Journal of Environmental Management 313 (2022) 115001

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Material flow cost accounting (MFCA) to enhance environmental entrepreneurship in the meat sector: Challenges and opportunities

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ARTICLE INFO

Keywords:
Material flow cost accounting
Agri-food industry
Meat industry
Food waste
Circular economy
Environmental entrepreneurship

ABSTRACT

The material flow cost accounting (MFCA) is one of the most broadly standardized tools accepted in environmental, social and economic research, which traces and quantifies material flows and stock in physical and economic units. Although its application has been recently developed in the field of resource and waste management, few academic articles have investigated its value towards food waste management, which represents a topical concern on a global scale. The present research applies the MFCA to investigate the material, energetic and economic costs associated with the Italian beef, pork and poultry production, exploring related challenges and opportunities towards the enhancement of the environmental entrepreneurship in the meat sector. The present countryside analysis is based on literature and empirical data collected during the Covid-19 pandemic. It highlights the need to improve knowledge on food waste issue under the economic perspective and its dual impact: when it is generated, in terms of income losses due to by-products and finished products sales failure, and when it is disposed, in terms of disposal costs sustained by farms, processing plants and distribution and sales centers. It is estimated that more than 0.45–0.50 Mt of fresh meat is wasted along the entire Italian agri-food chain, equal to more than 242–268 million euros, to which additional energy and water losses should be added (435–481 million euros). MFCA results are useful for business decisions, highlighting quantities, qualities and costs otherwise not considered in common financial reports.

1. Introduction

Food waste measurement represents one of the most important challenges towards food waste minimization (Corrado et al., 2019; European Commission, 2021a). Being topical nowadays, food waste have been accounted among national and international strategies, becoming part of the crucial Sustainable Development Goals (SDGs) in terms of sustainable consumption and production (Fonseca et al., 2020; United Nations, 2021), as well as part of the Farm to Fork Strategy towards a fair, healthy and environmental-friendly food system (European Commission, 2021b). Similarly to other commodities, food follows the production-consumption-disposal lifecycle pattern (Islam and Huda, 2019), impacting the environment twice: the first time, when it is produced; and the second time, when it is disposed (Scherhaufer et al., 2018; Moraes et al., 2021). Therefore, the issue has even been considered among circular economy actions all around the world, such as the new circular economy action plan (European Commission, 2021c; Fidélis et al., 2021), one of the main building blocks of the European Green Deal (Fetting, 2020).

On a global scale, food waste represents one of the most impacting waste streams (Barrera and Hertel, 2021), generating over 1.3 billion tons of food (Xue et al., 2017; Gustavsson et al., 2011) and being responsible for over 3.3 Gigatons of CO_2 equivalent emissions (FAO, 2013; Ritchie and Roser, 2020). Further, food waste affects social and economic perspectives. It has been estimated that more than 1 trillion dollars (United Nations Environment Programme, 2021a, 2021b) are lost due to logistic inefficiencies, technological disruptions and unsustainable consumption behaviors among companies and consumers (Canali et al., 2017). Considering food waste quantification per product group along the entire agri-food chain (Caldeira et al., 2019), more than 129 million tons (Mt) of food are wasted in the European Union, of which fruit and vegetables account for approximately 59 Mt, cereals for over 15 Mt and meat for 14 Mt. In order to reach sustainable development goals and tackle food waste, the European Commission has increased the efforts to measure food waste and inedible parts, enacting the Commission Delegated Decision (UE) 2019/1597 as regards a common methodology and minimum quality requirements for the uniform measurement of levels of food waste (OJEU, 2019). It states that

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https://doi.org/10.1016/j.jenvman.2022.115001
Received 17 September 2021; Received in revised form 7 March 2022; Accepted 28 March 2022
Available online 2 April 2022
0301-4797/

the in-depth measurement should be performed by each State member on a regular basis, per stage of the supply chain, every four years.

The material flow cost accounting (MFCA), based on the mass-balance approach proposed by the European Commission, represents a helpful tool to manage complex resources and waste streams (Kokubu and Tachikaw, 2013). As standardized by the ISO14051, the MFCA is defined as a tool to trace and quantify flows and stock of materials within a certain organization in physical and economic units (Jasch, 2009; ISO, 2011). MFAC is considered as an attractive decision-support tool in resource, waste and environmental management. Therefore, considering that the mass-balance approach is successfully applied to food waste streams (Allesch and Brunner, 2015), whereas the MFCA is still undiscovered and unapplied by researchers and academics, the present research illustrates its application to the Italian meat system analysis. Meat represents the third largest food category wasted in the European Union (Caldeira et al., 2019) and its production is more than 15% of the Italian agri-food value (Ismea 2019a, 2019b; 2019c). Based on these considerations, the present paper explores MFCA opportunities and challenges towards the enhancement of the environmental entrepreneurship in the meat sector, highlighting quantities, qualities and costs otherwise not considered in common financial reports. Although theoretical and technical studies in the field of food waste have been published, several efforts are still necessary to understand specific sector dynamics from managerial and public authorities' perspective, and this work tries to add one more action towards environmental entrepreneurship.

2. Literature review

In recent years, food waste research has spread, becoming one of the most topical concerns among environmental and sustainability researchers. It has gained recognition and priority as a global issue in 2011, when the FAO published the first study on global food waste (Gustavsson et al., 2011; Evans et al., 2013), whereas an intense upsurge has been recorded after the introduction of the SDGs (United Nations, 2021), driving authors towards the environmental and social assessment of food waste consequences. Researchers have highlighted a strong nexus between food waste, energy use and water consumption (da Rosa et al., 2021), stressing the need to promote sustainable processes towards food waste reduction (Zan et al., 2022), as well as natural resources protection (i.e., energy, water) and environmental security (Afkhami and Zarrinpoor, 2022). In addition, researches have been influenced by the Commission Delegated Decision (UE) 2019/1597, which addressed food waste measurement through the proposal of five measurement methodologies (i.e. diaries, questionnaires or in-depth interviews, mass-balance approach, direct measurement or waste composition analysis) and imposed its assessment at least every 4 years at country-level (OJEU, 2019). A large number of studies have been analyzing households' food consumption and food waste behaviors through questionnaires and food diaries, as illustrated by Ammann et al. (2021), Scalvedi and Rossi (2021) and Herzberg et al. (2020), whereas a few contributions have adopted the mass-balance approach to measure food waste along the entire food supply chain. Among the most significant, Amicarelli et al. (2020) have quantified food waste streams in the Italian potato industry, Caldeira et al. (2019) have explored food waste per product group in the European Union and Beretta et al. (2013) have quantified food waste streams and the potential for their reduction in Switzerland. However, although the aforementioned methodology proposes quantitative and qualitative tips for agri-food sector analyses providing a better understanding of the supply chain metabolism and emphasizing hidden and virtual flows associated to resource consumption and waste generation, scarce research has been so far carried on.

Walz and Guenther (2020) have indicated three main different reasons for choosing MFCA: (a) economic reasons, such as the identification of explicit or hidden costs; (b) environmental reasons, such as the reduction of waste of the minimization of the environmental impacts; and (c) organizational reasons, such as the enhancement of processes quality towards environmental entrepreneurship (Piwowar-Sulej et al., 2021), defined as "the process of discovering, evaluating, and exploiting economic opportunities of market failures which detract from sustainability, including those that are environmentally relevant". As stated by recent research (Hummels and Argyrou, 2021; Makhloufi et al., 2021), the environmental entrepreneurship aims at capturing eco-friendly opportunities while pursuing economic savings, and its success depends on the companies' ability to acquire and leverage organizational knowledge to tackle unsustainable failures, such as food waste (Szulecka et al., 2019). To this extent, it is supposed that MFCA could enhance corporate environmental performances decreasing financial and physical losses (Hyršlová et al., 2011), representing an appropriate source for decision-making and implementing of win-win relationships in the meat supply chain (Chang et al., 2015).

The MFCA has been recently applied to manufacturing systems like the textiles and garment industry to reduce negative product costs of ladies' lingerie companies (Dechampai et al., 2021), to the health service industry to minimize waste and save the environment from avoidable damages (Arieftiara et al., 2021), to the wastewater treatment plants to reduce the loss of investments and minimize waste generation and waste disposal costs (Ho et al., 2021) and to the hotel sector to explore either physical or monetary losses and improve resource efficiencies (Nyide, 2016). Kokubu and Kitada (2015) have explored the role of the MFCA under a managerial perspective, discussing its difference from other environmental management tools, enhancing MFCA capability to reconcile the environment and the economy by deeply understanding the manufacturing process. Such a tool supports resources efficiency increase through cost reductions, adding an innovative perspective to the existing environmental management tools (Schaltegger and Zvezdov, 2015; Yagi and Kokubu, 2018), like life cycle assessment or the ecological footprints (Bierer et al., 2015). However, few authors have implemented the MFCA in the agri-food sector, as illustrated by May and Guenther (2020) in the black currant juice production, by Dekamin and Barmaki (2019) in the soybean production and by Fakoyal and van der Poll (2012) in the brewery process, while no significant results have been obtained investigating the restaurant industry food waste scenario (Christ and Burritt, 2017). Considering the scarce application of MFCA on global scale, academic, managerial and governmental appreciation is still missing, and several efforts are required in the agri-food sector.

3. Research methodology

As stated by the ISO14001, the MFCA is based on the material balance principle, defined as the comparison of physical quantities of inputs, outputs and inventory changes in a quantity center over a specified time period (Jasch, 2009). However, compared to other conventional material and cost accounting tools (e.g., material flow analysis, companies' balance sheets), the MFCA isolated energy, water, materials and other overhead costs (i.e., CO_2 emissions) associated with lost resources, enabling companies to generate financial benefits and reduce adverse environmental impacts through the accounting of *explicit* and *hidden* cost flows. The present research, as proposed by reference literature (Hendriks et al., 2000; Christ and Burritt, 2016; Islam and Huda, 2019), applies a comprehensive and systematic approach, as follows: (a) identification of the functional unit and the system boundaries; (b) definition of natural resources and materials associated with the "Italian meat system"; (c) application of the material flow analysis with reference to beef, pork and poultry meat, highlighting material and energy flows (i.e., quantitative/qualitative material model); (d) measurement of explicit and hidden costs with reference to material, energy and emissions' flows (i.e., monetary model); (e) evaluation of results and interpretation.

3.1. System characteristics: definitions, functional unit and boundaries

The "Italian meat system" has been divided into two subsystems: the first one (so-called "meat flows" subsystem) investigates the entire meat flows (see Fig. 1a), and the second one (so-called "energy and waste flows" subsystem) accounts energy and water associated flows (see Fig. 1b). Fig. 1 illustrates both subsystems, providing either input or output flows along the entire food supply chain. Farm management encompasses breeding activities with reference to water and energy flows, whereas feedstock production is not considered in the present research. Slaughterhouse encompasses several operations, as follows: stunning, bleeding, dressing, splitting and evisceration, chilling, cutting and deboning (Heinz and Hautzinger, 2007). Retail and food service activities include further deboning operations.

As per system definitions, the present research explores food waste intended as "food (including non-edible parts) discharged, lost, degraded, consumed by pets or utilizes in non-food or energy fields" (Beretta et al., 2013; Galanakis, 2020). Although the FAO (2011) distinguishes between food loss and food waste, identifying food loss as occurring during the upstream stages of the food supply chain and food waste as occurring during the downstream stages, the authors refer to food waste considering both items. In addition, as proposed by Hartikainen et al. (2018), the concept of "side flow" has been considered, which encompasses food still expected to be consumed by humans, contaminated foods, foods used as feed and foods left in the field, composter or sent to waste treatment. In terms of material flows, three main outputs have been considered: (a) fresh meat; (b) co-products, specifically offal and other edible fractions different from fresh meat but still available either for food or non-food sector; and (c) by-products, composed by non-edible part addressed to non-food sectors. Thus, food waste is intended as the thrown away fraction of either final products, co-products and by-products.

The material flow analysis, intended as a "systematic assessment of the state and change of materials flows and stock in space and time" (Brunner and Rechberger, 2017), has been conducted to estimate and balance input and output flows in the Italian meat system. The functional unit, essential to assess energy and water meat-related flows, has been defined as 1 ton (t) of fresh meat. Then, in order to provide a comprehensive outlook of the entire Italian system, results have been extended to the entire Italian production (Ismea, 2019a; Istat, 2020, 2021). Beef meat includes calves (57%), cows and heifers (30%), steers (12%) and bulls (1%), pork includes pigs (93%), piglets (4%) and baconers (3%), whereas poultry includes chickens (94%), turkey (4%) and guinea fowls, geese and ducks (1%). As concerns the system boundaries, a gate to grave analysis has been carried out (Garcia--Herrero et al., 2018), considering upstream stages (i.e., farm management), core stages (i.e., slaughterhouse and packaging activities) and downstream stages (i.e., retail, food service and households' consumption). In addition, transport assumptions have been included: (a) 16 t trucks to move animals from farm to slaughterhouse (175–350 km); and (b) 26 t trucks to move fresh meat from meat processing plants to retail stores (100–200 km).

Data elaborations have been conducted through the STAN 2.6. (substance flow ANalysis) software, which balances material and substance flows and does not contain an internal database. As to develop a clear system, which represents real experiences as accurately as possible without compromising its easy understanding (Rubinstein and Kroese, 2016), uncertain quantities are expressed in ±5% in weight and are assumed as normally distributed on the basis of their mean values and normal distributions. Thus, a 95% confidence interval has been calculated through STAN 2.6. as well as rounding rules (Rechberger et al., 2014; Cencic, 2016a, 2016b).

3.2. Data acquisition, flows inventory and general assumptions

Subsystem 1 ("meat flows") and subsystem 2 ("energy and water flows") data sources have been collected through national and international reports, scientific articles, official databases and companies' data (see Appendix I, II, III). As far as the materials flows, the first step has regarded the identification of the number of slaughtered animals in Italy during the Covid-19 pandemic, their live and dead weight and their related slaughtering coefficient (Istat, 2021). Subsequently, the carcass allocation coefficients at slaughterhouse gate and at retail, as well as deboning ones at retail and food service, have been collected according to literature. Referring to poultry meat production, different from beef and pork meat one, and remembering that fresh chicken meat is retailed

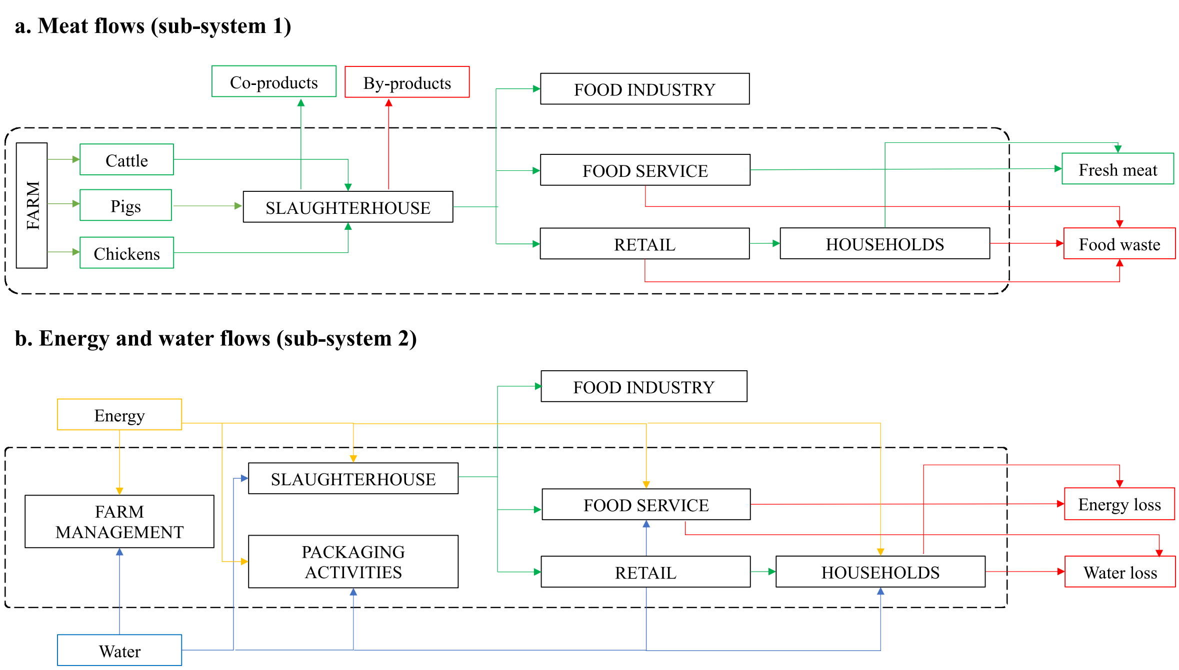

Fig. 1. General system for the Italian meat industry. Notes: Green lines = Meat flows. Yellow lines = Energy flows. Blue lines = Water flows. Red lines = Food, energy and water losses. . (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and consumed with bones, an additional deboning has not been considered. At last, literature food waste at households and food services coefficients have been considered. The research triangulation has helped authors in decreasing the bias of single observations, merging primary to secondary data (Eisenhardt, 1989, 2002; Stake, 2006). Table 1 illustrates materials inventory according to either subsystem 1 or subsystem 2.

Once the material flows have been established (i.e., quantitative/qualitative material model), energy and water flows have been assessed (Table 2). As to cope with the challenges of developing a model able to represent a real system as accurate as possible without compromising its easy understanding (Rubinstein and Kroese, 2017), energy and water flows associated with beef, pork and chicken have been assumed equal. In addition, energy associated with packaging production, packaging activities and packaging End-of-Life (EoL) has been estimated.

The third step was the assignment of monetary values to inputs, outputs and inventory items (Christ and Burritt, 2016), to create the quantitative economic model. In line with ISO (2011), common cost categories have been classified in material costs (i.e., raw materials, operating materials, water), energy costs (i.e., fuel for electricity), waste management costs (i.e., disposal costs) and additional costs (i.e., CO_2 emissions). Material flow costs have been assigned according to average prices defined in national reports and tariffs, as well as from international reports and statistics. Waste management costs have been derived from May and Guenther (2020), whereas CO_2 emission costs have been estimated from OECD (2021). As concerns average live weight and fresh meat prices, as well as carcasses and by-products (i.e., bones, tendons, fats) disposal prices, values have been collected according to Istat (2020), ISMEA (2021), Ministry of Economic Development (2021) and Ministry of Agricultural, Food and Forestry Policies (2020), as illustrated in Appendix I (a, b, c, d, e). Table 3 summarizes beef, pork and poultry cost inventory.

4. Results

The material flow analysis for the entire Italian meat system reports all input and output streams along the entire agri-food chain, from slaughterhouse to households and food services' consumption (see Fig. 2a). Cattle, pigs and chickens are transported from farm to slaughterhouse and then washed from manure and other pollutants. During slaughtering, edible co-products (0.17–0.18 Mt) and inedible by-products (1.10–1.22) are generated and addressed either to food or non-food uses. Among the inedible by-products, different typologies have been illustrated, as follows: (a) inedible offal, addressed to rendering (0.64–0.71 Mt); (b) blood (0.14–0.16 Mt); (c) skin and feathers (0.19–0.21 Mt); and (d) other residues addressed to incineration (0.13–0.14 Mt). As concerns carcasses, it is estimated that approximately 0.31–0.34 Mt are intended for food services purposes, whereas 1.77–1.96 Mt to retail and then to household consumption. At these stages, an additional deboning occurs, generating 0.34–0.38 Mt of bones, tendons and fats addressed to disposal. Last, fresh meat available for human consumption has been estimated at 1.63–1.80 Mt, whereas

Table 1
"Meat flows" (sub-system 1) inventory.

Process	Sub-process	Unit	Beef	Pork	Poultry
Slaughterhouse	Co-products (edible)	t	0.04	0.06	0.02
	Inedible offal	t	0.18	0.08	0.18
	Blood	t	0.03	0.03	0.04
	Skin and feathers	t	0.07	0.00	0.06
	Other	t	0.08	0.03	0.00
	Carcass	t	0.61	0.80	0.71
Carcass allocation	Food industry (out of boundaries)	t	0.13	0.70	0.13
	Food service	t	0.12	0.06	0.12
	Retail	t	0.75	0.24	0.75
Food service	Fresh meat	t	0.67	0.79	0.59
	Deboning	t	0.33	0.21	0.41
Retail	Fresh meat	t	0.66	0.77	1.00
	Deboning	t	0.34	0.23	0.00
Households	Fresh meat (address to human consumption)	t	0.95	0.10	0.92
	Food waste	t	0.05	0.05	0.08

(Source: Personal elaboration by the authors)

Table 2
"Energy and water flows" (sub-system 2) inventory.

Process	Sub-process	Input	Unit	Value
Farm management	Mother cow management	Nonrenewable energy	GJ	15.00
	Mother cow management	Water	kL	110.00
	Feed operations	Nonrenewable energy	GJ	32.00
	Feed operations	Water	kL	830.00
	Farm management	Nonrenewable energy	GJ	11.00
	Farm management	Water	kL	27.00
Packaging activities	Packaging production	Renewable energy	GJ	1.28
	Packaging production	Nonrenewable energy	GJ	3.90
	Packaging production	Water	kL	1.70
	Packaging activities	Renewable energy	GJ	0.25
	Packaging activities	Nonrenewable energy	GJ	9.20
	Packaging activities	Water	kL	29.00
	Packaging End-of-Life	Nonrenewable energy	GJ	0.01
Slaughterhouse	Slaughterhouse activities	Renewable energy	GJ	2.80
	Slaughterhouse activities	Nonrenewable energy	GJ	29.00
	Slaughterhouse activities	Water	kL	44.00
Food service	Food conservation	Renewable energy	GJ	0.13
	Food conservation	Nonrenewable energy	GJ	4.70
	Food conservation	Water	kL	1.10
Households	Home conservation	Renewable energy	GJ	0.13
	Home conservation	Nonrenewable energy	GJ	4.70
	Home conservation	Water	kL	1.10

(Source: Personal elaboration by the authors)

Table 3
Beef, pork and poultry costs' inventory (million euro/Mt).

Cost category	Item	min.	max.
Material costs	Cattle (for slaughtering)	3297	3644
	Pork (for slaughtering)	1302	1439
	Poultry (for slaughtering)	979	1082
	Cattle carcass	2632	2909
	Pork carcass	4057	4484
	Poultry carcass	2755	3045
	Co-products (edible offal)	7125	7875
	Inedible offal	428	473
	Blood	7410	8190
	Skin (raw leather)	10,735	11,865
	Beef fresh meat	16,758	18,522
	Pork fresh meat	7477	8264
	Poultry fresh meat	10,032	11,088
	Water	1653	1827
Energy costs	NRE (fuel)	1457	1610
	RE (biodiesel)	499	551
Waste management costs	Energetic recovery	14	16
	Carcases beef disposal	817	903
	Carcases pork disposal	228	252
	Carcases poultry disposal	219	242
Additional costs	CO_2 emissions	57	63

Notes: NRE = Nonrenewable energy; RE = Renewable energy.

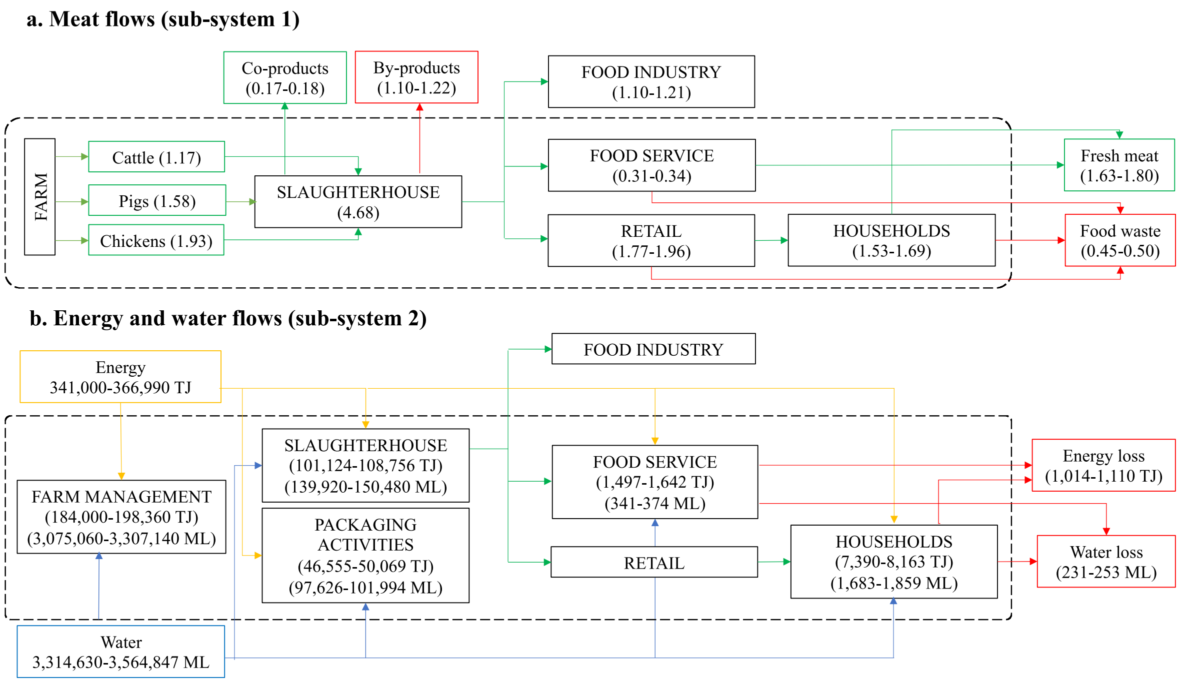

Fig. 2. Material flow analysis for the entire meat system (Mt, TJ, ML). Notes: Green lines = Meat flows. Yellow lines = Energy flows. Blue lines = Water flows. Red lines = Food, energy and water losses. Meat flows are expressed in Mt. Energy flows are expressed in TJ. Water flows are expressed in ML. Energy and water losses are "hidden" within food waste. See Appendix II (a, b, c, d) for detailed calculations. . (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

food waste (i.e., wasted fraction of fresh meat, bones, skin and other residues) has been assessed at 0.45–0.50 Mt.

As illustrated by the subsystem 2 (see Fig. 2b), the total amount of energy required has been evaluated in 341,000–366,990 TJ (TJ), whereas the water requirement along the entire food supply chain in 3,314,060–3,307,140 ML (ML). The largest amount of energy and water consumption occurs at farm management and breeding operations, as well as at slaughtering and packaging activities (i.e., packaging production, packaging activities and packaging End-of-Life). As concerns food service and households' operations, energy and water consumption are related to food conservation (i.e., cooling systems). In terms of transportation, it is estimated that more than 511–1023 TJ are required to move livestock from farm to slaughterhouses, whereas approximately 119–240 TJ to transport fresh meat from slaughterhouses to retail stores

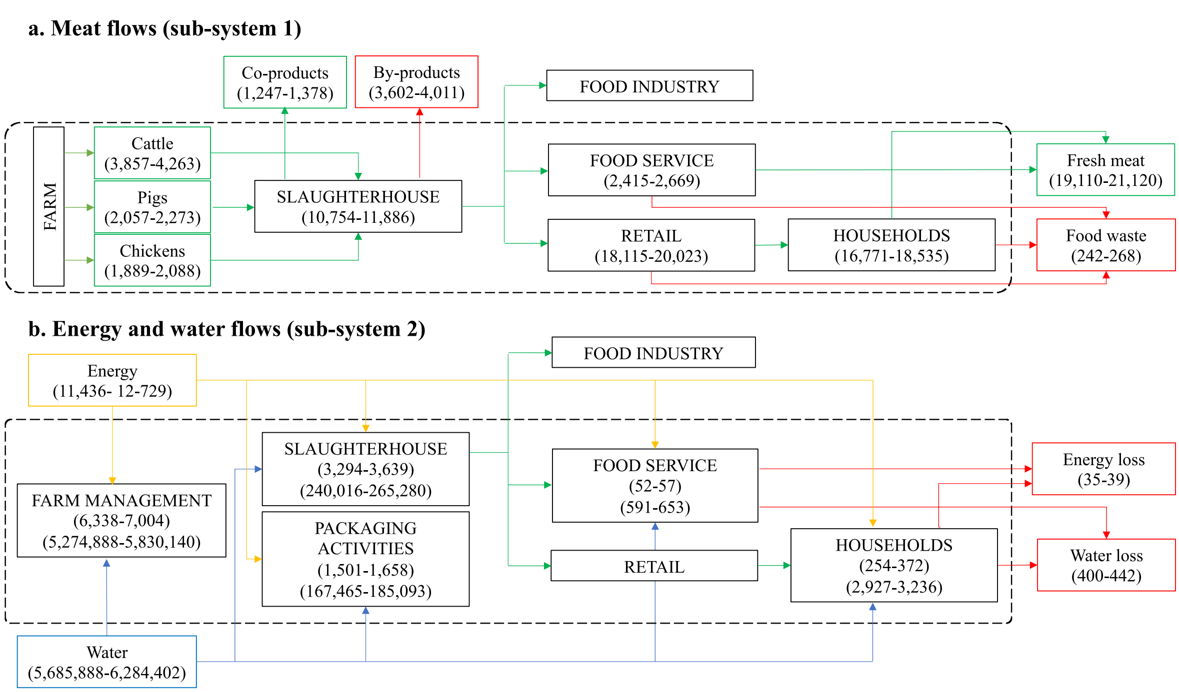

Fig. 3. Material flow cost accounting in million euros. Notes: Green lines = Meat flows. Yellow lines = Energy flows. Blue lines = Water flows. Red lines = Food, energy and water losses. Meat, energy and water flows are expressed in million euros. Energy and water losses are "hidden" within food waste. See Appendix III (a, b) for detailed calculations. . (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and food services, with associated CO_2 emissions estimated in 46,581–93,161 t from farm to slaughterhouse and 7630–15,260 t from slaughterhouse to retail.

As far as the MFCA concerns, Fig. 3 isolates materials, energy, water and other overhead costs associated with resources consumption and losses, highlighting either explicit or hidden cost flows. An amount of 7804–8625 million euros spent on the purchase of live animals generates an amount of 10,754–11,886 million euros in terms of carcasses sales (+37.8%), to which an additional income due to co-products sales should be added (1247–1378 million euros). If by-products are properly collected and addressed to other non-food uses, the estimated companies' income could increase, as follows: (a) inedible offal, by 287–317 million euros; (b) blood, by 1121–1239 million euros; (c) skin and feathers, by 2136–2316 million euros. However, an amount of 58–94 million euros (negative costs) should be accounted for other by-products disposal. Then, considering the energy costs, companies' revenue should be reduced by 3294–3630 million euros, which currently represent the energetic costs for slaughterhouse activities. In detail, approximately 125–138 million euros are spent to acquire renewable energy (i.e., biodiesel), whereas more than 3169–3502 million euros to purchase nonrenewable energy (i.e., traditional diesel). Along with the entire food supply chain, additional revenues estimated at food service (2415–2669 million euros) and at households (16,771–18,535 million euros) should be compared to energy and water (i.e., cooling systems and food conservation), which amounts respectively to 52–57 million euros (energy) and 591–653 million euros (water) at food service, and approximately 254–372 million euros and 2927–3236 million euros at households. Regarding missed revenues embedded within food waste, disposal costs (242–268 million euros) should be accounted, to which energy losses (35–39 million euros) and water losses (400–442 million euros) should be added. As regards explicit transport costs and hidden CO_2 emissions costs, they have been respectively estimated at 31–35 million euros and 4.6–5.1 million euros. On a national level, is estimated that more than 0.45–0.50 Mt of fresh meat is wasted along the entire Italian agri-food chain, equal to more than 242–268 million euros, to which additional energy and water losses should be added (435–481 million euros) as hidden losses.

Table 4 illustrates average energy, water and food waste disposal costs associated with carcasses and fresh meat market values along the entire food supply chain. In addition, transport explicit costs and CO_2 emissions hidden costs have been added and for a comprehensive comparison, slaughterhouse, food service and household stages are considered have been also considered.

Table 4
Energy, water and food waste disposal costs compared to fresh meat market values.

Process	Item	Average value (million euro)	Ratio to market value
Slaughterhouse	Carcasses market value	11,320	100%
	Co-products market value	1312	11.595%
	By-products market value	3237	28.598%
	Food waste	76	0.673%
	Energy costs	3466	30.620%
	Transportation costs	26	0.234%
	CO_2 emissions costs	4	0.037%
Food service	Fresh meat market value	2498	100%
	Food waste	43	1.759%
	Energy costs	54	2.181%
	Water costs	622	24.890%
	Transport costs	0.95	0.038%
	CO_2 emissions costs	0.10	0.004%
Households	Fresh meat market value	17,616	100%
	Food waste	211	1.198%
	Energy costs	313	1.777%
	Water costs	3	0.018%
	Transport costs	4	0.027%
	CO_2 emissions costs	0.52	0.003%

Notes: Revenues are estimated under the assumption that all edible co-products and inedible by-products are sold at market prices. Water at food service and households is consumed within cooling systems for food conservation. Food waste at retail has been accounted at household stage.

5. Discussion

5.1. Opportunities and challenges of the MFCA in the meat industry

The implementation of the MFCA at sectorial level provides useful insights under three different perspectives (i.e., economic, environmental and organizational), as already discussed by Walz and Guenther (2020). As highlighted by the present research, the systematic analysis of either mass streams or economic costs allows the identification of explicit and hidden costs, helping managers to comprehend the *dark side* of by-products and food waste disposal and increase environmental entrepreneurship. Under the economic perspective, the analysis reveals that food waste impacts twice: first, in terms of income losses due to by-products and finished products sales failure (Blum, 2020); secondly, in terms of disposal costs sustained by farms, processing plants, distribution and sales centers (Badgett and Milbrandt, 2021). Further, food waste has a negative economic impact also at households, since it links to a financial resource waste otherwise available for other purposes (Conrad, 2020). For instance, according to the quantitative and qualitative results of the present research, it emerges that by-products as blood, skin, feathers and other inedible offal may still have an economic value, and companies (e.g., slaughterhouse) should implement their collection and adopt industrial symbiosis and circular economy principles to gain economic benefits and reduce disposal costs (Bux and Amicarelli, 2022; Nishitani et al., 2022). To this extent, the adoption of the MFCA at micro level (i.e., single industrial plant) provides either economic or environmental quantitative and qualitative data. MFCA helps companies to reach high levels of transparency and share information about their stock of by-products and waste. This level of information, highly detailed and easily usable by other companies, could help in realizing economic revenue and environmental savings by selling by-products and waste instead of disposing (Nishitani et al., 2022).

Therefore, it is definitely clear that food waste issue in the meat industry should not be underestimated. The environmental impacts associated with meat production and consumption are among the most significant on global scale (Djekic and Tomasevic, 2016). If additional impacts are assumed to be associated with fresh meat consumption and by-products disposal, the issue amplifies its burden. Moreover, among the opportunities offered by the use of the MFCA at micro and meso level, it emerges the exact identification of the inefficient stage along the entire supply chain, as well as the economic quantification of the resources associated with such an unsustainable stage. For instance, at slaughterhouses, the present analysis presents detailed data on energy and water consumption associated with meat production. Considering the non-renewable energy input, the MFCA provides useful and concrete data to positively evaluate the transition from nonrenewable energy resources to renewable ones. Not to consider the transition towards green fuel (e.g., biodiesel) instead of traditional fuels in the field of transportation, which would allow the reduction, at the same time, of either the CO_2 emissions into the atmosphere (54,211–108,421 t) or their associated costs (4.6–5.1 million euros), currently not considered in the context of national accounting systems.

One more opportunity offered by the use of the MFCA regards the detection of socio-economic savings at households, assuming different food waste scenarios at upstream stages (e.g., sustainable consumption behavior, different disposal alternatives). In the current case, an economic loss of 674–749 million euros (including energy and water of cooling down) has been assessed, without accounting the nutritional losses and the associated environmental impacts, for instance the greenhouse gasses emissions due to food disposal. Further, quantitative and qualitative data could be used to inform and educate consumers, helping them to reach sustainable consumption and waste behaviors through clear and transparent diagrams (Rubinstein and Kroese, 2017). For instance, in the field of by-products valorization, the MFCA could be used as an instrument to plan separate collection strategies at slaughterhouse or retail, representing an important tool in decision-making by identifying by-products market value (i.e., positive output) and avoided disposal costs (i.e., economic savings).

5.2. Theoretical implications

According to a theoretical perspective, the present research contributes to the scarce empirical studies applying the MFCA in the field of food waste reduction through the proposal of economic, environmental and organizational insights. The rising information, although presented with reference to the meat industry, can act as a motivator for single companies and managers that aim to generate at the same time financial benefits and reduce adverse environmental impacts. The MFCA principles can be applied to organizations that produce either goods or services, regardless their size, structure, location, management and accounting systems (Christ and Burritt, 2016), therefore it seems to be suitable for agri-food sector research. Then, its paradigms can be extended along the entire supply chain, from upstream to downstream stages, allowing the development of a holistic approach and improving materials and energy efficiency towards environmental entrepreneurship.

It arises that the adoption of both mass-balance and material cost accounting methodologies could strengthen the unbreakable bond between economic growth and environmental protection (Huang et al., 2020). Such approaches offer a univocal outlook of the business experience and of the resources and waste streams along the entire supply chain, providing disaggregated and detailed information to operators, more interested in revenues rather than in materials requirement (Eweje, 2011). By-products valorization could enhance companies' incomes, which represents the main concern under the profit maximization theory, and even help in reducing energy use and water consumption towards social responsibility and environmental sustainability goals (Alexander, 2007; Pham et al., 2021). Circular economy and sustainable entrepreneurship cannot be detached from the adoption of innovative business models which rely on environmental accounting methodologies. Further, efficient waste and by-products accounting, collection and valorization techniques require the creation of long-term partnerships among farmers, suppliers, manufacturers, retailers and consumers (Donnet et al., 2020).

5.3. Limitations and future research directions

As concerns limitations of the present research, the country-side analysis does not provide specific results with reference to the Italian meat industry under technical or operational perspective. However, in the light of the aforementioned scarce empirical applications of such a methodology in the scientific literature, it represents a useful guide for the application of MFCA.

Among several restraints, the most alarming ones are exemplified by the use of adjustable data and estimates, and the adoption of highly volatile uncertainties. Nevertheless, if single-plants approaches were adopted instead of country-level ones, relying on data currently existing within the individual companies, the limits of data availability would be surpassed.

Future research directions should be addressed at enlarging the system boundaries of the present study, including an environmental and economic analysis of feedstock production and transportation. Feed production represents a challenge for resource and waste management, due to its contribution to land use, eutrophication, climate change and energy use. Feed production strategies are still required to achieve large cost-benefits ratios under economic and environmental perspectives (Mouri and Aisaki, 2015; Cheng et al., 2022).

6. Conclusions

The present research, estimating food waste costs up to 242–268 million euros, plus 435–481 million euros for energy and water hidden losses, achieves an extra step towards sustainable resources and waste management, highlighting the role of the MFCA in boosting the environmental entrepreneurship in the meat sector. Leveraging on the economic aspects, at present more stressed by companies compared to socio-environmental ones, the MFCA could be proposed as a key instrument to develop environmental entrepreneurship, helping to pursue both private economic interests and public sustainability goals.

However, one of the first emerging challenges is the still suspicious companies' attitude toward the implementation of economy and environment blending strategies. A sustainable development model requires a systematic and analytical planning of companies' activities, from procurement to sales, even considering internal and external accounting. Such a planning regards even more so the agri-food activities, enslaved by the problems of limitation and scarcity of resources and called to solve the damages generated by an ever-increasing consumer society. To this extent, a food waste dual impact must be considered: on companies' side excluding incomes, and on social side leaving people without still edible, nutritious and sufficient food. Further, it is surprising that the number of studies applying the MFCA, despite being an internationally standardized methodology, is still low. A doubt arises regarding its complexity of application at companies' level, being business accounting staff mainly oriented towards common national accounting systems. Data collection is one of the most critical topics concerning the implementation of mass-balance approaches and it makes extremely complex country-side analyses. The degree of training, skills and competence of companies' workforce, whose attitude toward the adoption of methodologies and approaches blending economy and environment under a single perspective is often apprehensive, may represent one of the most crucial features of the whole subject.

Credit author statement

Christian Bux: Conceptualization, Methodology, Software, Resources, Data Curation, Validation, Writing - Original draft.
Vera Amicarelli: Conceptualization, Methodology, Software, Writing - Review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.115001.

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