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ABSTRACT

In agricultural life cycle assessment (LCA), the choice of allocation methods to spread out impacts between coproducts is an important issue, as they may induce different conclusions in impact levels. We proposed a biophysical allocation method to dispatch the upstream environmental burdens and the use of raw materials to the body-related coproducts of beef cattle production system at slaughterhouse stage.

The method is designed to build a relationship between coproducts of the beef cattle production system and their associated net energy requirements for body growth. So it doesn't take into account the fate of the different coproducts, but only their building costs (i.e., energy needed for building tissues). A combination of metabolic growth model (Gompertz function) and models of energy cost of tissues was used to estimate the energy requirements for body growth from birth to slaughter age. The allocation factors were calculated based on the energy requirements attributed to build body tissues characterized by their chemical compositions (protein and lipid) with exclusion of waste. Finally, this method was compared with other allocation methods (e.g., physical, economic).

The biophysical allocation reflects a physical and biological relationship between the coproducts as required by ISO standard. It provided a moderate allocation factor for human food due to their chemical characterics compared to the other physical allocation methods. In addition, the data required is specific to species and less influenced within a predefined system than economic allocation.

This study provides a generic and robust biophysical allocation method to handle the coproducts in beef cattle system. The method can be considered as an original contribution to the international debates on the allocation methods in LCA applied to livestock products, especially among the stakeholders of the meat value chains.

Keywords: Gompertz function, animal co-products, body tissue composition, physiological function

1. Introduction

Allocating the environmental burdens and the use of raw materials among these co-products is an important issue in attributional life cycle assessment (LCA). Several methods exist for doing so, and ISO 14040/14044 (ISO 2006) recommends a hierarchical choice of allocation methods. Ideally, allocation should be avoided by expanding the system to include additional functions of co-products, or by dividing the process into several sub-processes with relative input and output data. When it is not possible to avoid allocation, one should attempt to attribute system inputs and outputs to co-products according to their underlying physical relationships (e.g., mass/energy allocation) under the condition that the co-products have similar characteristics. Only when a physical relationship alone cannot be applied as the base of allocation, should one establish other relationships among co-products (e.g., economic allocation). For agriculture, physical and economic allocations are "classic" methods commonly used in LCA (van der Werf and Nguyen, 2015; ADEME 2010; Cederberg and Stadig 2003). Mass allocation reflects a physical relationship; it sometimes cannot show the causality between animal-related co-products. Protein allocation reflects the function of products from agricultural systems to provide protein to humans or animals (Nguyen et al. 2012); however, it fails to consider multiple characteristics of co-products. Switching among one single characteristic (e.g., protein, lipid) as an allocation indicator may change results, because the functions of co-products vary greatly according to their final uses (e.g., human food or biofuel) (LEAP 2014). Economic allocation, often used in LCA, reflects marketable values of agri-food co-products according to their uses, such as food, feed and biofuel (EPD 2012; PAS 2050 2008). However, it seems insufficiently robust, due to temporal and spatial fluctuations in market prices of co-products, and the values of co-products at production lever cannot reflect their values after the transformation (Gac et al. 2012). To overcome the causality and functional problems of the classical physical allocation procedure, a biophysical allocation method was developed based on the energy required to produce co-products (IDF 2010). Few studies have used biophysical allocation to divide environmental burdens among livestock co-products (Nguyen et al. 2013; Wiedemann et al. 2015). They used allocation factors based on feed energy requirements. These energy requirements result from animal physiological processes (e.g., maintenance, growth, activity, lactation, gestation) to produce milk/wool and live animals in production systems and reflect the underlying biophysical relationship among co-products. However,

these studies only considered livestock co-products at the farm gate; none used biophysical allocation for body tissues that emerge from animal processing, which have different destinations (e.g., human food, tanning, composting). We developed a new biophysical allocation method to handle body-related co-products in an LCA of a meat-production system at the slaughterhouse gate. Our allocation method combines a generic metabolic growth model, which was widely used to predict body growth (increase in chemical composition) and a model to predict energy requirements as a function of protein and lipid growth for each tissue (Fig. 1), which should reflect a physico-chemical relationship among tissues.
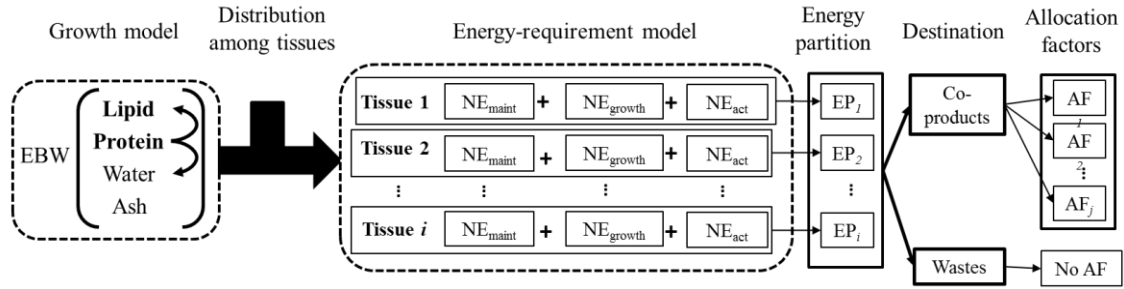
Figure 1 Model design to calculate biophysical allocation factors for body tissues combining a body-growth model and an energy-requirement model (**EBW**: empty body weight, **NE$_{maint}$**: net energy for maintenance, **NE$_{growth}$**: net energy for growth and **NE$_{act}$**: net energy for activity).

2. Methods (or Goal and Scope)

The biophysical allocation rule is based on 4-step method: the prediction of body growth with a Gompertz function, the calculation of net energy for maintenance, growth and activity, the calculation of energy partition for tissues, and finally the calculation of the allocation factor.

The method first predicts potential body growth rate from birth until maturity using a growth function. We chose the Gompertz function, based on available information from the literature (Emmans 1997; Hoch and Agabriel 2004a; Johnson et al. 2012; van Milgen et al. 2008; Whittemore et al. 1988), to model dynamics of body tissues. The Gompertz function requires few parameters, and its input data are readily accessible. In addition, its parameter values are based on biological characteristics of the animal modeled, rather than being simply mathematically fitted values (Wellock et al. 2004). These studies provide a theoretical and practical basis to calibrate the parameters of the same function adapted to different animal species.

The growth of the protein (kg) after birth is predicted by the Gompertz function as:
$$PROT(t) = PROT_0 * \exp(\frac{\mu*(1-\exp(-D*t))}{D}) \quad (1)$$

where μ is the Gompertz coefficient, which indicates the initial rate of protein growth, and PROT$_0$ is protein mass at birth. Gompertz parameter D can be derived as:
$$PROT_m = PROT_0 * \exp\left(\frac{\mu}{D}\right), when\ t \rightarrow +\infty \quad (2)$$

where PROT$_m$ is protein weight at maturity, which defines the upper limit of the asymptote of protein growth. Solving for D:
$$D = \mu/\ln(\frac{PROT_m}{PROT_0}) \quad (3)$$

According to Johnson et al. (2012), empty body weight (EBW), meaning body weight minus digestive content weight, includes protein (PROT), lipid (LIP) and water (W) contents, but the ash content is excluded because of its small percentage (less than 2% for cattle). Thus, there is:
$$EBW(t) = PROT(t) + LIP(t) + W(t) \quad (4)$$

Then, relationships between these component and EBW are assumed to follow the equations:

$$W(t) = \lambda * PROT(t) \qquad (5)$$
$$LIP(t) = f * EBW(t) \qquad (6)$$
$$PROT(t) = \left[\frac{1-f}{1+\lambda}\right] * EBW(t) \quad (7)$$

where λ is a constant ratio of body water to protein, which indicates the linear relationship between protein and water, and f is the normal content (%) of lipid in EBW, which is assumed to increase linearly with EBW from birth to maturity.

Combining equations (5), (6) and (7), lipid growth is described as a function of protein content:

$$LIP(t) = \frac{1}{2a(t)} * \left(-b(t) - \sqrt{b(t)^2 - 4a(t)c(t)}\right) \qquad (8)$$

in which
$$a(t) = (f_m - f_0)/(EBW_m - EBW_0) \quad (8a)$$
$$b(t) = (f_0 - 1) + a(t) * [2 * PROT(t) * (1 + \lambda) - EBW_0] \quad (8b)$$
$$c(t) = f_0 * PROT(t) * (1 + \lambda) + a(t) * PROT(t) * (1 + \lambda) * [PROT(t) * (1 + \lambda) - EBW_0] \quad (8c)$$

where f_0, f_m is the lipid content (%) in EBW at birth and at maturity, respectively, and EBW_0 is EBW at birth. Johnson et al. (2012) describe the derivation in detail.

Equations 1-8 predict total protein and lipid gain during normal growth. To predict protein and lipid gain of individual tissue, we assumed that the percentage of protein (p_i) and lipid (q_i) in each tissue were constant during the growth period. Thus, there are:

$$PROT_i(t) = PROT(t) * p_i \quad (9)$$
$$LIP_i(t) = LIP(t) * q_i \qquad (10)$$

Once protein and lipid contents were known, we used them as variables to calculate the metabolic energy requirements (step 2). Indeed, metabolic energy requirements can be described according to a hierarchical flux of energy: from energy intake (gross energy) to digestible energy, where loss of digestibility occurs (feces), then to metabolizable energy (loss of energy due to methane emission and urine), and finally to net energy (loss of energy due to heat production) (NCR 1998; Noblet and Van Milgen 2004). We used net energy to express requirements because it directly reflects the amount of energy used by an animal's body for biological processes. Body metabolism is based on the biological processes of maintenance, growth and activity. The maintenance function requires energy to maintain normal metabolic functions of the animal ("energy for maintenance"). The growth function requires energy to increase body weight ("energy for growth"). The activity function requires energy to obtain food, water and shelter ("energy for activity") (IPCC 2006). All of this energy consumption can be estimated as a sum of net energy requirements for body tissues. Body metabolism is influenced by multiple factors, such as nutritional, genetic and environmental parameters (Micol et al. 1993). We considered only normal requirements for potential body growth and did not consider these factors. Therefore, we assume that the animal has *ad libitum* access to feed and that energy intake will meet its total metabolic energy requirements.

We used net energy for maintenance (NE_{maint}) to express the energy required for the animal's basic metabolic function, when no body weight is gained or lost (no weight change). Several studies investigated the energy system for animal growth and body composition and assumed that maintenance energy is directly proportional to the protein mass in the body (Emmans 1994). We kept this assumption because it enables allocating NE_{maint} to body tissues that have different protein contents. We used the following equation to calculate NE_{maint}, which equals the energy required to synthesize protein minus the energy lost as heat during protein degradation (Johnson et al. 2012):

$$NE_{maint}(t) = \left(\frac{1}{Y_{P,s}} - Y_{P,d}\right) * k_{P,d} * \varepsilon_P * PROT(t) \qquad (11)$$

where $Y_{P,s}$ is the efficiency of protein synthesis, $Y_{P,d}$ is the efficiency of protein degradation, ε_P is protein energy content, and $k_{P,d}$ is the protein degradation coefficient, which can be determined given the fractional synthesis rate ($k_{P,s}$) and the net accretion of proteins. Thus, there is a balance between synthesized proteins and degraded proteins:

$$PROT * k_{P,d} = PROT * k_{P,s} - Net\ accretion\ of\ proteins \quad (11a)$$

According to Lobley et al. (1980), the fractional synthesis rate varies among tissues:
$$k_{P,s}\ for\ whole\ body * total\ protein = \sum k_{P,s}\ for\ tissue * tissue\ protein \quad (11b)$$

By definition, net energy requirements for growth (NE_{growth}) indicate the energy for protein and lipid retention in the body; so, the rate of NE_{growth} can be described by the growth rate of protein and lipid in individual tissues, following this equation:
$$\frac{dNE_{growth}}{dt} = \frac{\varepsilon_P}{Y_{P,s}} * \frac{dPROT}{dt} + \frac{\varepsilon_L}{Y_{L,s}} * \frac{dLIP}{dt} \quad (12)$$

where $Y_{L,s}$ is the efficiency of lipid synthesis, ε_L is the lipid energy content, and dPROT/dt (dLIP/dt) is the rate of protein (lipid) retention in potential growth, which can be estimated according to the model of body weight prediction mentioned above. Therefore, NE_{growth} for a given day can be expressed as:
$$NE_{growth}(t) = \frac{\varepsilon_P}{Y_{P,s}} * [PROT(t) - PROT(t-1)] + \frac{\varepsilon_L}{Y_{L,s}} * [LIP(t) - LIP(t-1)] (13)$$

As for net energy for activity (NE_{act}), Johnson et al. (2012) assumed that NE_{act} was a function of EBW with a constant coefficient. They argued that the coefficient for activity energy depends on rearing conditions (e.g. stall, pasture), and the activity costs based on this assumption correspond to the empirical curve response in the Australian Feeding Standards (SCA 1990). However, to obtain a more generic model for calculating NE_{act} than this country-specific model, we applied the method of IPCC (2006):
$$NE_{act}(t) = C_{act} * NE_{maint}(t) \quad (14)$$
where the coefficient (C_{act}) corresponds to the animal's feeding situation. We assumed that energy requirements for activity are modest ($C_{act} = 0.17$ for cattle, Table 10.5 of IPCC (2006)).

The third step allows the calculation of energy partition for tissues. Since the net energies for maintenance and growth are directly related to the protein and lipid contents in the body, we assumed that both were attributed to tissues according to their protein and lipid percentages:
$$NE_{maint,i}(t) = \left(\frac{1}{Y_{P,s}} - Y_{P,d}\right) * k_{P,d} * \varepsilon_P * PROT(t) * p_i \quad (15)$$
$$NE_{growth,i}(t) = \frac{\varepsilon_P}{Y_{P,s}} * [\Delta PROT(t)] * p_i + \frac{\varepsilon_L}{Y_{L,s}} * [\Delta LIP(t)] * q_i \quad (16)$$
$$NE_{act,i}(t) = C_{act} * NE_{maint,i}(t) \quad (17)$$
where $\Delta PROT(t)$ ($\Delta LIP(t)$) is calculated as the difference in protein (lipid) weight between the initial (at birth) and final protein (lipid) contents on day t, and p_i and q_i are the percentages of protein and lipid of tissue i out of the total protein and lipid contents of the body, respectively. We assumed that the percentages of protein and lipid in each tissue were constant during growth and that $\sum p_i = \sum q_i = 1$.

The last step (4) allows calculating the allocation factor according to ISO 14040/14044 rule i.e. all the inputs/output are allocating to the co-products excluding de facto tissues considered as waste from the allocation procedure :
$$F_{allo,j} = \frac{EP_j}{\sum_j EP_j} \quad (18)$$

The method was tested on beef cows. We assumed that growth starts at birth, with 50 kg of EBW_0 composed of 12 kg of protein and 3 kg of lipid until slaughter age at 495 EBW_1. The mature weight (EBW_m) was assumed to be 600 kg, with 105 kg of protein and 180 kg of lipid. The categories of beef products and co-products were defined according to CMWG (2015): human food (edible tissues such as muscles or the liver), category 1/2 (C1/C2) by-products (tissues considered as waste), spreading/compost (e.g., digestive contents) and four C3 co-products - processed animal protein (e.g., blood), gelatin (e.g., bone), fat and greaves, hide for tanning.

3. Results (or LCI)

The simulation ran from birth until maturity (1041 days), and we calculated allocation factors at slaughter age (509 days). Metabolic energy requirements were calculated for each tissue. Although both protein and lipid increased over time, growth rates differed for carcass and non-carcass tissues (Fig. 2). The deposition rate of carcass protein is higher than that for non-carcass protein due to its increasing proportion during fattening. Likewise, lipid deposition in carcass tissues is slightly higher than that in non-carcass tissues.
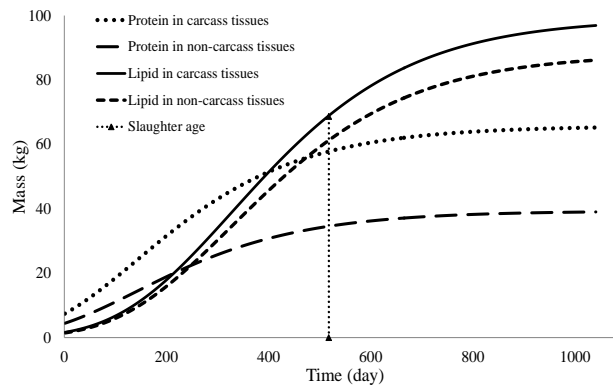

Figure 2: 1Growth curves of protein and lipid mass in carcass and non-carcass tissues as functions of time (per day) for beef cow from birth to maturity (the vertical line indicates slaughter age).

Total net metabolic energy requirements at slaughter age, calculated as cumulative energy requirements during the growth period, were 31,539 MJ, of which 56% was energy for maintenance, 34% was energy for growth and 10% was energy for activity. The rates of energy for maintenance and activity increased with body growth, while the rate of energy for growth decreased, since protein and lipid growth rates decreased. Metabolic energy requirements were attributed differently to carcass and non-carcass tissues; at slaughter age, carcass tissues required about 43% of total net energy, while non-carcass tissues required the remaining 57% (29% for the GIT, 5% for the liver, and 23% for the others). According to equation (11), energy requirements for maintenance depend on both the protein content of a tissue and its protein degradation rate. Therefore, the GIT and carcass tissues required a high percentage of total energy for maintenance, while the liver and other non-carcass tissues required little energy for their maintenance. Conversely, metabolic energy requirements for growth are a function of protein and lipid growth rates; so, carcass tissues had higher metabolic energy requirements than non-carcass tissues (Fig. 3)
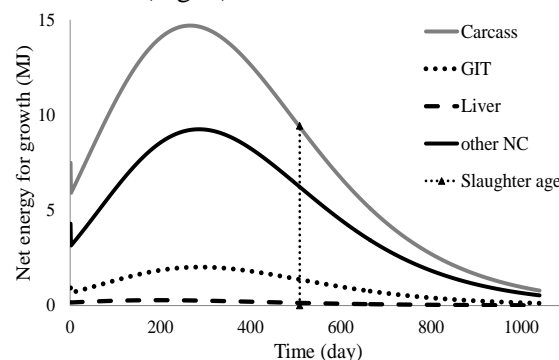

Figure 3: Net energy requirements for growth of different tissues: carcass, gastrointestinal tract (GIT), liver and other non-carcass tissues (other NC) as a function of time (day) for beef cow from birth to maturity (the vertical line indicates slaughter age).

Finally, when comparing allocation methods according to destinations of body tissues (Fig. 4), the biophysical allocation method induced smaller level of allocation for human food (50%) than mass (56%) and protein (62%) based methods, and higher level than dry matter (38%) based method. Economic allocation was significantly different from the other methods. Since economic allocation is based on economic values of co-products, the edible co-products as human food under economic allocation had an allocation factor of 95%, compared to 38-62% for the other four allocation methods.

However, economic allocation method induced smaller allocation factors for C3 co-products than other physical allocation methods. For co-products destined to processed animal protein, the biophysical allocation method induced higher level of allocation (17%) than other methods, because some high energy-required GIT tissues were classified as pet food. Gelatin had similar allocation factors (6-10%) among methods (except economic allocation). Fat and greaves together had a higher allocation factor using the DM allocation method (36%) than the others (1-19%) due to a larger percentage of adipose tissues (e.g., tallow and fat). Hide for tanning had higher allocation factors under protein allocation (12%) than others (4-7%), due to its higher protein contents.
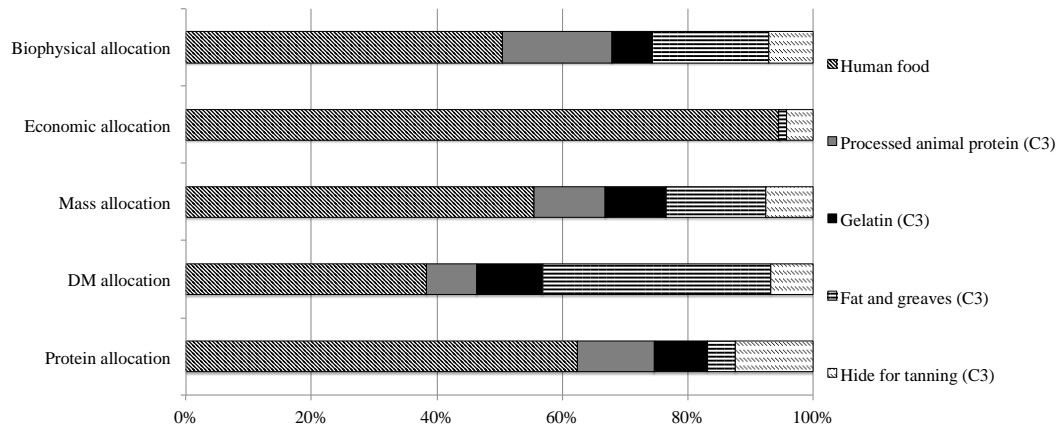

Figure 4: Allocation factors for different product destinations of beef cow at slaughter age according to biophysical, economic, mass, dry matter (DM) and protein allocation methods C3: category 3 according to CMWG (2015))

4. Discussion

The first submodel of simulation predicts protein and lipid growth based on the Gompertz function. It indicates that lipid increases quadratically and protein increases more linearly (Fig. 10), which was confirmed by the literature review of Owens et al. (1995). Although we applied the Gompertz function for genetically standardized animal growth, it can be adjusted easily with observed data to consider variability among animal types, species and environmental conditions, because only 3 parameters are required (i.e., Gompertz coefficient μ, Gompertz parameter D and protein mass at birth $PROT_0$).

The second submodel calculates metabolic energy requirements of different tissues. The common view is that the NE_{maint} is a function of average metabolic body weight (i.e., $BW^{0.75}$), which estimates the average metabolic energy requirements (per day) of an animal (IPCC 2006). However, such an exponential function cannot make a direct link between body tissues and metabolic energy requirements. Therefore, it cannot reflect that certain visceral organs have higher maintenance requirements than muscle tissues (Ortigues and Doreau 1995). We used a linear equation to calculate NE_{maint} as a function of protein content in individual body tissues. The energy-related parameters $Y_{P,d}, Y_P$, ε_P were assumed to be constant, and their values were those commonly used for cattle (Emmans 1997; Johnson et al. 2012; Roux 2014). The protein degradation rate k_P varies among cattle tissues, which indicates high requirements for NE_{maint} of several visceral organs, especially GIT organs. However, such detailed data may not be available for other animal gender, breeds or species. In such situations, we suggest using a single value of k_P for each tissue as well as for the entire body. In this way, NE_{maint} is determined only by tissue protein content. Future research could estimate metabolic energy requirements for each tissue to obtain additional data for k_P.

The biophysical allocation method is in accordance with the ISO (2006) standard, since it reflects mechanisms underlying a physical relationship (i.e., metabolic energy requirements) among co-products. Biophysical allocation considers multiple characteristics (i.e., protein and lipid contents) of co-products, which may help to decrease differences among stakeholders (e.g., meat producers vs. leather producers) points of view, who may prefer different allocation rules. Unlike the protein

allocation method, in which co-product impacts are driven only by their protein contents, biophysical allocation reflects the energy cost of building tissues upstream, regardless of their fates downstream. It also reveals the cause-effect relationship between tissues according to the energy required to maintain their physiological functions. It is a change in perspective as it proposes a rule based on building the co-products, while the other methods are based on outputs characteristics (weight, price, chemical composition), and therefore on their destination and use. These destination and use of the co-products are typically under the concern of the different stakeholders with different points of view difficult to conciliate. The biophysical method taking into account the composition of tissues and their metabolic role induces a higher allocation factor on inner organs compared to the other methods. This is particularly sensitive for tissues classified in C1-C2 by-products. Although energy partition indicates that tissues as C1-C2 by-products had large energy requirement ratios, their allocation factors were zero according to ISO standard. It is a specific characteristic in Europe, for cattle, where these products are not targeted to human food, but waste. It would not be the same for other species (e.g. pig), or other cultural context where these products have more diverse uses. Although biophysical allocation factors varied over time, once the growing time is fixed (by setting the final EBW), the parameters are not influenced, unlike in economic allocation. Moreover, the biophysical allocation method can be applied to dairy farming systems to allocate impacts to milk, calves and live animals at the farm gate, and then to allocate impacts of live animals to their body tissues when sent to slaughter.

Although biophysical allocation factors varied over time, once the growing time is fixed (by setting the final EBW), the parameters are not influenced, unlike in economic allocation. Moreover, the biophysical allocation method can be applied to dairy farming systems to allocate impacts to milk, calves and live animals at the farm gate, and then to allocate impacts of live animals to their body tissues when sent to slaughter. For example, net energy for lactation should be attributed to milk production (Thoma et al. 2013), and the IPCC (2006) provides a method to calculate this net energy as a function of milk production and its fat content. Therefore, this new method is robust and flexible enough for application to different animal types (e.g., dairy or beef cows). Our study focused on development of the new method for calculating allocation factors, without using it to estimate environmental impacts. Thus, future research should include a complete LCA in which the potential impacts resulting from different allocation methods are compared.

5. Conclusions

Biophysical allocation follows the hierarchical rule of the ISO standard and can differentiate characteristics of livestock co-products. This method does not consider the fate of co-products but considers only the cost of building them. This approach can be considered an original contribution to international debates on allocation methods applied to livestock products in LCA. It should be considered and discussed by stakeholders in livestock-production industries.

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