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28th CIRP Conference on Life Cycle Engineering

Environmental Impact Allocation of Agri-food Co-products

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Abstract

In the context of strengthening sustainability of production systems, agri-food products become the target of environmental evaluation using life cycle assessment (LCA). Most of agri-food production systems include multifunctional processes, a common challenge occurs regarding the way to partition impacts among co-products. This is known as the allocation problem. Many approaches have been introduced, leading to different results. One major question that LCA practitioners face is the allocation method choice. The extensive literature review achieved in this study allowed the identification of the most used and acknowledged allocation methods. A cross-analysis unveiled a strong link between allocation choice and decision-makers' objectives. Hence, this paper proposes to identify the LCA scope, and to use a contextual reasoning to choose the allocation method. These findings were tested on two LCA studies involving agri-food co-products: deteriorated apples and wheat straw. It was validated and discussed in line with the ISO 14044:2006 guidelines.

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Keywords: co-product; life cycle assessment; allocation; agri-food; environmental impact; case studies

1. Introduction

During the last few years, assessing the environmental impact of agri-food products, especially the carbon footprint, has sparked a striking interest among the sustainability community [1]. This has been mainly the result of the life cycle structure of agri-food products, and most commonly among the harvesting phase at the raw material level. This complexity is defined by the increasing number of outputs yielded when extracting agri-food crops such as fruits, vegetables, plants, meat and many others [2]. When evaluating the environmental impact of these products, researchers, practitioners and decision makers tend to use life cycle assessment (LCA), which has been defined by ISO 14044:2006 as a compilation and assessment of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle [3, 4, 5]. In this context, agri-food product systems are hugely challenging due to the fact that many products are produced simultaneously without the

possibility of subdivision. In most agri-food product systems, waste can be valorised into value-added products such as the valorisation of cow manure into a fertilizer in the cow meat and milk product system [2]. In these cases, outputs having considerable positive economic values are called co-products [6]. Since agri-food production systems are mostly ruled by nature, these co-products are obtained in a joint production where co-products volumes are dependent. But in some cases, agri-food co-products volumes can be humanly managed in the way cattle are fed to produce more meat than milk for example. In this case, the agri-food co-products are obtained from a combined production [7,8]. In such kind of life cycle complexity that agri-food co-products are raising, the major concern of how environmental impacts of inputs and outputs should be divided among the co-products. This is most referred to as allocation, and has been defined by ISO as the partitioning of impacts and resources consumption between the co-products [3]. Co-product allocation is one of the most challenging topics in LCA, and requires further research to

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determine how the partitioning should be conducted [7]. The main objective of this study is to provide practitioners with an operational approach to help overcome the allocation challenges when dealing with agri-food co-products. This will be conducted through an exhaustive state of art study on the different approaches used to handle co-products in LCA studies.

2. Literature Review

Many methods have been introduced in the literature to tackle the environmental allocation problem in LCA. One of the most used allocation methods in the literature is the economic allocation, or as some authors refer to it as the “market-value allocation”, which considers that the distribution of the environmental impacts should be fully based on the relative gross sales value of each co-product, as this is the main cause for which the multi-product process has been designed [9]. In other words, the percentage given to each co-product will be defined by its share in total sales [10]. This is one of the main methods that has taken the system causality as the perspective of the allocation [9]. According to Mackenzie [11], the economic allocation is the most commonly used method when conducting an LCA study in the agricultural sector, which is dominated by co-products from vegetable origins such as crops. One frequent error that some LCA practitioners make when applying the economic allocation is applying the partitioning based on the end-user price instead of the immediate value after production [12]. Another method would be the biophysical allocation. This form of allocation is based on physical relationships between the co-products and the outputs [11], pushing the environmental impacts to be partitioned according to physico-chemical properties such as the mass and the energy content [13]. According to the ISO 14044 standard, whenever avoiding allocation is not possible, the LCA practitioner should give preference to the bio-physical allocation through a physico-chemical property that reflects a quantitative change relationship between the inputs and the outputs of the studied system [3, 14]. The application of the energy-based allocation leads the outputs to be partitioned according to the amount of energy stored in the co-products, also known as the energy content. This form of allocation is considered to be more accurate due to its direct association with the biophysical flows [15]. Although many authors have cautioned against the use of the energy-based allocation due to the lack of causality between the inputs and the outputs in some cases, Ayer [16] has showed its relevance in the context of agri-food production systems. Moreover, despite being referred to as a bio-physical allocation, the energy-based allocation reflects an economic consideration among agri-food resources since their market value is mainly defined by their energy content. When dealing with co-products intended for livestock feed, it is only fair to consider their metabolizable energy contents for one type of animal [17]. The mass allocation defines the co-products’ proportional masses as the distribution criterion for the environmental impacts [17]. During a carbon footprint and energy use study conducted by Winter [17, 19] on Norwegian seafood products, it has been demonstrated that mass

allocation is stable overtime, unlike economic allocation which varies with the possible price fluctuations. The limit of this allocation methodology is that it only provides a quantitative perspective when evaluating the co-products without necessarily taking into consideration their functionalities defined by their qualities [18]. Since many industries with multi-product processes are bound to respect certain policy requirements, Gnansounou [21, 22] introduced a rather unconventional allocation approach that takes into account the compliance of each co-product with the policy requirements. One way to evaluate the environmental impact of a co-product is through system expansion. The principle of this method is to allocate the totality of the impacts to the studied product, which is most of the time the main product for which the product has been designed initially [23]. Then, the system is expanded to take into account all the avoided impacts that were to happen if the other co-products were not produced by finding a substitutional production system of the co-products and subtracting their impacts from the studied product [23]. This form of evaluation where the LCA practitioner uses system expansion as an approach to represent the effects of an action on the global environmental impacts is called the consequential LCA (CLCA) [24]. When conducting an attributional LCA, system expansion remains optional next to the conventional allocation procedures. However, when using the consequential approach, the only accurate way to handle a co-product is through system expansion [25, 26]. In fact, the ISO standards and the ILCD handbook endorse the usage of system expansion and puts it as the first approach to apply when subdividing the multifunctional process is not possible [2, 12, 27, 28]. Svanes [15] introduced a combination of allocation methods such as a mass and economic allocation in the context of agri-food products, in which the mass of each co-product can be either taken as it is, if the co-product is intended to be consumed by humans, halved in the case of animals, and reduced by quarter if planned to be incinerated. Hybrid allocation can also be a combination of the conventional allocation approach and the system expansion approach as proposed by Cherubini [29]. Recycling and reusing in a production system are common forms of end-of-life recovery approaches that reinject a specific function in the original system in a different quality state, and thus the newly generated product should be considered as a distinct co-product of the original product when conducting an environmental assessment [12, 31].

This choice diversity has sparked many debates at the allocation method level of LCA studies where co-products are involved. This led us to investigate the way an allocation method should be chosen by LCA practitioners. This research question that is raised in this paper is presented in the following section.

3. Allocation Choice Issue

When co-products are part of the system boundaries, environmental impacts have to be divided among these outputs. Due to the existence of dozens of very common allocation methods, the biggest challenge in the LCA study is the choice of the partitioning approach. When the results are

slightly or not sensitive to the chosen allocation method, this dilemma becomes irrelevant. But in a lot of cases, a huge sensitivity could be observed on the final results. When changing the allocation method, Wardenaar has observed the variation of the allocation factor of the studied co-product rapeseed oil from 70% when using the economic allocation, to 55% when using the bio-physical allocation [32]. This ambiguity can lead decision-makers to take actions that might hinder achieving planned outcomes for which the LCA study was initiated. The choice of the allocation approach is among the most discussed issue in LCA, despite the existence of the ISO guidelines and other handbooks inspired from ISO [1, 4, 12]. These latter have not been updated since 2006, and they do not fully take into consideration the framework of the LCA study as designed by decision-makers and practitioners. This can lead to random allocation choices and a lack of scientific rigor in the conduct of the study [22, 33]. Therefore, the topical and recurring need for the right allocation method to choose in LCA has sparked this research project. The research question that it tries to answer can be formulated as follows: which allocation method should a practitioner choose when conducting an LCA study involving co-products?

4. Case Study 1 – Deteriorated Apples

4.1. Case description

The first case study is about the supply chain of apple cider vinegar, which is a product that has been consistently consumed over the years for different uses [34]. The production of apple cider vinegar involves many delicate steps that have not been assessed before from an environmental perspective in the literature. For this reason, we have decided to conduct an LCA study to assess the environmental impacts of the production of apple cider vinegar from deteriorated apples in a farm in Midelt, central Morocco, as part of a social entrepreneurial project that supports small apple farmers through valorising their deteriorated apples.

The scope of the current case study is an attributional LCA study from cradle to gate, covering all processes from the orchard phase to the final bottling and packaging phase in the farm. Distribution, consumption and end-of-life stages will not be considered in the study. The functional unit on which the production system will be assessed is the production of 1 litre of apple cider vinegar with a 5% acidity degree in 250 ml labelled glass bottles which will last for 10 years. Since the apples used in the production are deteriorated, they are considered to be co-products of the normal apples intended for the fruit market.

4.2. Allocation results

Allocation has to be conducted at the apple production level between normal apples and deteriorated apples. Our literature review findings were used to choose the allocation method. Two main parameters have guided the choice: the LCA approach and the goal of the study. Since the system boundaries were limited to the production system, the

allocation choice was oriented to the attributional approach. Taking into account the aim of the study, the focus was directed around the conventional attributional approach. At this step, the aim was to estimate the exact impacts of the co-products despite their importance in the production system. Considering both the impossibility of subdividing the production system, and the possibility of substituting normal apples by pears in the local market, system expansion becomes the most relevant method. Since the study was not comparative, the classical subtractive system expansion was preferred by the decision maker. Due to local fruit market demand, normal apples can be substituted by pears produced as the only value-added products in their production system. Since apples and pears have the same energy content [39], it will take 1 kg of pears to substitute 1 kg of normal apples. In the farm used in the study, when producing 6.5 kg of apples, 3 kg are good quality apples intended for the fruit market, and the remaining 3.5 kg get damaged and considered as second-rate products. In SimaPro, we assigned the production of all 6.5 kg of inputs to damaged apples, and we added 3 kg of pears with a negative sign for the subtractive aspect of the system expansion as illustrated in the allocation line of the last column in the illustrated in the inventory table of both allocation scenarios below:

Table 1. Climate change impact inventory in kg CO₂ eq for the production of 1L of packed vinegar using both study objectives.

Life cycle stage	Inputs	Clim. Change economic allocation	Clim. Change system expansion
Economic allocation			
Apple production	3.5kg	0.283	
Economic factor	36.8%	0.368	
Impact value of production		0.368*0.283=	0.104
System expansion			
Apple production	6.5kg		0.525
Subtraction of pear	-3kg		-0.0153
Impact value of production			0.51
Pre-fermentation			
	Transport	0.00349	0.00349
	Water	0.000788	0.000788
Vinegar production			
	Barrels	0.00283	0.00283
Packaging			
	Glass bottle	1.02	1.02
	Stickers	0.0299	0.0299
	Printing ink	0.00627	0.00627
	Cardboard	0.0979	0.0979
Distribution			
	Transport	0.222	0.222
Total (in kg CO₂ eq)		1.48	1.89

The total climate change impact of the studied functional unit is 1.89 kg CO₂eq. Due to the low environmental impact, the study results become a marketing strength that the producers can use to target customers who are sensitive to

climate change issues. To stay relevant to this new objective, we decided to use a purpose-based approach in order to base the allocation on the economic importance of each co-product since the aim is in the same mind-set. We used the economic allocation using market data provided by the producers. Since the local market value of normal apples is 0.8 \$/kg and those of deteriorated apples is 0.4 \$/kg. Considering the fact that these two co-products can only be obtained simultaneously with a volume ratio of 3.5 deteriorated apples to 3 good quality apples during each production of 6.5 kg in this system. Using these information, we have found an allocation factor of $(0.4*3.5)/(0.4*3.5+0.8*3)=36.8\%$ for deteriorated apples. The newly obtained impact in the climate change category is 1.55 kg CO₂eq. A considerable decrease on the climate change impacts of 21.7% as observed in Fig. 1, which supports the new objective.

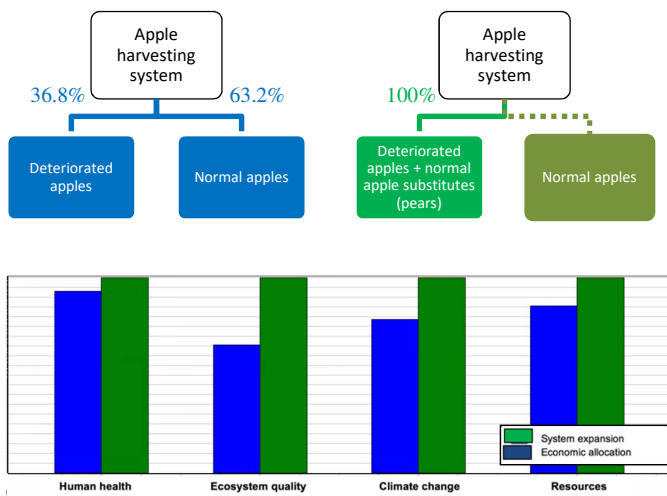


Fig. 2. Comparison of impact results for the first case study.

5. Case Study 2 – Wheat Straw

5.1. Case description

In the second case study, the production of mudbricks from wheat straw is the main system of focus. Mudbricks are a type of bricks produced from a mixture of soil and water with a vegetable fibre such as vegetable straws [35, 36]. This study builds up on both a need analysis during an innovation project for straw buildings [37] and a straw brick LCA study [38].

The attributional approach is the most relevant since the aim of the study is to reduce losses at the wheat farm where 40% of straw is wasted with a lean management approach. The assessment will be conducted from cradle to gate, covering all processes from the straw extraction to the last drying phase where the output is the final product. The functional unit of this case study is 1 kg of wheat straw mudbrick with a density of 1544 kg/m³ which will last for 25 years.

5.2. Allocation results

Similarly, an allocation factor should be defined for wheat straw at the end of the wheat production system. The main goal of the decision makers is to find improvement

opportunities for eco-friendly construction materials in a lean perspective, the recommended method to use is the economic allocation since it will allow decision-makers to valorise as much as possible their scrap and waste in order to balance the allocation factors between the main products and the newly obtained by-products [15]. By doing this, the allocation factors of the main products will be more balanced, and the product losses reduction will be optimized. Using the economic allocation. Market values of both wheat straw and wheat grains are 42.5 \$/t and 311.36 \$/t [40]. The straw/grain ratio of wheat equals 1.6 [41]. Since 40% of straw is wasted, only 60% of straw will be considered in the allocation phase, thus the new ratio equals 2.66. Using these data, we found an allocation factor of nearly 5%. In this case study, the production system is divided into two main steps.

We then simulated a context where a conventional attributional LCA was conducted with a purpose-led mind-set since both co-products do not have the same main functional property. The data gap in market research of straw pushed us to assume a market demand scenario. In a year, customers would ask for 5 tons of straw grains for flour production, and 2 tons of wheat straw for live feedstock. Using the market value of each as presented before, the new allocation factor equals nearly 5.2%. This stability is caused by the small market value of straw compared to grain. We imagined an extreme case where wheat straw would get an allocation factor of 20%, and we have found that the climate change results for the studied functional unit go from 0.0118 kg CO₂eq to 0.0138 kg CO₂eq as illustrated in Table 2. These results remain stable due to the small used quantity of wheat straw in the production system. Therefore, the final results are not sensitive to the choice of the allocation methods.

Table 2. Climate change impact inventory in kg CO₂ eq for the production of wheat straw mudbricks using both the resulting factor and the simulated one.

Life cycle stage	Inputs	Climate change 5%	Climate change 20%
Wheat production	0.02kg	0.01344	0.01344
Allocation		0.05	0.2
		0.01344*0.05=	0.01344*0.2=
Impact value		0.000672	0.00269
Mudbrick production	Transport	0.000499	0.000499
	Soil	0.000788	0.000788
	Water	0.00014	0.00014
	Electricity	0.000761	0.000761
Total (in kg CO₂ eq)		0.0118	0.0138

6. Discussion

As introduced in section 2, many ways to handle co-products when conducting an LCA study are possible. Although the ISO guidelines are well described and widely used, they do not link the aims of the study with the chosen allocation method [3]. This shortcoming has been raised on numerous case studies, and authors have recommended to include the goal of decision maker in the allocation method. Although many paths are possible, only one allocation method should be used, and the choice should be justified with a link

to the LCA scope. To give more value to the contextual aspect of the claiming-based method, this has been one of the suggested methods in the state of art since no update was conducted over the ISO standards nor other well referenced papers due to its recent introduction by Gnansounou [21]. Applications were conducted on two case studies to use the literature findings. In the first case study, changing the context of the LCA study yielded a decrease of 21.7% in the climate change impacts of the apple cider vinegar. This decrease supports decision-makers' goal of marketing the apple cider vinegar. A close attention should be paid to the normal apple co-product system so its sustainable performance won't be hindered. This proves how dynamic the allocation method choice making can be, and supports the claims of Sandin [30] and Parsons [42] on the control of the LCA decision context and objectives on the choice of the partitioning methodology. However, in the second case study, the allocation choice had no effect on the final results due to the low used quantity of wheat straw which weighs only 1.4% of the total used resources. For this reason, the allocation didn't necessarily help achieve the goals defined by decision-makers. Allocation choice can only be an issue when results can be harshly affected by allocation methods. Accordingly, and based on the results of the two case studies of this research, it is recommended to invest time in the allocation method choice making only for LCA studies where co-products have a considerable influence on the results. The choice making should also take into account the studied impact category. This strengthens the causal relationship between the co-products and their burdens.

7. Conclusion

This paper presents a state of the art on the most referenced allocation methods used to assess the environmental impact of agri-food co-products. The choice of the allocation method has a strong correlation with the aims of the study as defined by decision makers. This allows practitioners to both justify their choice, and discuss the results with alternative scenarios for sensitivity analysis. These claims have been tested on two LCA case studies involving agri-food co-products as system inputs. The first case study is about the production of cider vinegar from second-rate and damaged apples. When decision makers decided to conduct an assessment to collect information for marketing purposes, the final climate change impact of apple cider vinegar decreased by 21.7% compared to the classical attributional scenario. This highlights the importance of the allocation method choice in accomplishing the LCA objectives. The second case study is about the production of mudbricks from wheat straw. In this case, the allocation method had no effects on the results due to the low used quantity of wheat straw. If for some case studies, such as the second one, the results of the environmental assessment remain unchanged after altering the allocation method, the allocation choice issue becomes irrelevant. Practitioners can simply use the economic allocation in these cases and justify the lack of allocation choice discussion by the results of the allocation sensitivity analysis. To conclude, as the main question in this paper involves dealing with agri-food co-

products at the allocation level when conducting an LCA, we suggest that the choice of the partitioning method remains in-sync with the objectives and the framework of the LCA study as defined by the different stakeholders of the assessed system. To use the full potential of these results, a methodological approach will be developed in the form of a decision-aid multi-level tree to guide the allocation choice and be deployed to other LCA practitioners to conduct more case studies on various types of agri-food co-products.

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