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LIFE CYCLE ASSESSMENT FOR EVALUATING MIXED FARMING SYSTEMS: A REVIEW AND RECOMMENDATIONS

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Abstract

The objective of this work was twofold: i) to characterise the main applications of the life cycle assessment (LCA) for assessing and representing mixed farming systems (MFS), and then ii) to propose a general methodological framework for conducting a comparative LCA of a case study of an MFS versus a specialised system in Romania. For this purpose, the main applications of LCA to MFS have been analysed in all its phases. Overall, the reviewed LCA studies highlighted the potential of MFS to improve environmental sustainability, but scarcity of real data hindered the assessment process. In addition, some studies focused on a single product rather than taking into account all products (crops and livestock) when comparing MFS with specialised ones. This may exclude interactions between farm components in the MFS and therefore may not reflect the overall impact of these systems. Therefore, an LCA based on a farm-level approach is recommended to provide a fairer comparison of MFS versus specialised systems.

***Key words**: environmental sustainability, farm-level approach, interactions, mixed farming.*

INTRODUCTION

Reconnecting crops and livestock at the farm and regional level would reduce the ecological footprint, close nutrient cycles, restore ecosystem functions, improve soil health, and increase resource use efficiency.

The positive effects of mixed farming systems (MFS) are mainly proven at the theoretical level (Veysset et al., 2014; Marton et al., 2016), but additional information and knowledge at the practical level are needed regarding their impacts (e.g., pest and disease control, GHGs, biodiversity, etc.) (Shut et al., 2021). MFS are complex multifunctional systems with multiple outputs and different interactions and synergies between farm components. Therefore, structured and specific methodological assessment frameworks are needed to deal with this complexity.

Life Cycle Assessment (LCA) is a standardized method (ISO, 2006a; 2006b) for assessing the environmental impact derived from the life cycle (LC) of products, services and systems.

Despite the growing interest in crop-livestock reintegration as a possible alternative to mitigate the negative effects of agricultural specialization, the literature on LCA of MFS remains scarce compared to other agricultural systems. Modelling the complexity of these systems with LCA is challenging.

In this context, this paper analyses the most relevant applications of LCA to MFS in order to provide an overview of the main characteristics of LCA to represent MFS and to derive a general methodological framework for conducting a comparative LCA of a case study of an MFS versus a specialised system in Romania.

MATERIALS AND METHODS

In order to provide an overview of the main characteristics of LCA to represent MFS, a review of the related scientific literature was conducted, taking into account: (i) recent environmental LCA studies on the MFS and; (ii) the comparison of different steps and components of LCA.

In this review, 8 relevant LCA studies on MFS were identified. These studies have been published between 2012 and 2020. The respective studies have been characterized and analysed in all the LCA phases (from the definition of the objective and scope to the interpretation of the results) (Figure 1).

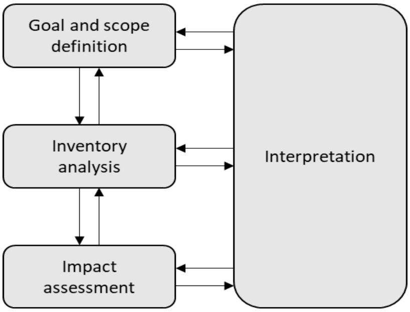

Figure 1. Phases of the common framework for LCA (ISO, 2006a; 2006b)

This review identifies the main components for the design of a methodological framework to conduct a fairer comparative LCA between a case study of MFS and a specialised system scenario in the Alexandria region of Romania.

RESULTS AND DISCUSSIONS

Table 1 shows the main features of the analysed LCA applications to MFS. The LCA applied to MFS was based on the common methodological framework for LCA proposed by ISO 14040 and ISO 14044 (ISO, 2006a, 2006b), which is structured in 4 steps (Figure 1): Goal and scope definition, life cycle inventory (LCI) analysis, impact assessment and interpretation.

The main goals of the analysed LCA applications to MFS were:
- Compare the environmental performance of MFS against other systems (Veysset et al., 2014; Marton et al., 2016; Parajuli et al., 2018; Costa et al, 2018), and alternative MFS scenarios (Vogel et al., 2020);
- Compare the environmental impacts of the different components of MFS (livestock, crops, etc.) (Eady et al., 2012; Parajuli et al., 2018; Paramesh et al., 2019) and;
- Assess the effect of climate change on the environmental impacts of MFS (Tendall et al., 2015).

The scope of these studies was limited to the first stage of the food supply chain i.e., from ‘cradle to the farm gate’. In the case of MFS, the farm is mainly divided into two main components: livestock production and crops, which have interactions between them.

Table 1. Main features of the LCA on mixed farming systems

Reference	Scope	FUs	Data sources	Impact categories
Eady et al. (2012)	Cradle to farm gate	- 1 t of grain; - 1 kg of greasy wool; - 1 animal	Farm documents; Literature and agricultural models; Ecoinvent 2.0 unit processes; Australian Unit Process LCI; LCA Food DK Library	GWP
Veysset et al. (2014)	Cradle to farm gate	1 kglw; UAA ha	Field survey (commercial farm data); Literature	GHG (GWP); NRE (with LCA); ANB
Tendall et al. (2015)	Cradle to farm gate	MJ dig. en. for humans	SALCA database; Ecoinvent	NRE; GWP; TOF; AP; FE; MWE; TER; AEP; TEP; HTP; LUC; ABL; RTB
Marton et al. (2016)	Cradle to farm gate	- 1 Kg FPCM; - Basket of products: 1 kg FPCM + CPLA	Swiss FADN; Literature; Experts; Ecoinvent v2.2	nrCED; GWP; aqEN; terrET; K use; P use
Parajuli et al. (2018)	Cradle to farm gate	Basket of products: 1 kgLW-SCC + 1 kgLW-Pigs”	Literature; Country statistcis; Ecoinvent v3	GWP; EP; NRE; PFWTox
Costa et al. (2018)	Cradle to farm gate	Composite FU (technological reference unit, TRU)	On the farm from the farm manager; Interviews; Official publications; Technical reports; Ecoinvent; Boustead Model 5.1	TRU; ARD; CC; PEC; AP; POC; FE; MWE; WS; FEC; LU; BI; SHI
Paramesh et al. (2019)	Cradle to farm gate	Basket of products: Total harvested weight produced at farm gate	Experimental site; Ecoinvent v3	GWP; NRE
Vogel et al. (2020)	Cradle to farm gate	1 kglw of beef cattle for fattening; 1 kg of grain (13% moisture)	Experimental field; Secondary data; Literature; Ecoinvent® v.3.01	GWP; AP; EP; AD

ABL = Potential aquatic biodiversity loss; AD = Abiotic depletion; AEP = Aquatic ecotoxicity potential; ANB= Apparent nitrogen balance; AP = Acidification potential; aqEN = Aquatic eutrophication N; ARD = Abiotic resource depletion; BI = Biodiversity indicators; CC = Climate change; EP = Eutrophication Potential; FU = Functional unit; FE= Freshwater eutrophication; FEC = Freshwater ecotoxicity; GHG = Greenhouse gas; GWP = Global warming potential; HTTP = Human toxicity potential; K = Potassium; kg FPCM= kg fat and protein corrected milk; kgLW = kg liveweight; LU = Land use; MJ dig. en. = Megajoules digestible energy for humans; MWE= Marine eutrophication; nrCED = Cumulative energy demand from fossil and nuclear sources; NRE = Non-renewable energy; P = Phosphor; PEC = Primary energy consumption; PFWTox = Potential Freshwater Ecotoxicity; POC = Photochemical ozone creation; RTB = Reduction of potential terrestrial biodiversity; SCC = Suckler cow calves; SHI = Soil health indicators; TEP = Terrestrial ecotoxicity potential; TER = Terrestrial eutrophication; terrET = Terrestrial ecotoxicity; TOF = Tropospheric ozone formation potential; TRU = Technological reference unit; UAA = Utilized agricultural area; WS = Water scarcity.

Thus, results may vary depending on the LCA approach followed (considering one product "product level" or integrating all products from all activities "farm level") and the way processes are attributed in MFS, especially when comparing these systems to specialized ones (Marton et al., 2016). The main benefits and interactions were found in Eady et al. (2012) and Parajuli et al. (2018). These interactions include the use of livestock manure as fertilizer on field crops and the use of the latter for animal feed (crop stubble, grazing). Eady et al. (2012) included benefits related to minimizing weed control and additional nitrogen (N) deposition for crops through sheep grazing, as well as N fixation by the legume in favour of the next non-legume crop in the rotation and the agronomic benefits of the "break crop" (excluding additional N) that increase cereal yields.

Given the importance of the magnitude of the reference flows, these authors argued the need to model farming systems in a way that recognizes the benefits transmitted between farming activities.

Different functional units (FUs) were used in the analysed LCA applications to MFS. Some are based on the farm approach "basket of products" such as (Marton et al., 2016; Parajuli et al., 2018; Paramesh et al., 2019) and others on the product approach considering one farm product (Veysset et al., 2014). The "basket of products" is a composite FU derived from the "farm approach", which considers all products generated by the farm. This approach is more practical than the "product approach" when assessing MFS, as it allows the whole farm to be considered, instead of focusing on one product of the farm. The product approach leads to limiting the identification of optimization opportunities (Marton et al., 2016). The FU "MJ dig. en." used in Tendall et al. (2015), can combine the dual objective of minimizing environmental impacts per area while maximizing agricultural production per area. In this study, the authors revealed that if "ha × y" were to be used as the FU, the trends observed for global warming potential (GWP) would be reversed. The use of combined FU reflecting other agricultural functions and food qualities, such as nutritional value could provide a more balanced assessment (Tendall et al., 2015). The MFS have multiple functions and can reduce the use of synthetic chemical inputs (fertilizers and pesticides) due to the different interactions in the farm (nutrient recycling, animal grazing, etc).

The MFS are multifunctional systems with multiple products. Dealing with multiple functions and products makes the selection of the FU even more complex for these systems. In any case, the choice of FU depends on the objectives of the LC study and the research typology, and may differ at the discretion of the practitioners (De Luca et al., 2018; Espadas-Aldana et al., 2019).

When applied to MFS, LCA faces the issue of how to adequately model the input-output of different activities involving multiple products and co-products as well as complex mutual interactions. Thus, selecting an appropriate method for allocating inputs to outputs is crucial. Several authors, including Eady et al. (2012) and Marton et al. (2016) showed that different allocation methods could affect the results.

Different co-product handling methods were used in the selected studies. Of these, the studies of Eady et al. (2012) and Marton et al. (2016) stand out, since they included the comparison of the results achieved with these different methods. The authors started the process, following ISO recommendations by dividing the farm into sub-processes. The allocation methods are based on two approaches: (i) attributional (economic and physical allocations) and; (ii) consequential (system expansion). In the literature, it is widely recognized that a consequential approach is more suitable for studying changes in production, while an attributional approach is more appropriate for describing a product. In the case of MFS, Marton et al. (2016) confirmed that system expansion (SE) was suitable to cope with the complexity of MFS, especially when comparing these systems with specialised ones. The SE is a "consequential" approach allowing environmental impacts to be attributed to the main product by modelling co-products as an avoided substitute product (avoided burden). However, SE makes the assessment process more complex, as it requires the collection of more data on substitutes, which are also derived from multifunctional systems, leading to circular reasoning (Wilfart et al., 2021).

For the other studies, the modelling process was reported in less detail using different methods depending on the objective such as, consequential (Parajuli et al., 2018); attributional for LCI and composite FU to avoid allocation of environmental and social burdens (Costa et al., 2018); mass-based allocation (Paramesh et al., 2019) and economic allocation (Vogel et al., 2020). Overall, important results and conclusions were obtained when investigating and using crop-handling methods in the LCA of MFS, however, more detail and transparency is needed on how these complex systems are modelled.

After setting system boundaries, the second step consists of collecting, quantifying and organizing the necessary data for the different elementary flows of materials, energy and emissions to build up the Life Cycle Inventory (LCI).

A representative LCI of the agro-system is needed to draw valuable conclusions for the decision-making process, which sometimes is not the case, as several LCA studies have pointed out (Nemecek and Erzinger, 2005; Renaud-Gentié et al., 2014, among others). In most of the analyzed LC studies (Table 1), the foreground data were related to statistical data and, therefore reliability and representativeness were not sufficiently taken into account. In addition, direct feedback from farmers and farm technicians is often not included, which is an important aspect in assessing the real environmental impacts of such a complex system as MFS. One notable study (Costa et al., 2018) included interviews with farmers and consultants. Stakeholder participation and farmer involvement is crucial to build a representative LCI model of the system under study and to understand farmers' choices and strategies (Pradeleix et al., 2022) and build useful decision support systems. Regarding background data, the most used LC database is Ecoinvent (Table 1). In general, this LC database and others more specific to the agri-food sector, such as Agribalyse, Agrifootprint, and Food LCA-DK, are based on data from specific times and sites, and should be used accounting for representativeness limitations. Therefore, investigation of site-specific data by LC practitioners is recommended to accurately model consumptions and emissions (Röös et al., 2010; Bellon-Maurel et al., 2014, among others).

Regarding impact categories, the most studied are GWP in kg CO_2eq and non-renewable energy use/demand/consumption (NRE) in MJ eq. Water scarcity was calculated in only one study (Costa et al., 2018). Biodiversity-related impacts were found only in two studies (Tendall et al., 2015; Costa et al., 2018) through the use of the SALCA and AgBalanceTM tools, respectively, while those related to soil health and quality were only included in Costa et al. (2018). Indicators related to biodiversity and soil quality are relevant in the context of MFS but are missing from agricultural LCAs in general (Notarnicola et al., 2017; van der Werf et al., 2020). Impacts related to nutrient use and balances, which are also of particular importance for MFS due to their recycling potential. The latter were only assessed in (Veysset et al., 2014) for N, in Marton et al. (2016) for phosphor (P) and Potassium (K) use and in Costa et al. (2019) for the three elements (N, P, K). Not including these aspects is likely to provide less information in the results when comparing the performance of these systems with others. Thus, more attention should be paid to these issues in future studies through the possible establishment of a common evaluation framework for the selection of relevant impact categories regarding MFS.

With respect to results, the comparison of the performance of MFS with specialized systems from a LCA perspective was reported in two studies (Veysset et al., 2014; Marton et al., 2016) (Table 2). These two studies showed contrasting results in terms of environmental impacts. These differences are mainly due to the different types of management in the evaluated farms and the different methodologies used. According to Veysset et al. (2014), the underperformance of MFS is mainly related to the independent management of MFS production units (livestock and crops) by farmers, which leads to higher input use and a low level of interactions between farm components. This, not only decreased nutrient recycling use and environmental performance, but economic outcomes. In addition, Veyset et al. (2014) focused on livestock products and did not include crop products in the comparison between MFS and specialized farms.

Table 2. Systems studied and main results in analysed LCA applications to MFS

Reference	Systems	Main hotspots/phases	Comparison of systems
Eady et al. (2012)	MFS	Stud rams Lupins	–
Veysset et al. (2014)	MFS and SS	Fertilisers Fuel	- Lower impact: SS - Higher impact: MFS
Tendall et al. (2015)	MFS	Pesticides Livestock-related fluxes for herd replenishment and feed inputs	–
Marton et al. (2016)	MFS and SS	Manure management Methane emission	- Lower impact: MFS - Higher impact: SS
Parajuli et al. (2018)	2 MFS: MFSGB and MFSWB	N_2O emission (fertilisers); Diesel consumption; Methane emission	- Lower impact: MFSGB - Higher impact: MFSWB
Costa et al. (2018)	2 MFS and CS	Livestock emissions Fertilisers; Zinc minerals in cattle feed	- Lower impact: MFS - Higher impact: CS
Paramesh et al. (2019)	MFS	Enteric methane emissions; Diesel consumptions; N_2O emissions (chemical fertilisers)	–
Vogel et al. (2020)	MFS	Methane emissions; Manure; fertilisers	–

MFS = Mixed farming system; SS = Specialised system; CS = Conventional system; MFSGB = MFS with a green biorefinery; MFSWB = MFS without a green biorefinery

In contrast, Marton et al. (2016) followed a "farm approach" by considering all farm products, including the interactions between different farm activities in MFS. Summarizing, taking into account the interactions and benefits (nutrient recycling, animal grazing, etc.) shared between farm activities in MFS, at the level of farmer strategy (practical level) and at the theoretical level, could affect the environmental and economic results at both levels.

In general, the rest of the studies confirmed that good MFS management, taking advantage of and expanding the interactions and synergies between farm activities, could mitigate environmental impacts.

General LCA methodological framework for the case study. The object of the study is a mixed crop-livestock farm in the region of Alexandria in Romania. The livestock farm keeps an average of 200 livestock units (LUs). The LUs include 160 heads of dairy cows and 40 heads of young stock. The crops cultivated in the agricultural area are maize, wheat and barley. Manure resulting from livestock activity is used as fertiliser for the crops, which in turn provides feed for the livestock activity. The animals do not leave the dairy cow farm and do not go to pastures at any time of the year. The goal of the study is to evaluate and compare the environmental impact of this system to a linear scenario (system with disconnected livestock and crops). Figure 2 shows the general diagram and the LCA boundaries for the studied MFS. The scope of the study is "cradle to farm gate", including the crop-livestock production chain from the extraction and use of raw materials and energy (electricity, fuel, water, fertilizers, pesticides, cleaning and medicines products, etc.) to the farm gate (Figure 2).

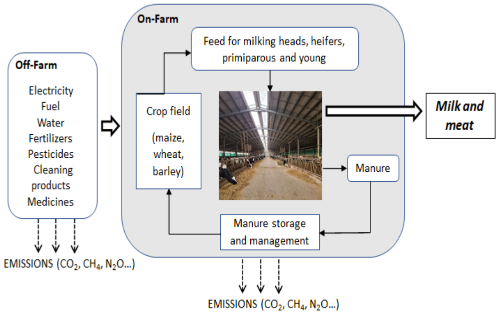

Figure 2. General flow diagram for the case study of MFS

Table 3 presents the main features of the LCA methodological framework for the case study. The main elements of the methodological framework have been derived from the recommendations and findings of the above literature review.

Table 3. Main features of the LCA methodological framework for the case study of MFS

Goal	Scope	FU	Data sources	Co-product handling method
Evaluate and compare the environmental impact of an MFS to a SS	Cradle to farm gate	A basket of products (Farm approach): 1 kg FPCM + the respective amounts of co-products live animals and crops	Detailed questionnaire to farmer Site-specific data (measurement of field emissions)	System expansion

MFS = Mixed farming system; SS = Specialised system; FPCM = kg fat and protein corrected milk

The selected FU is a basket of products including milk, live animals sold for meat and crops (farm level). Thus, a farm-level approach is applied which takes into account all products of the farm to allow a fairer comparison of the environmental impacts of mixed and specialised farming systems. The allocation method is based on a consequential approach (system expansion). As mentioned above, a consequential approach is more suitable for studying changes in production.

The primary data for the compilation of the LCI is collected using a detailed questionnaire for a real farm located in the Alexandria region of Romania. Background data on input manufacturing and emissions (mineral fertilisers, pesticides, cleaning products and medicines, electricity, etc.) are extracted from the ecoinvent database. Field emissions of CO_2, CH_4 and N_2O are estimated through site-specific measurements.

The Life Cycle Impact Assessment (LCIA) is carried out using the ReCiPe midpoint (H) method (Huijbregts et al., 2017) with openLCA v.1.11.0 software in order to quantify the environmental impacts and to identify the main hotspots. Midpoint indicators are recommended to represent impacts stemming from agricultural production because they are easily understandable for communicating results, and because a limited number of indicators can effectively summarise relevant information (Mouron et al., 2006; Tendall & Gaillard, 2015).

CONCLUSIONS

In this study, the most relevant applications of LCA to MFS have been analysed. Our review revealed the complexity of conducting LCA of these systems and comparing relative studies due to the multifunctionality, the generation of multiple co-products and interactions between different farm components, as well as the use of different methodologies and approaches.

LCA of MFS should be conducted by considering the different interactions and synergies in the MFS at the whole farm level rather than at the product level. Stakeholder participation and real data are needed to carry out evaluations at the regional level, and thus, propose optimization strategies for the design of public policies aiming at promoting these systems under good management to achieve greater sustainability.

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