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ALYNE MARTINS MACIEL

LIFE CYCLE ASSESSMENT OF MILK PRODUCTION

JUIZ DE FORA
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Dissertação apresentada ao Programa de Pós-graduação em Ecologia Aplicada ao Manejo e Conservação dos Recursos Naturais, da Universidade Federal de Juiz de Fora como parte dos requisitos necessários à obtenção do título de Mestre em Ecologia aplicada ao Manejo e Conservação dos Recursos Naturais.

Orientador: Dr. Nathan Oliveira Barros
Co-orientador: Dr. Marcelo Henrique Otenio

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RESUMO GERAL

A Avaliação do Ciclo de Vida (ACV) é uma ferramenta para avaliar e quantificar o impacto ambiental na cadeia de produção de produtos e serviços de consumo. Esta ferramenta pode propor melhorias nos processos produtivos e consequentemente auxiliar na redução dos impactos. A produção de leite provoca impactos ambientais em escala regional e global. Assim, no capítulo 1, com o objetivo de avaliar o papel do biodigestor anaeróbio na mitigação dos impactos ambientais da produção leiteira, foram avaliadas duas fazendas produtoras de leite aplicando a metodologia ACV. A primeira é a fazenda Embrapa, que possui o biodigestor anaeróbio para o tratamento de efluentes. Nesta fazenda realizou-se a análise com e sem o biodigestor anaeróbio (AD e NAD1, respectivamente). A segunda é a fazenda Colinas, que não contém o biodigestor anaeróbio (NAD2). Já no capítulo 2, a fim de investigar se a escolha do software influencia os resultados da ACV comparou-se dois softwares, o OpenLCA® 1.6.3., o único de código aberto, e o SimaPro® 8.5.2., o software comercial mais utilizado mundialmente. Utilizou-se as ACVs dos cenários AD e NAD2 na comparação. Ambas as fazendas estão no estado de Minas Gerais, Brasil. Como unidade funcional foi adotado 1 kg de leite corrigido por proteína e gordura. Para avaliar os impactos ambientais, e comparar as ferramentas dos dois softwares, o método CML 2001 (baseline), versão 4.4, foi usado, considerando as categorias de impacto: acidificação potencial, depleção de ozônio, uso de energia, eutrofização, mudança climática e oxidação fotoquímica. O biodigestor anaeróbio se mostrou como boa alternativa para reduzir o impacto ambiental em todas as categorias avaliadas. AD teve menor potencial de impacto para acidificação, eutrofização, mudança climática, uso de energia, oxidação fotoquímica e depleção de ozônio, em média entre 25% e 38% menor do que NAD1 e NAD2, respectivamente. De forma qualitativa, os softwares SimaPro e OpenLCA possuem interface acessível para a modelagem de ACV, e oferecem praticamente os mesmos recursos. Quantitativamente o software SimaPro apresentou resultados diferentes do OpenLCA, para o cenário AD, na maioria das categorias de impactos avaliadas, onde o recurso "produto evitado", utilizado em ambas as ferramentas de software, pode ser a principal causa da diferença. Os resultados do cenário NAD2 foram similares em ambos softwares. A categoria de mudança climática foi a que apresentou valor mais próximo em ambos os softwares e cenários. Portanto, conclui-se que ambos os softwares podem ser utilizados para a realização de ACV da produção leiteira, devendo atentar-se quanto a utilização da função “produto evitado”. Ademais, todos os

impactos avaliados foram significativamente reduzidos com a presença do biodigestor anaeróbio.

GENERAL ABSTRACT

Life Cycle Assessment (LCA) is a tool for evaluating and quantifying the environmental impact in the production chain of consum products and services. LCA can propose improvements in the productive processes and consequently help to reduce the impacts. Milk production causes environmental impacts on a regional and global scale. We evaluated, in chapter 1, two milk production farms by applying the LCA methodology, aiming to evaluate the role of the anaerobic digester in the LCA of milk production as mitigation of the environmental impacts. One farm performs the treatment of effluents by anaerobic digestion, the Embrapa farm, we performed the analysis on this property with and without the anaerobic digester (AD and NAD1, respectively). The second is the Colinas farm that does not contain the anaerobic digester (NAD2). In addition, in order to investigate whether the choice of software influences the results of LCA, in chapter 2 our study aimed to compare two software. One is the only open source software, OpenLCA® 1.6.3., and another is commercial software, most used worldwide, SimaPro® 8.5.2. For this comparison, we used the LCA of the AD and NAD2 scenarios. The farms are in the state of Minas Gerais, Brazil. We adopted 1 kg of fat and protein milk corrected as functional unit. To assess of environmental impacts, and to compare the software tools, the method CML 2001 (baseline), version 4.4, was used considering the following categories of impact: potential acidification, ozone depletion, energy use, eutrophication, climate change and photochemical oxidation. The anaerobic digester is a good alternative to reduce the environmental impact in all categories evaluated. DA has lower potential impact for acidification, eutrophication, climate change, energy use, photochemical oxidation, and ozone depletion, on average 25% and 38% than NAD1 and NAD2, respectively. In a qualitative way, the SimaPro and OpenLCA software has friendly interface for modeling and offer practically the same resources. Quantitatively, the SimaPro software presented results different from OpenLCA, for AD scenario, in most of the impact categories, where the "avoided product", feature used in both software tools, may be the main cause of the difference. The results of the NAD2 scenario were similar in both software. The climate change category was the one that presented the closest value in both software and scenarios. We conclude that both software can be applied to perform LCA of dairy production, and attention should be paid to the use of the "avoided product" function. In addition, the presence of the anaerobic digester reduces all the evaluated impacts significantly.

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INTRODUÇÃO GERAL

Para sustentar os atuais padrões de consumo e produção são utilizados diversos recursos da natureza, gerando diversos tipos de poluição e impactos ambientais. Dessa forma, surge a metodologia denominada Ecologia Industrial, que trata da relação existente entre indústria e meio ambiente, e indica os impactos ambientais causados pelo sistema industrial nos ecossistemas naturais, que o mantém. O termo “Ecologia Industrial” foi definido em 1997 por Erkman, onde o autor descreve que a metodologia tem o objetivo de minimizar o impacto do sistema industrial sobre o ambiente. A Ecologia Industrial é abrangente, possui uma visão integrada de todos os componentes do sistema industrial, em que este pode ser visto como um certo tipo de ecossistema, e seus relacionamentos com a biosfera (ERKMAN, 1997).

Outra proposta que surgiu com o mesmo objetivo é conhecida como Economia Circular, que enfatiza a importância de se otimizar a utilização dos recursos naturais da forma mais sustentável possível (MOTTA, 2016). Nessa proposta, o sistema produtivo sai de um processo linear e passa para um processo circular, onde visa o reaproveitamento dos resíduos sólidos, aumentando a utilização de materiais e energia, em que o principal objetivo é a redução do desperdício em todo o ciclo de vida dos produtos.

O conceito de sustentabilidade tornou-se um fator chave nos últimos anos. O desenvolvimento sustentável foi descrito como o desenvolvimento que permite atender as necessidades das gerações atuais, sem comprometer que as necessidades das futuras gerações possam ser atendidas” (ONU BR, 2016). A ISO 14001:2004 é uma norma que auxilia na administração de empresas e padroniza a implantação de um Sistema de Gestão Ambiental, para que seja possível identificar o que não está ocorrendo como planejado e, assim, melhorar continuamente de forma a garantir a proteção ambiental.

Como consequência, surge a Avaliação do Ciclo de Vida (ACV), regida pelas normas 14040 e 14044 (ISO 2006a,b). A ACV é considerada como umas das mais completas “ferramentas ambientais” existentes, é uma das principais metodologias para métricas ambientais e uma importante ferramenta de gerenciamento e tomada de decisões, com vistas a garantir maior sustentabilidade de produtos e serviços (MOTTA, 2016; KHOSHNEVISAN et al., 2018). A ACV permite quantificar os impactos ambientais de forma holística, compila entradas e saídas de recursos materiais e energéticos envolvidos em sistemas produtivos, e traduzem este valor em impactos ambientais (CREMIATO et al., 2018; GOGLIO et al., 2018). Além disso, é um dos métodos mais aceitos internacionalmente para tornar a produção mais sustentável.

O primeiro estudo que utilizou a metodologia que conhecemos hoje como ACV foi realizado nos Estados Unidos, em 1969, solicitado pela Coca-Cola para determinar qual tipo de material para a fabricação de garrafas utilizava menos recursos naturais e energia. Atualmente, em vários países a ACV é utilizada em políticas públicas, na Alemanha, por exemplo, orienta o reuso e a reciclagem; na França a ACV é aplicada em todos os produtos industrializados; no México, no Peru e no Chile, a ACV é obrigatória na legislação de biocombustíveis (COELHO et al., 2016). Porém, no Brasil não há ainda instrumentos que possam incorporar a ACV nas políticas públicas.

No Brasil a implementação da ACV ainda está se estabelecendo. A falta de banco de dados nacional completo com informações sobre os inventários do ciclo de vida de produtos brasileiros, o custo elevado de um estudo de ACV, aliado a complexidade da ferramenta, contribuem para a dificuldade de implementação (MOTTA, 2016). No país, a produção acadêmica engloba principalmente os setores produtivos de construção civil, automobilístico, de embalagens, de energia, de mineração, químico, agropecuário, etc (COELHO et al., 2016).

Para alcançar a redução dos impactos ambientais nos sistemas produtivos de forma significativa, diversos setores precisam ser estudados. A relevância do setor agrícola e pecuário no Brasil e os potenciais impactos ambientais têm motivado diversas linhas de pesquisa direcionadas a elevar o desempenho ambiental dos sistemas de produção. E dessa forma, com a identificação dos pontos de maiores impactos, utilizando-se da ferramenta de ACV, por exemplo, é possível buscar soluções ambientais que atendam ao desenvolvimento econômico.

Um dos setores mais importantes do complexo agroindustrial é a pecuária leiteira. A produção mundial de leite em 2016 foi de 798 milhões de litros (FAO, 2016). A Europa e a Ásia produziram juntas dois terços do leite, 67,5% do total. O continente americano respondeu por 22,7% desse volume, já a América do Sul ficou com7,8%. Com 35,1 bilhões de litros produzidos anualmente, o Brasil é o quarto maior produtor de leite do mundo (EMBRAPA, 2018). Dessa forma, a pecuária leiteira possui grande importância no Brasil, do ponto de vista social, é uma das principais atividades praticadas por pequenos e médios produtores, e a respeito do setor econômico, o leite ficou em sexto lugar entre os principais produtos do agronegócio brasileiro (CONFEDERAÇÃO DA AGRICULTURA E PECUÁRIA DO BRASIL, 2016).

Porém, o setor leiteiro também é uma das mais importantes fontes de emissão de gases de efeito estufa (GEE), além de contribuir para a degradação dos recursos naturais, eutrofização, acidificação, entre outros impactos (FAMIGLIETTI et al., 2019). Nos últimos anos a conscientização sobre a necessidade de reduzir as emissões de GEE da atividade pecuária, incluída entre os principais responsáveis pela poluição ambiental e mudança climática, se elevaram (BALDINI et al., 2018). O armazenamento e manejo dos dejetos gerado pelos animais, incluindo urina, fezes, cama utilizada e água e alimento desperdiçados, possuem grande potencial de emissão de GEE, e potencial de causar diversos outros impactos como eutrofização e acidificação (EMBRAPA, 2018).

Contudo, os impactos ambientais, incluindo as emissões de GEE, podem ser reduzidos com o correto manejo dos dejetos animais. A digestão anaeróbia, realizada por biodigestores, representa uma das formas mais sustentáveis de tratar os dejetos, podendo reduzir os impactos ambientais da produção leiteira (MASSARO et al., 2015). Biodigestores são constituídos por uma câmara hermeticamente fechada, sem nenhum contato com o ar atmosférico, onde o material orgânico sofre degradação anaeróbia devido à ação dos microrganismos metanogênicos que degradam o material orgânico e liberam gás metano, dessa forma, a matéria orgânica é transformada em biogás (MACIEL et al., 2019) O biogás gerado durante a digestão anaeróbia pode ser usado como energia renovável, o que representa uma solução eficiente de mitigação de emissão de GEE (PASSOS et al., 2017; SAHOTA et al., 2018). Além disso, o efluente final produzido é rico em nutrientes e pode ser utilizado como fertilizante orgânico em diversas culturas, evitando assim a compra e uso de fertilizantes convencionais (MENDONÇA et al., 2016; PASSOS et al., 2017, LIJÓ, et al., 2017; MACIEL et al., 2019).

Dessa forma, ao se referir ao desenvolvimento sustentável, é imprescindível a utilização de um indicador que, por meio de valores numéricos, determine o quanto o padrão de produção e consumo está exigindo da natureza (RECKMANN et al., 2012). Para isso, existem alguns softwares que auxiliam na realização da ACV. Onde o software mais utilizado mundialmente é o SimaPro® (PRÉ-SUSTAINABILITY, 2018), e existe ainda o OpenLCA®, também bastante utilizado, que é o único software gratuito para o gerenciamento de informações do ciclo de vida (GreenDelta GmbH, 2018). A existência de um software gratuito auxilia na disseminação de estudos de ACV, tanto no setor acadêmico quanto industrial.

Nesse contexto, objetivou-se neste trabalho, no capítulo 1, avaliar pela primeira vez no Brasil e de forma integrada os impactos ambientais da produção leiteira, utilizando a ferramenta de ACV, e quantificar os impactos ambientais que são mitigados a partir da utilização de sistemas biodigestores. Para isto, realizou-se a ACV de 2 fazendas produtoras de leite, a primeira é a Embrapa Gado de Leite, que possui um biodigestor instalado para o tratamento dos dejetos animais. Na fazenda da Embrapa realizou-se duas modelagens, uma em escala real, e outra desconsiderando o sistema biodigestor, AD e NAD1, respectivamente (Figuras 1 e 2, respectivamente). A segunda fazenda é a Colinas, que não possui biodigestor para tratar os dejetos animais, e foi chamada de NAD2 (Figura 3).

Além disso, buscou-se identificar no capítulo 2 deste trabalho se a escolha do software, SimaPro® ou OpenLCA®, pode influenciar nos resultados da ACV. Para esta análise, utilizou-se as ACVs realizadas no capítulo 1, das modelagens AD e NAD2.

Fluxogramas das fazendas

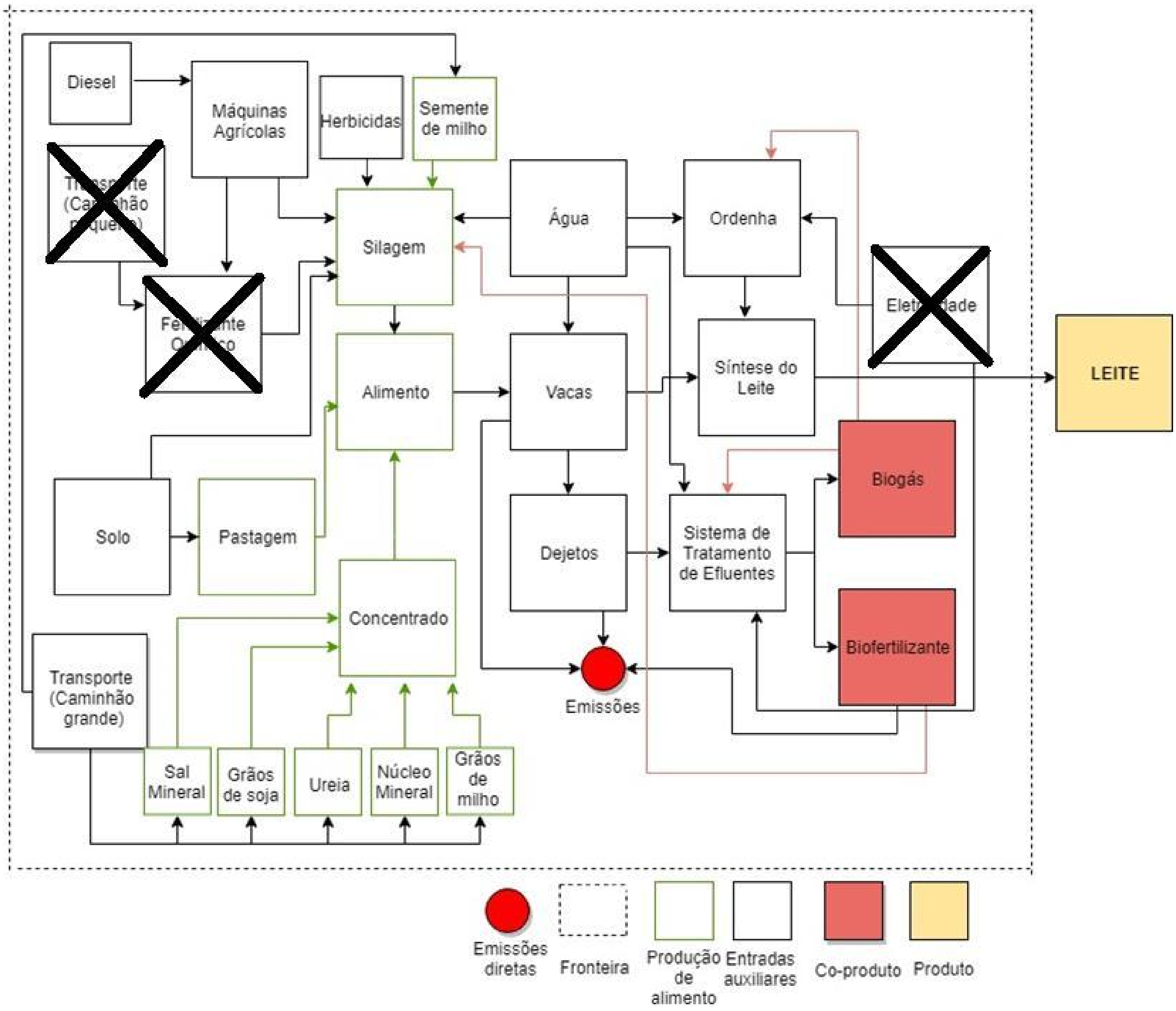

Figura 1. Fluxograma da fazenda Embrapa Gado de Leite, em escala real (AD).

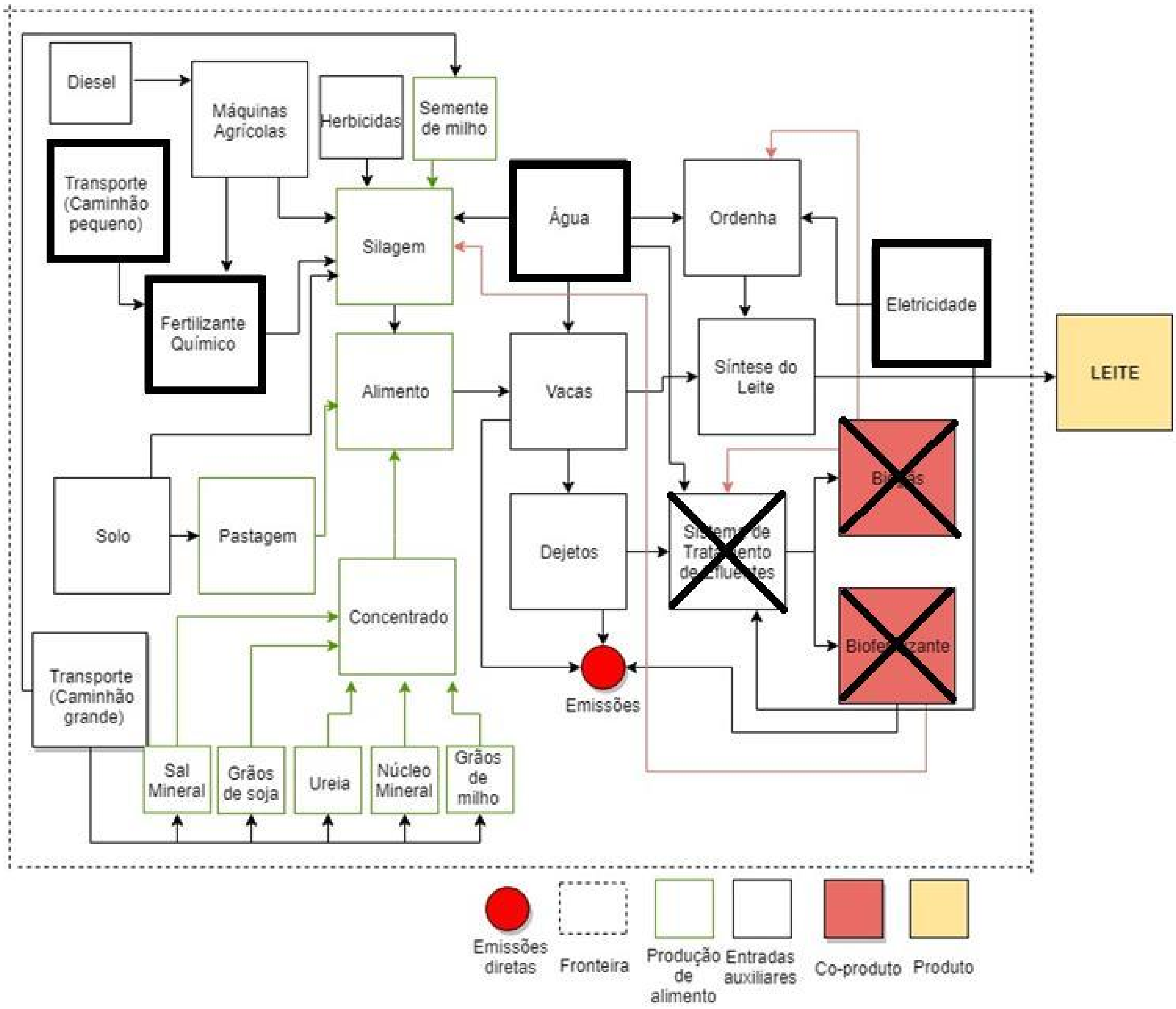

Figura 2. Fluxograma da fazenda Embrapa Gado de Leite, modelada sem o biodigestor (NAD1).

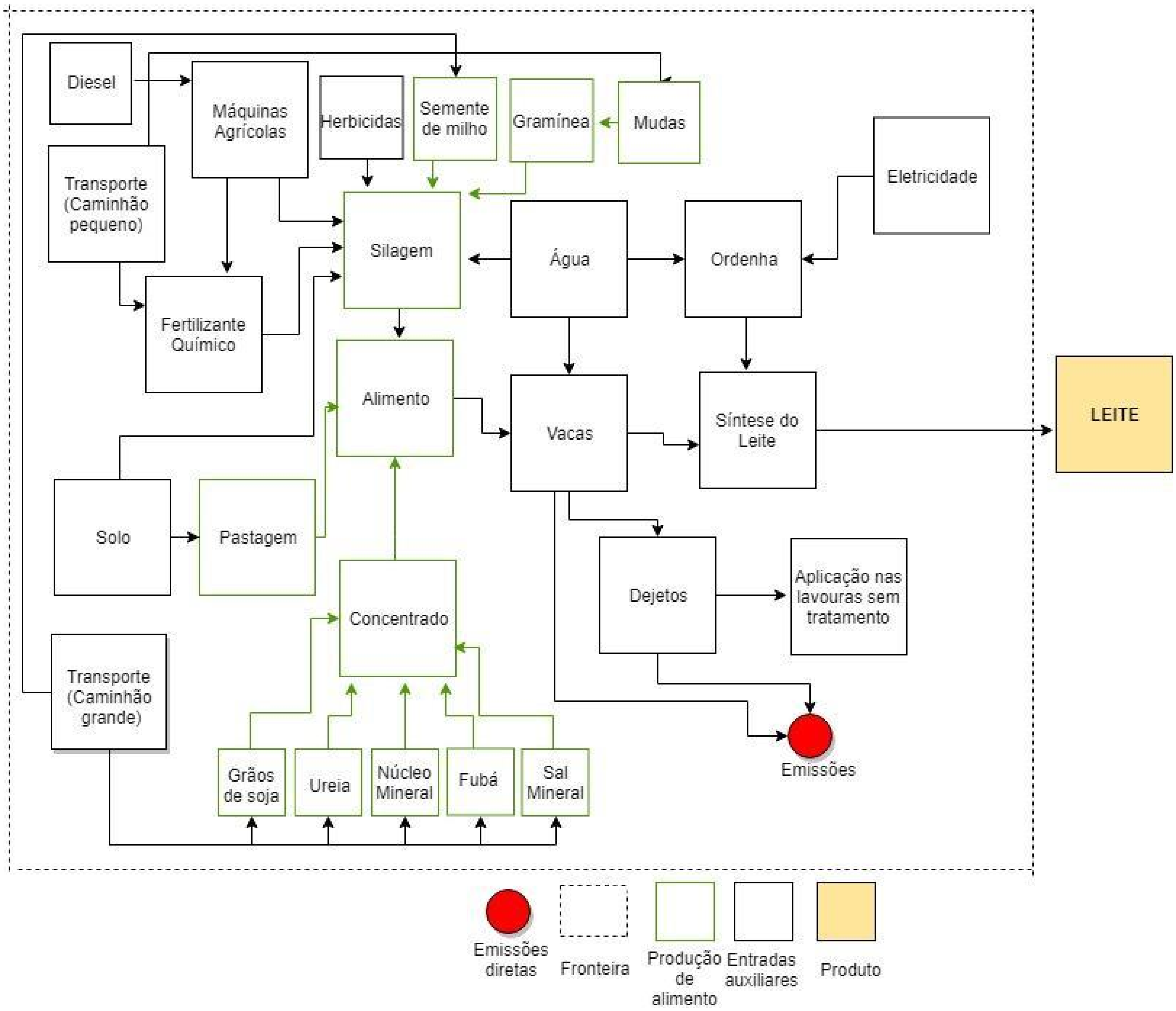

Figura 3. Fluxograma da fazenda Colinas, em escala real (NAD2).

Hipóteses deste trabalho:

Hipótese 1 – A utilização de sistemas biodigestores para tratamento dos dejetos animais reduz os impactos ambientais da produção de leite.

Hipótese 2 – As ferramentas de software de ACV, SimaPro e OpenLCA, apresentam os mesmos resultados.

CAPÍTULO 1

ANAEROBIC DIGESTER REDUCES LIFE CYCLE IMPACTS OF MILK PRODUCTION

ABSTRACT

Dairy farming causes environmental impacts on the regional and the global scale. We evaluated the environmental impacts of two milk production farms by applying the Life Cycle Assessment (LCA) methodology. One of them performs the wastewater treatment by anaerobic digestion. To identify the role of the anaerobic digester on the LCA, we carried out an analysis in this property with and without the anaerobic digester (AD and NAD1, respectively). The second farm does not contain the anaerobic digester (NAD2). The farms are in the state of Minas Gerais, Brazil. We adopted 1 kg of fat and protein corrected milk as a functional unit. The software OpenLCA© was applied. AD has lower potential impact for acidification, eutrophication, climate change, energy use, photochemical oxidation, and ozone depletion, on average 25% and 38% than NAD1 and NAD2, respectively, which demonstrates that the presence of the anaerobic digester reduces all the evaluated impacts significantly.

Keywords: LCA; environmental impacts; dairy sector; manure management; livestock.

1. INTRODUCTION

Tropical farming is of great importance in dairy production, where Brazil stands out as the fourth largest dairy producer in the world (EMBRAPA, 2018). The livestock and agriculture sectors are projected to expand with a growing world population, and so are the associated environmental impacts (GOGLIO et al., 2018). Milk production has a major effect on environmental degradation and resource depletion, causing many impacts, including eutrophication, acidification, photochemical oxidation, ozone depletion among others (BACENETTI et al., 2016; BAVA et al., 2018; WANG et al., 2018). In addition, if considered globally, the livestock sector plays an important role in climate change, it represents 14.5 percent of human-induced greenhouse gas (GHG) emissions (GERBER et al., 2013).

Anaerobic digestion represents one of the most sustainable ways to treat wastewater that comes from cattle (MASSARO et al., 2015). The biogas, generated during anaerobic digestion, is used as renewable energy, which represents an efficient solution to reduce the environmental impact of dairy farming, and brings a GHG mitigation effect. (PASSOS et al., 2017; SAHOTA et al., 2018). Moreover, the produced digestate, rich in nutrients, is used as an organic fertilizer in crops cultivation, thus avoiding the purchase and the use of conventional fertilizers (MENDONÇA et al., 2016; PASSOS et al., 2017, LIJÓ, et al., 2017).

In Brazil, there is a committee, established by the Federal Low Carbon Agriculture Plan, which aims to reduce GHG emissions by the treatment of animal waste, including the process of anaerobic digestion and the electricity production from biogas (PLANO A. B. C., 2018). However, it is necessary to quantify the environmental impact that could be reduced by means of the anaerobic digesters.

In this sense, Life Cycle Assessment (LCA) is a methodology that allows quantifying the environmental impacts holistically, evaluating and calculating the resources consumed, the emissions, and the waste (CREMIATO et al., 2018; GOGLIO et al., 2018). This study aimed, firstly, to evaluate the environmental impacts of milk production systems using the LCA tool and, secondly, to verify how much the environmental burden can be decreased with the anaerobic digestion of wastewater. The LCA was applied in two farms: (1) the Embrapa farm, which treats wastewater using anaerobic digestion, and it was modeled in with and without the anaerobic digestion (AD and NAD1, respectively), and (2) the Colinas farm, which does not contain an anaerobic digester to treat wastewater (NAD2).

2. MATERIAL AND METHODS

To identify potential environmental impacts, concerning each activity of the milk production process, the LCA is performed under ISO 14040:2006 (ISO 2006a) and ISO 14044:2006 (ISO 2006b) standards, which describe the Requirements and Guidelines, and the Principles and Structure, respectively.

The ISO 14040 standards, adopted in this study, separate LCA into four phases, including: definition of the LCA goal and scope (which includes the functional unit and boundaries of the system); inventory analysis phase (all inputs and outputs, encompassing all the system life cycle); impact assessment (where the potential impacts of the system are quantified through impact indicators); and life cycle interpretation (evaluates strategies that can be used to reduce environmental impact) (CREMIATO et al. 2018).

The standards recommend that the allocation procedures should be avoided (ISO 14044 2006b). Therefore, in this study, 100% of the potential environmental impacts evaluated concern the milk system. Several studies have shown that the choice of the allocation method influences the final results of milk production performance since meat is also produced. However, this influence is more significant for European systems and it does not apply to Brazil since in this the country has an independent meat production system (DE LÉIS et al., 2015).

2.1 Goal and scope definition

The aim of this study was to evaluate the environmental impacts of two milk production farms, identifying the major impacting processes and estimating the impact reduction due to the use of anaerobic digestion of wastewater. We conducted the study on farms that operate with semi-intensive management systems, located in Minas Gerais, Brazil. The Embrapa farm, an experimental field station of Embrapa Dairy Cattle, operates with an anaerobic digester system for wastewater treatment. Two models were adopted for this farm: AD, in real conditions, and NAD1, simulating the removal of the anaerobic digester. The Colinas farm, NAD2, operates without anaerobic digester.

2.1.1 Functional Unit (FU) and system boundaries

The use of FU allows comparisons with other dairy farms that work with different breeds or use different types of feed for the herd (IDF, 2015). The environmental impacts of farms were evaluated with the FU established as one kilogram of Fat and Protein Corrected Milk (FPCM) leaving the farm gate. We calculated FPCM using the formula defined by the International Dairy Federation (Equation 1; IDF, 2015).

$$1\text{kg FPCM} = 1 \text{ kg milk} * (0.1226 * F + 0.0776 * TP + 0.2534), \qquad (1)$$

where FPCM = fat protein corrected milk, F = fat (%) and TP = True protein (%).

For the Embrapa farm (AD and NAD1), the percentage of fat and of true protein were 3.91% and 3.22%, respectively. For the Colinas farm (NAD2), the percentage of fat and of true protein were 3.89% of 3.20%, respectively.

There are, on average, 100 and 80 animals, on the Embrapa and the Colinas farm, respectively, among these, generally, an average of 80% are in the lactation phase. Productivity per cow is 19.3 kg and 18 kg at the Embrapa and the Colinas farm, respectively.

For both subsystems, boundaries are from "cradle-to-farm gate". The inputs include: planting of maize, transport, diesel fuel, electricity, acquisition of materials to the farm, the use of materials needed to manage the herd, milking, milk cooling and storage, until the generation, disposal and treatment of wastes, emissions from manure management, among other inputs and outputs. The gate is the delivery of milk to dairy transporters, going through all the necessary processes until the production cycle is completed. We considered cows in the lactation phase and in the dry phase. Calves were not considered in the study, only cows of reproductive age.

2.2 Life cycle inventory (LCI)

Real data of each farms processes, during one year of production, from 2017 to 2018, were collected through interviews with specialists and employees from various sectors of its respective farm (primary data). They provided details about the amount of milk produced by each farm, animal diets, cropping systems, fuel consumption, electricity used for milking parlor, and others. We considered for transport an average distance between farms and factory producers, and lorry weight (unit in t.km).

However, when it was not possible to use primary data, the background data, or secondary data, we obtained numbers from Ecoinvent databases (2016), scientific articles and technical reports. We used the Ecoinvent database for external inputs and outputs such as the production of chemical fertilizers, feed, diesel fuel, pesticides, as well as for off-farm activities and others.

2.2.1 GHG emissions from cattle

We used data from the literature to quantify the greenhouse gases emissions from manure management and from enteric fermentation animal. The environmental impact of livestock farming is linked to emissions such as CH_4, nitrous oxide (N_2O), among others, resulting from manure management and enteric emissions. The CH_4 production is related to the quantity and quality of food consumed and to the animal's diet type. These factors are influenced by age, weight, growth rate and milk production (WILLERS, 2014).

The method proposed by the IPCC is the most recommended for GHG estimation (BALDINI et al., 2017). CH_4 enteric emissions were estimated following the Tier 2 IPCC (IPCC, 2006) method, where all the informations relating to these calculations are described in Appendix A.

The production of manure generated daily by dairy cattle corresponds to approximately 10% of their body weight (KONZEN and ALVARENGA, 2008). This amount represents approximately 45 to 48 kg/cow/day. These data were used to calculate the waste produced on the studied farm.

Regarding the nitrous oxide (N_2O) and CH_4 emissions from manure, both depend on the nitrogen and carbon content present, storage time and type, type of treatment of the wastes and subsequent application in the soil (AMON et al., 2006; IPCC 2006). We calculated the CH_4 and N_2O emissions from manure management using the study carried out by Amon et al. (2006) that evaluated the emissions rate occurred during the treatment, storage and application of the waste in the soil, after the anaerobic digestion and without treatment.

2.2.2 The Embrapa farm description

The Embrapa farm treatment system, in AD, is composed of a continuous anaerobic plug-flow digester, operated in real scale with hydraulic retention mean time of 32 days, responsible for the residues treatment generated by dairy cattle. The digester is filled with washing water from the *free stall* floor, after that, the water passes through the anaerobic digestion process, and proceeds to the stabilization pond. The final effluent, the water that pass thought the anaerobic digester (digestate), stored in the pond, is pumped again to wash the corrals and is reused, on average, for 20 to 25 days, being characterized as reused water (MENDONÇA et al., 2017).

In AD, fertilizers are combined in organic and inorganic, the latter is obtained from the digestate of the anaerobic digestion. For the digestate application in the crops, technical and scientific studies were carried out, which attest to the viability of the operation. With the use of the anaerobic digester, the Embrapa farm saves water, fertilizers, and electricity.

The biogas obtained from the anaerobic digestion is transformed into electrical energy, which is sufficient to perform all the farm activities that involve the milk production, such as the pumping used in the wastewater treatment system and the milking operations (MENDONÇA et al., 2017). The main characteristics of the biogas produced in the Embrapa farm are shown in Table 1.

Table1. Main characteristics of the biogas produced in the Embrapa farm

Adapted from (MENDONÇA et al., 2017).

Parameter	Unit	Value
Biogas productions[1]	$m^3\ month^{-1}$	378.5 to 2186.1
Energy potential[1]	$KWh\ month^{-1}$	2070 to 19168
Average methane content	%	65 (±0.06)

1- The volumetric production of biogas and the energy potential varied because they depend on the organic load applied.

Wastewater treatment data, such as the anaerobic digester and the motor generator of electricity, was considered with the average useful life, 20 years, and converted to the FU. Inventories of inputs, outputs, and emissions of the whole process were elaborated for the system (see Table 2).

Table 2. Life Cycle Inventory of AD scenario

Parameters	Input/Output	Unit	Quantity for FU
Silage Production			
Land	Input	Hectare	0.00002
Maize seed	Input	Kg	0.00004
Fertilizer (planting) [1]	Input	Kg	0.01727
Fertilizer (coverage)[1]	Input	Kg	0.01919
Herbicides	Input	Liters	0.00013
Packaging for fertilizers and herbicides[2]	Input	Kg	0.00685
Fuel (Machines)	Input	Liters	0.00444
Pasture			
Land	Input	Hectare	0.00010
Animal food preparation			
Maize feed	Input	Kg	0.13370
Soybean feed	Input	Kg	0.08022
Urea	Input	Kg	0.00223
Mineral salt	Input	Kg	0.00668
Fuel (Machines)	Input	Liters	0.00226
Water			
Animal water feed	Input	Liters	3.23422
Energy			
Biogas	Input	kWh	0.08205
Transport			
Big lorry	Input	Ton*km	0.07725
Small lorry	Input	Ton*km	0.01119
CH_4 emission			
Enteric fermentation [3]	Output	Kg of CH_4	0.02142
Manure management [4]	Output	Kg of CH_4	0.00410
N_2O emission			
Manure management [4]	Output	Kg of N_2O	9.5225E-5
Wastewater treatment			
Biogas[5]	Output	Kg	0.03
Digestate[5]	Output	Kg	8.095854922
Anaerobic digestion[6]	Input	Item	8.87217E-08
Electricity Generator [6]	Input	Item	8.87217E-08

[1] NPK fertilizer, considering the organic and inorganic fraction.

[2] Quantity in kg of packaged product.

[3] Calculated on the basis of information supplied by IPCC (2006).

[4] Calculated on the basis of information supplied by Amon et al. (2006).

[5] Calculated on the basis of information supplied by Mendonça et al., 2017.

[6] Considering a service life of 20 years.

For the Embrapa farm, a second model was also carried out, NAD1, in which the wastewater treatment was disregarded to evaluate the effect of the anaerobic digestion. In this model, we eliminated the inputs and outputs by biogas and the digestate produced. In addition, in the software, it was necessary to modify the sources of the electric energy used in the farm. We converted the fertilizer from organic to inorganic, as well as other inputs related to these flows were modified, such as increasing the values related to packaging and transportation of fertilizers. The LCI of NAD1 is shown in Table 3.

Table 3. Life Cycle Inventory of NAD1 scenario

Parameters	Input/Output	Unit	Quantity for FU
Silage Production			
Land	Input	Hectare	0.00002
Maize seed	Input	Kg	0.00004
Fertilizer (planting)	Input	Kg	0.01727
Fertilizer (coverage)	Input	Kg	0.01919
Herbicides	Input	Liters	0.00013
Packaging for fertilizers and hebicides[1]	Input	Kg	0.01708
Fuel (Machines)	Input	Liters	0.00444
Pasture			
Land	Input	Hectare	0.00010
Animal food preparation			
Maize feed	Input	Kg	0.13370
Soybean feed	Input	Kg	0.08022
Urea	Input	Kg	0.00223
Mineral salt	Input	Kg	0.00668
Fuel (Machines)	Input	Liters	0.00226
Water			
Animal water feed	Input	Liters	3.23422
Energy			
Electricity grid	Input	kWh	0.08205
Transport			
Big lorry	Input	Ton*km	0.07725
Small lorry	Input	Ton*km	0.03410
CH_4 emission			
Enteric fermentation[2]	Output	Kg of CH_4	0.02142
Manure management[3]	Output	Kg of CH_4	0.01234
N_2O emission			
Manure management[3]	Output	Kg of N_2O	7.3250E-5
Manure			
Solid and liquid	Output	Kg	2.93000

[1] Quantity in kg of packaged product.

[2] Calculated supplied by IPCC (2006).

[3] Calculated supplied by Amon et al. (2006).

2.2.3 The Colinas farm description

The management of animals is also semi-intensive in the Colinas farm. The Colinas farm does not have the anaerobic digester for wastewater treatment from cattle. The waste from animals, when confined, are removed by water and applied to the soil. However, since there is no technical follow-up, no study was carried out to obtain the correct dosages of application in the crops. We cannot consider this operation as a substitute for chemical fertilizers. In this case, in the Colinas farm, the use of chemical fertilizer is the only one considered. The LCI of NAD2 is shown in Table 4.

Table 4. Life Cycle Inventory of NAD2 scenario

Parameters	Input/Output	Unit	Quantity for FU
Silage Production			
Land	Input	Hectare	0.00002
Maize seed	Input	Kg	0.00004
Fertilizer (planting)	Input	Kg	0.01913
Fertilizer (coverage)	Input	Kg	0.01913
Herbicides	Input	Liters	0.00008
Packaging for fertilizers and herbicides[1]	Input	Kg	0.03835
Fuel (Machines)	Input	Liters	0.00077
Pasture			
Land	Input	Hectare	0.00001
Animal food preparation			
Maize feed	Input	Kg	0.21429
Soybean feed	Input	Kg	0.12857
Urea	Input	Kg	0.01786
Mineral salt	Input	Kg	0.00564
Bicarbonate			0.00536
Water			
Clean	Input	Liters	0.00213
Animal water feed	Input	Liters	5.00000
Energy			
Electricity grid	Input	Kwh	0.11730
Transport			
Big lorry	Input	Ton*km	0.11483
Small lorry	Input	Ton*km	0.00119
CH_4 emission			
Enteric fermentation[2]	Output	Kg of CH_4	0.02251
Manure management[3]	Output	Kg of CH_4	0.01379
N_2O emission			
Manure management[3]	Output	Kg of N_2O	8.2250E-5
Manure			
Solid and liquid	Output	Kg	3.29000

[1] Quantity in kg of packaged product.

[2] Calculated supplied by IPCC (2006).

[3] Calculated supplied by Amon et al., (2006).

2.3. Life Cycle Impact Assessment (LCIA)

From the primary data, collected on the farms, and secondary data, obtained from the Ecoinvent® 3.3 databases, the LCI data from the Embrapa and the Colinas farms were inserted into the OpenLCA © 1.6.3 software.

AD has additional co-products other than milk production, such as electricity and organic fertilizers. We did not consider, for this model, electricity and fertilizer as products in the allocation, but we considered as credits (BATTINI et al., 2014, CHERUBINI et al., 2015a). Due to avoided emissions, we used these credits like emissions related to electricity from the grid and chemical fertilizers, including all processes related to the amount of these flows (BATTINI et al., 2014; CHERUBINI et al., 2015a; BACENETTI et al., 2016; HANSERUD et al., 2018).

We quantified the potential impacts according to CML 2001 (baseline) version 4.4, which was developed by the Center for Environmental Science of the University of Leiden, The Netherlands (GUINÉE, 2002). The assessment method follows the problem, oriented by midpoint approach, and provides data on categories of impact assessment, such as climate change, acidification, eutrophication, energy use, ozone depletion, photochemical oxidation, among others. The CML method is the most widely adopted in studies of milk LCA (BALDINI et al., 2017).

2.4. Data Uncertainty Analysis

According to NBR 14044 (ISO 2006b), uncertainty analysis is a procedure performed to quantify the uncertainty introduced in the LCI data, such as the cumulative effects of the model imprecision, the input uncertainty, and the data variability. The standard describes the importance of performing this procedure as a way of attesting the results reliability presented in the Life Cycle Impact Assessment (LCI) phase.

Uncertainty analyses was performed with data quality matrix (Pedigree Matrix) combined with the Monte Carlo statistical method (MEDEIROS et al., 2018). The Pedigree Matrix is composed of five indicators of data quality, for each indicator was assigned a score from 1 to 5, where 1 is the highest quality grade and 5 is the worst quality grade (WEIDEMA, 2013). The LCI input and output data were scored according to the uncertainty factors, of the Matrix Pedigree, available in the OpenLCA software tool and the score assigned for each input and output data can be observed in Appendix A, Table A2. The Monte Carlo simulation consists of a random sampling of the probability of each uncertain parameter, and is a very effective method to evaluate results, besides being one of the most recommended parameters for studies of LCA (CHERUBINI, 2015b; MULLER et al., 2016).

We performed the data uncertainty analysis based on the Pedigree Matrix available in OpenLCA®, using the lognormal distribution. The Monte Carlo simulation was also performed in OpenLCA®, considering 10,000 independent simulations and a 95% confidence interval. In the Monte Carlo simulation, a random variation of the input parameters occurs according to the uncertainty distributions, and the final results obtained were exported in Excel format for analysis (GreenDelta GmbH, 2017). In addition, the OpenLCA software tool also provides the results of the qualitative assessment of the environmental impacts, with scores in general for each category evaluated.

3. RESULTS AND DISCUSSION

3.1 Life Cycle Impact Assessment (LCIA)

The farm that had adopted the anaerobic digester (AD) showed lower environmental impact for all impact categories analyzed when compared to the models without anaerobic digester (NAD1 and NAD2) (Figure 1). Our results, thus, support the adoption of anaerobic digesters as a way of reducing the impacts of milk production, as it has been suggested (BATTINI et al., 2014; BACENETTI et al., 2016). When compared to NAD1 (the same farm without the anaerobic digestion) and to NAD2 (the farm that does not adopt anaerobic digester), AD had, on average, 25% and 38% less impact, respectively, for the categories: climate change, acidification, eutrophication, energy use, ozone depletion, photochemical oxidation (Figure 1).

The use of anaerobic digestion reduces the impacts of milk production in several ways. First of all, it results in biogas production, the main product of anaerobic digestion, which can be used as renewable energy (LIJÓ et al., 2017; SAHOTA et al., 2018). Due to energy solutions, we estimated biogas to reach the potential of being the fastest growing renewable energy source (SAHOTA et al., 2018). In addition, it decreases the use of electricity from the grid.

After that, the anaerobic digestion has as co-product, the digestate, which is used as NPK fertilizers for crops production. The digestate contains essential nutrients for the plant, among these the ammoniacal nitrogen is the most abundant, also, it has considerable amounts of potassium, calcium, phosphorus, and magnesium (MENDONÇA et al., 2016). In addition, the digestate production replaces the use of chemical fertilizer, avoiding associated impacts such as the extraction of raw material and the inputs of production such as packaging and transportation. Besides that, it solves an environmental liability, which is the large volume of animal waste generated daily, and that, if disposed of in the environment, cause various environmental damages.

Moreover, although NAD1 and NAD2 do not have the anaerobic digester for the wastewater treatment, when NAD1 with NAD2 are compared, NAD1 had on average 16% less impact (Figure 1). NAD1 has higher milk productivity than NAD2, and, therefore, this scenario uses less resource per FU, such as transport and fertilizers, and requires fewer food resources like maize and soybean per FU, as shown in LCI. In other words, NAD1 needs fewer animals for milk production, is more productive and intensive, which provides less emission (WANG et al., 2018). These factors make NAD2 less sustainable for all impact categories assessed when compared to NAD1. To corroborate this study, the increase of milk productivity led to better results, in which potential acidification and eutrophication showed the largest reductions followed by climate change and others (BACENETTI et al., 2016).

In general, for both scenarios, the main process responsible for causing the impacts is food production (Figures 2 and 3), which include soybean, maize, and urea, together with the necessary upstream inputs, such as transports, silage production, and food preparation for the animals. Nguyen et al. (2011) point out that in agriculture, on average, 96% of the environmental impacts come from the animal feed production phase, considering the upstream and downstream processes involved. Agricultural production, essential to animal feed, is highly dependent on inputs such as land, fertilizers, fuel, machinery, pesticides, and electricity (Silva et al., 2010), which causes diverse damages to the environment. Thus, feed production stage dominated other sub-systems in terms of environmental impacts and its role in other sustainability indices was undeniable, how it was also found in another study (RAFIEE et al., 2016).

Another process that has great influence in the impact categories is GHG emissions from cattle, mainly for climate change and photochemical oxidation (Figure 3). Emissions of cattle GHG includes enteric emissions from cow and manure management emissions. The milking process also has influence in many impacts, in this study were considered the use of energy, the cleaning and the auxiliary materials for the milking machine operation, milking parlour and milk room (ECOINVENT, 2016). In addition, as Figure 3 clearly shows, the main advantages in AD scenario are to avoid the use of electricity from the grid and of chemical fertilizers. Thus, the AD scenario has positive impacts (beneficial), which minimize the negative impacts of the total sum (these shown below the red line in Figure 3).

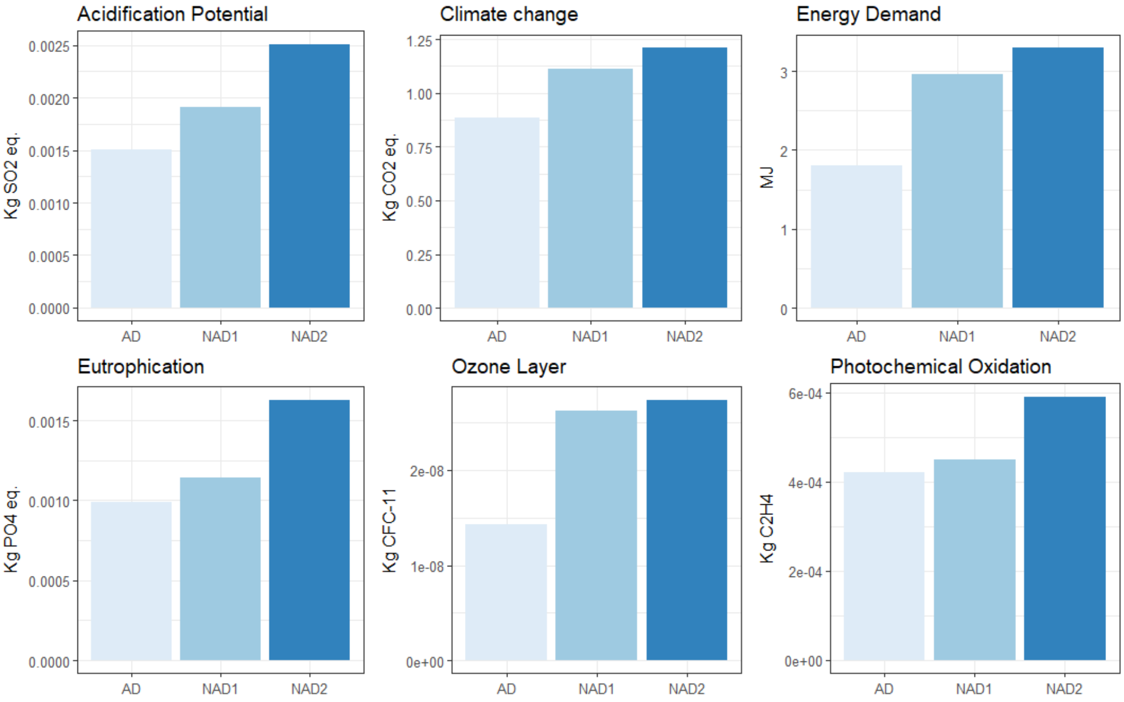

Figure 1. Results of the impacts comparing the scenarios with anaerobic digester (AD) and without anaerobic digester (NAD1 and NAD2).

For more impacts category see Table A3 in Appendix A.

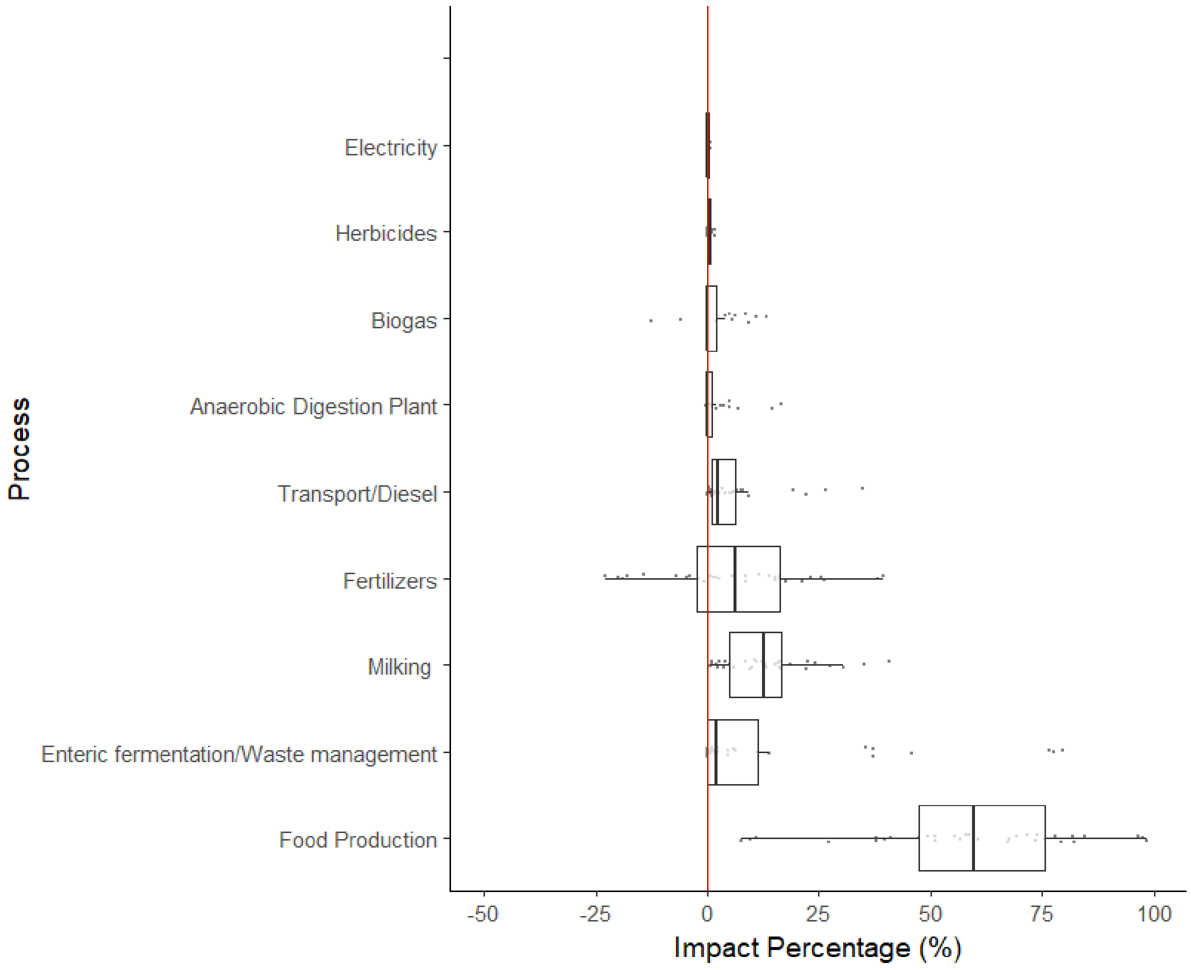

Figure 2. Box Plot of processes contribution to all impact categories

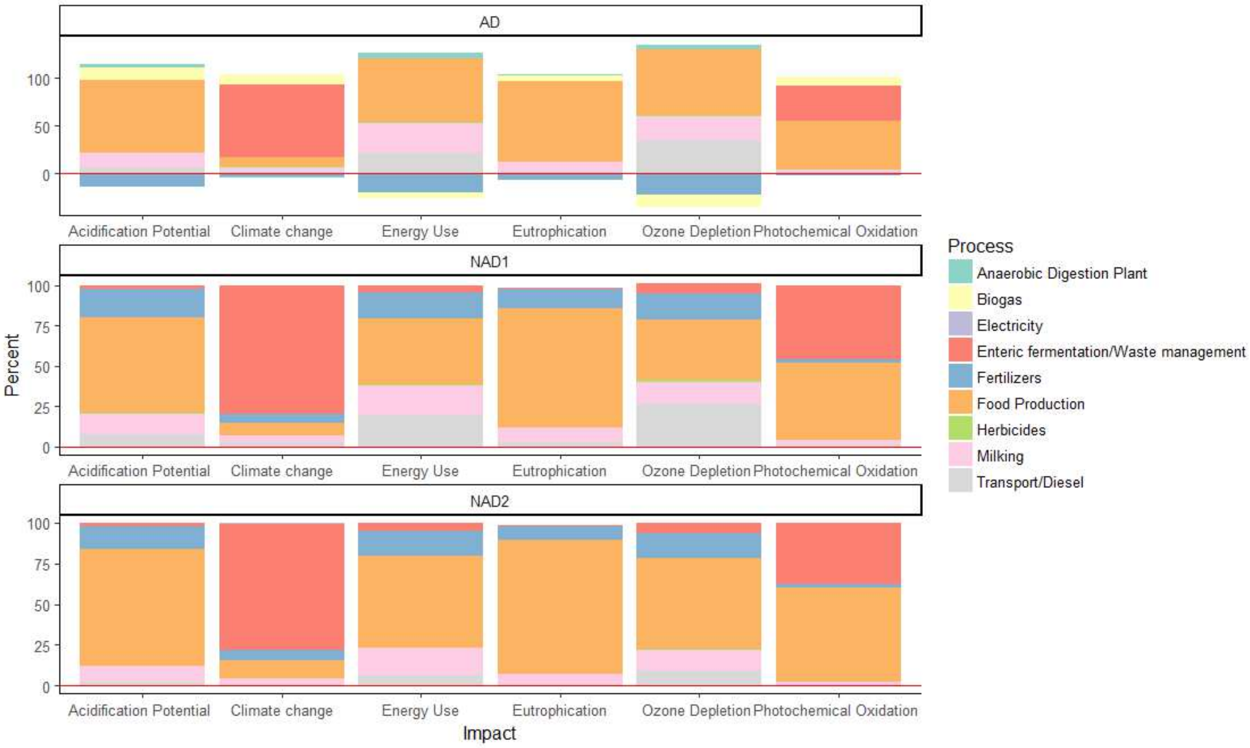

Figure 3. Influence of each process for each impact category for scenarios with anaerobic digester (AD) and without anaerobic digester (NAD1 and NAD2)

3.2 Main Impacts Mitigated

Acidification Potential

The deposition of pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NOx), ammonia (NH_3), and N_2O on the soil and on the water results in the acidification process. The presence of an anaerobic digester system reduces the acidification by avoiding the emissions of these compounds coming from chemical fertilizers, for example (BARTL et al., 2011; ACERO et al., 2015). The anaerobic digestion of animal waste promotes benefits, like the reduction of methane, dinitrogen monoxide and ammonia emissions, and the electricity production from renewable sources (BALDINI et al., 2017, BAVA et al., 2018). As a result, the AD had acidification potential 21% and 40% lower than NAD1 and NAD2, respectively. To corroborate with this study, Bacenetti et al. (2016) pointed out that an impact reduction ranging from 29% can be achieved for acidification thanks to the anaerobic digestion.

Chemical fertilizers accounted for about 14% of the acidification impacts on NAD2, and about 18% on the NAD1 (Figure 2). Along the milk production chain, the food production phase is the main factor responsible for acidification for both models (Figure 3). To confirm the results, an LCA of pig production in Brazil obtained that the emissions related to animal feed and the field emissions from maize crops, were also the main source of impacts in the acidification category, with 55% of the total emissions of NH_3 (CHERUBINI et al., 2015a).

Climate Change

Due to the anaerobic digestion, AD has impact 21% and 27% lower than NAD1 and NAD2, respectively, for climate change. This reduction is due to lower CH_4 emissions from animal waste, which is converted into biogas and subsequently into c carbon dioxide (CO_2), a gas with lower potential for atmospheric heating (the CH_4 gas has a greenhouse effect 23 times that of CO_2) (NESHAT et al., 2017). The exploitation of the biogas as a renewable energy source can reduce the impact, which is also in line with climate-friendly farming practices (NESHAT et al., 2017; PLANO A. B. C., 2018). The results of this study are in agreement with other studies that show the efficiency of the anaerobic digester in the reduction of GHG emissions (AMON et al., 2006; BATTINI et al., 2014; FAMIGLIETTI et al., 2019). Renewable energy is a significant component of reducing GHG emissions, and biogas plays a remarkable role (GIWA et al., 2017)

The animals' enteric fermentation together with the manure management were identified as important hotspots concerning climate change, followed by food production for animal feed, encompassing all upstream processes (Figure 2). Other case studies on dairy cattle LCA showed that, concerning all phases analyzed, the critical points were the enteric emissions, the fertilizer production and use, the manure management, the food production and transportation, and the low productivity, as reported in this study (ZANGHELINI et al., 2011; SEÓ et al., 2017; WANG et al., 2018).

Eutrophication

The eutrophication related categories are mainly influenced by nutrients discharged into the water, such as phosphorus and nitrogen compounds (LIJÓ, et al., 2017). The presence of the anaerobic digester reduced the impacts of this category, in which the AD has a 13% and 40% lower environmental impact potential than NAD1 and NAD2, respectively. The main reason for this result could be the difference between manure disposal and manure management system (WANG et al., 2018). In the AD scenario, a large volume of animal waste generated daily, which would be disposed of into the environment, is transformed in biogas and organic fertilizers. Hence, this reduction is probably an effect of the digestate use as a nitrogen and phosphorus source, which avoids the environmental impacts related to the inputs of the chemical fertilizers manufacture and transportation, which should be acquired in the absence of the digestate. To confirm the results other study supported that the organic fertilizer production is a favorable from an environmental point of view, for eutrophication, due to credits of the avoided chemical fertilizer (LI et al., 2018).

The food production, that considers upstream impacts, such as input transport and fertilizer use, among others related, is the main responsible for eutrophication in both scenarios (Figure 2). During the cultivation stages of maize and soybean are generated the most important environmental aspects for eutrophication, that are the release of nitrate and of phosphate into the water and the emission of ammonia to air (ALVARENGA et al., 2012). An LCA to compare conventional and organic systems were performed where the results indicated more eutrophication of the conventional system, since food production is higher in this one, along with all upstream related inputs (Thomassen et al., 2008; TSUTSUMI et al., 2018). In addition, the higher values for the conventional system were mainly due to the more input of chemical concentrates and fertilizers in the farm.

Energy Use

When considering the energy use impact, non-biological resources are taken into account, such as fossil fuels, minerals, metals, etc. (ACERO et al., 2015), so the life cycle emissions for AD are lower, since this scenario uses the anaerobic digester for electricity production. Once renewable energy is a significant component of reducing emissions, the biogas play a remarkable role (GIWA et al., 2017). Thus, AD has a 39% and 45% lower environmental impact than NAD1 and NAD2, respectively.

The most striking flows for Energy Demand are food production, followed by the milking (Figure 3). The transport and the diesel process also have an important influence on this impact. Many studies, that agree between each other, have focused on the environmental aspects of dairy farming, and they have concluded that feed production is the main contributor to the energy use and to the environmental pollution (FATHOLLAHI et al., 2018; WANG et al., 2018). In addition, the agricultural machinery operations are responsible for the main share of the environmental load for energy use, because, for this aspect, the diesel fuel consumption plays a key role (BACENETTI et al., 2016).

Ozone depletion

The ozone depletion category refers to the reduction of the stratospheric ozone layer due to anthropogenic emissions of substances such as chlorofluorocarbons (CFCs), halons, and hydrochlorofluorocarbons (HCFCs) (ACERO et al., 2015). Processes such as the use of diesel in farm machinery and the transportation of inputs, like fertilizers and feed for livestock, are primarily responsible for these emissions. Of all dairy production chain, the electricity use is also responsible for ozone depletion (LEDGARD et al., 2016; FAMIGLIETTI et al., 2019). In addition, ozone formation can be increased due to higher methane emissions from enteric fermentation and manure management (NEMECEK and ALIG, 2016).

AD has a 46% and 48% lower environmental impact potential than NAD1 and NAD2, respectively. The AD scenario is the lowest emissions due to fewer emissions from enteric fermentation and waste management. Moreover, due to avoided fertilizers, that includes the transport avoided, among other emissions (Figure 3). In addition, also due to biogas use and to avoided electricity production, relevant values of emissions are prevented (MASSARO et al., 2015). In this study, the milking process includes electricity use, transport use and many processes as food production and fertilizers (for NAD1 and NAD2). For this reason the food, the transport and the milking processes had greater influence on the results. The LCA of milk production in Portugal showed that the GHG emissions, transport, and fertilizers are the most striking factors, which agree with this study results (GONZÁLEZ-GARCÍA et al., 2013).

Photochemical Oxidation

Photochemical oxidation depends on the amounts of carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxide (NO), ammonium, and non-CH_4 volatile organic compounds (ACERO et al., 2015). The main factors responsible for this impact in both scenarios are the food production for cattle and the CH_4 emissions from enteric fermentation and manure management (Figure 3). The present study is also similar to that one found in Portugal about the LCA of milk producing, which reported that the CH_4 emissions from the enteric fermentation and the management of animal waste are the main responsible (GONZÁLEZ-GARCÍA et al., 2013). Also corroborating with this study, this impact category is influenced predominantly by volatile organic compound (VOCs), NOx and CH_4, in which, the release of VOCs was mainly from the manure of dairy cows, nitrogen oxides were originated mainly from the use of fossil diesel, for food transportation, while CH_4 was originated from the enteric fermentation (CHOBTANG et al., 2016).

AD has almost 7% and 29% lower environmental impact potential than NAD1 and NAD2, respectively. The photochemical oxidation is the impact where the AD and the NAD1 scenarios showed the lowest difference for the result value. In addition, the biogas has negative interference in AD. Battini et al., (2014) have reported that the anaerobic digestion with the production of electricity is an effective technology to significantly reduce global environmental impacts of dairy farms, however, local impacts may increase, as photochemical oxidation. The authors describe that the lower emissions of methane from storage and the credits from substituted electricity, in fact, are not enough to compensate the increase in NOx emissions from the combustion of biogas. This may explain the small difference in AD and NAD1 results.

3.3. Productivity affecting GHG emissions

The results of GHG emissions for the Embrapa and the Colinas farms, which were obtained using the IPCC (2006) methodology, are higher than those presented by the IPCC (2006), MCT (2010), and WILLERS (2014), in all of them, the emission is around 70 kg CH4/year/animal (Table A1, Appendix A). In the calculations performed for this study, the values were higher due to the high milk yield of the animals, which is around 19.3 and 18 kg per animal/day, respectively. On the other hand, the average milk production presented by MCT (2010) is 4.045 kg per animal/day. A higher level of productivity per animal can reduce GHG emissions, and other related impacts (SEÓ et al., 2017). However, when dividing the enteric emission per one kilogram of Fat and Protein Corrected Milk, the UF, the resulting emission of this study, is lower than that shown on MCT (2010), and on WILLERS (2014).

In Brazil, the lack of adequate management means that productivity per animal is not as efficient as in other countries, even when the breeding system is intensive (ZANGHELINI et al., 2011). The authors point out that increasing productivity per animal, from changes in the breeding system, is necessary to reduce the environmental impacts of dairy farming. The optimization of the use of concentrated foods, seeking the dosage according to milk production, can represent a better environmental performance for the semi-intensive system. The increase in milking frequency is a solution that generates economic advantages for the farmers, considering that it does not need any structural investment and that the feeding is adequate for the growth of the milk production (BACENETTI et al., 2016). The authors point out that the increasing in milking frequency, coupled with the insertion of the anaerobic digestion, reduced most impact potentials, mainly acidification, climatic changes, and eutrophication.

3.4 Data Uncertainty Analysis

The Monte Carlo simulation estimates how much variation in the inventory data could modify the environmental impact quantity results for the categories evaluated (NIERO et al., 2014). This simulation provides a quantitative evaluation of the data and provided for each impact category the mean, the median, the maximum, the minimum and the standard deviation (Table 5). Thus, the results were verified by means of uncertainty analysis based on the Monte Carlo simulation and the Pedigree Matrix to improve the robustness and transparency (NIERO et al., 2014). The pedigree matrix was used supplemental to the Monte Carlo simulation method, with provides the qualitative evaluation (Table 6) (WEIDEMA et al. 2013; OPITZ & MENZEL, 2018). When estimating the data uncertainty with the pedigree matrix, five categories and scores were used (R= Reliability; C= Completeness; T= Temporal correlation; G= Geographical correlation; FT= Further technological correlation). For each indicator was assigned a score from 1 to 5, where 1 is the highest quality grade and 5 is the worst quality grade (WEIDEMA, 2013).

The uncertainty analysis provides information on the dissemination of the result due to dissemination in the input data and other sources of uncertainty (classified according to the Pedigree Matrix, Table 5 and 6) (ROSENBAUM et al., 2017). Uncertainties were observed for the AD, NAD1 and NAD2 scenarios (Table 6). NAD1 showed three scores of value equal to 5 (Table 6), the worst quality, that may be associated with the fact that this scenario was modeled of AD, it is not a real farm. AD and NAD1 shown two scores of value equal to 5. The variability and stochastic errors found are due to uncertainties in measurement, variation in specific processes, temporal variations, and use of secondary data, among others. Therefore, in general, the quality indicators indicate that both scenarios has from considerable to good quality data.

All the mean deviation presented values higher than result initially presented by the software, for both scenarios (Table 5). Therefore, both scenarios, AD, NAD1 and NAD2, show results very close of present in our initiate result, and continues to demonstrate the same impact to support that the adoption of the anaerobic digester reduces the environmental impacts for all the categories evaluated. In conclusion, the Monte Carlo analysis support that our results for all categories evaluated has good aspects quantitative and qualitative, the variation in the inventory data did not cause an expressive effect on our data.

Table 5. Uncertainty analysis (quantitative indicator) from Monte Carlo Simulation and Pedigree Matrix for the Embrapa and Colinas farms (AD, NAD1 and NAD2 scenarios, respectively). SD=Standard deviation, Max = Maximum, Min= Minimum, Med= Median

Impact category	**AD**					**NAD1**					**NAD2**				
	Mean	**SD**	**Min**	**Max**	**Med**	**Mean**	**SD**	**Min**	**Max**	**Med**	**Mean**	**SD**	**Min**	**Max**	**Med**
Acidification Potential (Kg SO_2 eq.)	0.0017	0.0023	-0.2151	0.0329	0.0017	0.0022	0.0004	-0.0090	0.0387	0.0021	0.0028	0.0003	-0.0085	0.0105	0.0028
Climate Change (Kg CO_2 eq.)	0.8934	0.3876	-35.8353	6.2700	0.8963	1.1312	0.0772	-0.7623	7.2861	1.1304	1.2330	0.0608	-0.5356	2.1146	1.2327
Energy Use (MJ)	1.9521	3.0203	-284.636	44.0636	1.9635	3.1845	0.4803	-13.0686	41.8692	3.1654	3.5452	0.3006	-10.1041	11.4702	3.5268
Eutrophication (Kg PO_4 eq.)	0.0011	0.0008	-0.0749	0.0120	0.0011	0.0013	0.0003	-0.0014	0.0122	0.0013	0.0019	0.0003	-0.0005	0.0121	0.0018
Ozone depletion (Kg CFC-11)	2.10E-8	2.35E-8	-2.01E-6	1.96E-7	1.92E-8	3.44E-8	1.26E-8	-3.79E-8	2.51E-7	3.19E-8	3.61E-8	1.23E-8	-3.8E-8	2.32E-7	3.35E-8
Photochemical oxidation (Kg C_2H_4)	0.0004	0.0001	-0.0126	0.0023	0.0004	0.0005	3.45E-5	-2.73E-4	2.73E-3	4.69E-4	0.0006	3.87E-5	-9.6E-6	0.0011	0.0006

Table 6. Quality indicators by Matrix Pedigree for the Embrapa and the Colinas farms (AD, NAD1 and NAD2 scenarios) R= Reliability; C= Completeness; T= Temporal correlation; G= Geographical correlation; FT= Further technological correlation

Impact category	**AD**					**NAD1**					**NAD2**				
	R	**C**	**T**	**G**	**FT**	**R**	**C**	**T**	**G**	**FT**	**R**	**C**	**T**	**G**	**FT**
Acidification potential	3	3	4	3	2	3	3	4	3	2	3	3	4	3	1
Climate change	2	2	3	3	1	2	2	2	3	1	2	2	3	3	1
Energy Use	1	1	5	2	1	1	1	5	2	1	1	1	5	2	1
Eutrophication	3	2	4	3	1	3	2	4	3	1	3	2	4	3	1
Ozone depletion	2	3	5	4	3	2	3	5	5	3	2	3	5	4	3
Photochemical oxidation	1	2	2	3	1	1	2	2	2	1	1	2	2	2	1

4. CONCLUSIONS

The results obtained in the study show that there is an effect of the anaerobic digester in the wastewater treatment, contributing significantly to the reduction of all environmental impacts analyzed. Mainly due to the avoided emissions from electricity use from the grid, and the avoided chemical fertilizers, among other emissions related, the AD scenario has lower impact potential for acidification, eutrophication, climate change, energy use, photochemical oxidation, and ozone depletion on average 25% and 38% than NAD1 and NAD2, respectively. Our results showed that for each kg of milk, for climate change, 21% of emissions were reduced due to the anaerobic digestion. In other words, on a farm that treats the manure with anaerobic digestion, are issued 0.8835 kg of CO_2 eq. per 1 kg of milk against 1.1622 kg of CO2 eq. (mean between NAD1 and NAD2) per 1 kg of milk for the farm that does not treat the manure. Each year 34.39 billion kg (35 billion liters) of milk are produced in Brazil (EMBRAPA, 2018). If all these farms adopted the anaerobic digester for treatment of animal manure, and consequent biogas production, 9.58×10^9 kg of CO_2 eq. would not be emitted per year. The Government of Brazil communicated to the Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC) the intended Nationally Determined Contribution (iNDC) of reducing greenhouse gas emissions by 43% at 2030, in relation to 2005 levels (iNDC, 2015). Therefore, the Brazil aim to reduce 1.2×10^{12} kg of CO2 eq (iNDC, 2015). If the 9.58 ×109 kg of CO2 eq. that would not be emitted per year due to the anaerobic digester was considered, a large part of mitigation actions would be achieved.

The establishment of the digester, together with practices that increase productivity per animal, are solutions we considered that should be adopted in the search for the improvement of the environmental performance of milk production.

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CAPÍTULO 2

CRITICAL COMPARISON OF TWO LCA SOFTWARES APPLIED TO MILK PRODUCTION

ABSTRACT

Life Cycle Assessment (LCA) is a technique to assess, quantify and improve consumer products and service, therefor helping to reduce their environmental impact. Here, we compare two LCA software (OpenLCA® 1.6.3. and SimaPro® 8.5.2) in order to investigate if the choice of software has influence on the results of LCA. For the software comparison, we perform LCAs of milk production in two dairy farms in Brazil. To assess of environmental impact the method CML 2001 (baseline), version 4.4, was used considering the following categories of environmental impact: potential acidification, ozone depletion, energy use, eutrophication, climate change, and photochemical oxidation. In a qualitative way, both software has friendly interface for modeling, and offer practically the same options. In a quantitative way, in general, the SimaPro shows discrepancies in results if compared with OpenLCA. The main cause of the difference in to impact results is the option to avoid product that is present in both software and used worldwide for LCA. The impact category climate change shows similar results using both software. We conclude that both software can be applied for milk production and the option to avoid product must not be used when LCA is applied for milk production, and attention should be paid to the use of the "avoided product" function.

Keywords: LCA; environmental impacts; dairy sector; SimaPro; OpenLCA.

1. INTRODUCTION

Life Cycle Assessment (LCA) is a technique for environmental management focused on environmental impacts throughout a product's life cycle and their associated supply chains. The methodology can be applied as a toolkit for quantify, evaluate, compare and improve goods and services in terms of their potential environmental impacts in order to achieve environmental sustainability objectives (BALDINI, 2017; FAMIGLIETTI et al., 2019). The methodology also provides a framework for identifying effective approaches to reduce environmental issues, such as preventing pollution or reducing resource consumption through systematic analysis. Additionally, LCA is recognized for its ability to assess the effect that changes within a production process can have on the overall balance of the environmental burden life cycle (RECKMANN et al., 2012; BALDINI, 2017).

To reach the sustainability goals it is essential to achieve a balance between the environmental and social issues and the economic growth (ISO 14001, 2004). Therefore, when referring to sustainable development, it is essential to use an environmental sustainability indicator, which indicates, through numerical values, how much the pattern of production and consumption is demanding of nature (RECKMANN et al., 2012). There are available software that help in the accomplishment of LCA, where the most used are: SimaPro (Pre-sustainability 2018), GaBi (PE-international 2018), Umberto (ifu Hamburg, 2018), OpenLCA (ORMAZABAL et al., 2014; GreenDelta GmbH, 2018).

The software OpenLCA®, developed by the German company GreenDelta GmbH in 2007, is the only free software available for life cycle information management (GreenDelta GmbH, 2018). One of the reasons to development OpenLCA was to make LCA accessible to everyone in both academia and industry. In addition, this software was created and developed with the support of the creators of another LCA software such as GaBi, SimaPro, and UNEP (United Nations Environment Programme) (ORMAZABAL et al., 2014).

The software SimaPro® is the most widely used as a tool for LCA. The software, developed by the Dutch company PRé Sustainability in 1990 and utilized in more than 80 countries, is available for educational and professional use.

Recent analyzes have shown the choice of software can change the results of the LCA (SPECK et al., 2016). By using the most important LCA software, SimaPro, and compare with another software, as OpenLCA, GaBi, Humberto, differences greater than 20% can be found in the results of the potential environmental impacts (SPECK et al., 2016; SILVA et al., 2017). However, open source software, OpenLCA, has been widely used and indicated as a useful and appropriate tool, which produces results that can be similar to those obtained with commercial software such as SimaPro, the most widely used in LCA (BUITRAGO & BELALCÁZAR, 2013).

In order to investigate if the choice of software has influence on the results of LCA, the present study aims to compare the software SimaPro® and OpenLCA®. For the comparison, we performed the LCA in two conventional dairy farms in Brazil.

2. MATERIAL AND METHODS

2.1 LCA methodology

The implementation of standard methodology is crucial for identification of each environmental impact associated to each activity of the dairy production. The LCA was performed based on ISO 14040:2006 (ISO 2006a) standards, for requirements and guidelines, and ISO 14044:2006 (ISO 2006b), for principles and structure. Based on the ISO 14040 we separate the LCA in four steps. First, the definition of the goal and scope of the LCA, that describes the functional unit and boundaries of the system; second, the inventory analysis that includes all inputs and outputs; third, the impact assessment, and fourth the life cycle interpretation.

2.1.1 The definition of the scope

The LCA was applied in two conventional dairy farms in Brazil. The scope was to assess trends and the magnitude of all environmental impacts reported by both SimaPro® and OpenLCA® software.

The two farms are located in the state of Minas Gerais, Brazil. The first one is at the Experimental Farm of the Brazilian Agricultural Research Corporation – Embrapa Dairy Cattle, which operates with semi-intensive management systems. This dairy farm operates with an anaerobic digester system for the treatment of bovine manure. The second dairy farm is the Colinas farm that operates without system for the treatment of bovine manure.

The use of Functional Unit (FU) allows comparisons of dairy farms that work with different breeds or use different types of feed for the herd (IDF, 2015). In our study, the FU was defined as one kilogram of Fat and Protein Corrected Milk (FPCM) that leave the farm gate. FPCM was calculated based on the formula defined by the International Dairy Federation (Equation 1; IDF, 2015).

$$1\text{kg FPCM} = 1 \text{ kg milk} * (0.1226 * F + 0.0776 * TP + 0.2534), \qquad (1)$$

where FPCM = fat protein corrected milk, F = fat (%) and TP = True protein (%).

The boundaries are from "cradle-to-farm gate", where the inputs include planting of maize, transport, diesel fuel, electricity, acquisition of materials to the farm, the use of materials needed to manage the herd, milking, cooling and storage of milk, until the generation, disposal and treatment of wastes (for the Embrapa Farm), emissions from manure management, among others inputs and outputs. The gate is the delivery of milk to dairy transporters, going through all the necessary processes until the production cycle is completed. Cows were considered in the lactation phase and in the dry phase. Calves were excluded from the surveys, considering only cows in production. In this study, the use of veterinary drugs was not included in the LCA, mainly because of the lack of data. Therefore, the inputs as drugs were excluded because the impact was estimated as insignificant (YAN et al., 2011; ROSS et al., 2014).

2.1.2 The Life Cycle Inventory (LCI)

The LCI is an inventory of the input and output data associated with the farms being studied. This phase involves collecting the necessary data to achieve the objectives of the study in question (ISO 14040 2006a). In this study, whenever possible, primary data were used. However, when the use of primary data was not possible, secondary data were obtained from databases, scientific articles, technical reports, and or obtained from the Ecoinvent® 3.3 database.

Primary data of each of the farm processes, during one year of production, from 2017 to 2018, were collected through interviews with specialists and employees from different sectors of the respective farms. They provided details about the amount of milk produced by each farm, animal diets, cropping systems, fuel consumption, electricity used for milking parlor, and others.

The Embrapa and the Colinas farms operate in a semi-intensive management system, where the feeding is alternated between the pasture, silage and the concentrate. There are about 100 and 80 animals for the Embrapa and the Colinas farms, respectively, where generally 80% are in the lactation phase. Animal reproduction is performed from artificial insemination. Milking is done twice a day. The data are shown in Embrapa and Colinas LCI (Table 1 and 2, respectively) which contains the input and output of the entire milk production process.

Life Cycle Inventory of the Embrapa farm

The Embrapa dairy farm is composed of an anaerobic digester (plug-flow), which operates in real scale with a mean hydraulic residence time of 70 days. The anaerobic digester is supplied with floor water (reuse water). The water that passes thought the anaerobic digester (digestate) is pumped again to wash the corrals, and reused on average for 20 to 25 days, characterizing as reuse water (MENDONÇA et al., 2017). The digestate contains essential nutrients for the plant, which is used in the crops. For the application of the digestate in the crops, technical and scientific studies were carried out, which attest to the viability of the operation (MENDONÇA et al., 2016). The biogas obtained from the anaerobic digester is transformed into electrical energy and the energy is sufficient to carry out all activities of the farm that involve milk production, such as the pumping system used in the effluent treatment system and milking operations (MENDONÇA et al., 2017). Besides solving an environmental liability, which is the large volume of animal waste generated daily, this practice reduces the production costs. Thus, due to the digester system, in this farm the use of water, fertilizers and electricity is reduced. Therefore, in the Embrapa farm due to the anaerobic digester, in addition to milk production, there are additional co-products such as electricity and organic fertilizers (digestate). Thus, for the model, electricity and fertilizer was not directly considered as products in the allocation, but indirectly considered as credits (BATTINI et al., 2014, CHERUBINI et al., 2015). These credits were applied because of their associated emissions that was avoided, such as emissions related to electricity, and chemical fertilizers, including all processes related to the amount of the flows. This process had been performed in the same way for both SimaPro and OpenLCA software.

Table 1. Life Cycle Inventory of the Embrapa farm

Parameters	Input/Output	Unit	Quantity for FU
Silage Production			
Land	Input	Hectare	0.00002
Maize seed	Input	Kg	0.00004
Fertilizer (planting) [1]	Input	Kg	0.01727
Fertilizer (coverage)[1]	Input	Kg	0.01919
Herbicides	Input	Liters	0.00013
Packaging for fertilizers and herbicides[2]	Input	Kg	0.00685
Fuel (Machines)	Input	Liters	0.00444
Pasture			
Land	Input	Hectare	0.00010
Animal food preparation			
Maize feed	Input	Kg	0.13370
Soybean feed	Input	Kg	0.08022
Urea	Input	Kg	0.00223
Mineral salt	Input	Kg	0.00668
Fuel (Machines)	Input	Liters	0.00226
Water			
Animal water feed	Input	Liters	3.23422
Energy			
Biogas	Input	kWh	0.08205
Transport			
Big lorry	Input	Ton*km	0.07725
Small lorry	Input	Ton*km	0.01119
CH_4 emission			
Enteric fermentation [3]	Output	Kg of CH_4	0.02142
Manure management [4]	Output	Kg of CH_4	0.00410
N_2O emission			
Manure management [4]	Output	Kg of N_2O	9.5225E-5
Wastewater treatment			
Biogas[5]	Output	Kg	0.03
Digestate[5]	Output	Kg	8.095854922
Anaerobic digestion[6]	Input	Item	8.87217E-08
Electricity Generator [6]	Input	Item	8.87217E-08

[1] NPK fertilizer, considering the organic and inorganic fraction.

[2] Quantity in kg of packaged product.

[3] Calculated on the basis of information supplied by IPCC (2006).

[4] Calculated on the basis of information supplied by Amon et al. (2006).

[5] Calculated on the basis of information supplied by de Mendonça et al., 2017.

[6] Considering a service life of 20 years.

For data on the effluent treatment system, such as the anaerobic digester and the electric generator, 20 years was considered as the useful life time, and carried out the conversion of how many items utilized to produce one kg of milk, corrected by protein and fat.

Life Cycle Inventory of the Colinas farm

For the Colinas dairy farm, the features are the same as Embrapa dairy farm, but without a wastewater treatment system. Waste from animals that are laid out on the ground, when confined, are removed by water and applied to the soil. However, since there is no technical follow-up, and no study was carried out to obtain the correct dosages of application in the crops this operation cannot be considered as a substitute for chemical fertilizers. In this case, in the Colinas farm, only the chemical fertilizer use was considered.

Table 2. Life Cycle Inventory of the Colinas farm

Parameters	Input/Output	Unit	Quantity for FU
Silage Production			
Land	Input	Hectare	0.00002
Maize seed	Input	Kg	0.00004
Fertilizer (planting)	Input	Kg	0.01913
Fertilizer (coverage)	Input	Kg	0.01913
Herbicides	Input	Liters	0.00008
Packaging for fertilizers and herbicides[1]	Input	Kg	0.03835
Fuel (Machines)	Input	Liters	0.00077
Pasture			
Land	Input	Hectare	0.00001
Animal food preparation			
Maize feed	Input	Kg	0.21429
Soybean feed	Input	Kg	0.12857
Urea	Input	Kg	0.01786
Mineral salt	Input	Kg	0.00564
Bicarbonato			0.00536
Water			
Clean	Input	Liters	0.00213
Animal water feed	Input	Liters	5.00000
Energy			
Electricity grid	Input	Kwh	0.11730
Transport			
Big lorry	Input	Ton*km	0.11483
Small lorry	Input	Ton*km	0.00119
CH_4 emission			
Enteric fermentation[2]	Output	Kg of CH_4	0.02251
Manure management[3]	Output	Kg of CH_4	0.01379
N_2O emission			
Manure management[3]	Output	Kg of N_2O	8.2250E-5
Manure			
Solid and liquid	Output	Kg	3.29000

[1] Quantity in kg of packaged product.

[2] Calculated supplied by IPCC (2006).

[3] Calculated supplied by Amon et al. (2006).

2.2 OpenLCA and SimaPro Software

The LCI data of the Embrapa and Colinas dairy farm were inserted into the OpenLCA © 1.6.3 and SimaPro® 8.5.2 software.

OpenLCA does not provide the databases necessary for the program to function, but it is possible to import databases from the Ecospold01 and Ecospold02 or ILCD formats (BUITRAGO & BELALCÁZAR, 2013; SILVA et al., 2017). In addition, it is possible to obtain a free license for educational institutions (educational use) of Ecoinvent® bases for countries that are not members of the Organization for Economic Cooperation and Development (OECD), as it is the case for Brazil.

SimaPro® is the software most used as a tool of the LCA, utilized as a benchmark. SimaPro comes with the ecoinvent v3 database, covering over 10,000 processes (PRÉ-SUSTAINABILITY, 2018). Allows access to the ecoinvent® database and manages inventories in the EcoSpold 2 format. Although SimaPro is not a free software, it is possible to obtain a license for educational use. In our study, we used the version SimaPro Faculty, unitary license, equivalent to the commercial version.

The Ecoinvent® 3.3 database was used for both software, with the ecoSpold2 format (Ecoinvent version 3). In addition, for the performance tests, the identical computer was used, where in OpenLCA, the option for “analysis calculation” was used and in SimaPro the “network calculation” was used, following the suggestion by NOI et al (NOI et al., 2017), performing the same type of analysis.

The OpenLCA/SimaPro ratio was calculated for each impact category for Embrapa and Colinas dairy farms by dividing the result of OpenLCA by the result of SimaPro.

2.3 CML 2001 method

The CML 2001 (baseline), version 4.4, developed by the Center of Environmental Science of the University of Leiden, The Netherlands was chosen to evaluate the potential environmental impacts (GUINÉE, 2002). CML is the most used method in studies of LCA (BARTL et al. 2011; ALVARENGA et al. 2012; ROCHA et al. 2014; BACENETTI et al. 2016; RAFIEE et al., 2016; RAU, et al., 2016; FUSI et al., 2016, BALDINI et al., 2017; FATHOLLAHI et al., 2018; RAMÍREZ-ARPIDE et al. 2018; SOTERIADES et al. 2018). Both OpenLCA® and SimaPro® can be applied in the standardization step of the CML 2001 method.

The CML method consider the following impacts categories: depletion of abiotic resources, acidification potential, climate change, energy use, eutrophication, freshwater, marine, terrestrial and human ecotoxicity, ozone depletion and photochemical oxidation.

In LCAs referred to dairy production, the climate change is the most widely studied impact category, followed by acidification potential, eutrophication potential, land use, energy use (BALDINI et al., 2017). Thus, in our study, we considered the following impact categories: climate change, acidification, eutrophication, energy use, ozone depletion, photochemical oxidation.

Climate change is defined as the global warming caused by the release of greenhouse gases (GHG) from anthropogenic actions (IPCC, 2006). The characterization model is based on factors developed by the IPCC and expressed as Global Warming Potential over the 100-year time horizon (GWP100), measured in the reference unit kg of CO_2 equivalent (BATTINI et al., 2014).

Acidification potential describes acid deposition in soil and water by pollutants, such as sulfur dioxide (SO_2), nitrogen oxides (NOx), ammonia (NH_3) and nitrous oxide (N_2O), which can cause damage to ecosystems and biodiversity loss (BARTL et al., 2011; ACERO et al., 2015). The method CML 2001 considers acidification caused by anthropogenic processes, such as acidification due to the use of fertilizers (ACERO et al., 2015).

Excessive nutrient uptake, such as nitrogen and phosphorus in water bodies, affects the balance of aquatic ecosystems (SEÓ et al., 2017), this phenomenon is known as eutrophication and it is a result of domestic or agricultural activities. For eutrophication impacts, the method CML 2001 considers emissions of ammonia, nitrates, oxides of nitrogen and phosphorus to air or to water. These molecules are recognized on a common basis, kg PO_4 -3 equivalents (IES, 2012).

For energy use category non-biological resources are considered, such as fossil fuels, minerals, metals, water, and others (ACERO et al., 2015). The calculation is performed by measuring the scarcity of a substance and depends on the amount of resources and the rate of extraction. The characterization factors are measured in Megajoule (MJ) of fossil fuels for the impact category.

The ozone depletion category refers to the reduction of the stratospheric ozone due to emissions of substances such as chlorofluorocarbons (CFCs), halons and hydrochlorofluorocarbons (HCFCs) (ACERO et al., 2015). The characterization method defines the ozone depletion potential of different gases in relation to the reference substance chlorofluorocarbon-11 (CFC-11), expressed in kg CFC-11 equivalent.

Photochemical oxidation formed by the reaction of volatile organic compounds and nitrogen oxides, in the presence of heat and sunlight (IES, 2012). The impact category depends largely on the amounts of carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxide (NO), ammonium and non-CH_4 volatile organic compounds. Photochemical oxidation is expressed in ethylene equivalent (C_2H_4).

3. RESULTS AND DISCUSSION

Software comparison

Both software, OpenLCA® and SimaPro®, are applicable for the CML 2001 method. However, when applying the CML 2001 method to the EMBRAPA dairy farm, the software might show a different effect on the results. On the other hand, when applied to the Colinas dairy farm the results were similar in both software, considering the majority of the impact categories (Table 3).

Despite applying the similar methodology, the results of impacts were higher when the software SimaPro is applied to the Embrapa dairy farm, especially in some impact categories, how acidification potential, eutrophication and energy use (Table 3). Previous study on LCA of different materials produced for packaging also demonstrated higher values when the software SimaPro was compared to the OpenLCA (SILVA et al., 2017), in addition, it was found that impact assessments can vary widely between GaBi, SimaPro, openLCA, COMPASS software programs (SPECK, 2014; SPECK et al., 2016). The authors explain that main cause of the differences found in software for LCA is probably due to the characterization factors. For instance, to GaBi and SimaPro software, different characterization factors were applied, varying according to impact category and type of substance (SPECK et al., 2016). Even when inputs are matched as closely as possible, implementations of a methodology supposedly common, across different LCA software systems, may provide different results (SPECK et al., 2016). Conversely, we used in our study the same method, CML 2001, and the same version, 4.4, in both software, thus, identical characterization factors were used.

Table 3. Impact of the production of 1 kg of fat and protein corrected milk at the Embrapa and the Colinas dairy farm, extracted from SimaPro and OpenLCA software.

Impact category	Embrapa dairy farm			Colinas dairy farm		
	OpenLCA	SimaPro	Ratio	OpenLCA	SimaPro	Ratio
Climate change (Kg CO_2 eq.)	0.8835	0.8811	1.00	1.2122	1.2022	1.01
Acidification Potential (Kg SO_2 eq.)	0.0015	0.0042	0.36	0.0025	0.0024	1.03
Eutrophication (Kg PO_4 eq.)	0.0010	0.0016	0.62	0.0016	0.0018	0.93
Energy Use (MJ)	1.8033	2.2141	0.81	3.2997	3.3630	0.98
Ozone Depletion (Kg CFC-11)	1.426E-8	1.759E-8	0.81	2.742E-8	2.622E-8	1.05
Photochemical Oxidation (Kg C_2H_4)	0.0004	0.0003	1.27	0.0006	0.0005	1.23

Different software introduces different types of deviations at each stages in the calculation, how have been suggested previously by Herrmann & Moltesen (2015). Our results have shown that different software could potentially lead to different conclusions concerning the process that has the higher impact in each category. The sum of all processes within each impact category is 100% (Figure 1 and 2). Because of the function "avoided product" the Embrapa dairy farm has beneficial impacts (those shown below the zero in Figure 1), that minimize the overall impact. Fertilizer and biogas processes are responsible for beneficial impacts in OpenLCA software. The SimaPro software shown only the electricity as beneficial impact, the fertilizer process is not considered a beneficial impact although it has small interference on the result. Energy use avoided is represented on SimaPro software as electricity while the OpenLCA represents energy use avoid as biogas (Figure 1), however, both software refer to an avoided electricity from the grid due to transformation of biogas to energy and the difference is only in nomenclature.

In both software and both dairy farms, the main impacts are related to food production followed by enteric fermentation and waste management (Figure 1 and 2). The process food production includes all impact related to animal food preparation and the series of upstream unit processes as activity of the transport to the seed processing center, land occupation, etc. The enteric fermentation/waste management process refers to emissions from enteric fermentation and emissions from type of manure management. The result of the influence of the processes for each impact category was similar in both software, especially considering the simulations for the Colinas dairy farm (Figure 2).

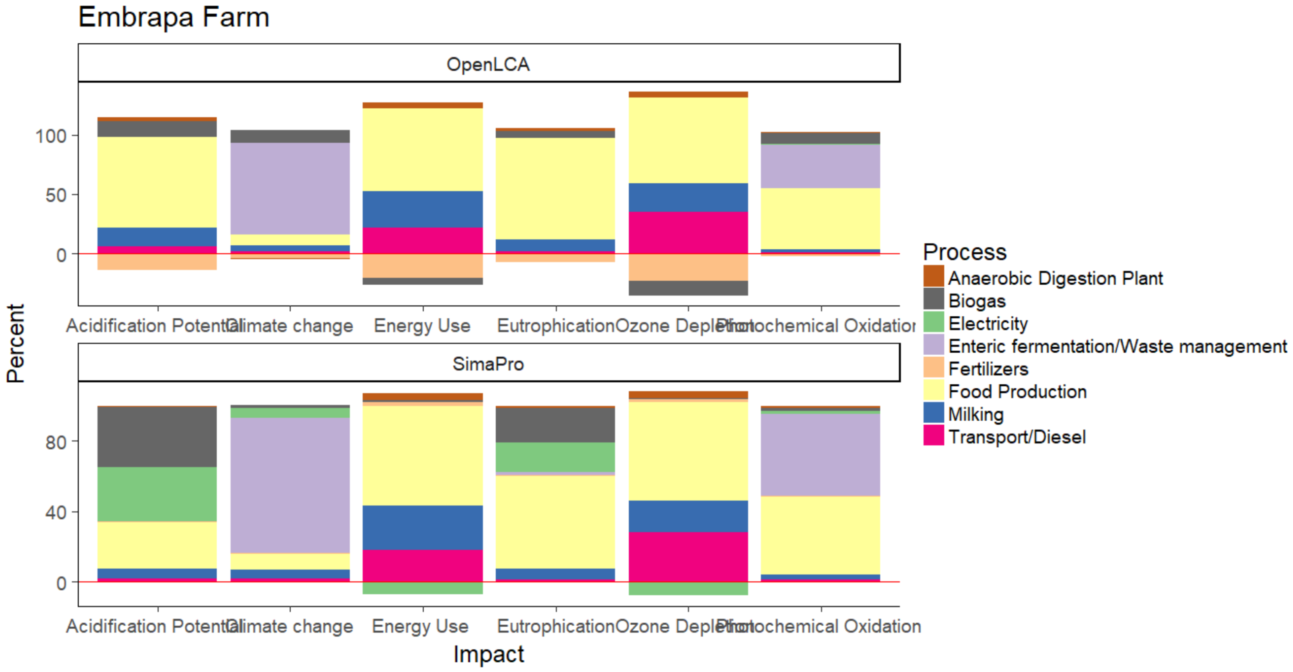

Figure 1. Influence of each process for each impact category for OpenLCA and SimaPro software, for the Embrapa Farm

SimaPro software represents energy avoided as electricity, and OpenLCA represents as biogas in the Figure 1.

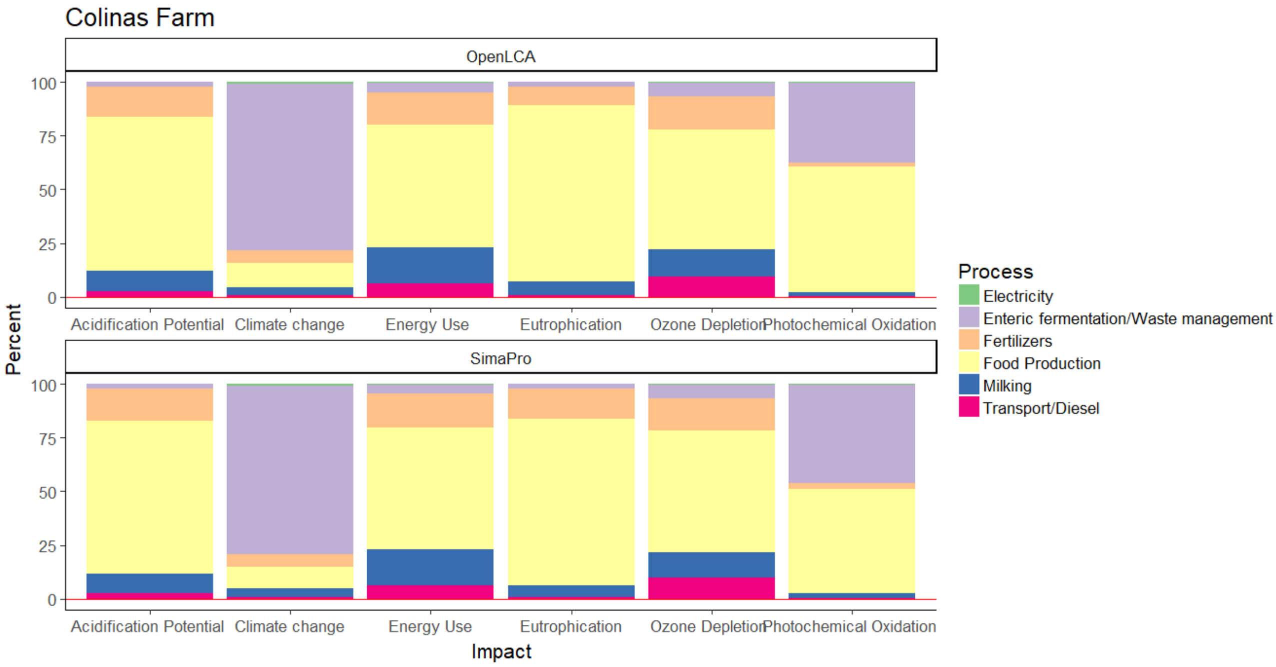

Figure 2. Influence of each process for each impact category for OpenLCA and SimaPro software, for the Colinas Farm

Both software packages allow results to be exported graphically and in tables to text editors, such as Word or Excel. In a qualitative way, both software are good for modeling, and offer similar options. However, OpenLCA software allows comparisons to be made more easily, by offering more visual results, showing the list of all impacts, and offering choice of how to perform modeling in the software (ORMAZABAL et al., 2014). Datasets availability and costs of investment are also highlighted among the main differences of the evaluated software (SILVA et al., 2017). The use of open source software can be a way to disseminate the studies of LCA, in order to make them more transparent and reproductive for academic or industrial sector.

It is important to underline that all the comparisons between LCA studies has to be done carefully as many assumptions and methodological decisions can differ and consequently affect the final results (FAMIGLIETTI et al., 2019). Hence, ordinary and even skilled LCA software users cannot be expected to have the capability to detect potential software errors (HERRMANN; MOLTESEN, 2015). The results of our comparison between both software for each impact category are described below.

Acidification Potential

The result from SimaPro software is three-fold higher than the result from OpenLCA software, being 64% larger in the acidification category, for the Embrapa dairy farm. According to SILVA et al. (2017) the result for Simapro software can be 22% higher for acidification when compared to OpenLCA software. The authors explain that the hotspots are different between the software, and the characterization factor, for some substances, was superior in SimaPro than OpenLCA. In our study the same characterization factors were used.

For the Embrapa dairy farm, the main processes for this impact category, in OpenLCA software, is food production with 76% of the total impact. The fertilizers process comes second with approximately 14%, however it was a beneficial impact. For the Simapro software, the main process related to acidification is biogas, with 34%, followed by electricity, with 31%, and the food production with 26% of the total impact.

For the Colinas dairy farm, the values of acidification potential are close for both software and the main processes responsible for impacts is food production with approximately 70% of the total acidification potential.

Climate changes

For the impact category of climate change the results were similar in both software, for both dairy farms analyzed. The difference is related to the beneficial impact. For the Embrapa dairy farm, the fertilizer process accounts for -4% (beneficial impact) on OpenLCA and the SimaPro does not have beneficial impact for this category.

The processes related to the emissions of greenhouse gases from animals are the ones that contribute the most for climate change. These emissions are related to the enteric fermentation of the animals and the management of the wastes, which, are responsible for 77% and 78% of the environmental impacts for the Embrapa and the Colinas dairy farm, respectively, in both software (Figures 1 and 2). A previous study, based on 70% of the world's bovine mil production, have described that enteric and manure related emissions accounted for 70–95% of the total dairy farm GHG emission (HAGEMANN et al., 2011), which is in agreement with our result.

Energy Use

The result from SimaPro is 18% higher than the result from OpenLCA for the Embrapa dairy farm in energy use impact category. In the OpenLCA software, there are 20% of beneficial impacts due to the use of organic fertilizers. Simapro does not consider this beneficial impact, which can explain the higher results for energy use for Simapro. The lower value for energy use and beneficial impact driven by avoided fertilizer production, have been suggested previously by Cherubini et al (2015) in an LCA of swine production. In this impact category, both software presents a result of positive impacts to the electricity. BATTINI et al., (2014) and CHERUBINI et al., (2015) that used the “avoided product” function also found the same effect due to anaerobic digestion. In total, there is a reduction of -7% and -6% the impacts for Simapro and OpenLCA, respectively.

Eutrophication

Considering eutrophication, the difference between the results of the software can be up to 38% higher for SimaPro, for the Embrapa dairy farm. The food production is the main process that increases the impact for both the OpenLCA and SimaPro software, with 86% and 53%, respectively (Figure 1). In the OpenLCA the fertilizer presents 7% of beneficial impact for the Embrapa dairy farm.

For the Colinas dairy farm, the result is similar, where the main responsible for total impact is the food production in both software, followed by the fertilizers that are responsible for 14% in the OpenLCA and for 9% in the SimaPro software for the total impact category.

Of all activities associated with milk production on dairy farms, the processes related to the production of cattle feed have important contributions to eutrophication impact category, mainly due to inorganic and organic fertilizers that emits NH_3 and nitrate (NO^{-3}) (CASTANHEIRA et al., 2010; BATTINI et al., 2014).

Ozone Depletion

For the impact category, ozone depletion, the result from the software Simapro is 19% higher than the result from OpenLCA software, considering the Embrapa dairy farm. For the Colinas dairy farm, the result is similar considering both software.

The process that contributes the most for the ozone depletion, in SimaPro software, is food production, with 56%, followed by transportation of inputs and use of diesel in the machinery of the farm, with 25% of the total impacts, considering the Embrapa dairy farm. Additionally, the electricity shown beneficial impacts (-8%) due to the avoided GHG emission. Still in the Embrapa dairy farm, the most impactful processes in the OpenLCA software are the same as those for the SimaPro, food production with 72%, followed by the transport process together with diesel, which carry 35% of the impacts. For this impact category, fertilizers and biogas has beneficial impacts (-23% and -12%, respectively). For the

Colinas dairy farm, the most impactful processes in the OpenLCA software are the same as those of for the SimaPro, food production with 56%, followed by fertilizers with 15% of the total impact.

It is important to highlight that the production of animal feed process also includes some impacts related to transportation, and to the use of diesel, which are processes upstream of food production. The transportation of the raw milk from the farms to the dairy factory, and the transportation in other phase of milk production are significant for ozone layer (BAVA et al., 2018; FAMIGLIETTI et al., 2019) which corroborate with our results.

Photochemical Oxidation

For photochemical oxidation impact the results for OpenLCA were 21% and 18% higher than those presented by Simapro, for both Embrapa and Colinas dairy farm, respectively. The results obtained by SILVA et al. (2017) are the opposite of the results of the present study, the authors found results for the photochemical oxidation from Simapro software approximately 66% higher compared to the OpenLCA software. The authors explain that different characterizations factors and different type of dataset formats were found on this impact category, and different reference units were used on their analysis. However, in our study the same characterizations factors, type of dataset formats and reference units were used.

In our study, The OpenLCA software demonstrated that the main factors responsible for the impact of photochemical oxidation are food production, with 51% of the total impact, followed by enteric fermentation and waste management emissions, with 37% of the impacts. In the SimaPro software, the enteric fermentation and waste management carry 47% of the impacts, followed by food production with 44% of impacts. For the Colinas dairy farm, food production is the most important process that is responsible for up to 49% and 58% of the total impact when the software SimaPro and OpenLCA are used, respectively. Additionally, the missions carry 46% and 37% of the photochemical oxidation impact for SimaPro and OpenLCA software, respectively.

The OpenLCA/SimpaPro ratio

The OpenLCA/SimaPro ratio was calculated, for each impact categories, for Embrapa and Colinas dairy farms (Table 3). All the OpenLCA/SimaPro ratio observed for the Embrapa dairy farm deviates from 1, and while the lower ration, 0.36, was founded for acidification potential, the greater ration, 1.27, was found for photochemical oxidation. For the Colinas dairy farm the OpenLCA/SimaPro ratio for all impact categories are close to 1, which means that both software gives similar results, the exception was observed for the photochemical oxidation where the OpenLCA/SimaPro ratio was 1.23.

The higher OpenLCA/SimaPro ratio that was found for Embrapa dairy farm can be explained due to the function "avoided products". The “avoided products” function is widely used in many studies (BATTINI et al., 2014; CHERUBINI et al., 2015; BACENETTI et al., 2016; HANSERUD et al., 2018). Here, the function was used in both software for the Embrapa farm, due to anaerobic digestion, where the biogas is the main product and the digestate is a co-product (LIJÓ et al., 2017). Thus, as animal waste is transformed into biogas and fertilizers, and because there is no purchase of chemical fertilizers and there is no use of electricity from the grid in the Embrapa farm, the function can be applied (CHERUBINI et al., 2015). On the other hand, the function was not applied in the case of the Colinas dairy farm since there is no anaerobic digestion or co-product in the production process of this dairy farm.

Aditionally, the Embrapa dairy farm may have presented higher OpenLCA/SimaPro ratio because it contains higher number of flows in the inventory, compared to the Colinas dairy farm, due to the anerobic digester, which raises substantially the amount of flows compared to the Colinas farm.

4. CONCLUSION

In a quantitative way, the SimaPro software shows result different from OpenLCA, in general. We found difference that ranges from 0% to 64% for the Embrapa dairy farm, and 0% to 18% to the Colinas dairy farm. The impact climate change has shown the most similar value in both farms.

In a qualitative way, both software has a good performance for modeling and offer practically the same options. Therefore, the LCAs performed in this study allows evidence that the resource "avoided product", present in SimaPro and OpenLCA software tools, can be the main cause of the difference to the results of impacts. In addition, our results prove that the software OpenLCA promote the beneficial impacts. In other words, when is necessary to use the recourse "avoided product" is better that use in the software OpenLCA.

Although we performed a robust analysis of software comparison, it is not possible based on this study to reach conclusions regarding others versions of SimaPro and OpenLCA different from the one that was used here. Moreover, the conclusion of our analysis must be restricted to type of LCA and software used. Nevertheless, is important to note that the use of open source software can be an interesting way to disseminate the studies of LCA, in order to make them more transparent and reproductive for both the academic and the industrial sector.

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CONCLUSÃO GERAL

A ACV possibilitou avaliar o impacto ambiental da produção de leite, auxiliando na identificação dos hotspots. Além disso, permitiu conhecer formas de tornar o ciclo da produção leiteira mais sustentável.

Os resultados obtidos no capítulo 1 mostram que há um efeito do biodigestor anaeróbio, para tratamento de efluentes, contribuindo de forma significativa na redução de todos os impactos ambientais analisados. A fazenda que possui o sistema biodigestor (AD), apresentou menor impacto para acidificação, eutrofização, mudança climática, uso de energia, oxidação fotoquímica e depleção de ozônio, em média de 25% e 38% do que aquelas fazendas que não possuíam (NAD1 e NAD2, respectivamente). Devido principalmente às emissões evitadas do uso de eletricidade advinda da rede, e da compra e uso de fertilizantes químicos, entre outras emissões relacionadas. De todos os processos realizados na fazenda, para a produção leiteira, a produção de alimentos é o que mais impacta. A implantação do biodigestor, aliada às práticas que aumentam a produtividade por animal, são soluções que devem ser adotadas na busca pela melhoria do desempenho ambiental da produção de leite.

No capítulo 2 os resultados mostram que, de forma quantitativa, o software SimaPro apresenta resultados de impactos diferentes do OpenLCA, em geral, que variam de 0% a 64% para a fazenda Embrapa (AD) e de 0% a 18% para a fazenda Colinas (NAD2). A categoria mudança climática foi a que apresentou valores mais próximos para ambos os softwares e fazendas. De forma qualitativa, ambos os softwares são bons para modelagem e oferecem praticamente os mesmos recursos. Portanto, as ACV realizadas neste estudo permitem evidenciar que o recurso "produto evitado", presente nas ferramentas de software SimaPro e OpenLCA, pode ser a principal causa da diferença nos resultados de impacto. No entanto, não é possível, com base neste estudo, chegar a conclusões concretas para outras versões do SimaPro e OpenLCA, ou outro software, ou também sobre outros tipos de LCA. É importante ressaltar que o uso de software livre pode ser uma forma de disseminar os estudos de ACV, a fim de torná-los mais transparentes e reprodutivos, seja no setor acadêmico ou industrial.

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SUPPLEMENTARY MATERIAL

Appendix A

Emissions of CH_4 from enteric fermentation

In order to estimate the gas emissions (CH_4) from the enteric fermentation of the animals, due to the digestive system of ruminants, calculation guides and methods were used as indicated by the IPCC (IPCC, 2006). All information regarding these calculations are described in the Report on Guidelines for National Greenhouse Gas Inventories (IPCC 2006 - Volume 4 - Agriculture, Forests and Other Soil Uses, Chapter 10 - Emissions from Livestock). Emissions of carbon dioxide (CO_2) from livestock are not considered in the IPCC (2006) since annual net emissions are considered zero. However, a part of the carbon returns as CH_4 and, therefore, CH_4 requires separate consideration, as was done in the present study.

The animal population is divided into subcategories. This study falls into the following category: high production cows, which have calved at least once and are mainly used for milk production (IPCC, 2006). Information regarding the average daily feed intake and the percentage of feed energy that is converted to CH4 were required (WILLERS, 2014). Meal consumption was measured in terms of gross energy (megajoules (MJ) per day) or dry matter (kilograms (kg) per day), the latter being the amount of food consumed directly (kg). Thus, the average consumption of ration was calculated measured in terms of gross energy (EB), that is, the energy used by the animals to perform the main activities such as gestation, feeding, maintenance, among others (WILLERS, 2014). The methods used to perform the calculations were performed based on the IPCC (2006) and on the study by Willers (2014), and are described below.

Maintenance energy (Me): It is the energy needed to keep the animal in balance, where body energy is neither gained nor lost, in MJ per day (Equation 2).

$$Me = Cfi \times W^{0.75} \qquad (2)$$

Where:

Me: Maintenance energy (MJ/day).

Cfi: coefficient that varies for each category of animals (MJ / day/kg, for lactating cows, is considered 0.386)

W: live animal weight (kg - in this study the mean weight was 500 kg).

Energy for Activity (Ea): It is the energy needed to obtain food, water and shelter. It depends on the management situation of each farm, intensive (confinement) or grazing. We performed a mean between the two types of management because the animals live in semi-intensive production systems (Equation 3).

$$Ea = Ca \times Me \qquad (3)$$

Where:

Ea: energy for animal activity (MJ / day);

Ca: dimensionless coefficient corresponding to the animal's food situation (0.085);

Me: maintenance energy (MJ / day), calculated from equation 2.

Energy for growth (Eg): It is the energy required for growth and weight gain, used only for young animals (Equation 4).

$$Eg = 22{,}02 \times (\frac{W}{(C \times Wl)})^{0.75} \times GW^{1.097} \; (4)$$

Where:

Eg: the energy required for growth (MJ / day);

W: mean live weight of the animals in the population (kg, 500 kg was considered, only adult cows);

Wl: live weight of an adult female in moderate body condition (kg, 500 kg was adopted);

C: coefficient without dimension with a value of 0.8 for females.

GW: gain weight animals, daily (kg/day, 0 was adopted, as the animals lose weight during the dry season and gain weight in the rainy season, a balance occurs).

Lactation Energy (El): The energy required for lactation, expressed as a function of the amount of milk produced and its fat content (Equation 5).

$$El = Milk \times (1.47 + 0.40 \times Fat)(5)$$

Where:

El: the energy required for lactation (MJ / day);

Milk: the amount of milk produced per day (kg/day, 19.3 kg milk/day were used for the Embrapa farm and 18 kg milk/day for the Colinas farm);

Fat: percentage of fat contained in milk (%, Colinas = 3.890%, Embrapa = 3.906%).

Energy for Gestation (Egest): It is the energy needed for gestation, given by a gestation period of 281 days, on average, during a year (Equation 6).

$Egest = Cg \times Me$ (6)

Where:

Egest: the energy required for gestation (MJ / day);

Cg: coefficient, for bovines the accepted value is 0.10;

Me: animal maintenance energy (MJ / day);

Ratio of net energy in the diet for maintenance (REM): It is the proportion of liquid energy available in a diet for the energy maintenance of animals (Equation 7).

$$REM = \left[1.123 - (4.092 \times 10^{-3} \times DE\%) + (1.126 \times 10^{-5} \times (DE\%)^2) - \left(\frac{25.4}{DE\%}\right)\right] \quad (7)$$

Where:

REM: the proportion of net energy available in a diet;

DE: is the digestibility rate of the animal in relation to the gross energy (% of the gross energy, considered 0.60, because the animals have a diet consisting of pasture, concentrates and silage).

Ratio of net energy available in the diet to growth (REG): It is the proportion of liquid energy available for growth in a diet to digestible energy consumed (Equation 8).

$$REG = [1.164 - (5.160 \times 10^{-3} \times DE\%) + (1.308 \times 10^{-5} \times (DE\%)^2) - (\frac{37.4}{DE\%})] \ (8)$$

Where:

REG: the proportion of net energy available for growth in a diet (%)

DE: is the digestibility rate of the animal, expressed as a percentage of gross energy (%, considered as 0.60%, because the animals have a diet consisting of pasture, concentrates and silage).

Gross Energy (GE): It is based on the net energy requirements and the energy availability characteristics of the feed (Equation 9).

$$GE = \frac{\left(\frac{Me+Ea+El+Egest}{REM}\right)+\left(\frac{Ec}{REC}\right)}{\frac{DE\%}{100}} \quad (9)$$

Where:

GE: gross energy (MJ/day);

Me: energy for the maintenance of the animal (MJ / day);

Ea: the energy required by the animal for its activities (MJ / day);

El: the energy required for lactation (MJ / day);

Egest: the energy required during the gestation period (MJ / day);

REM: the proportion of net energy available in a diet (%);

Eg: energy for the growth of the animal (MJ / day);

REG: the proportion of net energy available for growth in a diet (%);

DE: is the rate of digestibility of the animal, expressed as a percentage of gross energy (%).

According to the IPCC (2006) and to WILLERS (2014), since the EB values are calculated, one should also calculate the feed intake in units of Kilograms of Dry Matter (DM) per day (kg/day). To convert EB into energy units for dry matter consumption (CMS), GE is divided by the energy density of the feed. The standard value of 18.45 MJ / kg indicated by IPCC (2006) may be used if specific feeding information is not available. With this, the CMS considered was equal to 3.5% of the body weight, considering that the adult cows weigh 500kg, CMS equals 17.5kg.

CH4 emissions from enteric fermentation

To estimated the emissions of CH4, Equations 10 and 11 were used.

$$EF = \left[\frac{GE \times \left(\frac{Ym}{100}\right) \times 365}{55.65}\right] \quad (09)$$

Where:

EF: emission factor (kg CH4 / head * year);

GE: gross energy intake (MJ / head * day);

The factor 55.65 (MJ / kg CH4) is the energy content of CH4;

Ym: conversion factor of CH4, the percentage of crude energy contained in the feed converted to CH4. This CH4 conversion factor depends on feed characteristics (digestibility and energy value) and production practices. Thus, Ym of 6.5% was recognized for the category of dairy cows.

$$Emission = EF_{(T)} \times \left(\frac{N_{(T)}}{10^6}\right) \quad (11)$$

Where:

Emissions: CH4 emissions from enteric fermentation (Gg CH4 / year); EF (T): emission factor for the population of adult cows (kg CH4 / head.year);

N (T): the number of heads of animals per category;

T: cattle category.

The results obtained for each step of the methodology applied to estimate the emissions are shown in Table A1.

Table A1- Result of animal enteric emission calculations for the Embrapa and Colinas farms

Results	**Embrapa**	**Colinas**
W (kg)	500	500
Me (MJ/day)	40.8445	40.8445
Ea (MJ/day)	3.4692	3.4692
Eg (MJ/day)	0.0000	0.0000
El (MJ/day)	58.5250	54.5832
Egest (MJ/day)	4.0814	4.0814
REM	0.4947	0.4947
REG	0.2720	0.2720
EB (MJ/day)	360.1186	346.8361
EF (kg/day)	153.5300	147.7001
$CH_{4enteric}$ (Kg CH_4/year/animal)	153.5300	147.7001

Table A2. Environmental impacts for all categories evaluated, per 1 kg of milk corrected by protein and fat, for Embrapa farm with and without anaerobic digester (AD and NAD1) and Colinas farm (NAD2)

Impact category	**AD**	**NAD1**	**NAD2**
Acidification Potential (Kg SO_2 eq.)	0.0015	0.0019	0.0025
Climate change (Kg CO_2 eq.)	0.8835	1.1123	1.2122
Depletion of Abiotic Resource (Kg Sb)	5.6199E-7	1.6182E-6	1.7953E-06
Energy Use (MJ)	1.8032	2.9657	3.2997
Eutrophication (Kg PO_4 eq.)	0.0010	0.0011	0.0016
Freshwater Ecotox. (Kg 1.4 DCB eq.)	0.1678	0.1806	0.2590
Marine Ecotoxicity (Kg 1.4 DCB eq.)	181.9214	268.5288	327.6587
Terrestrial ecotoxicity (Kg 1.4 DCB eq.)	0.0410	0.0407	0.0645
Human Ecotoxicity (Kg 1.4 DCB eq.)	0.1223	0.1677	0.2127
Ozone Depletion (Kg CFC-11)	1.4251E-8	2.6193E-8	2.7420E-8
Photochemical Oxidation (Kg C_2H_4)	0.0004	0.0005	0.0006

Table A3. Notes assigned according to data quality and Pedigree Matrix (MP) by Monte Carlo uncertainty calculation, for AD, NAD1 and NAD2

EMBRAPA (AD)	**Indicator Score (MP)**	**EMBRAPA (NAD2)**	**Indicator Score (MP)**	**COLINAS (NAD2)**	**Indicator Score (MP)**
Parameters		**Parameters**		**Parameters**	
Silage Production		**Silage Production**		**Silage Production**	
Land	1,4,1,1,1	Land	1,4,1,1,1	Land	2,4,1,1,1
Maize seed	1,4,1,1,1	Maize seed	1,4,1,1,1	Maize seed	1,4,1,1,1
Fertilizer (planting)	1,4,1,1,1	Fertilizer (planting)	1,4,1,1,1	Fertilizer (planting)	1,4,1,1,1
Fertilizer (coverage)	1,4,1,1,1	Fertilizer (coverage)	1,4,1,1,1	Fertilizer (coverage)	1,4,1,1,1
Herbicides	1,4,1,1,1	Herbicides	1,4,1,1,1	Herbicides	1,4,1,1,1
Packaging for fertilizers and herbicides	1,4,1,1,3	Packaging for fertilizers and herbicides	1,4,1,1,3	Packaging for fertilizers and herbicides	1,4,1,1,3
Fuel (Machines)	2,4,1,1,1	Fuel (Machines)	2,4,1,1,1	Fuel (Machines)	2,4,1,1,1
Pasture		**Pasture**		**Pasture**	
Land	1,2,1,1,1	Land	1,2,1,1,1	Land	1,2,1,1,1
Animal food preparation		**Animal food preparation**		**Animal food preparation**	
Maize feed	1,3,1,1,1	Maize feed	1,3,1,1,1	Maize feed	1,3,1,1,1
Soybean feed	1,3,1,1,1	Soybean feed	1,3,1,1,1	Soybean feed	1,3,1,1,1
Urea	1,3,1,1,1	Urea	1,3,1,1,1	Urea	1,3,1,1,1
Mineral salt	1,3,1,1,2	Mineral salt	1,3,1,1,2	Mineral salt	1,3,1,1,2
Fuel (Machines)	2,4,1,1,1	Fuel (Machines)	2,4,1,1,1	Bicarbonato	1,4,1,1,1
Water		**Water**		**Water**	
Animal water feed	1,4,1,1,1	Animal water feed	1,4,1,1,1	Clean	2,4,1,1,1
Energy		**Energy**		Animal water feed	2,4,1,1,1
Biogas	1,4,1,1,1	Electricity grid	1,4,1,1,1	**Energy**	
Transport		**Transport**		Electricity grid	2,4,1,1,1
Big lorry	1,4,1,1,1	Big lorry	1,4,1,1,1	**Transport**	
Small lorry	1,4,1,1,1	Small lorry	1,4,1,1,1	Big lorry	1,4,1,1,1
CH_4 emission		**CH_4 emission**		Small lorry	1,4,1,1,1
Enteric fermentation	1,2,1,2,1	Enteric fermentation	1,2,1,2,1	**CH_4 emission**	
Manure management	1,2,1,2,1	Manure management	1,2,1,2,1	Enteric fermentation	1,2,1,2,1
N_2O emission		**N_2O emission**		Manure management	1,2,1,2,1
Manure management	2,4,1,3,1	Manure management	2,4,1,3,1	**N_2O emission**	
Wastewater treatment		**Manure**		Manure management	2,4,1,3,1
Biogas	1,4,1,1,1	Solid and liquid	2,2,1,2,2	**Manure**	
Biofertilizer	1,4,1,1,1			Solid and liquid	2,2,1,2,2
Anaerobic digestion	1,4,1,1,3				
Electricity Generator	1,4,1,1,3				

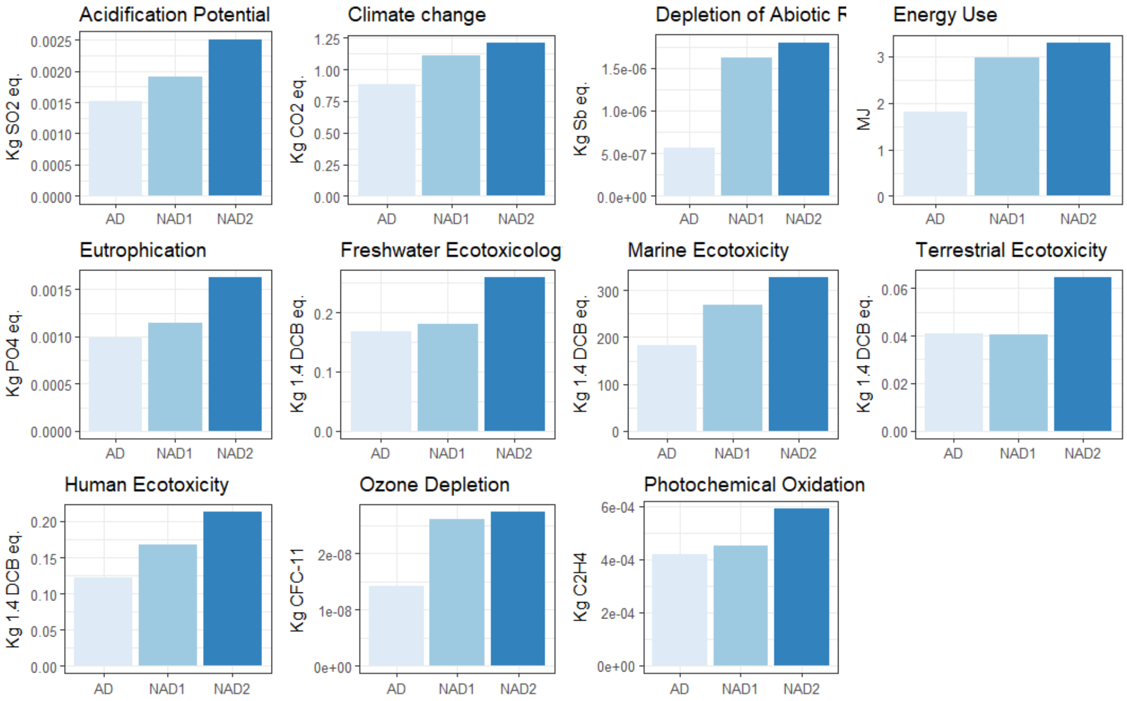

Figure A1 - Results of all category of impacts comparing the scenarios with anaerobic digester (AD), and without anaerobic digester (NAD1 and NAD2).

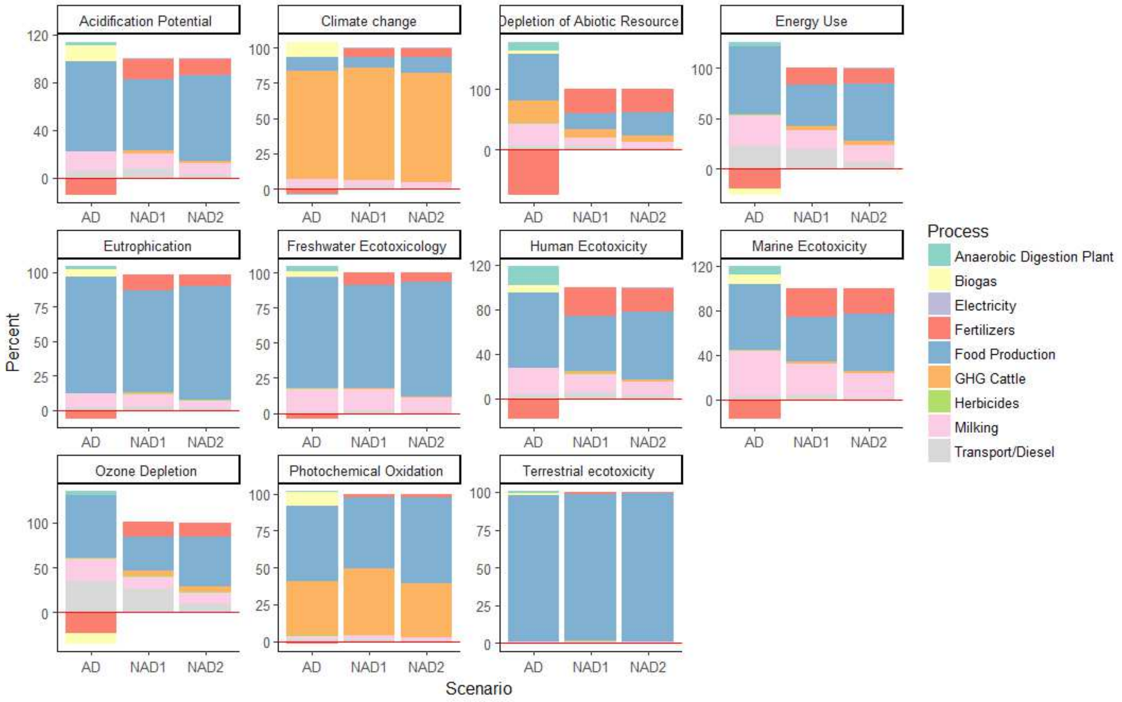

Figure A2 – Influence of each process for each impact category for AD, NAD1, and NAD2 scenarios