. 149, pp. 479-488.

Carni Sostenibili (2015), "The sustainability of meat in Italy", available at: https://www.carnisostenibili.it/wp- content/uploads/2014/10/Summary-Sustainable-Meat.pdf (accessed 16 September 2020).

Cesari, V., Zucali, M., Bava, L., Gislon, G., Tamburini, A. and Toschi, I. (2018), "Environmental impact of rabbit meat: the effect of production efficiency", *Meat Science*, Vol. 145 No. 2018, pp. 447-454.

Chauhan, A., Debnath, R.M. and Singh, S.P. (2018), "Modelling the drivers for sustainable agri-food waste management", *Benchmarking: An International Journal*, Vol. 25 No. 3, pp. 981-993.

Corepla (2019), "Relazione sulla gestione, 2019", available at: https://www.corepla.it.accessed17.February.2021.

De Boni, A. and Forleo, M.B. (2019), "Italian halal food market development: drivers and obstacles from experts' opinions", *Journal of Islamic Marketing*, Vol. 10 No. 4, pp. 1245-1271.

De Marco, O., Lagioia, G., Amicarelli, V. and Sgaramella, A. (2009), "Constructing physical input- output tables with material flow analysis (MFA) data: bottom-up case studies", in Sangwon, S. (Ed.), *Handbook on Input-Output Economics in Industrial Ecology*, Springer, Netherlands, pp. 161-187.

Deshpande, P.C., Philis, G., Brattebø, H. and Fet, A.M. (2020), "Using Material Flow Analysis (MFA) to generate the evidence on plastic waste management from commercial fishing gears in Norway", *Resources, Conservation and Recycling: X*, Vol. 5, 100024.

Dicecca, R., Pascucci, S. and Contò, F. (2016), "Understanding reconfiguration pathways of agri-food value chains for smallholder farmers", *British Food Journal*, Vol. 118 No. 8, pp. 1857-1882.

Djekic, I. and Tomasevic, I. (2016), "Environmental impacts of the meat chain – current status and future perspectives", *Trends in Food Science and Technology*, Vol. 54 No. 2016, pp. 94-102.

EDPCoop (2020), "Environmental product declaration of coop beef meat", available at: https://www.environdec.com/library/epd495 (accessed 12 February 2021).

Eisenhardt, K.M. (1989), "Building theories from case study research", *Academy of Management Review*, Vol. 14 No. 4, pp. 532-550.

Eisenhardt, K.M. (2002), "Building theories from case study research", in Huberman, A.M. and Miles, M.B. (Eds), *The Qualitative Researchers' Companion*, Sage Publications, Thousand Oaks, California, CA.

Esposito, B., Sessa, M.R., Sica, D. and Malandrino, O. (2020), "Towards circular economy in the agri-food sector. A systematic literature review", *Sustainability*, Vol. 12, p. 7401.

European Commission (2018), "Communication from the commission to the European parliament, the Council, the European economic and social committee and the committee of the regions on a monitoring framework for the circular economy", available at: https://ec.europa.eu/environment/circular- economy/pdf/monitoring-framework.pdf.

Eurostat (2021), "Agricultural production - livestock and meat", available at: https://ec.europa.eu/eurostat/statistics-explained/index.php/Agricultural_production_-_livestock_and_meat.

FAO (2013), *Food Wastage Footprint. Impacts on Natural Resources, Summary Report*, FAO, Rome.

FAO (2020), *The State of Food and Agriculture, 2020. Overcoming Water Challenges in Agriculture*, Publisher: FAO, Rome.

Favuzzi, N., Trerotoli, P., Forte, M.G., Bartolomeo, N., Serio, G., Lagravinese, D. and Vino, F. (2020), "Evaluation of an alimentary education intervention on school canteen waste at a primary school in Bari, Italy", *International Journal of Environmental Research and Publich Health*, Vol. 17 No. 7, 2558.

Feijoo, G. and Moreira, M.T. (2020), "Fostering environmental awareness towards responsible food consumption and reduced food waste in chemical engineering students", *Education for Chemical Engineers*, Vol. 33, pp. 27-35.

Fiore, M.A., Contò, F. and Pellegrini, G. (2015), "Reducing food losses: a (dis)-opportunity cost model", *Rivista Di Studi Sulla Sostenibilita*, No. 1, pp. 151-166.

Fiore, M., Spada, A., Contò, F. and Pellegrini, G. (2018), "GHG and cattle farming: Co-assessing the emissions and economic performances in Italy", *Journal of Cleaner Production*, Vol. 172 No. 20, pp. 3704-3712.

Floricel, S. (2020), "Understanding the nature and effects of digital games in promoting sustainability", *Global Economic Observer*, Vol. 8 No. 2, pp. 125-134.

Frischknecht, R., Jungbluth, N., Althaus, H.J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Namecek, T., Rebitzer, G. and Spielmann, M. (2005), "The Ecoinvent database: overview and methodological framework", *International Journal of Life Cycle Assessment*, Vol. 10, pp. 3-9.

FUSIONS (2016), *Estimates of European Food Waste Levels*, available at: https://www.eu-fusions.org/phocadownload/Publications/Estimates%20of%20European%20food%20waste%20levels.pdf.

Galanakis, C.M. (2020), "Food waste valorization opportunities for different food industries", in Galanakis, C.M. (Ed.), *The Interaction of Food Industry and Environment*, Academic Press.

Geng, J., Hao, H., Sun, X., Xun, D., Liu, Z. and Zhao, F. (2021), "Static material flow analysis of neodymium in China", *Journal of Industrial Ecology*, Vol. 24, pp. 114-124.

Ghani, L.A., Mahmood, N.Z. and Ali, N. (2015), "Coupling material flow analysis (MFA) and geographic information system (GIS) methodologies for screening flow and emission of biomass energy in the agricultural system", *Proceedings of 2017 International Conference on Imaging*, Signal Processing and Communication, pp. 180-185.

GURI (Gazzetta Ufficiale della Repubblica Italiana), *Decreto 14 febbraio 2013, n. 22. Regolamento recante disciplina della cessazione della qualifica di rifiuto di determinate tipologie di combustibili solidi secondari (CSS)*, available at: https://www.arpa.veneto.it/temi-ambientali/rifiuti/file-e-allegati/normativa/normativa-nazionale/2013/DM%2014-2-13%20n_22.pdf.

Hamerschlag, K. and Venkat, K. (2011), "Meat eater's guide. To climate change + health. Lifecycle assessment: methodology and results", Environmental Working Group and Clean Metrics Corp.

Hashimoto, S. and Moriguchi, Y. (2004), "Proposal of six indicators of material cycles for describing society's metabolism: from the viewpoint of material flow analysis", *Resources, Conservation and Recycling*, Vol. 40 No. 3, pp. 185-200.

Hashimoto, S., Moriguchu, Y., Saito, A. and Takafumi, O. (2004), "Six indicators of material cycles for describing society's metabolism: application to wood resources in Japan", *Resources, Conservation and Recycling*, Vol. 40 No. 3, pp. 201-223.

Havenvid, M.I., Håkansson, H. and Linné, Å. (2016), "Managing renewal in fragmented business networks", *IMP Journal*, Vol. 10 No. 1, pp. 81-106.

Heinz, G. and Hautzinger, P. (2007), *Meat Processing Technology for Small to Medium Scale Producers*, RAP Publication, Bangkok, 2007/20. FAO.

Henchion, M., McCarthy, M., Resconi, V.C. and Troy, D. (2014), "Meat consumption: trends and quality matters", *Meat Science*, Vol. 98 No. 2014, pp. 561-568.

Hendriks, C., Obernosterer, R., Müller, D., Kytzia, S., Baccini, P. and Brunner, P.H. (2000), "Material flow analysis: a tool to support environmental policy decision making. Case-studies on the city of Vienna and the Swiss lowlands", *The International Journal of Justice and Sustainability*, Vol. 5 No. 3, pp. 311-328.

Inalca (2018), *Hamburger surgelati. EDP – Dichiarazione ambientale di prodotto*, available at: https://www.montanafood.it/wp-content/uploads/2019/03/S-P-00711-Montana-Frozen-Hamburger-2018-Italian-version.pdf.

ISMEA (2019a), *Allevamento bovino da carne. Scheda di settore*, available at: http://www.ismeamercati.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/3515#MenuV.

ISMEA (2019b), *Carne suina e salumi - Scheda di settore*, available at: http://www.ismeamercati.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/3516#MenuV.

ISMEA (2019c), *Avicoli e uova – Scheda di settore*, available at: http://www.ismeamercati.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/3517.

ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale) (2016), *Rapporto Rifiuti urbani Edizione, 2016*, available at: www.isprambiente.gov.it.

Istat (2020a), *Comunicato stampa. L'impatto del Covid-19 sul comparto degli allevamenti*, available at: https://www.istat.it/it/archivio/251036.

Istat (2020b), *Macellazioni – Carni Rosse, dati mensili*, available at: http://dati.istat.it/Index.aspx?DataSetCode=DCSP_MACELLAZIONI.

Jacobi, N., Haas, W., Wiedenhofer, D. and Mayer, A. (2018), "Providing an economy-wide monitoring framework for the circular economy in Austria: status quo and challenges", *Resources, Conservation and Recycling*, Vol. 137, pp. 156-166.

Joint Research Center (2010), *Evaluation of the Livestock Sector's Contribution to the EU Greenhouse Gas Emissions (GGELS)*, Joint Research Centre, Institute for Environment and Sustainability, Climate Change Unit, Ispra.

Ju, M., Osako, M. and Harashina, S. (2016), "Quantitative analysis of food products allocation into food consumption styles for material flow analysis of food", *Journal of Material Cycles and Waste Management*, Vol. 18 No. 3, pp. 589-597.

Kim, J., Rundle-Thiele, S. and Know, K. (2019), "Systematic literature review of best practice in food waste reduction programs", *Journal of Social Marketing*, Vol. 9 No. 4, pp. 447-466.

Lagioia, G., Calabrò, G. and Amicarelli, V. (2012), "Empirical study of the environmental management of Italy's drinking water supply", *Resources, Conservation and Recycling*, Vol. 60, pp. 119-130.

LCAfood.dk (2007), *LCA Food Database*, available at: http://www.lcafood.dk (accessed 12 February 2021).

Lederer, J., Gassner, A., Fellner, J., Mollay, U. and Schremmer, C. (2021), "Raw materials consumption and demolition waste generation of the urban building sector 2016-2050: a scenario-based material flow analysis of Vienna", *Journal of Cleaner Production*, Vol. 288, 125566.

Leray, L., Sahakian, M. and Erkman, S. (2016), "Understanding household food metabolism: relating micro-level material flow analysis to consumption practices", *Journal of Cleaner Production*, Vol. 125, pp. 44-55.

Lombardi, M., Rana, R. and Fellner, J. (2021), "Material flow analysis and sustainability of the Italian plastic packaging management", *Journal of Cleaner Production*, Vol. 287, 125573.

Magalhães, V.S.M., Ferreira, L.M.D.F., César, A.S., Bonfim, R.M. and Silva, C. (2020), "Food loss and waste in the Brazilian beef supply chain: an empirical analysis", *International Journal of Logistics Management*, Vol. 32 No. 1, pp. 214-236.

mit.gov.it (2021), *Costo chilometrico medio relativo al consumo di gasolio delle imprese di autotrasporto per conto terzi*, available at: https://www.mit.gov.it/mit/mop_all.php?p_id=11897.

Mondéjar-Jiménez, J.A., Ferrari, G., Secondi, L. and Principato, L. (2016), "From the table to waste: an exploratory study on behaviour towards food waste of Spanish and Italian youths", *Journal of Cleaner Production*, Vol. 138 No. 1, pp. 8-18.

Mosna, D., Bottani, E., Vignali, G. and Montanari, R. (2021), "Environmental benefits of pet food obtained as a result of the valorisation of meat fraction derived from packaged food waste", *Waste Management*, Vol. 125, pp. 132-144.

Nebbia, G. (1998), "Produzione di merci a mezzo di natura", *Consumi e Società*, Vol. 12 No. 2, pp. 38-43.

OJEU (Official Journal of European Union) (2009), *Regulation (EC) No 1069/2009 of the European Parliament and of the Council of 21 October 2009 - Laying down Health Rules as Regards Animal By-Products as derived Products Not No Human Consumption and Repealing Regulation (EU) No 1774/2002 (Animal By-Products Regulation)*, available at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009R1069.

OJEU (Official Journal of the European Union (2019a), *Commission Delegated Decision (EU) 2019/1597 of 3 May 2019*, available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri5OJ:L:2019: 248:TOC.

OJEU (Official Journal of the European Union) (2019b), *Commission Delegated Decision (EU) 2019/1597 of 3 May 2019 Supplementing Directive 2008/98/EC of the European Parliament and of the Council as Regards a Common methodology and minimum Quality Requirements for the uniform measurement of Levels of Food Waste, L.248/77. 2019*, available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2019.248.01.0077.01.ENG.

Our World in Data (2020), *Environmental Impacts of Food Production*, available at: https://ourworldindata.org/environmental-impacts-of-food#citation (accessed 31 March 2021).

Poore, J. and Nemecek, T. (2018), "Reducing food's environmental impacts through producers and consumers", *Science*, Vol. 360 No. 6392, pp. 987-992.

Rahman, S.M. and Kim, J. (2020), "Circular economy, proximity, and shipbreaking: a material flow and environmental impact analysis", *Journal of Cleaner Production*, p. 120681.

Rajkovic, S., Bornhöft, N.A., van der Weijden, R., Nowack, B. and Adam, V. (2020), "Dynamic probabilistic material flow analysis of engineered nanomaterials in European waste treatment systems", *Waste Management*, Vol. 113, pp. 118-131.

Roe, B.E., Phinney, D.M., Simons, C.T., Badiger, A.S., Bender, K.E. and Heldman, D.R. (2018), "Discard intentions are lower for milk presented in containers without date labels", *Food Quality Preferences*, Vol. 66, pp. 13-18.

Schanes, K., Dobernig, K. and Gözet, B. (2018), "Food waste matters - a systematic review of household food waste practices and their policy implications", *Journal of Cleaner Production*, Vol. 182, pp. 978-991.

Secondi, L. (2019), "Expiry dates, consumer behavior, and food waste: how would Italian consumers react if there were no longer 'best before' labels?", *Sustainability*, Vol. 11 No. 23, p. 6821.

Spada, A., Fiore, M., Monarca, U. and Faccilongo, N. (2019), "R&D Expenditure for new Technology in livestock farming: impact on GHG reduction in developing countries", *Sustainability*, Vol. 11 No. 24, p. 7129.

Spiertz, J.H.J. and Ewert, F. (2009), "Crop production and resource use to meet the growing demand for food, feed and fuel: opportunities and constraints", *NJAS - Wageningen Journal of Life Sciences*, Vol. 56 No. 4, pp. 281-300.

Stake, R. (2006), *Multiple Case Study Analysis*, Guildford Press, New York.

Statista (2021a), *Per Capita Consumption of Meat Worldwide from 2016 to 2018, with a Forecast for 2028, by Region*, available at: https://www.statista.com/statistics/1037429/per-capita-consumption-of-meat-worldwide-by-region/.

Statista (2021b), *Number of Cattle Worldwide from 2012 to 2020 (In million Head)*, available at: https://www.statista.com/statistics/263979/global-cattle-population-since-1990/.

Sustainable Development Foundation (2020), *L'Italia del riciclo*, available at: https://www.fondazionesvilupposostenibile.org/wp-content/uploads/dlm_uploads/Italia-del-riciclo-2020-Rapporto.pdf.

Tamura, S. and Fujie, K. (2014), "Material cycle of agriculture on Miyakojima island: material flow analysis for sugar cane, pasturage and beef cattle", *Sustainability*, Vol. 6 No. 2, pp. 812-835.

Tell, J., Hoveskog, M., Ulvenblad, P., Ulvenblad, P.O., Barth, H. and Ståhl, J. (2016), "Business model innovation in the agri-food sector: a literature review", *British Food Journal*, Vol. 118 No. 6, pp. 1462-1476.

Tilley, E., Ulrich, L., Lüthi, C., Reymond, Ph. and Zurbrügg, C. (2014), *Compendium of Sanitation Systems and Technologies*, 2nd Revised ed., Swiss Federal Institute of Aquatic Science and Technology (Eawag), Duebendorf, p. 175.

United Nations (2015), *Transforming Our World: The 2030 Agenda for Sustainable Development*, available at: https://sdgs.un.org/2030agenda (accessed 9 July 2020).

United Nations (2021), *Sustainable Development Goals*, available at: https://www.un.org/sustainabledevelopment/.

United Nations Environment Programme (2021), *Food Waste Index Report 2021*, United Nations Environment Programme Publications, Nairobi.

Westbroek, C.D., Bitting, J., Craglia, M., Azevedo, J.M.C. and Cullen, J.M. (2021), "Global material flow analysis of glass: from raw materials to end of life", *Journal of Industrial Ecology*, Vol. 25 No. 2, pp. 333-343.

Wyngaard, S.R. and Kissinger, M. (2019), "Materials flow analysis of a desert food production system: the case of bell peppers", *Journal of Cleaner Production*, Vol. 227, pp. 512-521.

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