UNIVERSITAT ROVIRA I VIRGILI

ASSESSMENT OF ENVIRONMENTAL AND SOCIAL IMPACTS DUE TO THE INCLUSION OF NOVEL SOLUTIONS FOR NUTRIENT RECOVERY: TOWARDS SUSTAINABILITY IN AGRICULTURE

Edilene Pereira Andrade

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EDILENE PEREIRA ANDRADE

TESI DOCTORAL – TESIS DOCTORAL- DOCTORAL THESIS
2022

DOCTORAL THESIS

Edilene Pereira Andrade

Assessment of environmental and social impacts due to the inclusion of novel solutions for nutrient recovery: Towards sustainability in agriculture

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We STATE that the present study, entitled "Assessment of environmental and social impacts due to the inclusion of novel solutions for nutrient recovery: Towards sustainability in agriculture", presented by Edilene Pereira Andrade for the award of the degree of Doctor, opting for an International Doctorate Mention, has been carried out under our supervision at the Chemical Engineering Department of the University Rovira i Virgili and the Institute of Agrifood Research and Technology.

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The research presented in this thesis was carried out with funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 713679 and from the Universitat Rovira i Virgili (URV).

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ACKNOWLEDGEMENTS

First, I always say that without God we don't get anywhere, He represents my strength and the will to always move forward.

Many thanks to IRTA and the GIRO group for all the shared coffee and meals and for the moments of fun in the Team Building and to provide a such nice and inspiring environment to develop my work. Especially to Assumpció Anton for all the dedication, patience, and teachings during my trajectory in my doctorate, she always has the best solutions for my questions. My thanks also go to August Bonmati, for trusting my work and making me very comfortable in the decisions I made. To all my colleagues in the LCA group (Ariadna, Marta, Miquel, Montse and Ralph) I would like to express my immense gratitude for all the knowledge, and especially to Erica Montemayor for her friendship and laughter together. I hope that my path and that of IRTA will cross again soon.

I would also like to thank the Rovira i Virgili University, the Department of Chemical Engineering, which made it possible for me to participate in the Martí Franquès Research Scholarship Program. Especially to my advisor Laureano Jiménez for always being so helpful and agile whenever I needed it.

This thesis is also dedicated to my parents, Edna and Carlos, the ones responsible for getting me here, thanks to their support and trust that it will always work out. Painho and Mainha, now you are going to have daughter as a doctor. To my siblings, Edicarla and Eric, thank you for always being so understanding. To my Pereira and Andrade families for always supporting my parents.

Finally, to my great love, Mateus, this victory is ours! Thank you for everything, for the support, for the shoulder so that I could cry in the most afflicted moments, for trusting us and for believing that together we can always do more.

ABSTRACT

Agriculture plays a major role when it becomes to food sustain, being strongly related to many sustainability challenges such as climate change, water scarcity, poverty and food insecurity. Therefore, there is a need to shift from an agri-food system aiming to increase productivity, to another one built around the broader principles of sustainable agriculture, which establishes fairer modes of production and consumption (Brunori et al., 2013). Several impacts can be addressed to agricultural practices, many of them need further studies, due to the low exploration of pathways between not common impacts, such as the use of mineral fertilizers and the impact on local communities, or the reduction of accidents due to the improvement of training in agricultural systems.

Currently, sustainable agriculture is more focused on environmental problems related to the use of primary resources. However, to achieve sustainability in its essence, it is necessary to evaluate, in addition to the environmental impacts, also the social and economic impacts (Petit et al., 2018).

The aim of this thesis is to assess the environmental and social impacts of novel technologies and solutions focused on nutrient recovery and recycling of nutrients in agriculture. To this end, the development of methodologies and set of indicators are proposed focusing on the main direct and indirect social and environmental issues in the sector. In addition, it is intended to assist end-users to prevent and mitigate, when possible, potential environmental and social impacts from the arable and livestock systems. Also, a user-friendly approach was developed to present social and environmental assessments for different stakeholders involved directly and indirectly in the sector. The final products are focused on agriculture, but they can be extended to other sectors, such as forestry or fisheries, following the proposed methodology.

Summarizing the sections of this thesis, the study presented in section 2 provides valuable insight into nitrogen emissions models, highlighting that it is not always possible to use mechanist models due to the amount (and quality) of input data required, but these models could be used to adjust short-cut models, helping to improve the evidence-based of results in life cycle assessment (LCA) studies. In section 3, we present the dashboard indicators (DBI), under a rapid assessment, reflected the most relevant environmental aspects and impacts about nutrient recovery in agriculture, being an effective way to benchmark against a baseline (i.e., the current situation in agricultural practices). However, although the DBI covered various aspects (i.e., the use of primary resources, emissions to the environment and resilience to climate change), they are not intended to replace the full assessments, for instance, using LCA. In section 4, the set of indicators enabled the identification of social hotspots and opportunities related to novel technologies applied in agriculture, for instance, the employability of highly skilled workers, attracting a highly qualified labour force to agriculture, increasing training and employee development, helping to reduce accidents at work, and the novel ways to properly deal with manure can promote a reduction in odour and other gases for local communities in the surroundings of livestock farms. However, novel technologies can be a new source of damage, for instance, due to the use of chemicals (e.g., acids) or working with heavy machinery, although these risks can be minimized/ controllable. Finally, the conclusions obtained from section 5, show that with the methodology adopted, environmental and social aspects of the process could be measured through the use of the same inventory, especially in the case of novel technologies with a low level of adaptation in society, but adapting to intended conditions, for instance, using monetary flows.

Keywords:

Nutrient efficiency, Nitrogen models, PSILCA, Dashboard indicators, S-LCA, E-LCA.

RESUMEN

Agricultura juega un papel importante cuando se convierte en proveedor de alimentos, estando fuertemente relacionada con muchos desafíos de sostenibilidad como el cambio climático, la escasez de agua, la pobreza y la inseguridad alimentaria. Por lo tanto, existe la necesidad de pasar de un sistema agroalimentario que apunta a aumentar la productividad a otro basado en los principios más amplios de la agricultura sostenible, que establece modos de producción y consumo más justos (Brunori et al., 2013). Se pueden abordar varios impactos de las prácticas agrícolas, muchos de ellos necesitan más estudios, debido a la baja exploración de las relaciones entre impactos no comunes, como el uso de fertilizantes minerales y el impacto en las comunidades locales, o la reducción de accidentes debido a la mejora de la formación de los trabajadores en los sistemas agrícolas.

Actualmente, la agricultura sostenible está más enfocada a los problemas ambientales relacionados con el uso de recursos primarios. Sin embargo, para lograr la sostenibilidad en su esencia, es necesario evaluar, además de los impactos ambientales, también los impactos sociales y económicos (Petit et al., 2018).

El objetivo de esta tesis es evaluar los impactos ambientales y sociales de nuevas tecnologías y soluciones centradas en la recuperación de nutrientes y el reciclaje de nutrientes en la agricultura. Para ello, se propone el desarrollo de metodologías y conjuntos de indicadores enfocados en los principales temas sociales y ambientales directos e indirectos del sector. Además, tiene por objeto ayudar a los usuarios finales a prevenir y mitigar, cuando sea posible, los impactos ambientales y sociales potenciales de los sistemas agrícolas y ganaderos. Conjuntamente, se desarrolló un enfoque fácil de usar para presentar evaluaciones sociales y ambientales para diferentes actores involucrados directa e indirectamente en el sector. Los productos finales están enfocados a la agricultura, pero pueden extenderse a otros sectores, como el forestal o la pesca, siguiendo la metodología propuesta.

Al resumir las secciones de esta tesis, el estudio de la sección 2 brinda información valiosa sobre los modelos de emisiones de nitrógeno, y destaca que no siempre es posible usar modelos mecánicos debido a la cantidad (y calidad) de los datos de entrada requeridos, pero estos modelos podrían usarse para ajustar los modelos abreviados, ayudando a mejorar los resultados basados en evidencia en los estudios de evaluación del ciclo de vida (ACV). En la sección 3, presentamos indicadores del tablero (IT), bajo una evaluación rápida, reflejaron los aspectos ambientales más relevantes y los impactos en la recuperación de nutrientes en la agricultura, siendo una forma efectiva de comparar con la línea de base (es decir, la situación actual en las prácticas agrícolas). Sin embargo, aunque el IT cubrió varios aspectos (es decir, el uso de recursos primarios, las emisiones al medio ambiente y la resiliencia al cambio climático), no pretenden reemplazar las evaluaciones completas, por ejemplo, utilizando ACV. En la sección 4, el conjunto de indicadores permitió identificar puntos críticos sociales y oportunidades relacionadas con nuevas tecnologías aplicadas en la agricultura, por ejemplo, la empleabilidad de trabajadores altamente calificados, atraer una fuerza laboral altamente calificada a la agricultura, aumentar la capacitación y el desarrollo de los empleados, ayudar para reducir los accidentes laborales, y las nuevas formas de tratar adecuadamente el estiércol pueden promover una reducción del olor y otros gases para las comunidades locales en los alrededores de las granjas ganaderas. Sin embargo, las nuevas tecnologías pueden ser una nueva fuente de daños, por ejemplo, debido al uso de productos químicos (p. ej., ácidos) o al trabajo con maquinaria pesada, aunque estos riesgos pueden minimizarse/controlarse. Finalmente, las conclusiones obtenidas del apartado 5, muestran que, con la metodología adoptada, se podrían medir aspectos ambientales y sociales del proceso mediante el uso del mismo inventario, especialmente en el caso de tecnologías novedosas con un bajo nivel de adaptación en la sociedad. pero adaptándose a las condiciones previstas, por ejemplo, utilizando flujos monetarios.

Palabras clave:

Eficiencia de nutrientes, Modelos de nitrógeno, PSILCA, Indicadores de tablero, ASCV, ACV.

RESUMO

A agricultura desempenha um papel importante quando se trata de prover alimento, estando fortemente relacionada a muitos desafios de sustentabilidade, como mudanças climáticas, escassez de água, pobreza e insegurança alimentar. Portanto, há a necessidade de passar de um sistema agroalimentar que tem o objetivo de aumentar a produtividade, para outro construído em torno dos princípios mais amplos da agricultura sustentável, que estabelece modos de produção e consumo mais justos (Brunori et al., 2013). Diversos impactos podem ser relacionados às práticas agrícolas, muitos deles carecem de estudos mais aprofundados, devido à baixa exploração de caminhos entre impactos não comuns, como o uso de fertilizantes minerais e o impacto nas comunidades locais, ou a redução de acidentes por melhoria da formação em sistemas agrícolas.

Atualmente, a agricultura sustentável está mais voltada para os problemas ambientais relacionados ao uso de recursos primários. No entanto, para alcançar a sustentabilidade em sua essência, é preciso avaliar, além dos impactos ambientais, também os impactos sociais e econômicos (Petit et al., 2018).

O objetivo desta tese é avaliar os impactos ambientais e sociais de novas tecnologias e soluções focadas na recuperação e reciclagem de nutrientes na agricultura. Para tanto, propõe-se o desenvolvimento de metodologias e conjunto de indicadores com foco nas principais questões socioambientais diretas e indiretas do setor. Além disso, destina-se a ajudar os usuários finais a prevenir e mitigar, quando possível, os potenciais impactos ambientais e sociais dos sistemas agrícolas e pecuários. Além disso, foi desenvolvida uma abordagem amigável para apresentar avaliações socioambientais para diferentes partes interessadas envolvidas direta e indiretamente no setor. Os produtos finais são voltados para a agricultura, mas podem ser estendidos a outros setores, como florestal ou pesqueiro, seguindo a metodologia proposta.

Resumindo as seções desta tese, o estudo apresentado na seção 2 fornece informações valiosas sobre os modelos de emissões de nitrogênio, destacando que nem sempre é possível usar modelos mecanicistas devido à quantidade (e qualidade) dos dados de entrada necessários, mas esses modelos podem ser usados para ajustar modelos de atalho, ajudando a melhorar os resultados baseados em evidências em estudos de avaliação do ciclo de vida (ACV). Na seção 3, apresentamos os indicadores do painel (IP), sob uma avaliação rápida, refletindo os aspectos e impactos ambientais mais relevantes sobre a recuperação de nutrientes na agricultura, sendo uma forma eficaz de referência em relação a uma linha de base (ou seja, a situação atual das práticas agrícolas). No entanto, embora o IP aborde vários aspectos (ou seja, o uso de recursos primários, emissões para o meio ambiente e resiliência às mudanças climáticas), eles não pretendem substituir as avaliações completas, por exemplo, usando ACV. Na seção 4, o conjunto de indicadores possibilitou a identificação de pontos críticos +sociais e oportunidades relacionadas a novas tecnologias aplicadas na agricultura, por exemplo, a empregabilidade de trabalhadores altamente qualificados, atraindo mão de obra altamente qualificada para a agricultura, aumentando a formação e desenvolvimento de funcionários, ajudando para reduzir os acidentes de trabalho, e as novas formas de lidar adequadamente com o esterco podem promover a redução do odor e de outros gases para as comunidades locais no entorno das fazendas de gado. No entanto, novas tecnologias podem ser uma nova fonte de danos, por exemplo, devido ao uso de produtos químicos (por exemplo, ácidos) ou trabalho com máquinas pesadas, embora esses riscos possam ser minimizados/controláveis. Por fim, as conclusões obtidas na seção 5, mostram que com a metodologia adotada, os aspectos ambientais e sociais do processo poderiam ser medidos através do uso do mesmo inventário, principalmente no caso de novas tecnologias com baixo nível de adaptação na sociedade, mas adaptando-se às condições pretendidas, por exemplo, usando fluxos monetários.

Palavras-chave: Eficiência de nutrientes, Modelos de Nitrogênio, PSILCA, Indicadores Dashboard, ASCV, ACV.

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1.INTRODUCTION

1. Introduction

Agriculture faces a great challenge, as it needs to produce more food and feed for a growing population, coupled with this, it must make use of a more efficient and sustainable production method (Doering and Sorensen, 2018). Sustainable agricultural practices seek to equitably promote environmental management, improve the quality of life for communities, increase food production and make farms more profitable (USDA, 2021). Thus, the current food system production urgently requires a transformation regarding productivity, resource use, and environmental impacts (Willet et al., 2019).

On one hand, the sector has a huge contribution to atmospheric and water emissions to the environment, but, on the other hand, it is one of the biggest levers for positive change (Fanzo et al., 2021). Food production and waste are responsible for around 40% of global greenhouse gas (GHG) emissions and it has a high contribution to several types of environmental degradation threatening the ecosystems, biodiversity loss, terrestrial ecosystem destruction, freshwater consumption, and water pollution due to overuse of nitrogen and phosphorus (Rockström et al., 2020). The Environment European Agency (EEA) reported that European agricultural systems emitted around 500 million tons of CO_2 equivalent (Mt CO2e), in which 35% is methane (CH_4) from enteric fermentation, 33% is nitrous oxide (N_2O) from agricultural soils, 17% from energy consumption in agriculture/forestry/fishing, 12% from manure management and 3% from other sources (EEA, 2021). In addition, ammonia (NH_3) emissions from the agricultural sector continue to rise, having an increase of 2.5 % in the 2014-2017 period (EEA, 2019). Regarding water pollution, agriculture is responsible on average for 77% of the total load of nitrogen into the environment, being the most prominent source, and livestock production is responsible for an estimated 81% of agricultural nitrogen input to aquatic systems (EC, 2013). Thus, it is essential to estimate these emissions in order to control and mitigate them in agricultural systems.

The Intergovernmental Panel on Climate Change (IPCC) proposed a classification in tiers (i.e. Tier 1, Tier 2, Tier 3) for the several methodologies to estimate emissions, dividing them according to their level of methodological complexity (Gitarskiy, 2019). Tier 1 approaches are basic methods, it should be used only in cases where more accurate data is unavailable, and as examples there are the emission factors from IPCC, to estimate GHG emissions. Tier 2 is an intermediate level, and as examples, there are the models SALCA nitrate (Richner et al., 2014) and SQCB (Zheng et al., 2014), both methodologies are used to estimate nitrate leaching. Eurostat promoted the use of a common methodology to calculate nutrients, nitrogen (N) and phosphorus (P), balances, the Gross Nitrogen Budget (GNB) and the Phosphorus budget (PB), by applying Tier 1 and Tier 2 methodologies (Kremer, 2013). Tier 3 approaches are the most demanding in terms of data requirements, and the most complex tools, usually involving programming and large databases. Mechanist models such as Daisy (Hansen et al., 2012), Animo (Rijtema and Kroes, 1991) and Epic (Sharpley and Williams, 1990), which include environmental and climate conditions to simulate nitrogen cycle under several equations and assumptions models are examples of Tier 3 models. Tiers 2 and 3 are normally deemed to be more accurate as they include several parameters aiming to simulate the crop and livestock real conditions. Ideally, Tier 3 models should be prioritized in the estimation of emissions, but the high amount of input data and high-level knowledge (e.g., programming skills) can be a burden its practical use. Calculated emissions can be used with indicators to take stock of progress on agriculture's impacts on the environment.

Over the years, the agricultural sector, especially the livestock and dairy sectors, has been increasingly criticized for their environmental as well as social impacts (Revéret et al. 2015). FAO (2020) listed several environmental and social impacts caused by arable and livestock systems. As examples of social effects and externalities there are health consequences (e.g., respiratory diseases), gender issues, as well as the formation of human and social capital. It is estimated that around 65% of poor working adults made a living through agriculture (World Bank, 2021). Regarding the environmental effects, it can be included externalities such as GHG emissions, water pollution, biodiversity preservation, and food waste (FAO, 2020).

Agriculture has a unique potential to provide beneficial contributions to the global carbon budget due to carbon fixation through photosynthesis, capturing carbon dioxide (CO_2) from the atmosphere (Northrup et al., 2021). In order to reduce the environmental footprint in agriculture, diverse technologies have been developed, and a combination of technologies to reduce emissions and increase soil carbon storage can allow the sector to reach net-negative emissions while keeping high productivity (Northrup et al., 2021). Examples of strategies to reduce gases emission are electrical synthesis of ammonia (Liu et al., 2020) manure surface acidification technology (Zhang et al., 2021) and covering the storage as an effective method to reduce the methane (CH_4) emissions. The use of mineral fertilizers can be controlled with technologies such as precision fertilization (Northrup et al., 2021), crop genetics for improved N use efficiency (Tracy et al., 2020) and biological synthesis as a potential low-emission N source (Liu et al., 2020). However, it is important to highlight that, by the use of these technologies, potential trade-offs, including consequences in the social sphere, can occur in the system. Scherer et al. (2018) also highlighted that pursuing social goals is often associated with higher environmental impacts. In the

Nutri2Cycle[1] 44 technologies are proposed for nutrient recovery and nutrient improving, aiming to contribute to close nutrients (nitrogen, carbon and phosphorus) in agriculture. Therefore, it is essential to be aware of environmental and social impacts from the inclusion of novel technologies in agricultural systems.

Several methodologies have been applied over the years to estimate environmental and social impacts in agriculture, aiming also to achieve sustainability. Regarding environmental impacts, Lampridi et al. (2019) reviewed agricultural sustainability studies and found that indicator-based tools, frameworks, and indexes, followed by multicriteria methods the most used approaches. The 28 agri-environmental indicators suggested by Eurostat are intended to monitor the integration of environmental concerns into the Common agricultural policy (CAP) (Eurostat, 2021). The 17 Sustainable Development Goals (SDG) proposed by the United Nations, can reflect both environmental and social impacts, with their 17 goals aiming to build stronger health systems, expanded social protection coverage, the resilience that comes from more equal societies, and a healthier natural environment (UN, 2020). Among those tools cited, some have gained greater acceptance and are widely used by the majority of practitioners worldwide, such as Life cycle assessment (LCA) (for environmental impacts), and Social Life Cycle Assessment (for social impacts) (Lampridi et al., 2019).

Life Cycle Assessment (LCA) examines impacts from the extraction of the raw materials/energy used as an input of the value chain of a product (also a process or service), through manufacture, distribution, use, possible re-use/recycling until its end-of-life, where the product has its final disposal (ISO 14040: 2006). On one hand, LCA focuses on environmental impacts, including impacts, for instance, on climate change, eutrophication and acidification. On the other hand, Social Life Cycle Assessment (S-LCA) helps to assess the socio-economic impacts that directly and indirectly affect different stakeholders, such as workers, local community and society, during a product life cycle (UNEP, 2020). That said, applying LCA and S-LCA provided short- and long-term information to help end-users better understand their current situation and development over time, identifying hotspots and other points for improvement in the value chain of the product (Kühnen & Hahn, 2017; Arcese et al., 2018).

Thus, this thesis is organized into five main sections. In section 1, the introduction is presented, where the background of environmental and social assessments used in agriculture and applied in the present work are established, as well as the literature gaps. Section 2 focuses on the accounting of nutrient emissions in agriculture and how the use of different methodologies to estimate those

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[1] European Union's Horizon 2020 research and innovation programme under grant agreement No 773682: https://www.nutri2cycle.eu/

emissions can impact Life Cycle Assessment (LCA) studies. For that, a set of 23 criteria that should be taken into account to characterize models and methods before the selection of an approach is proposed, representing an important step in order to standardize the estimation of nitrogen losses in LCA. In section 3, a set of indicators for a rapid assessment of novel technologies focused on nutrient recovery and nutrient efficiency in agriculture is presented. This allows to provide an environmental assessment for technologies with low and intermediate technology readiness level (TRL) and to identify hotspots considering the foreground system. Then in section 4, the focus on social assessments starts, by the selection of relevant indicators to address social hotspots and other issues that should be addressed in order to increase sustainability in agriculture. The social life cycle assessment (S-LCA) performed for different technologies allowed to provide a prospective view of the potential beneficial social aspects that could be improved in agriculture and to show potential harmful aspects due to the inclusion of these novel technologies. Finally, in section 5, we apply methods developed in a real case study. An environmental and social LCA is performed for a novel technology for ammonia recovery from livestock manure, in order to decrease nutrient losses to the environment. This study enabled to assess, from a social perspective, higher social impacts for this technology due to ‘fair salary’, ‘trade unionism - and the ‘value added total’ of the inputs used in the technology. and lowest impacts were related to ‘men in the sectoral labour force’, ‘fatal accidents’ and ‘frequency of forced labour’. From an environmental perspective, impacts of this novel technology are concentrated on ‘climate change’, ‘ecotoxicity, freshwater’, ‘particulate matter’, mainly due to ammonia emissions associated with the technology. Assessing both and environmental aspects can provide a more integrate sustainable perspective. In Figure 1, we present an overview of the methods and studies performed in this thesis.

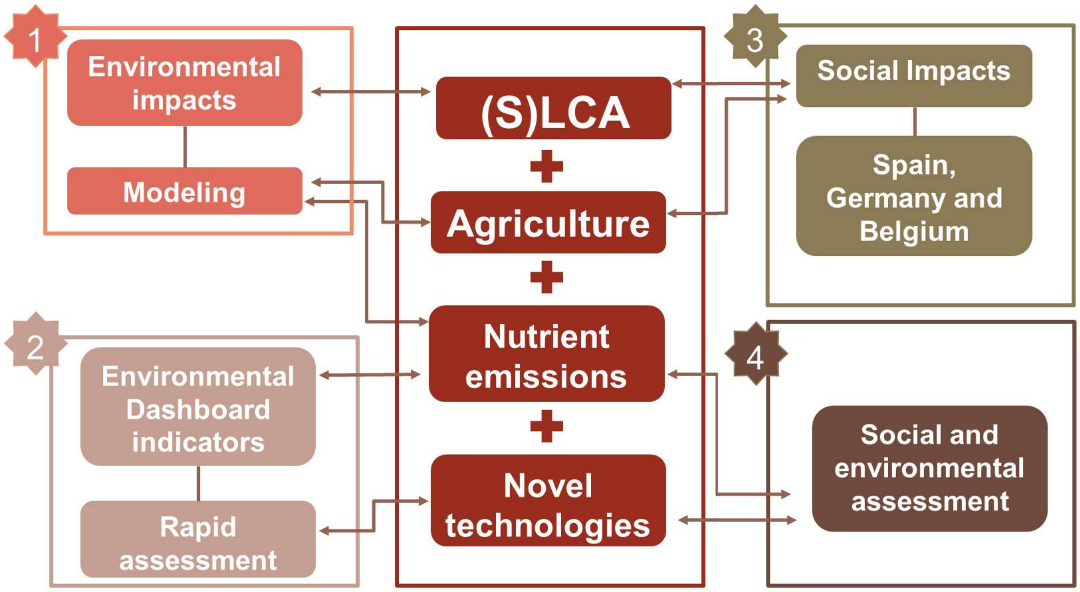

Figure 1: Overview of the methods and studies performed in the thesis.

1.1 Objectives

In this doctoral thesis, the main objective is to advance in nutrient management and efficiency in agricultural field. This is ensured by developing methods to examine and apply indicators to provide environmental and social assessments, which are applied to test novel technologies for nutrient recovery and improvement of nutrient efficiency in agriculture. This main objective is addressed in sections 2, 3, 4, 5, divided into the specific objectives below:

- To conduct a review and test a methodology for a selection of models and methods to estimate nitrogen emissions from agricultural practices (see section 2)
- To carry out the estimation of nitrogen emissions from agriculture under different models and methods and their results applying the life cycle perspective (see section 2)
- To provide and test a set of indicators for a rapid environmental assessment of novel technologies for nutrient recovery and nutrient efficiency improvement in agriculture (see section 3)
- To perform an S-LCA of novel technologies for nutrient recovery and nutrient efficiency improvement in agriculture with low level of adaptation in the society (see section 4)
- To apply an integrate approach involving a social and environmental LCA of a novel technology for ammonia recovering adapting both the LCA and S-LCA methodologies (see section 5)

1.2 Nutrient emissions in agriculture

1.2.1 Nitrogen emissions in agriculture

The intensification of agriculture to supply the increasing global demand for food has led to an increase in N recovery in livestock but also an increased N surplus (Bouwman et al., 2013). Food production is one of the major water pollution sources, due to the consistently intensive nutrient loss generated, being nitrogen (N) and phosphorus (P) with a high risk according to the planetary boundaries (Steffen et al., 2015; Hu et al., 2018).

The major anthropogenic perturbation of both the N and P cycles arises from fertilizer application (Steffen et al., 2015). However, pollution from agriculture have multiple sources, for instance, use of pesticides, nitrogen deposition, irrigation for crop production, animal manure loss to waterbody for livestock production, wasted feed, use of fuel and energy, agrotechnical procedures, and post-harvest residue burning (Hu et al., 2018; Murawska and Prus, 2021). Significant fractions of N are lost through emissions of ammonia (NH_3), nitrous oxide (N_2O), and nitric oxide (NO). The three gases have a huge potential to cause environmental impacts, NH_3 contributes to eutrophication and acidification, N_2O is a potent greenhouse gas and NO contributes to tropospheric ozone chemistry. In addition, large fractions of N and P in watersheds enter groundwater through leaching and surface runoff and are transported in freshwater, causing eutrophication aquatic systems (Bouwman et al., 2013).

In the EU, agriculture is responsible for over 92% of the NH_3 emissions, in which livestock manure (including natural fertilisers) accounts for 78%, and the remaining 22% of the emissions are related to the use of mineral fertilisers (Eurostat, 2020). According to Figure 2, ammonia emissions (kg NH_3/ha) in EU, in the period of 2000 to 2019, have an average of 20.5, varying between 21.2 (2000) and 19.7 (2019), representing a reduction of 8% in total emissions (Eurostat, 2020). More effort should be done in order to provide a better environment for society since agriculture is increasingly demanding more resources.

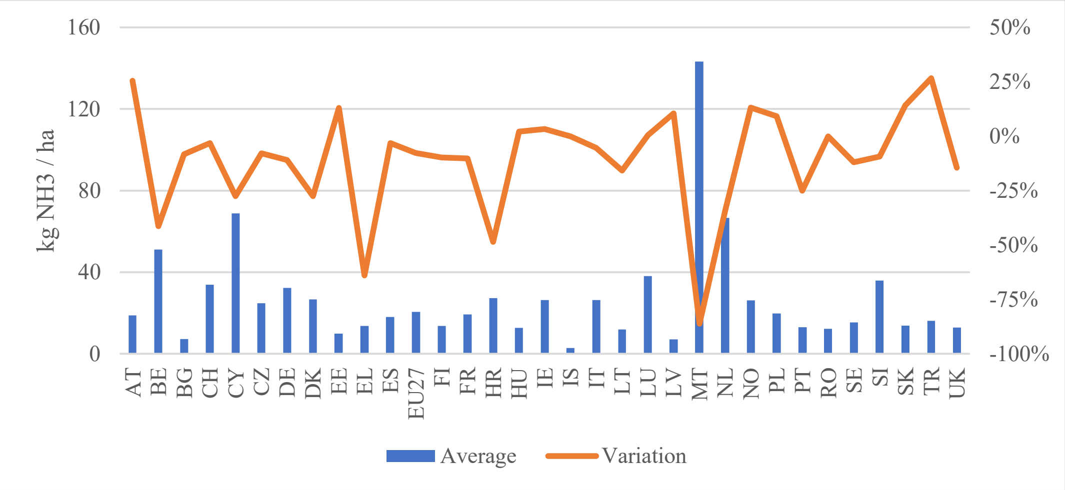

Figure 2: Ammonia emissions (kg NH_3/ha) in Europe, from agriculture, average and variation from 2000 - 2019

Legend: AT = Austria, BE = Belgium, BG = Bulgaria, CH = Switzerland, CY = Cyprus, CZ = Czech Republic, DE = Germany, DK = Denmark, EE = Estonia, ES = Spain, EU 27 = European Union 27 countries, FI = Finland, FR = France, HR = Croatia, HU = Hungary, IE = Ireland, IS = Iceland, IT = Italy, LT = Lithuania, LU = Luxembourg, LV = Latvia, MT = Malta, NL = the Netherlands, NO = Norway, PL = Poland, PT = Portugal, RO = Romania, SE = Sweden, SI = Slovenia, SK = Slovakia, TR = Turkey, UK = United Kingdom.

N_2O emissions from agricultural soils are the largest source of total N_2O emissions in the EU-27, and they increased by 3 % between 2010 and 2019 (Figure 3). Emissions of N_2O from agriculture were highest in France and Germany in the period 2010 – 2019, accounting for 100 and 115 Gg CO_2 eq, respectively. Although changes in agricultural practices have led to relative differences in the amount of N_2O emitted, it is still necessary to interpret trends of N_2O emissions especially related to methodological problems with estimating N_2O emissions from agricultural soils faced for some countries (Eurostat, 2020).

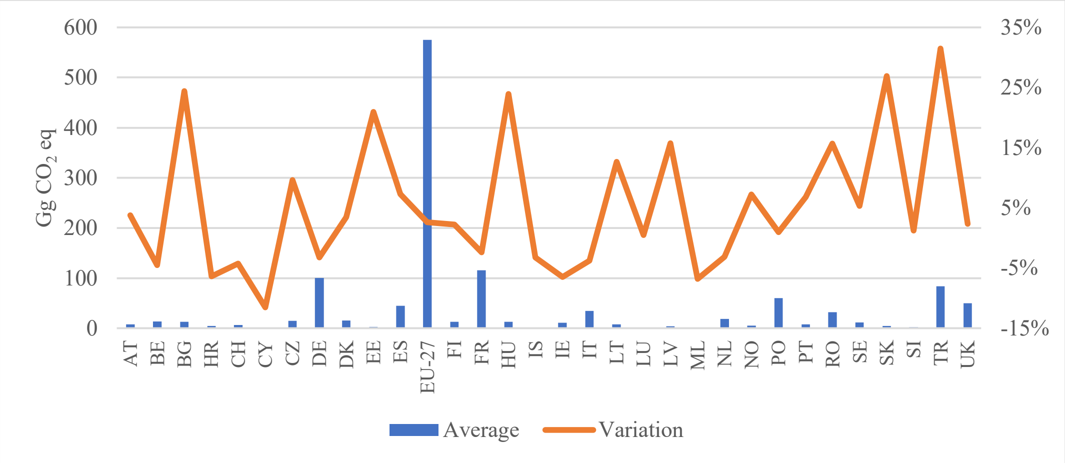

Figure 3: Nitrous oxide emissions from agriculture (Gg CO_2 eq) in Europe, average and variation from 2010 – 2019

Legend: AT = Austria, BE = Belgium, BG = Bulgaria, CH = Switzerland, CY = Cyprus, CZ = Czech Republic, DE = Germany, DK = Denmark, EE = Estonia, ES = Spain, EU 27 = European Union 27 countries, FI = Finland, FR = France, HR = Croatia, HU = Hungary, IE = Ireland, IS = Iceland, IT = Italy, LT = Lithuania, LU = Luxembourg, LV = Latvia, MT = Malta, NL = the Netherlands, NO = Norway, PL = Poland, PT = Portugal, RO = Romania, SE = Sweden, SI = Slovenia, SK = Slovakia, TR = Turkey, UK = United Kingdom.

European Commission (EC) vision fixed priorities up to 2024, and regarding consumption, production and trade, EC emphasises the proposal for a European Green Deal (EGD), that aims for Europe to be the first climate-neutral continent by 2050. The EGD has an ambitious package of measures that should enable sustainable green transition, by including an initial roadmap of key policies ranging from ambitiously cutting emissions, investing in research and innovation, and preserving Europe's natural environment (EU, 2019). In addition, sustainable soil management was defined by FAO (FAO, 2017) in the Voluntary Guidelines for Sustainable Soil Management (SSM), which contributes to addressing global challenges, and meeting international goals such as the 2030 Agenda for Sustainable Development, the Zero Hunger Challenge, Farm to Fork and Climate Law. In SSM, Farm to Fork and Climate Law, there are ambitious objectives to be reached by 2030 for nutrient emissions, for instance, reducing 50 % nutrients excess, 20 % fertiliser reduction, and increasing organic farming at 25 % of agricultural lands. To ensure achievement of these objectives correctly, emissions accounting, is a crucial need. In addition, it is essential to be sure that the methodology applied is adequate for diverse situations where it is applied.

More details on nitrogen cycle and emissions can be found in section 2.2.2, and for more information regarding impacts of nitrogen emissions, see section 4.2.3.

1.2.2 Methodologies to estimate nitrogen emissions

Researchers in agricultural subjects models the estimation of N losses (i.e., emissions, leaching and runoff) using different approaches, according to their goals, resource availability (e.g., time, data and financial resources) and their skills to work with available models and agricultural systems studied (Avadí et al., 2022).

The models to estimate N emissions can vary from simple models (Tier 1) to robust simulation models (Tier 3). Simple models usually use empirical equations with or without parameters, based on regressions on emissions datasets, such as IPCC emission fractions for N_2O and NH_3 emissions, and the Sustainable Quick Check for Biofuels (SQCB) (Faist et al., 2009) to estimate nitrate leaching in perennial crops. Usually, results from simple models require few and available input variables, such as, the amount of fertilizer applied, irrigation and precipitation on the field (Buczko et al., 2010). On the other hand, robust models, such as functional or mechanistic and dynamic biogeochemical/crop models, involve complex simulation of nitrogen cycle using several parameters and equation. As highlighted in Cannavo et al. (2008), only a few models within the modeling continuum are capable to model N dynamic forces across agricultural systems.

Robust process-based models are essential to support farm mass balance accounting. However, recognizing that the variation between process-based models' results can be large, it is required to compare and better understand the strengths and limitations of various models (Veltman et al., 2017). Avadí et al. (2022) compared the results of STICS model (Brisson et al., 2003), a robust and mechanistic model using Ecoinvent v3 data (Nemecek and Schnetzer, 2011), World Food LCA database v3 (Nemecek et al., 2014), Indigo-N v1/v2 (Bockstaller and Girardin, 2010) and AGRIBALYSE v1.2/v1.3 (Koch and Salou, 2015, 2016), Calculateur AzoteViti (Bellon-Maurel et al., 2015) and Mineral fertiliser equivalents (MFE) calculator (Brockmann et al., 2018), and FAO N balances (Roy et al., 2003). They focused on the estimation of nitrogen emissions, NH_3 volatilisation, NO_3 leaching, NO_x and N_2O emissions. As results, they found that Ecoinvent model (simple model) predicted significantly lower values for NH_3 than AGRIBALYSE (simple model focused on France) and STICS (robust model), no significant differences were found regarding N_2O emissions; Ecoinvent and AGRIBALYSE predicted significantly higher NO_3 leaching than STICS, values of Indigo-N (robust model) were close to those of STICS regarding N_2O and NO_3 leaching. They highlighted important discrepancies among models especially for nitrate leaching, due to the level of simplification of some models, showing that depending on the model used, results can have huge influence on the environmental assessment provided.

Veltman et al., (2017) compared five process-based models (two whole-farm models, two field-scale models and one animal-based model) to estimate carbon, nitrogen and phosphorus flows and potential global warming impact (GWI) (CH_4 and N_2O) associated with milk production at the animal, field and farm-scale. Their results predicted highly variable emissions of N_2O and NH_3 to air across models, and they highlighted that further investigation is necessary to understand how anaerobic digestion influences manure composition and subsequent emissions of N_2O and NH_3 after organic fertilizers use on the field (Veltman et al., 2017).

Finally, Cannavo et al. (2008) compared 51 approaches for modeling nitrogen dynamics to assess environmental impacts of cropped soils. Between the models, they included the Daisy (Hansen et al., 2012), Animo (Rijtema and Kroes, 1991) models - both applied in the project Nutri2Cycle[2], in which this thesis was developed on -, Indigo (Bockstaller and Girardin, 2010) and STICS (Brisson et al., 2003). They summarized models' performance of the simulations compared to field measurements as poor (> 60% difference), fair (30 – 60 % difference), good (5 – 30 % difference), and very good (< 5% difference), regarding several stages of N cycle, such as mineralization, leaching and uptake, nitrification, denitrification, volatilization, and symbiotic N fixation. Their results reveal that nitrate leaching is the N loss process is covered by all models, due to the level of world concern about surface water and groundwater pollution, but N emissions from denitrification (N_2O) and volatilization (NH_3) and their environmental impacts has been paid less attention to calculate them with models. Furthermore, they suggested that the creation of models that could be used in different pedoclimatic contexts (i.e., a microclimate integrating soil conditions, effects of its temperature, water content and aeration), for sensitivity purposes, and providing correction functions considering the main explanatory factors of a process (Cannavo et al., 2008). For example, it is important to verify that the model is able to adapt to new conditions (i.e., apply calibrations, update internal parameters) for which it was not previously developed. Thus, it is essential a better definition of which models functions for each situation, in order to obtain more reliable results.

More details on models and methods to estimate nitrogen emissions can be found in sections 2.2.1 and 2.2.3.

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[2] European Union's Horizon 2020 research and innovation programme under grant agreement No 773682: https://www.nutri2cycle.eu/

1.2.3 Technologies for recovery of nutrient emissions

Undesirable wastes can become useful tools when well-managed (e.g., application of technologies for nutrient efficiency and recovery) instead of letting them be released contaminating soil, air, and water resources, creating an unsafe environment (Ahmed et al., 2019).

Nutrient recovery is a process that enables the removal and concentration of nutrient by-products from agricultural residue (e.g., manures or anaerobic digestate as an output from anaerobic digesters), to improve nutrient management on agricultural operations with an excess of nutrients, producing a concentrated nutrient by-product to facilitate transportation for final disposal or to be potentially transformed into a commercially nutrient product (Hallbar Consulting, 2017).

For agriculture, the list of common and developing technologies and practices for recovery and reuse is dominated by the technologies in which manure is recovered and used as a substrate (Rosemarin et al., 2020). It is included, among others, anaerobic digestion for biogas production, struvite precipitation, ammonia stripping, solid-liquid manure separation and drying, pyrolysis, algal cultivation and practices to reduce runoff losses such as cover crops to trap nitrogen and artificial wetlands (Table 1). Several of those technologies are included in the project Nutri2Cycle, selected to help close N, C and P cycles in agriculture.

Table 1: List of examples of technologies and solutions for nutrient recovery in agriculture retrieved from Rosemarin et al. (2020), Hallbar Consulting, (2017), Ahmed et al. (2019) and Dadrasnia et al. (2021).

Technology/solution	Description
Anaerobic digestion	The technology can be applied to different organic substrates, including manure, sewage sludge and other organic wastes to produce biogas. The effluent, digestate, can be further processed or be used as a fertilizer on agricultural land.
Struvite precipitation	It involves the precipitation of equimolar amounts of P and N from various waste streams due to the addition of magnesium at high pH. The product, struvite, is an efficient P fertilizer, also containing some N, and it has a slow release of fertilizing compounds.
Ammonia stripping	This involves stripping of gaseous ammonia from liquid waste streams at high temperatures and pH. The stripped ammonia can be absorbed with an acid producing an ammonia salt solution with low pH, that can be used as a fertilizer, for example, ammonium sulphate, which fits for soils with neutral or alkaline reactions.
Cultivation of cover crops	Cultivation of cover crops is used to capture nutrients and reduce N leaching from the soil since they cover the ground preventing runoff and erosion.
Biodrying/composting	The application of bio-thermal drying processes stabilizes the solid fraction of manures and has been carried out frequently for pasteurization purposes or biofuel production. The final dried product can be used as an organic fertilizer (with less N) and the application of these materials enhance the soil structure. The application of composting technologies to valorize animal manure adds value to the high-quality final product obtained, which better meets the requirements of the fertilizer market.
Bioleaching	Bioleaching is a low-cost technology based on nutrient solubilisation from solid substrates by a leaching microorganism, either through direct or indirect metabolism. This technology is a cost-effective process due to the capability of using chemically bound metals which are already present in sufficient quantities in wastes, but it slowly releases phosphorus and nitrogen compared with undesirable heavy metals.
Thermochemical treatments (such as incineration, gasification, hydrolysis, and hydrothermal carbonization)	Thermochemical treatments could convert biomass into gases and ash residues and reduce the bulk volume of wastes. In addition, they can produce energy. Incineration produces gaseous pollutants which are introduced to the atmospheric environment. Gasification produces synthesis gases, bio-oil, and biochar. Hydrolysis is a promising technology to manage animal manure and add value by producing biochar as a fertiliser. Hydrolysis requires large sums of energy to evaporate moisture from manure while generating a low gas output. Hydrothermal carbonization is a low energy-intensive technology and has been applied to treat digested and fresh manure through first hydrolysis of the biomaterial by carbonization, having as a final product is a valuable solid char and is used as a sustainable sorbent for pollutants.
Membrane filtration	Membrane technologies target treating effluents containing compounds that may be either retained or pass through a thin physical barrier depending on operating temperature and applied pressure. Microfiltration and ultrafiltration membranes are basically aimed to remove particles, while reverse osmosis and nanofiltration membranes can be applied as nutrient recovery techniques.
Compaction	It is a physical technique, based on compacting and pelletizing processes to manage and store solids contained in manure. The high equipment cost and energy demand required for compaction make the technology economically unfeasible in some activities such as poultry farming.

It is important to be aware that trade-offs may occur when using organic fertilizer (e.g., from crop residues, digestates and compost on croplands). Optimizing crop yields with these reuse products, not only N content should be the focus, but to apply the correct N and P nutrients to match the requirement of the crop and avoiding excessive amounts of P being applied to fields (Szögi et al., 2015). In addition, if its use entails potential increments in water consumption and energy, these should be considered.

Finally, some several tools and measures can be used to save or help recycle nutrients, but they will depend on the context in which the technology is applied and on local circumstances, sometimes being more useful to combine measures and tools for a more sustainable nutrient recycling practice (Rosemarin et al., 2020).

Reviews of technologies and practices for circular nutrient solutions and nutrient recovery from wastes can be checked in Foged et al. (2011), Hallbar Consulting, (2017), Ahmed et al. (2019), Rosemarin et al. (2020), and Dadrasnia et al. (2021).

More details on technologies for nutrient recovery and related impacts can be found in sections 3.2.3 and 4.2.2.

1.3 Sustainability in agriculture

In the agricultural sector, the idea of sustainability has gained prominence since the publication of the Brundtland Report (Brundtland, 1987), and a sustainable model should seek to accomplish production while ensuring the availability of resources for future generations (Velten et al., 2015; Marcelino Aranda et al., 2017).

As an approximation, the three pillars of sustainability (social, environmental, and economic) can be seen as separate systems, each of them relying on its principles of performance and quality, normative claims and policy goals (Sabato et al., 2021) (Figure 4):

- Environmental sphere: based on the imperative of preserving the natural environment, with the goal of preventing deterioration due to the depletion of natural resources and pollution.
- Economic sphere: based on the promotion of economic growth.
- Social sphere: based on the (re)distribution of welfare, preventing social risks and ensuring social justice, equity, and cohesion.

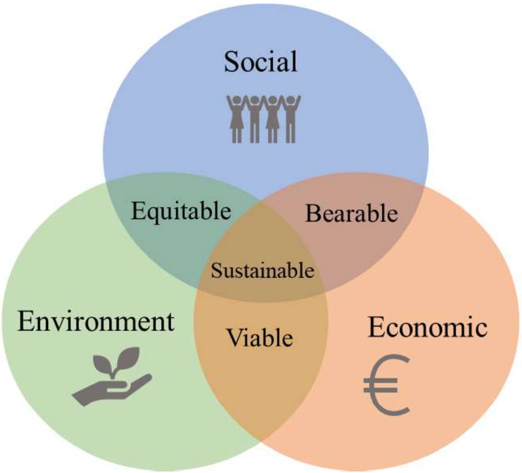

Figure 4: Sustainability Venn diagram adapted from Oscar et al. (2011)

1.3.1 Environmental assessment in agriculture

Indicators are the fundamental units of agricultural trade-off analysis and should convey reliable information relevant for assessment and decision-making (Kanter et al., 2018). The use of agri-environmental indicators (AEIs) seeks to describe the current state and potential trends of environmental conditions in agriculture, highlighting especially the hotspots in the system (EC, 2011). A set of indicators is an effective way for comparison between countries and can be used for policy monitoring or evaluation, and for prospective assessment. In this section, the set of AEIs proposed by the European Commission (EC) and the Organisation for Economic Co-operation and Development (OECD) (EC, 2011) will be highlighted. More details on indicators used for environmental assessments can be found in sections 3.3.1 and 3.3.2.

The AEIs proposed by the European Commission track the integration of environmental concerns into the Common Agricultural Policy (CAP) in agriculture at EU, national and regional levels. The set of 28 indicators proposed can be used to provide information on the farmed environment, to track and assess the impact of agricultural and environmental policies on environmental management of farms, to help policymakers and to illustrate agri-environmental relationships in an easy-friendly format to the broader public. As examples of the AEIs, there are mineral fertiliser and pesticides consumption, cropping and livestock patterns, manure storage, gross nitrogen balance, ammonia and GHG emissions, etc. (EC, 2011) (Table 2). The AEIs proposed by the EC were applied, for instance, in Namiotko et al., (2021), for a multi-criteria decision-making approach for sustainable agricultural development.

Table 2: Set of indicators proposed by the European Commission (EC, 2011)

Agri-environmental indicator
1. Agri-environmental commitments (archived)
2. Agricultural areas under Natura 2000
3. Farmers' training level and use of environmental farm advisory services
4. Area under organic farming
5. Mineral fertiliser consumption
6. Consumption of pesticides
7. Irrigation
8. Energy use
9. Land use change
10.1 Cropping patterns
10.2 Livestock patterns
11.1 Soil cover
11.2 Tillage practices
11.3 Manure storage
12. Intensification/extensification
13. Specialisation
14. Risk of land abandonment
15. Gross nitrogen balance
16. Risk of pollution by phosphorus
17. Pesticide risk
18. Ammonia emissions
19. Greenhouse gas emissions
20. Water abstraction
21. Soil erosion
22. Genetic diversity
23. High nature value farmland
24. Production of renewable energy
25. Population trends of farmland birds
26. Soil quality (archived)
27. Water quality - Pesticide pollution
28. Landscape - state and diversity

The OECD works on a different set of AEIs, aiming that those policymakers and the wider public could be interested in the development, trends and the use of agri-environmental indicators for policy purposes. The AEIs proposed by the OECD covers agriculture in the broader economic, social and environmental context, farm management and the environment, use of farm inputs and natural resources and environmental impacts of agriculture. The OECD Compendium of agri-environmental indicators (OECD, 2013) includes 18 indicators divided in five themes, soil, water, air and climate change, biodiversity, agricultural inputs and outputs (Table 3). The AEIs proposed by OECD were used, for instance, in Kasztelan and Nowak (2021) for construction and verification of an index to assess the green performance of agriculture. Other examples of agri-environmental indicators are presented in Musumba et al. (2021) and in Smith et al. (2017).

Table 3: Agri-environmental indicators proposed by OECD (2013)

Theme	Indicator title	Indicator definition
Soil	Soil erosion	1. Agricultural land affected by water and wind erosion, classified as having moderate to severe water and wind erosion risk
Water	Water resources	2. Agricultural freshwater withdrawals 3. Irrigated land area 4. Irrigation water application rate
	Water quality	5. Nitrate, phosphorus and pesticide pollution derived from agriculture in surface water, groundwater and marine waters
Air and climate change	Ammonia	6. Agricultural ammonia emissions
	Greenhouse gases	7. Gross total agricultural greenhouse gas emissions (methane and nitrous oxide, excluding carbon dioxide)
	Methyl bromide	8. Methyl bromide use, expressed in tonnes of ozone-depleting substance equivalents
Biodiversity	Farmland birds	9. Populations of a selected group of breeding bird species that are dependent on agricultural land for nesting or breeding
	Agricultural land cover	10. Agricultural land cover types – arable crops, permanent crops and pasture areas
Agricultural inputs and outputs	Production	11. Agricultural production volume
	Nutrients	12. Gross agricultural nitrogen and phosphorus balances, surplus or deficit
	Pesticides	13. Pesticide sales
	Energy	14. Direct on-farm energy consumption 15. Biofuel production to produce bioethanol and biodiesel from agricultural feedstocks
	Land	16. Agricultural land use area 17. Certified organic farming area 18. Transgenic crops area

Not necessarily all the indicators are relevant for the several scenarios that can be developed in agriculture. For instance, for novel technologies for agricultural nutrient recovery, indicators such as methyl bromide or risk of land abandonment, are not so relevant compared to greenhouse gases and ammonia, but they will require time and effort to be measured. Thus, it is relevant to establish a reduced set of agri-environmental indicators that can provide a better overview, including beneficial and harmful effects, of the system or scenario assessed.

1.3.2 Social assessment in agriculture

Social innovation represents a complex process of introducing new products, processes or programs that have a huge influence on the basic routines, resources, or beliefs of the social system in which the innovation occurs and can have durability and broad impact (Peters et al., 2018).

Food supply chain involves several actors each linked through value-adding activities engaged in the stages of production, aggregation, processing, distribution, consumption, and disposal of food products, originated from agriculture, forestry, or fisheries activities (Desiderio et al., 2022). For each supply chain echelon, more than a few social impacts are involved and linked, such as, social learning among farmers, rural communities' development and autonomy, consumers participation, housing issues, food waste and related impacts, and consumers studies (Vittuari et al., 2016).

To achieve sustainable production and consumption of agriculture it is fundamental to include the entirety of the supply chain and the actors involved at each stage along the way, requiring more in-depth analyses of social dimensions (Desiderio et al., 2022). Due to severe criticism of the negligence of the social dimension in sustainability conceptions and assessments from social science, this dimension has been increasingly integrated during the last decade (Janker et al., 2019).

Despite the increased integration of the social dimension into food supply chain research studies, it is still required a useful general framework to seek social sustainability (Eizenberg and Jabareen, 2017). Desiderio et al. (2022) highlighted that the social dimension of sustainability in food supply chains has yielded a lack of agreement regarding what to consider and how to measure it. They provided a review of thirty-four tools and indicators for social sustainability applied in the food supply chain, focusing on five different stages: production, processing, wholesale, retail and consumer. As examples of the tools found there are: 4AGRO, a tool for sustainability assessment of farms (Gaviglio et al., 2017); MESMIS, Framework for Assessing the Sustainability of Natural Resource Management (López-Ridaura et al., 2002); SAFA, Sustainability Assessment of Food and Agriculture systems (FAO, 2014b); and social life cycle assessment (S-LCA) (UNEP/SETAC, 2020). As social hotspots in agriculture and food value chain for intervention, they raised the wholesale traders with substantial impact in rural production areas and larger markets, working conditions for stakeholders, food security, education to food waste and young generations, being this last one particularly important since they represent the future of society and must be enabled to express their perceptions and perspectives (Desiderio et al., 2022).

The European Green Deal (EGD) tackles socio-ecological challenges, especially those that relate to social implications of environmental issues and policies, aiming to promote a fair transition (Sabato et al., 2021). For instance, the EGD recognizes the need to involve and support consumers in the decarbonization of the energy system, focusing on households that are not able to pay for energy services required to ensure a basic standard of living and social housing, which could address the risk of energy poverty in Europe. In addition, EGD refers to the impact of the transition on employment, especially in the sectors and territories facing processes of industrial restructuring due to the low-carbon transition (i.e., fossil fuel mining and exploration, and greenhouse gas-intensive activities).

The awareness that agriculture has on the world has increased the introduction of good practices focusing on environmental and economic aspects; but from a social perspective, there is a potential gap for improvement and implementation (Desiderio et al., 2022). In addition, although the interconnections among the dimensions of sustainability do need further examination, it is essential that an individual evaluation of each dimension can be achieved first (Janker et al., 2019). In Table 4, it is presented social indicators in the tools 4AGRO (Gaviglio et al., 2017), MESMIS (López-Ridaura et al., 2002) and SAFA (FAO, 2014b). Indicators applied in S-LCA will be presented in section 1.4.3.

Table 4: Set of indicators used in different tools to assess social sustainability in food supply chains

Tool		
4AGRO	MESMIS	SAFA
Social indicators		
Products of territory: - Quality of the products - Rural buildings - Landscape and territory	*Stability, resilience, reliability:* - Permanence of coffee producers in the system	- Right to quality of life - Wage level - Capacity development - Fair access to means of production
Short food supply chain, related activities: - Short food supply chain - Related activities	*Capacity for change:* - Producers and area cultivated per system	- Fair pricing and transport contracts - Rights of suppliers
Work: - Work - Sustainability of the employment - Training	*Distribution of benefits, and decision-making:* - Decision-making mechanisms - Distribution of returns and benefits	- Employment relations - Forced labour - Freedom of association and right to bargain
Ethics, human development: - Livestock management - Associations and social implications - Cooperation *Society, culture, ecology:* - Waste management - Accessibility to farm spaces - Sustainable use of materials - Education	*Participation:* - Attendance to assemblies and other events - Number of producers trained - Reliance on external resources	- Nondiscrimination - Gender equality - Support to vulnerable people - Safety and health training - Safety of workplace, operations and facilities - Indigenous knowledge - Food sovereignty - Health coverage and access to medical care - Public health

Taking into account that several social indicators are available; a well-justified set of indicators is essential to carry out a social assessment assertive and not using all indicators. The identification of hotspots and improvement points in the evaluated system can be done with an adequate set of indicators. Until now, there is no set to evaluate new technologies to be applied in agriculture like, for instance, the ones selected in Nutri2Cycle project. Therefore, it is a gap that must be covered with this thesis.

More details on social impacts of agricultural practices can be found in sections 4.2.1 and 4.4.1.

1.4 Life cycle assessment

1.4.1 Life cycle assessment

Life cycle assessment (LCA) is the most widely tool used to assess environmental impacts in agriculture (van der Werf et al., 2020). LCA addresses the environmental aspects and potential environmental impacts since raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (ISO 14040:2006), focusing on negative impacts rather than including positive impacts (van der Werf et al., 2020).

There are four phases in an LCA study (ISO 14040:2006) (Figure 5) :

1) Goal and scope definition: It defines the aim of the study, and the breadth and depth of the study are established. In this phase, product function, functional unit and reference flow are established. In addition, initial choices such as system boundaries, data categories, inputs and outputs, data quality and a critical review are also detailed.
2) Inventory analysis (Life Cycle Inventory – LCI): The second phase of LCA involves the data collection required to achieve the goals of the defined study, it represents the inventory of input/output data concerning the system under study. An LCI can be built based on multiple sources, such as primary data, academic literature, LCI databases and expert opinion. Regarding agriculture, data for fertilizer consumption, oil machinery, water for irrigation, N and P emissions will be included, for instance.
3) Impact assessment (Life Cycle Impact Assessment – LCIA): The purpose of the third stage is to provide additional information to help assess a product system’s LCI results, translating the numbers collected to an environmental significance. In LCIA, the selection of the relevant impact categories, assignation the elementary flows to the impact categories (classification), modeling potential impacts using conversion factors obtaining an indicator for the impact category (characterisation), and three optional stages normalisation in which is expressed potential impacts relative to a reference, grouping in which sorting or ranking the impact indicators can be done, and the final one in which relative weighting of impact categories is applied.
4) Interpretation: The final phase of an LCA summarises the results of an LCI and an LCIA, or both, discussing as a basis for conclusions, recommendations and decision-making considering the goal and scope defined in earlier phases.

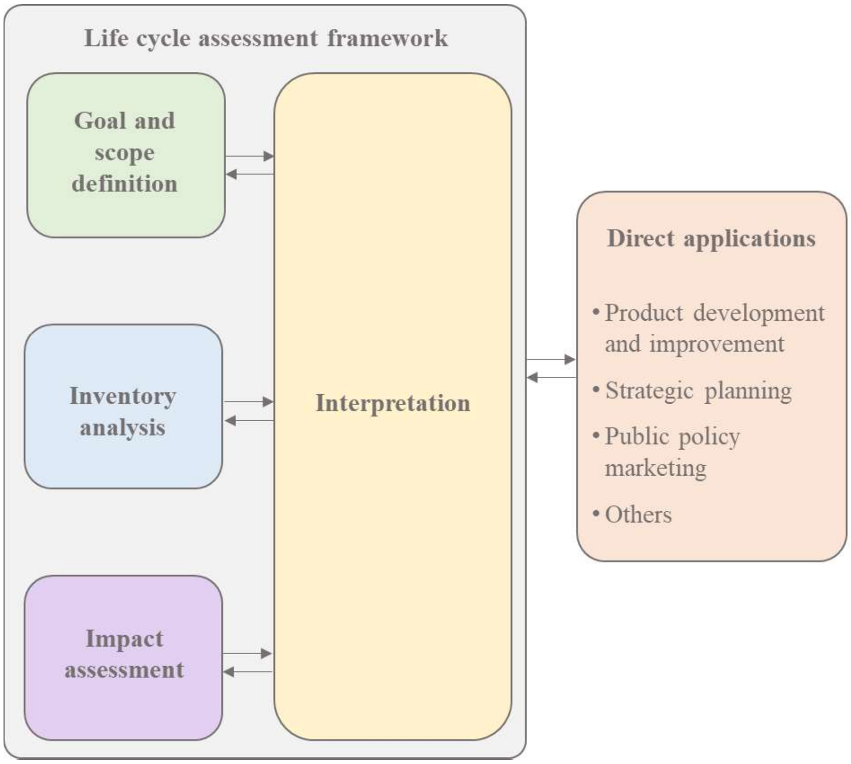

Figure 5: Life cycle assessment framework retrieved from ISO 14040:2006 (2006)

By performing an LCA, it is possible to identify how the practices contribute to the overall environmental impact of the production system, illustrating strengths as well as opportunities for improvement (Jacob-Lopes et al., 2021). LCAs can be useful tools for farmers, farmer groups, and policy-makers, by allowing the improvement of farmers' abilities to make decisions about their system's energy use, pointing practices provoking high or low environmental impacts, and supporting green marketing strategies highlighting opportunities for improved practices using self-audit tools (Greenhut et al., 2013; Jacob-Lopes et al., 2021).

1.4.1.1 Product environmental footprint

The EC initiative Product Environmental Footprint (PEF) is a multi-criteria measure of the environmental performance of a good or service throughout its life cycle, seeking to reduce the environmental impacts of goods and services taking into account supply chain activities (EC-JRC, 2012). The Product Environmental Footprint (PEF) Guide (EC-JRC, 2012) provides a method for modeling the environmental impacts of the flows of material/energy and the emissions and waste streams associated with a product throughout its life cycle.

The impact categories assessed and recommended default LCIA method in the PEF methodology (EC-JRC, 2012) are detailed in Table 1.

Table 5: List of the impact categories to be used to calculate the PEF profile retrieved from EC-JRC (2012)

Impact category	Indicator	Unit	Recommended LCIA method
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg $CO_{2\ eq}$	Baseline model of 100 years of the IPCC (based on IPCC (2013))
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 $_{eq}$	Steady-state ODPs 1999 as in WMO assessment
Human toxicity, cancer	Comparative Toxic Unit for humans (CTU$_h$)	CTUh	USEtox model (Rosenbaum et al., 2008)
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTU$_h$)	CTUh	USEtox model (Rosenbaum et al., 2008)
Particulate matter	Impact on human health	disease incidence	UNEP recommended model (Fantke et al., 2016)
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	kBq U^{235}_{eq}	Human health effect model (Frischknecht et al., 2000)
Acidification	Accumulated Exceedance (AE)	mol $H+_{eq}$	Accumulated Exceedance (Seppälä et al., 2006; Posch et al., 2008)
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N_{eq}	Accumulated Exceedance (Seppälä et al., 2006; Posch et al., 2008)
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P_{eq}	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N_{eq}	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTU$_e$)	CTUe	USEtox model, (Rosenbaum et al., 2008)
Land use	- Soil quality Index - Biotic production - Erosion resistance - Mechanical filtration - Groundwater replenishment	- Dimensionless (pt) kg biotic production - kg soil - m^3 water - m^3 groundwater	- Soil quality index based on LANCA (EC-JRC) - LANCA (Beck et al. 2010) - LANCA (Beck et al. 2010) - LANCA (Beck et al. 2010) - LANCA (Beck et al. 2010)
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 world $_{eq}$	Available WAter Remaining (AWARE) (Boulay et al., 2018)
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb_{eq}	CML 2002 (Guinée et al., 2002; van Oers et al., 2002)
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML 2002 (Guinée et al., 2002; van Oers et al. 2002)

Several pilots for Product Environmental Footprint Category Rules (PEFCRs) have been carried out, focusing on the most important parameters, reducing the time, efforts, and costs involved in conducting a PEF study, allowing comparability between different PEF studies. Agricultural products such as beer, coffee, feed for food-producing animals, meat (bovine, pigs and sheep), olive oil and pasta already have their PEFCRs pilots performed.

Details on how nitrogen emissions are estimated in PEF can be found in section 2.2.3.

1.4.2 Social Life Cycle Assessment

Social Life Cycle Assessment (S-LCA) is a methodology to assess the social impacts of products and services across their life cycle and can either be applied on its own or in combination with E-LCA and/or Life Cycle Costing (LCC) (UNEP/SETAC, 2020). The methodology follows S-LCA is in large part based on the ISO 14040 framework for E-LCA, including Goal and Scope, (Social) Life Cycle Inventory (S-LCI), (Social) Life Cycle Impact Assessment (S-LCIA) and Interpretation (

Figure 6).

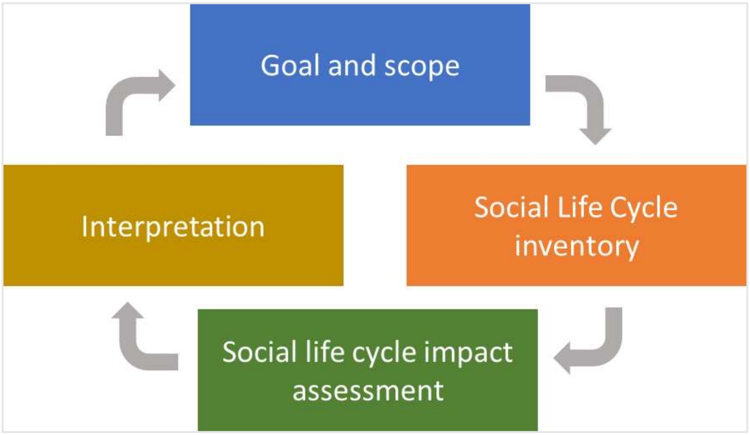

Figure 6: The four iterative phases of S-LCA (adapted from UNEP/SETAC, 2020).

S-LCA differs from other social impact assessment techniques because it focuses on products or services and their life cycle, also includes the entire life cycle and is based on a systematic process of collecting and reporting about social impacts and benefits across the life cycle (UNEP/SETAC, 2020).

According to the S-LCA guidelines, the product life cycle can involve and affect different stakeholder groups (UNEP/SETAC, 2020), from suppliers of raw materials and/or components to waste management employees. Five main stakeholder groups are introduced by the S-LCA guidelines: workers, consumers, society, local community, and value chain actors (not including consumers).

The Social Life Cycle Inventory (S-LCI) is about collecting data for all unit processes within the system boundaries (UNEP/SETAC, 2020). S-LCI involves steps such as identification the data to be prioritized for collection, collecting data for the selected/relevant stakeholders and subcategories, collecting site-specific (primary) and generic (secondary) data for unit processes and activity variables (UNEP/SETAC, 2020). Secondary data can be collected through a literature review or existing databases, for instance, Product Social Impact Life Cycle Assessment (PSILCA) database, Social Hotspots Database (SHDB), International Labour Organization (ILO) database and The World Bank Group (WBG). For more information on PSILCA database see section 4.2.1.

Although there are several studies available about suitable social indicators for S-LCA, there is not yet a commonly accepted set of indicators established by the scientific community which is still a controversial topic (Hauschild et al., 2008). In addition, it could be also questioned if such a set of indicators is feasible due to the high variety of systems existent.

The guidelines for social life cycle assessment of products and organizations 2020 (UNEP/SETAC, 2020) do not present specific indicators; 40 methodological sheets, representing each subcategory, are proposed by Traverso et al. (2021) (Table 6). Even more important than using all indicators presented in the methodological sheets, it is, after establishing the scope of the study, to identify the stakeholder groups and their hotspot social impacts mainly affected (Benoît-Norris et al., 2011). The details for a selection of indicators for a S-LCA can be found in section 4.2.3.

Table 6: Subcategories selected in the Methodological sheets for subcategories in S-LCA retrieved from UNEP/SETAC (2020)

Stakeholder					
Worker	Local community	Value chain actors	Consumer	Society	Children
Subcategory					
- Freedom of association and collective bargaining - Child labour - Fair salary - Working hours - Forced labour - Equal opportunities / discrimination - Health and Safety - Social benefits / social security - Employment relationship - Sexual harassment - Smallholders including farmers	- Access to material resources - Access to immaterial resources - Delocalization and migration - Cultural heritage - Safe and healthy living Conditions - Respect of indigenous rights - Community engagement - Local employment - Secure living conditions	- Fair competition - Promoting social responsibility - Supplier relationships - Respect of intellectual property rights - Wealth distribution	- Health and safety - Feedback mechanism - Consumer privacy - Transparency - End-of-life responsibility	- Public commitments to sustainability issues - Contribution to economic development - Prevention and mitigation of armed conflicts - Technology development - Corruption - Ethical treatment of Animals - Poverty alleviation	- Education provided in the local community - Health issues for children as consumers - Children concerns - Regarding marketing practices

In the social life cycle impact assessment (S-LCIA), the inventory data is aggregated within subcategories and categories through the selection of impact categories and characterization methods and models, the classification of inventory data into subcategories and impact categories and the calculation of results characterizing impacts according to subcategory indicators (Traverso et al., 2021). By calculating those impacts, it is possible to provide a more friendly approach to present the magnitude and the significance of the data collected in the inventory phase (Traverso et al., 2021).

Different from environmental LCA, not completely accepted characterization model has been developed yet to calculate social impacts for S-LCA. Chhipi-Shrestha et al. (2015) provided a critical review on the social life cycle impact assessment method (S-LCIA), highlighting that despite two methods for impacts calculation the S-LCIA method could be developed by combining them. The two main types of impact assessment in S-LCA are: type I can be seen as a reporting approach with the use of performance reference points (PRP) and type II aims at including cause-effect chains or impact pathways (IP) in the analysis (Sureau et al., 2020). PRP uses ordinal scales, typically from of 1 to 5 levels, corresponding to thresholds, targets, or objectives that set different levels of social performance or social risk to estimate the magnitude of potential social impacts (UNEP/SETAC, 2020). On the other hand, Impact Pathway (IP) assessments are based on social mechanisms, related to a certain impact subcategory, in which it is attempted to measure social consequences through midpoint and/or endpoint indicators[3]. Differently from type I, in type II LCIA, practitioners consider the link between phenomena in the assessment, for instance, the use of an hazardous input or the exposure to certain working conditions (e.g. heat and harmful gases) in a production process and the potential impacts on workers' health (Sureau et al., 2020).

Recent literature reviews concerning S-LCA are presented in Petti et al. (2018), Mesa Alvarez and Ligthart (2021), Dubois-Iorgulescu et al. (2018), Pollok et al. (2021). Other recent literature reviews focusing on specific products can be seen in Macombe et al. (2013), focused on biodiesel production; and Gompf et al. (2020), focused on mobility services. Finally, examples of recent studies of S-LCA in agriculture and technologies in agriculture can be found in Souza et al. (2018), for ethanol production technologies in Brazil; in Prasara-A and Gheewala (2018), for Thai

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[3] A midpoint approach is more related to elementary flows, accounting for all parameters along the cause-effect chain between the inventory data and category endpoints for a particular impact category (Ismaeel, 2018). Midpoint modelling includes points where it is possible to derive the characterization factors and express the significance of emissions or extractions with a greater level of certainty and reliability, but it includes more complex calculation processes (Bare and Gloria, 2008). On the other hand, assessment using endpoints, depends on the type of receptor (human health, ecosystems, resources), geographical scale (global, regional and local), magnitude and priority of abatement (high, medium and low priority) and if it is affecting air, water, soil or resources (Goedkoop et al., 2013). Endpoint modelling allows better controlled and knowledgeable weighing process, which may also incorporate economic considerations (Ismaeel, 2018).

2. ENVIRONMENTAL ACCOUNTING OF NUTRIENT CYCLING MODELS

This study is available in:

Andrade, E.P., Bonmati, A., Esteller, L.J., Montemayor, E., Vallejo, A.A., 2021. Performance and environmental accounting of nutrient cycling models to estimate nitrogen emissions in agriculture and their sensitivity in life cycle assessment. Int. J. Life Cycle Assess. 26, 371–387. https://doi.org/10.1007/s11367-021-01867-4

2. Performance and environmental accounting of nutrient cycling models to estimate nitrogen emissions in agriculture and their sensitivity in life cycle assessment

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https://doi.org/10.1007/s11367-021-01867-4

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ABSTRACT

Purpose

Several models are available in the literature to estimate agricultural emissions. From Life Cycle Assessment (LCA) perspective, there is no standardized procedure for estimating emissions of nitrogen or other nutrients. This article aims to compare four agricultural models (PEF, SALCA, Daisy and Animo) with different complexity levels and test their suitability and sensitivity in LCA.

Methods

Required input data, obtained outputs, and main characteristics of the models are presented. Then, the performance of the models was evaluated according to their potential feasibility to be used in estimating nitrogen emissions in LCA using an adapted version of the criteria proposed by the United Nations Framework Convention on Climate Change (UNFCCC), and other relevant studies, to judge their suitability in LCA. Finally, nitrogen emissions from a case study of irrigated maize in Spain were estimated using the selected models and were tested in a full LCA to characterize the impacts.

Results and discussion

According to the set of criteria, the models scored, from best to worst: Daisy (77%), SALCA (74%), Animo (72%) and PEF (70%), being Daisy the most suitable model to LCA framework. Regarding the case study, the estimated emissions agreed to literature data for the irrigated corn crop in Spain and the Mediterranean, except N_2O emissions. The impact characterization showed differences of up to 56% for the most relevant impact categories when considering nitrogen emissions. Additionally, an overview of the models used to estimate nitrogen emissions in LCA studies showed that many models have been used, but not always in a suitable or justified manner.

Conclusions

Although mechanistic models are more laborious, mainly due to the amount of input data required, this study shows that Daisy could be a suitable model to estimate emissions when fertilizer application is relevant for the environmental study. In addition, and due to LCA urgently needing a solid methodology to estimate nitrogen emissions, mechanistic models such as Daisy could be used to estimate default values for different archetype scenarios.

KEYWORDS: IPCC TIERs, UNFCCC, nitrate leaching, ammonia volatilization, nitrous oxide, PEF, Daisy, Animo, SALCA

2.1 Introduction

Appropriate resource management in agricultural systems is the responsibility and a challenge of the agronomic sector and environmental policies, especially to match growing demand and crop production (Wuepper *et al.* 2020). The objective of agricultural production is to provide safe and good quality food in such a way to minimize adverse impacts on the environment. To sustain food production, around 75% of the reactive nitrogen added to agroecosystems is created by human activities, and the excess of nutrients is a severe problem and threatens the environmental balance (Rockström *et al.* 2009). In particular, nitrogen (N) emissions to air, soil and water may have several adverse effects. For instance, climate change is affected by nitrous oxide (N_2O) emissions, and nitrogen oxides (NO_x) form acid when interacting with water, oxygen and other chemicals, contributing to acidification (Frischknecht and Jolliet 2016). In the same way, marine eutrophication is the consequence of nitrate (NO_3^-) emissions exposure to aquatic systems (Wolf 2010) and pollution of groundwater due to NO_3^- leaching may cause a decrease in freshwater resource quality and hence affect human health (Ward *et al.* 2018).

For assessing impacts from agriculture, the Life Cycle Assessment (LCA) is a broadly accepted and used methodology (Notarnicola *et al.* 2017; Nitschelm *et al.* 2018). Agricultural systems LCA can use LCA to calculate the environmental costs on goods and services by quantifying all emissions and resource consumption. However, to use LCA, there is a need to estimate the sources of nutrients (e.g. nitrogen, phosphorus) responsible for the most significant impacts on the environment (Groenendijk *et al.* 2005).

According to input data needs and the degree of complexity, the IPCC (2006) classifies in three different Tiers the methodological approaches for estimating nutrient emissions. Models that are considered Tier 1 use the default emission factors (EF) provided, for instance, by IPCC. Tier 2 models are very similar to Tier 1, but EFs and other parameters applied are country-specific. Tiers 3 models are the most detailed; therefore, it can estimate the emissions with greater certainty than Tiers 1 and 2.

While there is no standardized methodology or models to estimate nutrient emissions in LCA, many methodologies have been used. Brentrup et al. (2000) proposed Tier 1 and Tier 2 models to estimate the most important nitrogen emissions (NH_3, N_2O, NO_3^-) related to agricultural production in LCA. Tier 2 models, for instance, SALCA (Nemecek *et al.* 2016) and AGRYBALYSE (Koch and Salou 2015), and Tier 3 models, such as DAYCENT in Kim & Dale (2005), DNDC in Goglio *et al.* (2014), STICS in Plaza-Bonilla *et al.* (2018) have also been used to estimate nitrogen emissions in LCA.

The guideline "Nutrient flows and associated environmental impacts in livestock supply chains" (FAO 2018) provides recommendations for building inventories in Life Cycle Assessment (LCA) regarding the level of specificity of the study. Tier 1 is recommended for a screening analysis, that allows the practitioner to overview the hotspots in the studied system. Tier 2 is recommended for supply chain and regional assessments, and Tier 3 should be applied to the product system. However, since those are recommendations, LCA practitioners are not forced to choose one model or other, but, for example, as Perrin et al. (2014) claimed, models used to estimate emissions can sometimes be used in inappropriate domains they were created.

In this sense, two Tier 3 dynamic models Animo and Daisy, the Tier 2 LCA emission method SALCA (Nemecek *et al.* 2015) and the Product Environmental Footprint (PEF) (EC-PEFCR 2018) were applied to estimate nitrogen emissions from agriculture in LCA. The two dynamic Tier 3 models, Animo (Rijtema and Kroes 1991) and Daisy (Hansen *et al.* 2000) have been used to estimate the nitrogen emissions to soil, air and water under the scope of the European Union's Horizon 2020 Project Nutri2Cycle (Grant agreement No 773682, https://www.nutri2cycle.eu/). The different models (for terminology consistency, all approaches will be referred to as models) are compared and discussed, considering their requirements and main characteristics. The specific aims of this study can be divided into:

1) Provide an overview of the selected models to understand their main characteristics and application in agricultural systems;
2) Compare PEF, SALCA, Daisy and Animo under the adapted criteria from the United Nations Framework Convention on Climate Change (UNFCCC) and other relevant studies to judge their suitability in LCA framework;
3) Perform a quantitative comparison using an irrigated maize production case study in Spain. Additionally, impacts were characterized considering the different emissions estimated;
4) Discuss how nitrogen emissions have been estimated in LCA agricultural studies found in literature and suggest how nutrient emission models should be used in LCA.

2.2 Methods

The assessment of the different emission accounting models included several steps:

1) Contextual background of the models (Section 2.1);

2) Introduction to the N cycle and its consideration and adaptation in the models (Section 2.2);
3) Description of criteria and subcriteria for the models' evaluation (Section 2.3);
4) Description of the case study performed (Section 2.4).

2.2.1 Contextual background of the models

In this section, an overview of the models is provided, also their application in agricultural systems.

The European Commission's and the Joint Research Center (JRC) developed the PEF model. The Swiss Confederation center for agricultural research (Agroscope) developed and recommended methods that established SALCA. The Agrohydrology group at the University of Copenhagen developed the mechanistic simulation model of agricultural fields model, Daisy, and Wageningen University and Research is the institution behind Animo model.

Regarding spatial scale, Daisy and Animo present the most detailed scale, site-specific nutrient emissions. SALCA appears to be the most limited in reproducing emission estimates, due to its focus on crops and farms in Europe or in temperate climate zone. PEF does not cover spatial scale.

SALCA, Daisy and Animo provide defaults crop parameters in the models' library. These default values are crucial for LCA practitioners who wish to use dynamic models to estimate emissions. Still, they do not have sufficiently detailed information to create a new crop dataset. The common crops simulated in all models are maize, potatoes, grassland and wheat.

One way to judge the accuracy and precision of a model is through validation of its parameters. Those parameters may come from field observations, model calibration, or user expertise (Hansen *et al.* 2012). Model calibration in Animo and Daisy can use yield. A simplified validation of the results can be made based on literature data from other studies, on similar conditions. PEF, SALCA, Daisy and Animo have already been calibrated and validated under different climatic types defined by Koppen-Geiger (Table 1).

Table 1: Summary of reproducibility and climate validation under different conditions

CLIMATE	PEF	SALCA	Daisy	Animo
Tropical/ Megathermal	Y*	N	N	Pinto (2016)
Dry (desert and semiarid)	Y*	N	Manevski *et al.* (2016)	Farmaha (2014)
Temperate/ Mesothermal	Y*	Nemecek *et al.* (2006)	Mueller *et al.* (1997)	Ritjema and Kroes (1991)
Continental /Microthermal	Y*	N	Pohanková *et al.* (2015)	Marinov *et al.* (2005)
Polar	Y*	N	N	N
Extreme weather conditions	Y*	N	N	Hendriks and Akker (2017)

* The PEF was created to be used worldwide, and there is no restriction for application in different climate conditions

PEF and SALCA are considered user-friendly models, due to its simplicity (PEF), adaptation to spreadsheets and use of parameters from literature (SALCA). Although Animo and Daisy cannot be considered as user-friendly models, due to the programming and the amount of input data required for the models, spreadsheet files or text editors are used to read their outputs.

All models provide a compiled bibliography (i.e., user guide, references, tutorial), which is especially helpful for non-experts or the beginners in the models. Moreover, Daisy offers strategies to deal with the lack of data, guiding users to minimize the effect of the assumptions on results and providing user support to help understand the model and the simulations performed. Strategies for unavailable data and user support for SALCA and, especially, for Animo would be useful for the practitioners.

Regarding the suitability of the models in LCA, SALCA and PEF were explicitly developed for LCA studies. Daisy and Animo are compatible with the LCA methodology since they provide the necessary emissions. Daisy was used to estimating emissions in LCA for garden waste management options (Hoeve *et al.* 2019), to quantify greenhouse gas emissions (Jensen *et al.* 2017) and estimate emissions in Danish cereal cropping systems (Kløverpris *et al.* 2016). SALCA, initially developed for Switzerland, has been extended to other countries with a temperate climate and has been used in several European projects that include LCA in its scope. PEF has already been used to assess the environmental performance of different agricultural products such as wines, pasta, and dairy products. Animo has not yet been used in LCA.

Uncertainty and sensitivity analyses are fundamental in LCA studies because can estimate emission ranges for results, and can develop scenarios appropriately. SALCA is the only model that does not consider the sensitivity and uncertainty of their parameters. The uncertainty and sensitivity of IPCC emission factors are considered for PEF. The uncertainty in Daisy was evaluated for the input parameters, obtaining a range between 5% to 95% comparing the measured monthly soil water content and the estimates from the model (Salazar *et al.* 2013). Jabloun *et al.* (2016) analyzed the sensitivity of the outputs showing that the weather conditions substantially influence the Daisy's outputs. Kroes and Roelsma (2007) evaluated the uncertainty related to the hydraulic parameters (measured and estimated) in Animo and concluded that there is a little influence (< 3% changes) on nitrate leaching. Hendriks *et al.* (1999) focused on solute transport adaptations in Animo, where demonstrated high sensitivity to oxygen diffusion parameters and can influence nitrogen processes such as mineralization, nitrification and denitrification.

2.2.2 Introduction to the N cycle and its adaptation in the models

In this section, the models' consideration of processes in N cycle are explained. In addition, the critical N emissions for the Life Cycle Inventory (LCI), namely, nitrification (N_2O and NO_x), nitrate leaching (NO_3^-), denitrification (N_2 and N_2O), volatilization (NH_3) are detailed (Figure 1) (Table 2).

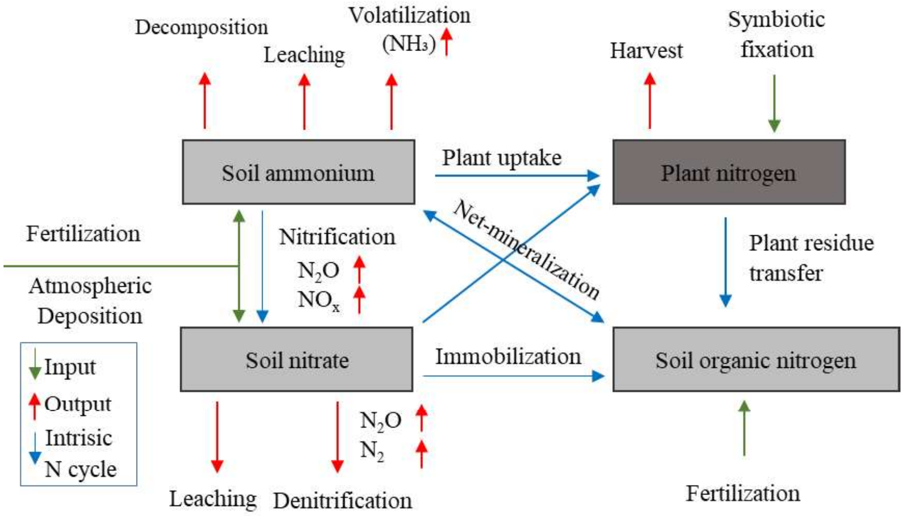

Figure 1: Nitrogen cycle and main processes (Adapted from Abrahamsen and Hansen, 2000)

Table 2: Summary of the parameters considered by the models

PARAMETER	PEF	SALCA	Daisy	Animo
Nitrogen fixation			x	
Decomposition			x	x
Immobilization/ mineralization		x	x	x
Nitrification		x	x	x
Atmospheric deposition			x	x
Ammonium leaching			x	x
Ammonium adsorption/ desorption			x	x
Plant uptake		x	x	x
Nitrate leaching	x	x	x	x
Denitrification	x		x	x
Volatilization	x	x	x	x

Nitrate (NO_3^-) leaching in agriculture can occur when excess nitrate fertilizer is applied and lost due to rain or irrigation, among other soil and crop properties, and through aerobic microbially driven nitrification of ammonium ions. NO_3^- leaching is estimated in PEF, using the EF 0.44 kg NO_3^-/kg N and the amount of fertilizer applied. In SALCA, this estimate is made using a balance between inputs (fertilization and irrigation) and outputs (plant uptake and background nitrogen emissions) using simplified equations. The process is more complex in Daisy and Animo, where nitrate inputs come from atmospheric deposition, fertilizers, and soil solution. They apply a water-balance model using Darcy's law (Cannavo *et al.* 2008).

Ammonia volatilization (NH_3) occurs typically when the nitrogen is in the form of urea, which can come mainly from animal manure or urea fertilizers. All models estimate NH_3 volatilization in a similar yet limited way, applying EF or volatilized fertilizer fractions. In PEF, different EFs (kg N/kg N applied) are used, for instance, 0.15 for urea and 0.1 for ammonium nitrate. In SALCA, NH_3 emissions depend on the type and quantity of fertilizer, N content of the fertilizer, pH, and the air saturation deficit. In Animo and Daisy, volatilization is not a function of climate conditions or incorporation depth. Thus the user must enter a value for a fraction of NH_4^+ that evaporates after applying the fertilizer. It is important to highlight that only Animo takes into account the fertilizer application practices (e.g. broad sprayer, hose, injection), illustrating a limitation in the other models since many studies have found that practices can influence NH_3 volatilization (Bittman *et al.* 2014; Soogard *et al.* 2002; Brentrup *et al.* 2000; with an example of its site-specific application and use in Montemayor *et al.* 2019).

Nitrous oxide (N_2O) emitted by soils can be produced by denitrification in anoxic conditions or by nitrification in the presence of O_2, being an intermediate emission of incomplete nitrification and denitrification reactions. In PEF, N_2O is estimated using the IPCC (2006) modified EF of 0.022 (kg N_2O/kg N applied). SALCA considers direct (from nitrogen oxide (NO-N)) and indirect (from NH_3 and NO_3^-) N_2O emissions, using the EF of 0.01 (kg N_2O-N/kg N applied) for that. N_2O is estimated by Michaelis-Menten kinetics in Daisy, depending on the availability of NH_4^+ and general heterotrophic respiration. In Animo, N_2O is estimated by an empirical equation that depends, among other parameters, on the concentration of NH_4^+, the water content in the layer, temperature and pH.

Denitrification is the process by which NO_3^- is reduced to N_2 in a total reduction or NO_2 and N_2O in a partial reduction. In PEF, total denitrification producing N_2 is assumed using the EF 0.09 kg N_2/kg N applied. Denitrification is not included in SALCA (Nemecek et al. 2016). In Daisy, denitrification is affected by temperature and water pressure and depends on a maximum fraction of converted nitrate, among other factors. Denitrification in Animo is considered a partial or complete reduction of available nitrate, depending on the respiration of organic matter, biodegradable organic matter, soil layer thickness and nitrate concentration. A denitrification rate is also required for limited nitrate conditions in Animo. For NO_x emissions, SALCA uses IPCC (2006) EF, 0.012 (kg NO_x-N/kg N applied), while PEF, Daisy and Animo do not estimate NO_x emissions.

Other parameters not detailed in this section can directly and or indirectly affect the N emissions estimations. For instance, in mineralization, nutrients released as soluble inorganic bioavailable forms, and the roots' nitrogen uptake establish a balance between the crop's demand and the supply by the soil. Equations available are in the Supplementary Material.

2.2.3 Description of the models and applied comparison metrics

A set of different criteria and sub-criteria, based on UNFCCC (2004), Vidal Legaz et al. (2016) and International Life Cycle Data (ILCD) (Wolf et al. 2010), were proposed to score and rank the models according to their user-friendliness and applicability for use as agricultural emission models in LCA studies. The criteria included are 'completeness of the model scope', 'environmental relevance', 'scientific robustness', 'availability, documentation, transparency & reproducibility', 'applicability & flexibility' and 'stakeholder acceptance' (Table 3). The possible scores were 1 (poor), 3 (good) and 5 (excellent).

Table 3: Criteria for comparing the models from the perspective of LCA

CRITERIA		DESCRIPTION AND SCORING
		COMPLETENESS OF THE MODEL SCOPE
Geographic coverage		1 = Local; 3 = Regional; 5 = Global
		ENVIRONMENTAL RELEVANCE
Spatial-temporal resolution	Temporal resolution of the input	1 = Annual; 3= Seasonal; 5 = Monthly or higher resolution
	Spatial resolution of the input	1= Global; 3= Regional/National; 5= Municipality/farmer scale
		SCIENTIFIC ROBUSTNESS
Transparency		1 = No clear modelling explanation, not easily understood; 3 = Processes are clearly modelled but not easily understood; 5 = Processes are clearly modelled and easily understood
Input data set/data requirements		1 = Extensive and detailed input parameters needed; 3= Application of a questionnaire in a farm, a simple dataset for meteorological and soil physical parameters; 5 = Small and basic parameter input, data obtained global databases or literature
Emission model peer-review and (peers) acceptance		1 = No (unpublished report); 3 = Partially (book or authoritative body report with some review process, or partial publication in a journal., including all parts of the model);5 = Yes (full peer-reviewed journal for all aspects of the model)
The model reflects up-to-date knowledge for the cause-effect chain		1 = not up-to-date; 3 = partially up-to-date; 5 = yes (state-of-the-art)
Tests of the emissions already conducted		1 = No; 3 = Tested for relevant products/scale and conditions but showing important limitations; 5 = Tested for relevant products/scale, different conditions, peer-reviewed and showing not relevant model limitations.
Uncertainty and sensitivity analysis		1 = No; 3 = Yes, but just for the outputs; 5 = Yes, including inputs and outputs
		AVAILABILITY, DOCUMENTATION, TRANSPARENCY & REPRODUCIBILITY
Accessibility of the emission model		1 = No free access/availability; 3 = Available under conditions/on request; 5 = Free access/Internet download
Accessibility of the model documentation		1 = Not accessible; 3 = Accessible with limitations (e.g. fee due, not available in the English language); 5 = Totally accessible
Accessibility of the input data		1 = High limitations (many input data not available in global databases, also data not related to common in LCA). 3 = Low limitations (some data too specific and not available in regional database). 5 = Totally accessible, all data are relatively easy to obtain.
Modelling assumptions and value choices		1 = Not described; 3 = Unclear/partial description; 5 = Comprehensive description
Completeness of the emission model documentation		1 = Very incomplete or no documentation; 3 = Partially comprehensive documentation; 5 = Fully comprehensive documentation
		APPLICABILITY & FLEXIBILITY
Compatibility with LCA methodology		1 = Not compatible; 3 = Not developed for LCIA but it fits the scope; 5 = Developed for LCA and tested
Usability of models for LCA practitioners		1 = Not used; 3 = Already used but in few situations; 5 = Already used in several studies
Related to IPCC TIER concept		1= TIER; 3 = TIER 2; 5 = TIER 3
Management operations consideration		1 = No; 3 = Partially includes; 5= Totally includes
Flexibility (Is it to change parameters and conditions in the model?)		1 = The model is static: no changes are possible; 3 = Change of conditions and (dis)aggregation of sources are possible; 5 = The model can be easily adapted to new conditions, and aggregation/ disaggregation of sources is possible
		STAKEHOLDER ACCEPTANCE
Model and model results		1 = Both difficult to understand; 3 = One of them is difficult to understand; 5 = Both easily understandable
Authoritative body behind the model		1 = No; 3= Yes, by one of several national bodies; 5= Yes, endorsed by multinational bodies
Academic authority behind the model		1 = Individual research; 3 = Well trusted on national body; 5 = Well trusted on international body
Neutrality across industries, products, or processes		1 = Yes; 3 = Partially; 5 = No

2.2.4 Case study: maize crop in Spain

A case study was used to compare the estimates calculated using the models. A scenario of irrigated maize (2013 – 2017) in Mediterranean climate using calcium ammonium nitrate (CAN) as fertilizer was used (Table 4).

Table 4: Main characteristics of the crop system used in the case study (Montemayor *et al.* 2019)

GEOGRAPHIC PARAMETERS		
Location		La Tallada d'Empordà, Girona
Coordinates		l: N42.08º L: E03.06
Climate		Arid
Soil type	-	Loam
Soil depth	m	0.7
Clay	%	18
Silt	%	48
Sand	%	34
Organic matter	%	2.5
Soil pH	-	8
Content N in irrigation water	kg NO_3^- /m^3	0.009
CROP DATA		
Moorish maize yield	t DM ha^{-1}	20.65
FERTILIZATION		
Total Calcium Ammonium Nitrate (CAN) applied	kg N ha^{-1}	170*

* Maximum value allowed by the Nitrate directive (ECC 1991)

The minimum parameters required to estimate N emissions in the models are shown in Table 5, and Supplementary Material 2. Concerning Daisy and Animo's set up, a calibration was provided to align the models' outputs with real field measurements using yields from maize crop rotations (2013 - 2017). Default values for parameters in Daisy and Animo were taken from the models' library.

Table 5: Minimum parameters required to estimate nitrogen emissions using PEF, SALCA, Daisy and Animo

<table>
<tr><th></th><th>PEF</th><th>SALCA</th><th>Daisy</th><th>Animo</th></tr>
<tr><td>Weather data</td><td>- None</td><td>- Average monthly precipitation</td><td colspan="2">- Main characteristics of the weather station
- Typical max and min temperature in a year
- Dry deposition of NH_4^+ and NO_3^-
- $[NH_4^+]$ and $[NO_3^-]$ in precipitation
- Global radiation (W/m²)
- Precipitation (mm/d)
- Reference evapotranspiration (mm/d)
- Air temp. (°C) (mean)
- Air temp. (°C) (max and min only Animo)
- Wind Speed (Animo)</td></tr>
<tr><td>Soil characteristics</td><td>- None</td><td>- pH
- Slope
- N in soil
- Coefficient related to rain washing
- Leaching coefficient as a function of the slope</td><td colspan="2">- Depth of the horizons, of max rooting, groundwater and existence of drainage
For each soil horizon (A, B, C…)
- Clay (%), Silt (%) and Sand (%)
- Humus (%)
- C:N
- Bulk density
Mualem van Genuchten model:
- α and n (shape parameters)
- K_{sat} (saturated hydraulic conductivity cm/d)</td></tr>
<tr><td>Fertilizer</td><td>- Amount
- Type (for NH_3 emissions)</td><td>- Type and amount
- N availability (organic fertilizers)</td><td colspan="2">- Dry matter fraction (%)
- Total C fraction (%)
- Total N fraction (%)
- NH_4^+-N fraction (%)
- NH_4^+ volatilization (emission fraction)</td></tr>
<tr><td>Crops and Field Management Activities</td><td>- None</td><td>- N uptake (fraction)
- N content in the water irrigation</td><td colspan="2">- Type of crop
- Date of ploughing, fertilization, sowing, irrigation and harvesting
- Information about storage organ (leaf, stem, stub)</td></tr>
<tr><td>Average yields (annual)</td><td>- None</td><td>- None</td><td colspan="2">- Dry matter (ton DM/ha)
- Yield (ton/ha)
- N content (kg N/ha)</td></tr>
</table>

Note that although PEF seeks to standardize emissions for certain agricultural products, the low amount of input data required to estimate N emissions can result in lower accuracy and representativeness. It is important to highlight also that the pilot phase of PEF did not include cultivation in the foreground system, but it is under review for future assessments.

In Daisy, to reduce the effect of extreme weather conditions, a simulation was done for a 100-year simulation, applying randomized weather-crop combinations. In Animo, a 5-year simulation was performed to initialize an adjusted soil organic matter pool (SOM) for better estimates in the model.

An automatic irrigation (30 mm/h in case the water pressure in the soil falls below –600 cm in the top 30 cm soil from May to September) had to be used in Daisy due to the impossibility to perform irrigation on specific days, as used in Animo. The nitrogen supplied by irrigation in SALCA was calculated multiplying the concentration of N in the water irrigation and total irrigation applied. Irrigation in SALCA was taken into account, adding it to monthly precipitation, in order to select a coefficient for soil leaching. For PEF, neither the N in irrigated water nor irrigation are considered.

Regarding the N estimates provided by Daisy and Animo, NO_3^- leaching was calculated for the 100 cm, depth of the root zone. N_2O (nitrification and denitrification) and NH_3 were estimated for the total soil profile. NO_3^- leaching in SALCA was estimated for 90cm of depth.

In the present work, the nitrogen balance in the field from the results obtained with the models includes as inputs: the mineral and organic fractions of fertilizers, atmospheric deposition, N in the irrigation water and fixation of atmospheric N by legumes. As sources of N production are losses to groundwater and surface water (via leaching and nitrate runoff), emissions to the atmosphere via ammonia volatilization, nitrification (N_2O and denitrification; and N absorption by crops and harvested N. The stock of N (N inputs minus N outputs) in the soil is a positive value (increasing) indicates that the input N is greater than the output, contributing to the increase in the stock of N. Otherwise, if the change in the stock of N is a negative (decreasing) value suggests liquid mineralization of organic N from the soil. Therefore the crop is taking nitrogen out of the soil. The strategy adopted for the N balance is the same used in the Daisy and Animal models.

It is essential to highlight that emissions estimated in dynamic models day by day, use precisely climate condition for the management operation performed, but much more detailed information is required, which can be an obstacle for LCA practitioners. The simulations made in Animo and Daisy were carried out in the most similar way possible, but, due to models' internal parameters, differences were found in the results provided.

The estimated emissions were inventoried in SimaPro software v. 8.5 (Pré Consultants, 2017) using a scenario provided by Montemayor et al. (2019). The impacts were characterized using the ILCD 2011 midpoint method to verify how variations in emissions estimations influence LCA impact results.

2.3 Results

2.3.1 Comparison under the criteria and sub-criteria proposed by UNFCCC and other authors for adequacy in the LCA studies

The model with the best total score was Daisy with 91 (79% of the maximum total score), followed by SALCA and Animo with 85 (74%) and PEF with 77 (67%). The percentage achieved for each model in the selected criteria is shown in Figure 2 and Table 6. Detail scored will be explained in this section, and further elaborated in Supplementary Material.

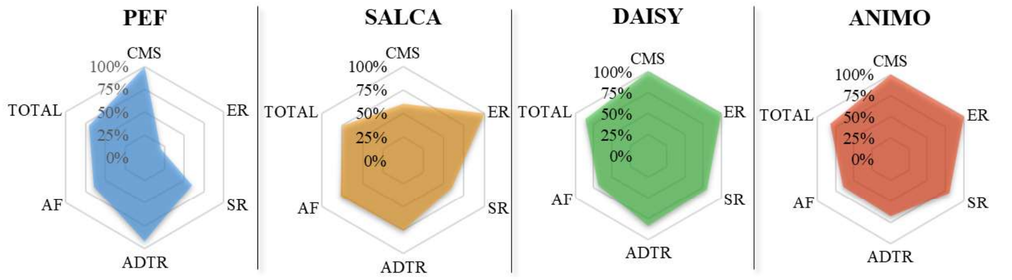

Figure 2: Comparison of PEF, SALCA, Daisy and Animo under adapted methodology proposed by UNFCCC (2004)

(ADTR = Availability, documentation, transparency & Reproducibility; CMS = Completeness of the model scope; ER = Environmental Relevance; AF = Applicability & flexibility; SR = Scientific robustness)

Table 6: Detailed scores regarding the qualitative assessment for comparing PEF, SALCA, Daisy and Animo models

CRITERIA AND SUBCRITERIA		MODELS			
		PEF	SALCA	DAISY	ANIMO
COMPLETENESS OF THE MODEL SCOPE					
Geographic coverage		5	3	5	5
ENVIRONMENTAL RELEVANCE					
Spatial-temporal resolution	Temporal resolution of the input	1	5	5	5
	Spatial resolution of the input	1	5	5	5
SCIENTIFIC ROBUSTNESS					
Transparency		1	5	5	5
Input data set/data requirements		5	3	1	1
Emission model peer-review and (peers) acceptance		3	3	5	5
The model reflects up-to-date knowledge for the cause-effect chain		3	3	5	5
Tests of the emissions already conducted		3	3	5	5
Uncertainty analysis		3	1	3	3
AVAILABILITY, DOCUMENTATION, TRANSPARENCY & REPRODUCIBILITY					
Accessibility of the emission model		5	5	5	3
Accessibility of the characterization model documentation		5	3	5	5
Accessibility of the input data		5	3	1	1
Modeling assumptions and value choices		3	5	5	3
Completeness of the emission model documentation		5	3	5	5
APPLICABILITY & FLEXIBILITY					
Compatibility with LCA methodology		5	5	3	3
Usability of models for LCA practitioners		5	5	3	1
Related to IPCC TIER concept		1	3	5	5
Management operations		1	3	5	5
Flexibility		1	5	3	3
Model and model results		5	5	3	3
Authoritative body		5	1	1	1
Academic authority		1	3	3	3
Neutrality across industries, products, or processes		5	5	5	5

3.1.1 ‘Completeness of the model scope’ and ‘Environmental relevance’

In ‘Geographic coverage’ sub-criteria, PEF, Daisy and Animo scored 5 due to their worldwide applicability. Daisy and Animo require a model calibration, and there is no spatial restriction for

PEF due its simplicity. SALCA scored 3 because it was developed to estimate emissions in Europe or temperate climate in the Northern Hemisphere.

3.1.2 ‘Scientific robustness’

SALCA, Daisy and Animo models scored 5 for ‘Transparency’ because the processes to estimate nitrogen emissions were clearly modelled and well-explained, PEF scored 1 because the emission fractions used are not adapted to different climate conditions and the system processes for cultivation are non-transparent. It was assumed, also taking into account Nemecek *et al.* (2016), that the less the ‘Input dataset/data requirements’, the better the model, as it requires less effort and time from the LCA practitioner. Thus, PEF scored 5, SALCA 3 and Daisy and Animo 1 since the last two need more input data (Table 2).

Regarding ‘Emission model peer review and (peers) acceptance’, Daisy and Animo scored 5 because they are peer-reviewed. SALCA and PEF are provided as guidelines, receiving a score of 3.

Daisy and Animo explain the entire nitrogen cycle and the interconnections within the cycle, receiving 5 in ‘The model reflects up-to-date knowledge for the cause-effect chain’. SALCA and PEF failed to receive the maximum score because the models are not as detailed as Daisy and Animo.

Daisy and Animo had ‘Tests of the emissions already conducted’, scoring 5. Although SALCA (3) has been used in LCA studies, it is not well-validated and has restricted use. The climate data in PEF (3) is not representative, so inconsistencies can be found compared to field measurements. PEF, Daisy and Animo scored 3 in ‘Uncertainty and sensitivity analyses’, and SALCA scored 1 because there is no information about those analyses for the model.

3.1.4 ‘Availability, documentation, transparency & reproducibility’

PEF, SALCA and Daisy scored 5 because the models provide an easy ‘Accessibility of the emission model’. PEF and SALCA provide documentation, and Daisy is an executable program, run in a text editor, that can be downloaded from of the University of Copenhagen website and uses its own programming language. Animo, though also an executable program run in a text editor, scored 3 because a request for access to the model is necessary.

SALCA scored 3 in ‘Accessibility of the characterization model documentation’ because the model is only available in German, which may represent a language barrier for many LCA practitioners. Daisy, Animo and PEF scored 5 because they provide useful documentation for a complete understanding of the models.

PEF scored 5 in 'Accessibility of the input data', because the amount and type of fertilizer are the only input data required. SALCA scored 3 as it is easy to obtain input data considering the inventory already created for the LCA study. Daisy and Animo scored 1 because some specific values may be more challenging to obtain, for instance, soil horizon characteristics, data for the groundwater or specific data related to the crop (e.g. leaves and roots).

Daisy scored 5 because it provides a document for 'Modelling assumptions and value choices', to help the user in cases with lack of data. SALCA and Animo scored 3 because assumptions are outlined in their reference documents. PEF scored 3 because it is not clear how the assumptions are made in the model, possibly due its simplicity. PEF, Daisy and Animo scored 5 in 'Completeness of the emission model documentation' because all the information required is described in the manuals. SALCA scored 3 since the manual was written for specific spatial conditions.

3.1.5 'Applicability & Flexibility':

PEF and SALCA obtained the maximum score in 'Compatibility with LCA methodology' and 'Usability of models for LCA practitioners' because they were created to estimate emissions in LCA studies. Daisy and Animo scored 3 in the former criteria because they were not developed for LCA, but fall within the scope. Daisy scored 3 and Animo 1 in the latter subcriterion because Daisy has already been used to estimate emissions in LCA, but in Animo they did not implemented that aspect.

For the subcriterion 'Related to IPCC Tier concept', it was assumed that the model that best includes the dynamics on the environment (Tier 3) is the best model for LCA. Thus, PEF scored 1, SALCA 3, Daisy and Animo 5.

PEF scored 1 in 'Management Operations' because they are not considered in the model. SALCA scored 3 because some (e.g. irrigation) are relevant for the model. Daisy and Animo scored 5, since management operations are crucial for the models' performance.

PEF scored 1 in 'Flexibility' because the model applies EF as default methodology. However, in the guideline (EC-PEFCR 2018) it is said that other nitrogen field model can be used under certain conditions. SALCA scored 5, because changes and assumptions in the model are easy to carry out since the model is based on equations. Daisy and Animo scored 3, because changes are possible, but since many equations and processes are involved, it is more complex to perform and track those changes.

PEF and SALCA obtained the best score in 'Model and model results' since they are easy to understand. Daisy and Animo scored 3 because the results are easy to interpret, but understanding the models requires more effort.

No 'Authoritative body' support the models, thus SALCA, Animo, Daisy scored 1 in the subcriterion. PEF scored 5 because the emission model used was recommended by European Commission, a well trusted international body. SALCA, Daisy and Animo scored 3 in 'Academic authority' as national research institutions provide them, and PEF scored 1. All models also scored 5 in 'Neutrality across industries, products or processes' because they use an unbiased, objective methodology.

The models scored very similarly, with a difference of 8% in the total score. The comparison intended to show that many models can fit the LCA scope, but considering different purposes. Further work is needed through guidelines or other documents, in what situations they should be applied, and to force LCA practitioners to respect this adequacy as the scope of this study is to judge whether the models are suitable for LCA purposes in general.

Furthermore, when estimating and applying the emissions provided by the models in a case study is it possible to identify the main differences and their effect on the impact categories in LCA when considering an entire system (e.g. machinery, water and fuel used).

2.3.2 Quantitative comparison: A case study of maize crop in Spain (Temperate/Mesothermal Climate)

PEF, SALCA, Daisy and Animo were used to estimate nitrogen emissions due to the use of mineral fertilizers in an irrigated maize crop system in Spain. (Table 7). Approaches for Animo and Daisy's calibration included adjusting, for instance, rates of photosynthesis, N uptake by the crop and N concentration in different plant organs. After calibration, the simulated crop yields in Daisy and Animo were only -3% and -4% of the observed yields, respectively, showing that the two models are able to produce reliable results for the system (Figure 3).

Figure 3: Calibration of Daisy and Animo models using the yield for irrigated maize in Spain

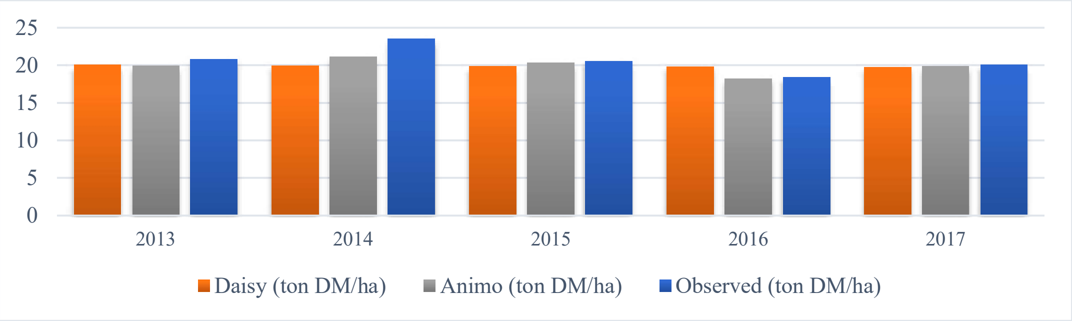

Table 7: Average (2013 – 2017) nitrogen components estimated with the models PEF, SALCA, Daisy, Animo

	SOURCE	PEF	SALCA	Daisy	Animo
Input (kg N/ha/y)	Fertilizer (mineral fraction)	170	170	170	170
	Deposition	-	-	15.6	14.7
	Irrigation	-	8.3	6.8	6.2
	Plant N fixation	-	0	0	0
	N in soil	-	-	-	-
	Seed	-	-	2.0	-
	Total input	*170*	*178.3*	*194.4*	*190.9*
Output (kg N/ha/y)	Leaching to groundwater ($N - NO_3^-$)	17.0	18.0	19.9	43.7
	Loss to surface water	-	-	0	0
	NH_3 Volatilization (N-NH_3)	3.4	3.7	3.4	3.6
	NO_2	-	1.2	-	-
	Nitrification (N-N_2O)	2.4	1.6	3.4	2.9[2]
	Denitrification (N-N_2O and N_2)	7.65[1]	-	6.7	0.7
	N uptake	265.6	265.6	190.3	199.0
	Total output	*296.8*	*290.1*	*223.7*	*249.9*
	Balance	-126.7	-111.8	-29.3	-59.0

[1] N_2 emissions

[2] A fraction was used to separate N_2O emissions

None of the models estimated all parameters. The most worrying estimates not considered are denitrification in SALCA (possible overestimation of N_2O emissions could increase the impact on climate change), and NO_2 in PEF, Daisy and Animo (possibly increasing impacts on photochemical ozone formation, particulate matter, and marine eutrophication). N from water irrigation in PEF, and dry and wet deposition in PEF and SALCA should be considered in the future as they can contribute to more N as input into the system. Seed's nitrogen supply was only considered in Daisy, but being 1% of the total input, it is not a significant loss for the other models in the present study. Irrigation was considered differently in Animo, Daisy and SALCA, and is responsible for the 18% variation in N irrigation.

Animo estimated the highest nitrate leaching (43.7 kg N/ha/y) and PEF the lowest (17 kg N/ha/y). SALCA and PEF do not consider the evapotranspiration in the soil, directly affecting the estimated emissions. In addition, irrigation modelled in Daisy may be decreasing the actual value of nitrate leaching, especially compared to Animo, since in Daisy less irrigation went to the crop system. The variation in results for nitrate leaching was 61%. The loss of nitrate due to surface runoff estimated resulted in zero in Daisy and Animo.

SALCA estimated the highest NH_3 volatilization (3.7 kg N/ha/y) and Daisy and PEF the lowest (3.4 kg N/ha/y), varying by 8%, being the lowest variation between the emissions. Although SALCA considers direct and indirect forms of ammonia volatilization, Animo considers the fertilizer application technique, and Daisy and Animo take into account the dry and wet deposition of NH_4^+ available in the air. Still, no significant difference was observed in the results.

SALCA is the only model that estimates NO_2 emissions, which means more impacts will be attributed to the system. However, this represents an advantage for the model in terms of coverage of nitrogen emissions.

PEF and SALCA estimate N_2O using EF, while Daisy and Animo consider the emission part from nitrification and another part from denitrification processes. In Daisy, the N_2O is directly estimated, but in Animo a fraction of 0.005 (fraction for loam soils in temperate climate regions from de Vries *et al.* (2003)) was applied to assume the amount of N_2O in total nitrification. In Animo and Daisy, a fraction of 0.02 (also from de Vries *et al.* (2003)) was applied to distinguish between N_2 or N_2O in the denitrification. For Daisy and Animo, N_2O emissions from denitrification are 0.134 and 0.002 kg N/ha/y. In summary, N_2O emissions (kg N-N_2O/ha/y) in PEF releases 2.4, SALCA 1.6, Daisy 3.5 and Animo 2.9. The variation in N_2O emissions was 54%. Regarding denitrification, N_2 emissions (an inert nitrogen emission) were considered for PEF.

The N uptake applied in PEF was the same as in SALCA. That said, SALCA applied the average yield and a crop uptake coefficient for N uptake (13 kg N/ ton DM). The variation in this output was 28%, 265.6 kg N/ha/y in SALCA (highest) and 190.3 kg N/ha/y in Daisy (lowest).

The highly negative N balance in PEF (-126.7 kg N/ha/y), is due to the limitation of N inputs considered and the ‘crop uptake’ being much higher than those estimated in Animo or Daisy. The balance in SALCA was -111.9 kg N/ha/y and did not consider N in soil and N mineralized as inputs into the system, although they have been used for NO_3^- leaching estimates. Again, crop uptake is a major contributor to the nigh negative balance in SALCA. Animo had the highest NO_3^- leaching output, resulting in an N balance of -59.3 kg N/ha/y. This high NO_3^- leaching was the distinguishing parameter that caused high N balance variation (59%) compared to the other mechanistic model Daisy, since other estimated emissions were similar. Daisy achieved the best balance (-29.3 kg N/ha/y) compared to the other models, considering that, although negative, is the closest to zero. According to the balances, there was a decrease in the soil mineral nitrogen stock.

2.3.3 Characterization of impacts in an LCA of maize crop in Spain

The impacts were characterized in the Simapro software (Pré Consultants 2017), using a scenario provided by Montemayor *et al.* (2019) and the models’ emission estimates (Table 8). The impact categories analyzed with the ILCD 2011 midpoint method were ‘Climate change (CC)’, 'Particulate Matter (PM)', 'Photochemical Ozone Formation (POF)', 'Acidification (AC)', 'Terrestrial Eutrophication (TE)' and 'Marine Eutrophication (ME)'. Impact assessment models recommended in ILCD 2011 (EC-JRC 2001) midpoint method are available in Supplementary Material 4.

Table 8: Fertilizer emissions used in a Spanish maize crop life cycle inventory for each N emission model, PEF, SALCA, Daisy and Animo

N EMISSION	PEF	SALCA	Daisy	Animo	VARIATION
N_2O (kg N_2O/ha/year)	3.8	2.5	5.5	4.6	54%
NH_3 (kg NH_3/ha/year)	4.1	4.5	4.1	4.4	9%
NO_2 (kg NO_2/ha/year)	-	5.3	-	-	-
NO_3^- (kg NO_3^-/ha/year)	75.3	79.7	88.1	193.5	61%

The impacts were calculated for 1 t of harvested maize dry matter (DM) (Table 9). Importantly, the variation in the values was caused only by the fertilizer emissions, since the ones related to machinery, fuels, and other emissions were maintained the same as in Montemayor *et al.* (2019).

Table 9: Impact characterization relevant to fertilizer emissions estimation using PEF, SALCA, Daisy and Animo models

IMPACT CATEGORY*	UNIT	PEF	SALCA	Daisy	Animo	VARIATION
CC	kg CO_2 eq/ton	2669	2073	3175	2907	35%
PM	kg PM2.5 eq/ton	4.17	4.22	4.17	4.19	1%
POF	kg NMVOC eq/ton	8.42	12.26	8.42	8.42	31%
AC	molc H+ eq/ton	25.60	29.62	25.60	26.51	14%
TE	kg N eq/ton	97.36	118.99	97.36	101.41	18%
ME	kg N eq/ton	21.00	23.53	23.90	47.74	56%

*Climate change (CC), Particulate Matter (PM), Photochemical Ozone Formation (POF), Acidification (AC), Terrestrial Eutrophication (TE), Marine Eutrophication (ME)

Although the impact variation among models was less than the variation in estimated emissions, the contribution of N from fertilizer input to impacts is evident. The 54% variation in N_2O emissions caused a 35% change in 'CC'. The 9% variation in NH_3 emissions, caused a 1% change in the impact on 'PM', (smallest change in the calculated impacts), and an 18% change in 'TE'. For 'POF', only SALCA provided NO_2 emissions, and these emissions caused a 31% change in impact. In 'AC', the NH_3 and NO_2 emissions caused a 14% change in the impact. The highest variation occurred in the impact category 'ME', with 56% change caused by a 61% variation in the NO_3^- leaching. SALCA had the largest impacts on 'PM', 'POF', 'AC' and 'TE' due to the additional emissions of NO_2, in addition to the emission of NH_3. PEF emissions had the lowest impact in all impacts categories selected, except on 'CC'.

A normalization procedure was carried out using the UE27 2010 methodology (Benini *et al.* 2010; Crenna *et al.* 2019) to compare the total impact and impact categories in the proposed scenarios

(Figure 4). Animo emissions caused the highest impact in the system, with a normalized score of 4.09, followed by SALCA (3.42), Daisy (3.29) and PEF (3.13), varying 23% in the normalized impact caused, only changing nitrogen emissions from fertilizer application. The models presented the same decreasing order of contribution in the impact categories: ‘PM’, ‘ME’, ‘TE’, ‘AC’, ‘CC’ and ‘POF’. However, the contribution of each impact category to the system is different. For instance, in ‘PM’, Daisy emissions contributed 25%, but in Animo the contribution was 20% of the total impact; in ‘ME’, 38% of overall impact was attributed to the NO_3^- leaching in Animo, but 22% in PEF. The different emissions directly affect the LCA final results, and this is also relevant when compared with other LCAs for irrigated maize crops or when calculating the system’s uncertainties.

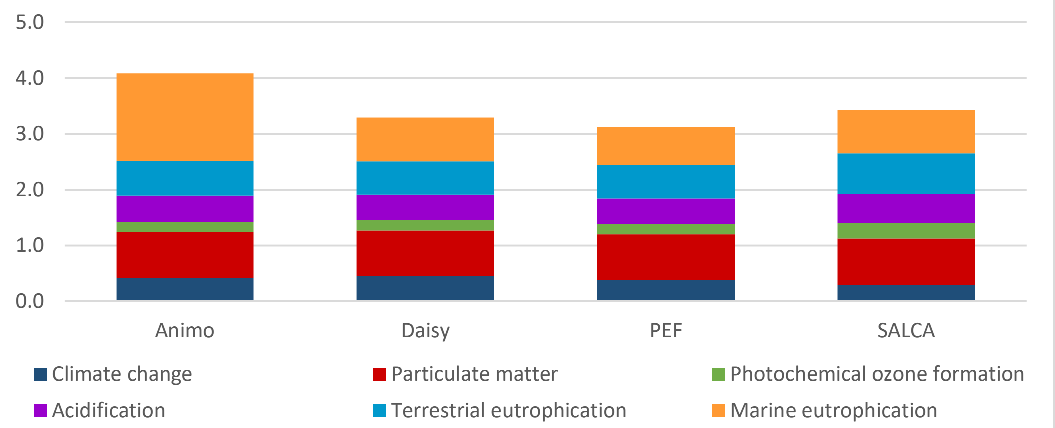

Figure 4: LCA results after normalization for impact categories associated with nitrogen emissions, for nitrogen emission models Animo, Daisy, PEF and SALCA.

2.4 Discussion

2.4.1 Comparison of model evaluation results with previous studies

Other studies comparing the models selected in this study have been performed (Wu and McGechan 1998; Cannavo *et al*. 2008; Bockstaller *et al.* 2009; Nitschelm *et al.* 2018; Peter *et al.* 2016) for various reasons and using different approaches.

Wu and McGechan (1998) compared Animo and Daisy (older versions) with two other mechanistic models (SOILN and SUNDIAL). Their results showed that Animo and Daisy have similarities, especially related to the effects of temperature and water content in the soil, but in denitrification significant differences due to the applied parameters are present. They also pointed out that ammonia volatilization is modelled to a limited extent on both models, depending on the EF entered by the user. Agreeing Wu and McGechan (1998), denitrification in this study had an 89% difference between the Daisy and Animo estimates, and ammonia volatilization had only 8% of the difference between the models, being quite simplified even in the mechanistic models.

Cannavo *et al.* (2008) compared 62 mechanistic and empirical models, including Animo and Daisy, to assess environmental impacts of cultivated soils due to nitrogen emissions. Unlike this study, Cannavo *et al.* (2008) did not explain the simulated N processes. However, they pointed out that no lower performance was observed between empirical and mechanistic models, as long as the empirical models are applied in the specific context for which they were developed, respecting their geographic coverage, also spatial and temporal resolution required for the study's goal and scope. In summary, they said that mechanistic and empirical models would provide different results due to the models' internal parameters, that was the same observed in the current work. The exception was for ammonia volatilization, in which all models obtained almost the same results, but this was expected since the models estimate ammonia volatilization simply and similarly.

Bockstaller *et al.* (2009) compared SALCA to three other models to test their capability as a farm management tool. SALCA obtained the best score for 'environmental scientific soundness' including coverage of agricultural production branches and coverage of production factors. However, SALCA was unable to cover all relevant environmental issues (e.g. biodiversity), and it was not considered user-friendly to farmers. Unlike the findings of Bockstaller *et al.* (2009), in the present study, SALCA is considered a user-friendly model compared to the mechanistic models, Daisy and Animo, but being related to the use by LCA practitioners.

Peter *et al.* (2016) and Torrellas *et al.* (2018) and compared Tier 1, Tier 2 and Tier 3 approaches to the estimation of greenhouse gases (GHG) in wheat crops and peach orchards, and emissions from a cow manure biogas plant in Catalonia, respectively. Both works used IPCC (2006) as Tier 1 model, Tier 2 model in Peter *et al.* (2016) was Bouwman *et al.* (2002) and in Torrellas *et al.* (2018) was regionalized EF to Catalonia. Regarding Tier 3 models, Peter et al. (2016) decided not to select any model justifying that, at the moment, there was no model readily available and easily implementable by the user, and Torrellas *et al.* (2016) used EF estimated from field measurement. Peter *et al.* (2016) found relevant differences in the estimates, up to + 50% between Tier 1 and Tier 2 models, similar to the current work (34%). In Torrellas *et al.* (2016) the difference between the results from Tier 1 and Tier 2 models were 24%, similarly obtained in the current work, and of 25% in average comparing Tier 1 and Tier 3 models, also similar to the 30% found in the present work. Both studies strongly recommended the use of higher Tier models to estimate nutrient emissions, and Peter *et al.* (2016) highlighted the convenient relation between reducing complexity and improving precision when using medium-effort (Tier 2 and Tier 3) models that is also expected and preferable to be applied in LCA studies.

Nitschelm *et al.* (2018) compared NO_3^- and NH_3 emissions provided by a Tier 3 model Syst'N in a cropping system with the emissions estimated using the risk tables provided by AGRIBALYSE, (Koch and Salou 2015), frequently used in LCA and similar to SALCA. For nitrate leaching, AGRYBALYSE models estimated emissions up to 67% lower than those estimated using Syst'N, similar to the differences found in this work, 58%, comparing SALCA and Animo's results. Regarding NH_3, the differences were from 28% to 63%, thus higher than in the current work. In addition, the authors recommended Tier 2 and Tier 3 models for farming systems at regional scales, and Tier 1 models for more general assessments such as national environmental labelling of food products.

2.4.2 Comparison of simulation results provided by the models to field observations

The validation of the models' simulation against field measurements is essential to confirm if the results are accurate. However, due to the lack of field measurement for that specific system (which is common in LCA), the results of the simulation were compared with other studies containing similar environmental conditions and field practices.

The estimated values for N uptake in irrigated maize under Mediterranean conditions ranged from 151 to 254 kg N/ha (Berenguer *et al.* 2009), 262 to 333 kg N/ha (Yagüe and Quílez 2010) and 155 to 300 kg N/ha (Biau *et al.* 2012). Results obtained for N uptake in Daisy (190.3 kg N/ha/y), Animo (199.1 kg N/ha) and SALCA (265.6 kg N/ha) are in agreement with the interval found in field studies. Therefore, all models adequately estimated N uptake, despite the 28% variation in the estimated emissions.

Nitrate Leaching Coefficient (NLC) in Mediterranean climate conditions, the interval for the nitrate leaching (kg N-NO_3^-/kg fertilizer applied) in irrigated maize crops was 0.11 to 0.37 (Lasa *et al.* 2011). Thus, SALCA (0.11), Daisy (0.12), and Animo (0.26) reached results similar to this value. The 0.10 in PEF is slightly below the minimum limit.

Bussink (1994) and Recio *et al.* (2018) observed rates of approximately 1.5% of total N applied using CAN ammonia volatilization under Mediterranean conditions. PEF (2.0%), SALCA (2.2%), Daisy (2.0%) and Animo (2.1%) reached rates very similar to those authors.

According to Cayuela *et al.* (2017), the general average EF N_2O (kg N-N_2O/kg N applied) for Mediterranean agriculture should be 0.005, being half of the value proposed by IPCC (0.01) and a quarter of the recommended value in PEF (0.022). Cayuela *et al.* (2017) also proposed an EF for irrigated crops, 0.0063. Therefore, N_2O emissions in this work should be between 0.83 kg N-N_2O /ha and 1.1 kg N-N_2O /ha. None of the models achieved these results, PEF and SALCA due to the EF applied, Daisy and Animo due to the uncertainty in N_2O emissions from nitrification and denitrification.

Denitrification calculated under Mediterranean climate in Teira-Esmatges *et al.* (1998) showed that (N_2O + N_2) losses represented 1.7% to 13.6% of the total N fertilizer applied. Therefore, the expected emissions between 2.89 kg N/ha and 23.21 kg N/ha were achieved by PEF and Daisy. The expected emissions values are summarized in Table 10.

Table 10: Comparison between estimated emissions in PEF, SALCA, Daisy and Animo and literature values, where green means estimated emissions are within the range of observed results, red means they are not within the range, and grey means it is not applicable

N PARAMETER	OBSERVED	PEF	SALCA	Daisy	Animo
N uptake (kg N/ha)	151 – 333[1]	-	265.60	190.30	199.10
NO_3^- leaching (NLC)	0.11 - 0.37[2]	0.10	0.11	0.12	0.26
Volatilization (%)	~ 1.5%[3]	2.0%	2.2%	2.0%	2.1%
N_2O (kg N_2O emitted/ha)	0.53 - 0.68[4]	3.8	2.5	5.5	4.6
Denitrification (kgN/ha)	2.89 - 23.21[5]	7.65	-	6.70	0.70
Within the range		Not within the range		Not applicable	

[1] Berenguer *et al.* (2009); Yagüe and Quílez (2010); Biau *et al.* (2012)
[2] Lasa *et al.* (2011)
[3] Bussink (1994) and Recio *et al.* (2018)
[4] Cayuela *et al.* (2017)
[5] Teira-Esmatges *et al.* (1998)

2.4.3 Nitrogen emissions models used in agricultural LCA studies

The use of IPCC (2006) EF for N_2O emissions appears to be the standard practice in LCA studies. However, as explained in Cayuela *et al.* (2017), the proposed factors are not adjusted for some climates, and the use of default EFs can result in erroneous emissions, as it happened with PEF and SALCA results. Mechanistic models also have been used to estimate N_2O emission in LCA, for instance, GREET 16 in Wang *et al.* (2007), DNDC in Goglio *et al.* (2014), DAYCENT in Kim and Dale (2005). Although Animo and Daisy did not fall within the range of observed emission results, a better calibration of the models and an adjustment of internal parameters can be done, meaning that for N_2O emissions, Tier 3 models, such Daisy and Animo, could provide more adjusted estimates.

EF's use for NH_3 volatilization is widespread but from different sources other than IPCC (2006) used in PEF. Thomassen *et al.* (2008), and Xue *et al.* (2016) applied EF from previous studies, that are more adjust to climate conditions than IPCC (2006) EF. Tier 2 models, such as SALCA, are an excellent alternative for reducing complexity and improving precision for NH_3 volatilization. Tier 2 models were used in Mancuso *et al.* (2019), Romero-Gámez *et al.* (2014) and Wu *et al.* (2018), but a validation such as that carried out in this study is necessary.

Tier 3 models are more common for the NO_3^- leaching estimations. The complexity of the estimate that can vary substantially under different climate conditions (i.e dry and wet climate) and management operations (i.e. irrigation, free drainage and drainage with pipes). For example, DAYCENT in Kim & Dale (2005), DNDC in Goglio *et al.* (2014), STICS in Plaza-Bonilla *et al.*

(2018), and Daisy, as aforementioned. Tier 1 models represented by different rates or EF have also been applied. For example, 0.25 for summer maize (Wang *et al.* 2007), and 0.26 for rice in Xue *et al.* (2016). Tier 2 models were applied in NO_3^- leaching estimate in Romero-Gámez *et al.* (2014). For NO_3^- leaching, Tier 3 models should be taken as first option to estimate this emission, since Tier 1 (PEF) and Tier 2 (SALCA) models may not be considering most parameters needed for a better estimate.

Usually, when authors use mechanistic models, all nitrogen emissions are estimated using the same model (Goglio *et al.* 2014, Kim and Dale 2005, Li *et al.* 2016, Plaza- Bonilla *et al.*, 2018). The scientific advantage of using mechanistic models is the calibration performed, making the results more credible and appropriate to the system. For the validation in the aforementioned studies, literature data was used in Goglio *et al.* (2014) and Ni *et al.* (2019), as it was provided in this study. In Wang *et al.* (2007) validation was assumed from Hu (2004), another strategy that could be adopted in LCA. However, no validation of results can no longer be an option in LCA.

According to Nemecek *et al.* (2016), the ideal model should be practical, calculates the results easily, be site- and time-dependent (but to apply under a wide range of situations), includes a collection of parameters and input data required. However, while no model complies all those important characteristics for LCA, mechanistic models, well-validated and calibrated for different situations, could be used to provide regionalized EF, as in Brown *et al.* (2002) and Yoshida *et al.* (2016), to be applied in lower Tier models to adjust N emissions.

2.5 Conclusions

PEF, SALCA, Daisy and Animo have important characteristics that make them useful and suitable for LCA, whenever their domains as fertilizer application emissions models are respected. Daisy was the model that best fitted to the criteria selected, achieving 77% of the total score. The proposed methodology could be used in other studies to compare models' suitability for estimating nitrogen or nutrients in LCA.

For the case study applied, the models estimated reliable results for almost all N emissions, except for N_2O. However, the characterization impact carried out showed differences in the impact categories analyzed. Other crops should have their emissions estimated under different models to corroborate with the results in this work.

More research must go into emission model comparisons, describing more complex agricultural systems (including double crops, organic fertilizer including manure by-products, cultivation on substrates etc.), to identify the best ways to estimate nitrogen emissions in LCA. Guidelines or methodologies are needed to guide the LCA practitioner to better describe and justify their agricultural inventory emissions choice. A sensitivity analyses that assess different models, literature values for similar crops, and field data could be used as a strategy to validate the results estimated.

Finally, it is not always possible to use mechanist models like Daisy or Animo to estimate nitrogen emissions in LCA, mostly due to the amount of input data required. However, after calibrations and validations, these models could be used to adjust EF, according to different climate conditions, crops and fertilizers used in the simplest models, such as SALCA or PEF. Therefore, LCA can benefit from using agricultural models, helping to improve their evidence-based results and recommendations.

Acknowledgements

We thank the project Nutri2cycle (773682) for the full support during this work and the CERCA Programme/Generalitat de Catalunya.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 713679 and from the Universitat Rovira i Virgili (URV).

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2.7 Supplementary material

The supplementary material can be accessed in the following link:

https://1drv.ms/x/s!AiM0z1iKRPTCgbl3DOw8VtYwTtAFKw?e=vSI4cY

3. AGRI-ENVIRONMENTAL INDICATORS TO ASSESS NOVEL TECHNOLOGIES

This study is available in:

Andrade, E.P., Bonmati, A., Esteller, L.J., Brunn, S., Jensen, L.S., Meers, E., Anton, A., 2022. Selection and application of agri-environmental indicators to assess potential technologies for nutrient recovery in agriculture. Ecol. Indic. 134, 108471. https://doi.org/10.1016/j.ecolind.2021.108471

3. Selection and application of agri-environmental indicators to assess potential technologies for nutrient recovery in agriculture

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https://doi.org/10.1016/j.ecolind.2021.108471

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Abstract

The adverse effects of agriculture and livestock production on the environment are well-known and require mitigation in order to achieve sustainability in the food production chain. This study focused on adverse effects related to biogeochemical flows of phosphorus and nitrogen cycles, which natural balances have been greatly disturbed by current practices. To assess the potential benefits and detrimental effects of proposed mitigation measures, adequate impact indicators are required. The challenge lies in identifying and providing indicators that cover the important aspects of environmental sustainability and allow a direct comparison of policy alternatives. A review of potential indicators that are also consistent with those used to indicate the performance of agricultural and general sustainability (i.e. the European Green Deal) led to the selection of fifteen agri-environmental indicators covering the main environmental issues in agriculture. The indicators identified offered an effective representation of environmental behaviour and would be useful in communicating a comprehensive 'dashboard' for professional end users of solutions to nutrient recovery and nutrient efficiency improvement in arable and livestock systems. The selected dashboard indicators (DBI) covered the dimensions of 'use of primary resources', 'emissions to the environment' and 'resilience to climate change'. Five case studies were investigated to test the DBI using an Excel questionnaire applying the qualitative approach of the Delphi method together with expert knowledge. As expected, the results indicated that there were potential benefits of the technologies in terms of improved 'nutrient recovery' and decreased 'nitrate leaching'. Potential disadvantages included increased electricity and oil consumption and greater ammonia volatilisation due to the increased use of organic fertilisers. The indicator 'water' received more neutral responses; thus, the specific technology was not expected to consistently affect the indicator. In relation to 'particulate matter', the results were indicated to be 'unknown' for some solutions due to the difficulty of predicting this indicator. Furthermore, methodologies for estimating quantitative values for the dashboard indicators were proposed, and a quantitative assessment was performed for the solution 'catch crops to recover nutrients', confirming the responses in the qualitative assessment. The dashboard indicators selected covered the main aspects of the solutions, identified in more comprehensive studies of environmental impacts, as being suitable for the rapid assessment of technologies for nutrient recovery in agriculture. As such, they can be used as a pre-screening method for technologies designed to improve the environmental sustainability of arable and livestock systems.

Keywords: agriculture, livestock, qualitative assessment, environmental impacts, European Green Deal, nitrogen, phosphorus

3.1 Introduction

The current food production system urgently requires transformation in terms of resource use, productivity and environmental impacts (Willet et al., 2019). The trade-off between food production and environmental impacts in both the arable and livestock sectors is reflected in the duality of elements such as nitrogen (N), phosphorus (P) and carbon (C). These are essential for plant growth and soil fertility, but in excess can be harmful to the environment. Excess fertilisation can cause nitrate (NO_3^-) contamination in groundwater and consequently a lack of potability and surface water pollution, leading to eutrophication problems and, in conjunction with high soil P levels, eutrophication of surface water. In addition, it can cause resource depletion in the form of natural gas used for fertiliser production, potentially increasing greenhouse gas (GHG) emissions (Galloway et al., 2018).

Sustainability in agriculture is usually assessed by means of agri-environmental indicators (Bélanger et al., 2012). With growing awareness of environmental problems in recent decades, numerous agri-environmental indicators (Piorr, 2003; Petit et al., 2018; Früh-Müller et al., 2019) and indicator-based methods (Van der Werf & Petit, 2002; Binder et al., 2010; Acosta-Alba & Van der Werf, 2011) have been developed to assess the adverse effects of cropping and farming systems such as gaseous emissions due to energy and agrochemical inputs and water pollution by nitrates, phosphates and pesticides etc.

An important challenge for the research community is to identify and provide understandable and scientifically-based indicators that are accessible and capable of summarising the different aspects and dimensions of sustainability in order to assist decision-makers, preferably in ways that allow a direct comparison of policy alternatives (Einarsson et al., 2018).

Originally introduced as a business performance monitoring tool, a dashboard is an instrument used for information management and reporting in different contexts to communicate complex information related to the current situation and historical trends to wider society (Eckerson, 2011). This concept has also been applied to environmental monitoring to provide an overview of the current situation and historical trends, and is designed to present key indicators with critical information for decisions that need to be made (Janes, Sillitti & Succi, 2013; Han et al., 2014).

There is currently a proliferation of novel technologies that are being designed to increase nutrient cycling and use efficiency while minimising the environmental impacts of agricultural production. Prioritisation of these technologies, both in terms of which ones require more research and which ones should be implemented through legislation is highly complicated in that the goal of the technologies and the context in which they can be applied can be very different. Therefore, a set of agri-environmental indicators is required, that is scientifically rigorous and at the same time easy to assess and communicate.

One of the aims of this study was to develop a dashboard of ‘nutrient recovery and environmental issues’ to present information in a user-friendly format to help track the progress being made towards agricultural practices that have a less detrimental impact on the environment and to support national monitoring and reporting. The dashboard should encourage stakeholder engagement in suggesting different technologies and support farmers’ decision-making in order to apply the most effective solutions to meet their goals. Furthermore, it should allow other stakeholders to have a better understanding of the relationship between the technologies applied and the potential environmental benefits being promoted.

Therefore, the main goal of the current study was to identify a set of indicators to assess solutions that are focused on nutrient recovery from arable and livestock production in order to compare and contrast current farm practices across Europe. A further objective was to test the indicators on different solutions to ensure that they cover the main aspects of the solutions being applied in agriculture.

3.2 Methodology

3.2.1 Review of agri-environmental indicators

With the aim of identifying useful indicators for the dashboard, a literature review of scientific articles and reports published in the Web of Science database up to July 2020 featuring agri-environmental indicators was undertaken to assess potential technologies for nutrient recovery and nutrient efficiency improvement. The keywords researched were 'agri-environmental', 'indicators' and 'impacts'. This study prioritised articles that provided a set of indicators, presenting a broader picture rather than a narrow focus.

3.2.2 Criteria for selecting relevant indicators for inclusion in the dashboard

During the selection of agri-environmental indicators for the dashboard, the following documents were considered, here referred to as international agreements, in order to confirm the relevance and feasibility of the chosen indicators:

- agri-environmental indicators (AEI) developed by the European Commission (EU-AI, 2020) (https://ec.europa.eu/eurostat/web/agriculture/agri-environmental-indicators). AEIs were developed to track the integration of environmental concerns in the Common Agricultural Policy (CAP) at European Union, national and regional levels. This set contains 28 indicators covering topics such as soil erosion, farming intensity, genetics and diversity. They can be used to track and assess agricultural impacts on the environment, inform decisions relating to agricultural and environmental policies, and serve as a tool to convey information to society.
- the European Green Deal (EGD) (https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en): The EGD is a set of proposals to make the EU's economy sustainable (EU 2020). It was created with the aim of transforming the EU into a modern, resource-efficient and competitive economy, and reducing GHG emissions by 55% by 2030 and by 100% by 2050, creating an economy dissociated from resource exploration. The EGD makes clear that massive public investment – relying on new technologies and sustainable solutions – is necessary and critical if these goals are to be achieved (EU 2020).
- the Common Agricultural Policy context indicators (CCI) (https://agridata.ec.europa.eu/extensions/DataPortal/cmef_indicators.html). The CCI is a set of performance indicators summarising information on agricultural and rural statistics that can be calculated from the impact indicator fiches available on the European Commission's website, as well as general economic and environmental trends. It is divided into 12 themes, such as environment and climate action, climate change and air quality.

3.2.3 Case studies to test the feasibility of the dashboard indicators

As part of HZ2020, the Nutri2Cycle (N2C) project aims to demonstrate the feasibility and sustainability of alternative technologies and management procedures for closing the nutrient (N, P and C) cycle in agriculture. The project splits the technologies and solutions into five research lines: (A) innovative solutions for optimised nutrient & GHG in animal husbandry; (B) innovative soil, fertilisation & crop management systems & practices; (C) tools, techniques & systems for higher-precision fertilisation; (D) biobased fertilisers (N, P) and soil enhancers (OC) from agro-residues; and (E) novel animal feeds produced from agro-residues.

Five technologies included in the HZ2020 Nutri2Cycle project, one from each research line and at different levels of maturity, measured by their technology readiness level (TRL), were selected to test the feasibility and relevance of the dashboard indicators. A summary of the solutions is presented in Table 1 and a detailed description is presented in Supplementary Material A.

Table 1: Technologies used to test the feasibility and relevance of the dashboard indicators

Solution (full name)	Description (main purpose)	Baseline for comparison	Research line	TRL
Farm scale anaerobic digestion (anaerobic digestion strategies for optimised nutrient and energy recovery from animal manure)	Digesting on-farm residues to produce on-site renewable energy and reduce GHG from manure storage. Small-scale anaerobic digestion is a tool for agricultural companies to increase self-sufficiency in terms of energy demand and thus be less dependent on fluctuating energy market prices.	Manure/crop residue management without processing	A	8
Catch crops for biogas production (catch crops to reduce N losses in soil and increase biogas production by anaerobic co-digestion)	Optimising nitrogen management in agriculture, by reducing the nitrate content in soil after harvesting the main crop. In addition, the use of catch crops as a co-substrate in the anaerobic digestion of livestock manure aims to increase biogas production in comparison with conventional anaerobic mono-digestion of manure. Finally, the use of digestate as fertiliser enables the nutrient loop to be closed.	Maize crop with mineral fertilisation and untreated manure	B	6-7
Precision fertilisation (precision fertilisation of maize using organic materials)	Combining precision fertilisation and manure application in maize.	Precision fertilisation using mineral fertilisers	C	4-5
Low-temperature ammonium-stripping (low-temperature ammonium-	Low temperature vacuum ammonium-stripping recovers ammonia from livestock slurry and obtains an ammonia salt that can be reused as a fertiliser. The recovered ammonia can be in the form of	Pig manure management without processing, where surplus livestock manure is	D	4

stripping using a vacuum)	ammonium sulphate or nitrate salt solution and can easily be transported to distant croplands.	exported to distant croplands		
Insect breeding as a protein source (insect breeding as an alternative protein source on solid agro-residues (manure and plant residues))	Bio-conversion of low-value side-streams to high-value insect biomass (consisting of protein, chitin and fat) with applications as feed, pet food and human food.	Residue and manure management without processing.	E	7

None of the technologies was at the highest level of maturity, TRL 9, where the technology has been implemented and proven to be effective, including in different situations (e.g., climate and soil conditions or in different countries). Some of the technologies were at the laboratory or prototype stage, thus the quantitative data would be too specific and uncertain to be considered as representative of the technology. In addition, the definition of baseline scenarios could be a sensitive issue. The current study followed the criteria used by the technology providers.

Considering the above specifications and limitations, an Excel-questionnaire file (Supplementary Material B) was developed asking technology providers in charge of the alternative solutions to provide agri-environmental assessments of the technologies. The Delphi method (Linstone & Turoff, 1975) was applied to assess the potential beneficial and harmful effects of the technologies, involving a structured communication technique that relies on a panel of experts. The Delphi method is widely applied and validated in different research areas and although it is subjective its credibility depends on the validity of the experts' evaluations (Toro et al., 2013). The Delphi method has proven valuable for forecasting and identifying and prioritising issues at an early stage (Okoli and Pawlowski, 2004). In this study, it was applied to technologies for nutrient recovery and enhancing nutrient efficiency. It should be noted that the Delphi method was not used to select the dashboard indicators, but rather to assess the potential effects of the technologies.

A qualitative approach was therefore applied to identify the potential 'positive', 'negative', 'neutral' and 'unknown' effects of the technologies. 'Positive' and 'negative' were used when the expert had knowledge about an expected beneficial or harmful effect on the indicator as a consequence of implementation of the technology. 'Neutral' meant that the indicator is not or not significantly affected by the technology, or the indicator is not related to the technology (e.g. renewable energy production is not related to the technology of precise fertilisation). 'Unknown' meant that the expert still does not know what type of effect the technology will have on the indicator due to its dependence on other conditions (i.e., climate and management operations), but a change could potentially be realistic.

The assessment comprised two rounds. First, the experts of each technology answered the questionnaire about the potential effects of implementation of the technologies. Second, the leading researchers in each research line asked the experts about their doubts in the qualitative assessment. The leading researchers had access to all the answers the experts gave concerning their research line.

3.2.4 Recommendation on developing dashboard indicators for a quantitative assessment

A qualitative assessment introduces the nature or direction of the effect (i.e. positive, negative, unknown, and neutral), providing a screening of the technology being evaluated and the relevance of the indicators. However, this kind of assessment does not present the magnitude of the effect, which is essential in order to compare different scenarios. Thus, a quantitative assessment needs to be undertaken, for instance to compare the same technology applied under different conditions to establish which produces better results.

There are several approaches for calculating these indicators, and they mostly depend on data availability. In the present study, methodologies following recommendations based on IPCC and IPCC Tiers were used to determine the quantitative calculation of DBI (Table 2). The IPCC Tiers represents the level of methodological complexity employed to quantify the indicator, usually divided into Tiers 1, 2 and 3. Tier 1 is the basic method, usually using default methods, for instance the IPCC's worldwide emission fractions Tier 2 is an intermediate option using country-specific methodologies, and Tier 3 represents the most data-intensive and complex methodologies (Yona et al., 2020). It should be noted that it was not always possible to provide different methodologies for the indicators considering the IPCC Tiers.

Table 2: Dashboard indicators and different TIERs to measure the indicators and a proposal to evaluate the grade of improvement of the technologies

Dashboard indicators	Guidelines for measuring the indicator
Use of primary resources	
Rock phosphate	Rock phosphate used to produce P fertilisers: Tier 1: production 1 kg of P fertiliser (rock phosphate), with 32% P_2O_5, requires 5 kg of phosphate ore (Colomb et al., 2014), thus by dividing the amount of P fertiliser avoided by 1.6 it is possible to establish the potential phosphate ore saved.
Natural gas[1]	Natural gas avoided by nutrient recovery (Wernet et al., 2016) Tier 1: 813 L natural gas / 1kg nitrogen fertiliser as N 273 L natural gas /1 kg phosphate fertiliser as P_2O_5
Oil	Oil used in machinery measured on the field. Tier 3: measured in the field.
Water	Water used on the field, including irrigation and other practices. Tier 3: measured in the field.

Nutrients recovered[9]	N (as N-NTK and N-NH_4) and P recovered from agricultural practices Tier 1: for organic fertilisers: composition of organic fertilisers (Avadí et al., 2020) Tier 3: measured in the field.
Emissions to the environment	
Ammonia (air)	Tier 1: emission fractions (EF) from EEA[2,3] (for livestock and crop production) Tier 2: methodologies from EEA[2,3] (for livestock and crop production) Tier 3: ammonia volatilisation emitted measured in the field or using mechanist models
Nitrous oxide (air)	Tier 1: EF from EEA can be used (for livestock)[1], IPCC methodology (for crop production)[4] Tier 2: mass-flow approach from EEA (for livestock and crop production)[1] Tier 3: nitrous oxide emitted measured on the field or mechanist models
Methane (air)	Tier 1: EF fraction from IPCC guidelines (for livestock)[4] Tier 2: country-specific EF calculated using IPCC methodology (for livestock)[4] Tier 3: methane emitted measured in the field (only relevant in rice production) or mechanist models
Nitrates (water)	Tier 1: EF from EC-PEFCR (2018)[5] Tier 2: empirical models, simple equations using country-specific parameters (e.g., SALCA-Nitrate[6]) Tier 3: leached nitrate measured in the field or mechanist models (e.g., Daisy and Animo)
Phosphorus (water)	Tier 2: Empirical models (e.g., SALCA-P[7], PLCI[8]) simple equations using country-specific parameters Tier 3: Phosphorus leached measured on the field or mechanist models (e.g. ,Animo)
Particulate matter (PM_{10})	Tier 1: EF from EEA (for livestock and crop production)[2] Tier 3: particulate matter measured in the field
Resilience to climate change	
Carbon footprint	Carbon footprint (CFP) simplified considering N_2O, CH_4, oil and energy consumption. Tier 1: characterization factors from Fazio et al. (2018) for carbon footprint. 1 kg CH_4 = 36.8 kg CO_2eq; 1 kg N_2O = 298 CO_2eq; 1 kg diesel = 3.6 kg CO_2eq; 1 kWh electricity = 0.498 CO_2eq Tier 2: 1 kg CH_4 = 368 kg CO_2eq; 1 kg N_2O = 298 CO_2eq; 1 kg diesel = 3.6 kg CO_2eq; 1 kWh electricity = emission fraction by country[9] (or updated value)
Non-renewable energy consumption	Non-renewable energy consumed in the field. Tier 3: Measured on the field.
Soil quality	Erosion factor Tier 1: USLE equation Tier 3: Measured on the field.
Renewable energy production	Tier 3: biogas (or methane) volume converted into renewable energy (kWh) (or heat to be added to natural gas system) produced on the field.

[1] To better describe the performance of the technologies, 'natural gas' was split into natural gas (N fertilizer) and natural gas (P fertiliser), and 'nutrients recovered'

[2] EMEP-EEA guidebook 3.b Manure management (ANNEX 1 in Ntziachristos & Samaras (2019)).

[3] EMEP-EEA guidebook 3.d Crop production and agricultural soils (ANNEX 1 in Ntziachristos & Samaras (2019)).

[4] Document 'Good practice guidance and uncertainty management in national greenhouse gas inventories' (Penman et al., 2000)

[5] Document 'Product Environmental Footprint Category Rules Guidance, version 6.3' (EC-PEFCR, 2018)

[6] Richner et al., (2014)

[7] Prashun (2006)

[8] Ten Hoeve et al., (2018)

[9] Emission fractions for the contribution of energy regarding Carbon footprint

3.3 Results

3.3.1 Review of agri-environmental indicators

This section reviews and takes stock of progress in selecting agri-environmental indicators to assess potential solutions for nutrient recovery in agriculture. Following the review, nineteen articles were selected for use as the basis for the set of dashboard indicators. Due to the large number of indicators in the reviewed articles (more than a hundred), a decision was made to present indicators covered in at least two different articles (Table 2). Furthermore, the indicators that represented the same environmental emissions or effects but had been termed differently were merged. For instance, ‘greenhouse gas emissions’ and ‘agricultural greenhouse gas budget’ were merged as ‘greenhouse gas emissions’. It should be noted that this is not a comparison of how those indicators are estimated or calculated, but only an assessment of their inclusion in the studies reviewed in Table 3.

The indicators that appeared most frequently in the selected articles were ‘nutrient (N and P) balance’, ‘soil organic carbon and soil organic matter’, ‘water use’, ‘greenhouse gas emissions’ and ‘nitrate leaching’.

The articles that covered the widest range of the selected indicators were Wheaton & Kulshreshtha (2013) (eleven), Kasztelan and Nowak (2021) (nine), Wheaton & Kulshreshtha (2017) (nine) and Viglizzo et al. (2006) (eight). Although none of these studies focused on solutions for nutrient recovery in agriculture, all of them focused on environmental sustainability performance or the environmental performance of agricultural practices, which was also the goal of the dashboard indicators.

Table 3: Review of agri-environmental and environmental indicators applied in agricultural and livestock practices

Indicators	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**Total**
Nitrate leaching	x				x	x	x					x					x	x	x	8
Pesticides	x			x		x				x		x				x		x		7
Manure management	x	x						x						x						4
Agricultural machinery	x					x	x	x						x						5
Fertiliser consumption	x						x		x				x		x	x		x		7
Crop diversity	x							x												2
Nutrient (N and P) balance		x	x	x		x	x	x	x				x	x		x	x	x		12
Organic fertiliser consumption		x						x						x						3
Greenhouse gas emissions		x		x	x					x	x				x			x	x	8
Water use		x		x		x						x	x		x	x	x		x	9
Ammonia volatilisation		x		x											x				x	4
Utilised agricultural area (UAA)			x									x								2
Energy consumption in agriculture				x		x							x		x					4
Risk of wind erosion				x		x						x								3
Renewable energy production from agriculture				x									x							2
Soil organic carbon (SOC) and soil organic matter (SOM)				x	x	x	x	x	x		x	x		x			x	x		11
Risk of soil erosion, soil quality						x		x				x						x		4
Phosphorus leaching						x				x		x			x		x	x	x	7
Risk of soil salinisation						x						x								2
Yield										x	x		x							3

Legend: 1 = Vesterager et al. (2012), 2 = Louwagie et al. (2012), 3 = Chen et al. (2014), 4 = Kasztelan and Nowak (2021), 5 = Dal Ferro et al (2018), 6 = Wheaton & Kulshreshtha (2013), 7 = Kubacka et al. (2016), 8 = Bélanger et al. (2015), 9 = Dolman et al. (2014), 10 = Gürlük and Uzel (2016), 11 = Kirchner et al. (2015), 12 = Wheaton & Kulshreshtha (2017), 13 = Fabiani et al. (2020), 14 = Bélanger et al. (2012), 15 = Pelzer et al. (2012), 16 = Tomaselli et al. (2020), 17 = Fegraus et al. (2012), 18 = Viglizzo et al. (2006), 19 = Eichler et al. (2020)

3.3.2 Agri-environmental indicators selected as dashboard indicators

The indicators selected should be credible and available, easily understandable, comparable, relevant for forecasting future scenarios, easily combined with socio-economic scenarios, and comparable between countries (Gupta & Sinha 1999). Based on the review conducted, the final set of indicators is shown below and a detailed explanation of these follows:

- nutrients (N and P) balance, referred to as ‘nutrients recovered’
- ‘water use’
- greenhouse gas emissions, split into ‘methane’ and ‘nitrous oxide’
- ‘nitrate leaching’
- ‘phosphorus leaching’
- ‘soil quality’
- ‘non-renewable energy consumption’
- fertiliser consumption, counted as the ‘natural gas’ used in the production of N and P fertilisers and ‘rock phosphate’ used to produce P fertilisers.
- agricultural machinery, counted as the ‘oil’ used in it
- ‘ammonia volatilisation’

In addition to these, the indicator ‘particulate matter’ was included due to its importance, particularly in the livestock sector. ‘Carbon footprint’ was also included to provide a balance between energy (from non-renewable sources) consumed and energy produced (from renewable sources), i.e. issues impacting climate change. Therefore, in order to provide a simple overview of the dashboard, the fifteen indicators selected for the dashboard were nested within three dimensions: ‘use of primary resources’, ‘emissions to the environment’ and ‘resilience to climate change’ (Table 4).

Table 4: Dashboard indicators aiming to assess nutrient recovery from agricultural solutions

Dimension	Dashboard indicator	Acronym	Positive when there is:
Use of primary resources	Rock phosphate	RP	reduction of consumption
	Natural gas	NG	reduction of consumption
	Oil	OI	reduction of consumption
	Water	WT	reduction of consumption
	Nutrients recovered	NR	improvement in it
Emissions to the environment	Ammonia (air)	NH_3	reduction of emission
	Nitrous oxide (air)	N_2O	reduction of emission
	Methane (air)	CH_4	reduction of emission
	Nitrates (water)	NO_3	reduction of leaching
	Phosphorus (water)	P	reduction of leaching
	Particulate matter (air)	PM	reduction of formation
Resilience to climate change	Carbon footprint	CFP	reduction of it
	Non-renewable energy consumption	NEC	reduction of consumption
	Soil quality	SQ	improvement in it
	Renewable energy production	REP	improvement in it

3.3.2.1 Use of primary resources

Phosphorus is a critical global resource and an essential nutrient for plants, animals and humans. Current, global reserves are known to be limited. Rock phosphate has been categorised as a 'critical raw material' in Europe by the European Commission (Bertrand et al., 2016). This non-renewable resource has taken around 15 million years to form, and around 80% of the resource extracted globally is used for food production, specifically to make P fertilisers (Roberts & Johnston 2015). There is a consensus that the quality of the remaining phosphate rock is declining due to unwanted clay particles and heavy metals in the mined phosphate rock. Furthermore, phosphates are mined outside the EU, making it a geopolitical issue. Rock phosphate can be included in AEI 5 'Mineral fertiliser consumption'.

Large amounts of natural gas and air are used to produce nitrogenous fertilisers (e.g., ammonia, urea, ammonium nitrate), the cost of which is closely linked to energy prices (EU, 2019). The consumption of fossil fuels, such as oil products and natural and derived gases, leads to resource depletion and emissions of GHG as well as other emissions to the air (EEA 2020). Therefore, efforts made in agricultural practices are expected to reduce the use of mineral fertilisers and consequently dependence on these fuels. Natural gas can also be included in AEI 5 and in EGD 2.1.6 where plans for agriculture include sustainable practices are encouraged, such as organic farming and a reduction in the use of chemical fertilisers.

Oil is mainly linked to agriculture through the use of machinery (e.g. cultivation of fields with tractors, tillage operations etc.). Oil and petroleum products contributed 53% of total energy consumption by agriculture in the EU-28 in 2017, and were the main fuel type in most countries (EU-AI 2020). One way of reducing oil use is to prioritise technological solutions that reduce tillage, sowing or harvesting practices. Oil can be included in AEI 11.2 'tillage practices', highlighting the importance of reducing soil disturbance or eliminating tillage and consequently reducing oil consumption.

Water use for irrigation is a major driving force behind water abstraction globally. In the EU, on average the agricultural sector accounts for 46% of total annual water use, with 90% of it being used in southern Europe (EU-AI, 2020). In coming years, climatic conditions, such as a decrease in precipitation in southern Europe together with the lengthening of the thermal growing season, may lead to a slight increase in the requirement of water for irrigation. Water use is one of the indicators that appeared most in the international agreements mentioned above: AEI 7 'Irrigation', AEI 20 'Water abstraction', CCI 39 'Water abstraction in agriculture' and EGD 2.1.7 'Preserving and restoring ecosystems and biodiversity'.

The recovery of nutrients can help close inefficiency gaps, thus improving the food supply chain (Verstraete et al., 2016). The European Commission is endeavouring to reduce nutrient losses by at least 50%, which will represent a reduction in the use of fertilisers of 20% by 2030 (EU 2020). Nutrient losses can be prevented by recovering nutrients from animal manure, for example, making a valuable contribution to improving the efficiency of nutrient management by moving Europe towards a more circular economy (Buckwell & Nadeu 2016). Nutrient recovery contributes to the indicator AEI 5 'Mineral fertiliser consumption' and EGD 2.2.3 'Mobilising research and fostering innovation'.

3.3.2.2 Emissions to the environment

Regarding emissions to the air, water and soil, the agricultural sector in Europe in 2015 emitted a total of 3751 kilotonnes of ammonia, making it responsible for 94% of total ammonia emissions across the region (EU-AI, 2020). Due to this high impact, ammonia volatilisation is included in AEI 15 'Gross nitrogen balance', AEI 18 'Ammonia emissions' and EGD 2.1.7. In addition, particulate matter, which is also related to ammonia emissions, is included in EGD 2.1.7.

Nitrous oxide (N_2O) is a potent GHG with a 100-year global warming potential that is 298 times greater than that of carbon dioxide (CO_2) (IPCC, 2001). Agriculture contributes to those emissions mainly through the use of fertilisers containing nitrogen, both in the form of mineral fertiliser and manure. Its contribution is accounted for in national GHG inventories, and is covered by AEI 15, AEI 19 'Greenhouse gas emissions', CCI 45 'Emissions from agriculture' and EGD 2.1.1 'Increasing the EU's climate ambition for 2030 and 2050'.

Methane (CH_4) is a GHG that mainly comes from the enteric fermentation of ruminants and the manure treatment chain. Methane is also included in national GHG inventories and is addressed in AEI 19, EGD 2.1.1 and CCI 45.

In general terms, agriculture is the greatest contributor to nitrate emission to European freshwaters (50 - 75%). Consequently, legislation has been put in place to address this issue. The Nitrates Directive (EEC, 1991) requires the establishment of nitrate vulnerable zones (NVZ) in areas where agricultural sources of nitrate have led or could lead to excessive concentrations in freshwater or threatened waters sensitive to eutrophication. Nitrate leaching is included in AEI 15, AEI 27.1 'Water Quality - Nitrate pollution', EGD 2.1.7 and CCI 40.

Vulnerability to phosphorus leaching refers to the combined risk of phosphorus loss to surface water by a combination of low sorption capacity, high erosion risk and increased risk of drainage and runoff. The contribution of agriculture to the phosphorus loads in surface water is estimated to be up to 50%, including wastewater from farms and seepage from manure stores and agricultural land (Bomans et al., 2005). Phosphorus leaching is included in AEI 16 'Risk of pollution by phosphorus', EGD 2.1.7 and CCI 40, and is covered by the European Water Framework Directive to achieve good ecological status in all surface waters (European Commission 2000).

3.3.2.3 Resilience to climate change

Regarding energy consumption, the evolution of energy prices is crucial for the viability and development of agricultural systems. Energy prices may lead to structural changes in production and farming systems, thus a reduction in energy consumption could improve the agri-food sector (Gomez et al., 2013). Novel technologies can produce biomass co-products, of animal or plant origin, which in turn are potential products as sources of renewable energy or fertiliser. Furthermore, novel technologies should ensure the reduction of energy consumption or use of cleaner energy and preferably both. These results are in line with circular economy values targeted by AEI 8 'Energy consumption', EGD 2.1.2 'Supplying clean, affordable and secure energy' and CCI 44 'Energy use in agriculture, forestry and food industry'.

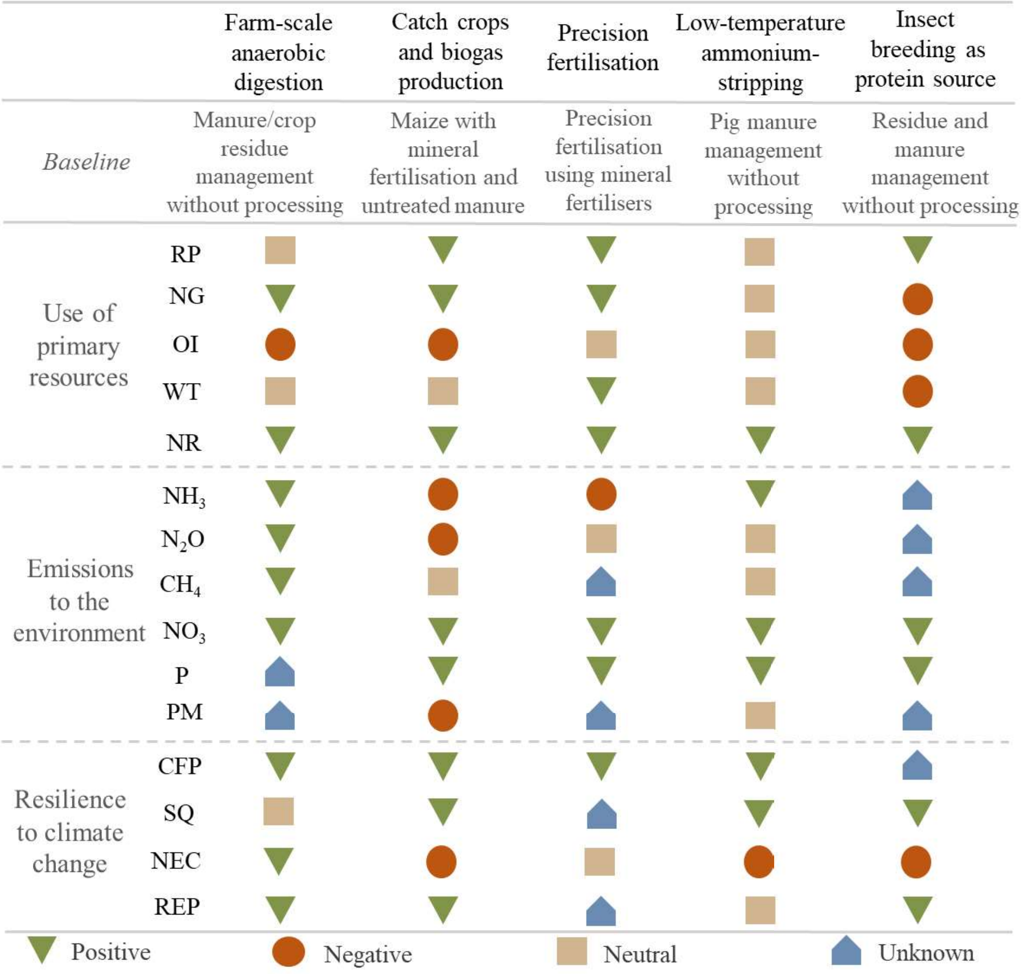
In Europe, out of total GHG emissions in 2017 contributing to climate change, 10% was emitted by the agricultural sector. In the period from 1990 to 2017, the sector reduced its emissions, measured by the indicator carbon footprint, by 104 million tonnes of CO_2-equivalents, corresponding to a 19% reduction (EEA 2021). However, Europe is already on track to meet its GHG emissions reduction for 2030 and the most ambitious goal that links energy sources and infrastructure to support decarbonisation and build a climate-neutral EU by 2050 (EU 2020). The carbon footprint (CFP) is included in EGD 2.1.1.

Soil is a valuable, non-renewable resource that offers a multitude of ecosystems goods and services. The main concern regarding soil quality is the prevention of erosion, maintenance of productivity and soil carbon coverage. Soil preservation is considered within AEI 21 'Soil erosion', AEI 26 'Soil quality', CCI 42 'Soil erosion by water' and in CCI 41 'Soil organic matter in arable land'.

3.3.3 Dashboard indicator results: Testing technologies for nutrient recovery from agriculture

A qualitative assessment of the dashboard indicators is not judged by the amount of reduction or increase of the indicator, but rather by the nature of the technology's potential impact compared with a baseline (Fig. 1). It is important to highlight that by changing the baselines scenarios, the potential effects can be also changed.

Figure 1: Dashboard including the potential impacts of the solutions for nutrient recovery and improvement of nutrient efficiency in agriculture



		Farm-scale anaerobic digestion	Catch crops and biogas production	Precision fertilisation	Low-temperature ammonium-stripping	Insect breeding as protein source
Baseline		Manure/crop residue management without processing	Maize with mineral fertilisation and untreated manure	Precision fertilisation using mineral fertilisers	Pig manure management without processing	Residue and manure management without processing
Use of primary resources	RP	■	▼	▼	■	▼
	NG	▼	▼	▼	■	●
	OI	●	●	■	■	●
	WT	■	■	▼	■	●
	NR	▼	▼	▼	▼	▼
Emissions to the environment	NH_3	▼	●	●	▼	⬟
	N_2O	▼	●	■	■	⬟
	CH_4	▼	■	⬟	■	⬟
	NO_3	▼	▼	▼	▼	▼
	P	⬟	▼	▼	▼	▼
	PM	⬟	●	⬟	■	⬟
Resilience to climate change	CFP	▼	▼	▼	▼	⬟
	SQ	■	▼	⬟	▼	▼
	NEC	▼	●	■	●	●
	REP	▼	▼	⬟	■	▼

▼ Positive ● Negative ■ Neutral ⬟ Unknown

Legend: RP=rock phosphate; NG=natural gas; OI=oil; WT=water; NR=nutrients recovered; NH_3=ammonia (air); N_2O=nitrous oxide (air); CH_4=methane (air); NO_3=nitrate (water); P=phosphorus; PM=particulate matter; CFP=carbon footprint; SQ=soil quality; NEC=non-renewable energy consumption REP=renewable energy production.

Overall, compared with the baseline established by the experts, all the solutions have the potential to have a positive impact on the indicators 'nutrients recovered' and 'nitrate leaching'. 'Farm-scale anaerobic digestion' was the technology that had the most positive impact potential (63%), followed by 'catch crops and biogas production' (50%), 'precise fertilisation' (56%), 'low-temperature ammonium-stripping' (38%), and 'insect breeding as an alternative protein source' (38%).

In terms of the indicators, the most 'positive' indicators were 'nutrients recovered'(100%) and 'nitrates' (100%). Potential negative impacts are expected from 'oil', 'electricity', 'ammonia', 'nitrous oxide' and 'particulate matter'. 'Water' and 'oil' were the indicators that received more neutral responses, meaning that compared with a baseline no changes are expected in the indicator or the indicator is not related to the technology. Finally, 'particulate matter' was the indicator that received 'unknown' more as a response. One plausible explanation is that the indicator is difficult to predict and calculate. In addition, as seen from the review, it is not usually used as an indicator in a set of agri-environmental indicators, despite its relevance.

A detailed qualitative assessment of the indicators is provided below for the technologies 'farm scale anaerobic digestion', 'precision fertilisation', 'low-temperature ammonium-stripping' and 'insect breeding as a protein source'. A quantitative assessment is provided for 'catch crops for biogas production' in section 3.4.

3.3.3.1 Anaerobic digestion strategies for optimised nutrient and energy recovery from animal manure

Anaerobic digestion (AD) has multiple environmental benefits such as the treatment and reduction of waste, renewable energy production and reduction in mineral fertiliser use (Vasco-Correa et al., 2018). However, compared with the baseline where manure and crop residues are not processed, no reduction or increase in rock phosphate is expected since all of the phosphate that is in the input material of the biogas plant is still available in the resulting digestate. In fact, the total amount of nutrients (N, P, K) remains unchanged during the AD process, even though the amount of mineralised N will increase due to the AD process. The remaining organic matter (OM) is more stable than raw feed, which might consequently have a positive impact on soil quality compared with the baseline using mineral fertiliser, although less OM is applied in the soil compared with untreated slurry. There is an increase in energy consumption in the biogas plant, but a reduction in non-renewable energy consumption is expected since the renewable energy produced can meet the demand for electricity (Lombardi & Francini, 2020). There will be a small increase in the amount of oil for the transportation of manure to the biogas plant.

Anaerobic digestion (AD) can transform waste and organic materials into renewable energy in the form of CH_4 (Kaffka et al., 2016). N_2O emissions after application in the field are expected to decrease because volatile solids that lead to oxygen consumption and stimulated denitrification are reduced in AD (Sommer et al., 2004) as the storage time of manure and crop residues will decrease substantially. Research shows that, CH_4 emissions on dairy farms can be reduced by up to 70% by applying small-scale AD compared with conventional manure treatment. When looking at total GHG-emissions, it can be concluded that this technology could lead to a reduction in emissions of up to 50% (Vergote et al., 2020). It is important to note here that the GHG indicator is heavily case dependent, and that the management of the installation is very important since this 50% reduction potential can fall substantially in the case of bad management, such as CH_4 leakage from the digestor reactor or from digestate storage. Similar reduction potentials are expected in the case of pig manure. Compared with the baseline scenario where manure is not treated, less ammonia will be volatilised after the AD (King et al., 2012). The nitrogen is more mineralised and more available for crops; thus, there are fewer nutrients to be leached, but this also depends on the rate of N application.

Heat and electricity from biogas will greatly increase, having a positive impact on the carbon footprint due to reduced GHG emissions and the production of renewable energy.

3.3.3.2 Precision fertilisation of maize using organic materials

Precision fertilisation is considered to be a powerful solution to mitigate the environmental impacts in agriculture (Bacenetti et al., 2020), anticipating greater fertiliser use efficiency and, a reduced need for fertilisers and the resources required to produce them. The technology can reduce the need for irrigation because the carbon content in the soil makes it more resilient to draughts, compared with the baseline where precise fertilisation uses mineral fertiliser.

Manure application can increase ammonia emissions, but no significant difference in N_2O emissions is expected when organic or mineral fertilisers are applied since these emissions are strongly related to soil moisture and temperature (Meng et al., 2005). The application of organic fertiliser using precision agricultural techniques can prevent N and P leaching, and although methane emissions and particulate matter formation were not covered by the solution, it might have an impact (Meng et al., 2005).

Reducing the use of mineral fertilisers by applying organic fertilisers can help reduce the carbon footprint (Knudsen et al., 2014). Furthermore, the application of organic fertiliser may help to increase effective soil organic matter (SOM) in the long term, contributing to carbon sequestration and closing the C cycle and helping improve soil quality (Banger et al., 2010).

3.3.3.3 Low-temperature ammonium-stripping using a vacuum

The use of pig manure and recovered ammonia can help to replace part of the mineral fertilisers in the system, consequently reducing consumption of rock phosphate and natural gas. The use of manure as a fertiliser also recovers nutrients (Tao et al., 2018). However, no differences are expected in these indicators compared with the baseline with untreated pig manure. The treated livestock manure, which will retain the phosphorus, can be applied close to the farm, instead of being exported, since N restrictions will be reduced. Vacuum stripping needs an energy input for pump operation and heating (Tao et al., 2018). Ukwuani and Tao (2016) report that vacuum thermal stripping requires only 2107 kWh/d energy to heat 66.6 m^3/d of digestate from 37 °C to 65 °C plus approximately 39 kWh/d energy to power the vacuum pumps. Thus, incorporating a vacuum can decrease energy demand by 56% with respect to traditional thermal ammonia stripping.

More than 60% of ammonia is expected to be recovered from livestock manure by applying this technology, representing a 13 t/year saving on N mineral fertiliser production (assuming a 1200 sow farm with livestock manure production of 18 m^3/d and 2000 mg N/L). Livestock manure storage in pits is a known source of ammonia emissions to the atmosphere (Kupper et al., 2020), but with the treatment of this manure, N is recovered and the resulting product is used as fertiliser in a non-volatile form, decreasing ammonia emissions. No changes are expected regarding N_2O and CH_4 emissions or PM formation. The recovery of N and P and reuse as fertiliser has the potential to reduce the loss of nitrates and phosphates.

3.3.3.4 Insect breeding as an alternative protein source on solid agro-residues (manure and plant residues)

Processing livestock manure with insects, for use as feed for animals, will recover nutrients such as nitrogen, phosphate, potassium and several other minerals. Parodi et al., (2020) reported recoveries of 38% nitrogen, 28% phosphorous and 14% potassium on a commercial (non-manure) feed. Recovery from manure is likely to be much lower. An insect facility will consume primary resources and valuable products such as natural gas (to create artificial climates in which insects thrive), oil (for the transportation of manure to insect facility and frass from it), and water (for cleaning). Electricity is also consumed to power equipment.

There will be fewer emissions from the organic waste because the manure will be used as feed for the insects, reducing the mass and nutrient contents of fresh manure (Newton et al., 2005). However, emissions related to insect production will come from manure processing and when the insect frass is applied on the field since the nutrients are still present in the frass. Primary air emissions such as N_2O and CH_4 have been quantified in several studies (Ermolaev et al., 2019; Mertenat et al., 2019; Pang et al., 2020; Parodi et al., 2020), since lowering gaseous emissions is essential for sustainability in the process. NH_3 emissions have also been detected, but the rate is hypothesised to be strongly correlated with the pH of the substrate, where a high pH leads to higher ammonia emissions (Parodi et al., 2020). NO_3^- and P may be present in the drain water of an insect facility after cleaning. Moreover, it should be noted that several existing black soldier fly (BSF) facilities struggle with complaints from neighbours due to the odour typically found there, but this aspect is more social than environmental.

Insects that can be fed food waste, with a resulting tiny carbon footprint, represent a massive opportunity for an animal feed industry that is desperate for new sources of high-quality, sustainable feed alternatives (Singh-Ackbarali & Maharaj, 2017). If insect frass is used for anaerobic digestion, renewable energy can be produced, although this has not been widely investigated, and BSF fat can be converted into biodiesel (Bulak et al., 2020).

3.3.4 Application quantitative DBI in the case study of 'catch crops and biogas production'

A quantitative assessment was performed to test the usefulness of the DBI and, while aware of some limitations, to validate the qualitative assessment using the Delphi method.

The digestate produced will partly replace the use of mineral fertilisers (in the baseline proposed), promoting an improvement of (reduction of) 100% in the indicators RP and NG (P fertiliser), and 76% in NG (N fertiliser). An improvement of 100% is also expected in REP because renewable energy is not produced in the baseline. In addition, there is a reduction in NO_3^- leaching (66%) due to the inclusion of catch crops, in CFP (33%) due to the renewable energy produced, and an increase of 4% in SQ since the catch crop covers the soil avoiding soil erosion. However, the inclusion of catch crops involves field operations such as sowing and harvesting, representing an increase of 28% in OI and of 37% in both EL consumption and PM formation.

Digestate management means a decrease in ammonia volatilization, during storage, and nitrous oxide emissions compared with untreated manure (Hou et al., 2015), but no change was verified since the storage of manure is not included in the scenarios. However, N emissions are usually higher during organic fertiliser application. In the scenarios created, there was an increase of 86% in NH_3 volatilisation and 44% in N_2O emissions, but these emissions can be reduced, for instance, by optimising application timing and rapid incorporation of manure.

It is important to highlight that NH_3 and N_2O emissions from untreated manure applied in the field will certainly impact on baseline emissions, but they are outside the scope of the present study since this would require an important system expansion. Furthermore, several indicators depend on the conditions in which the solution is applied and on the baseline with which it is compared. Therefore, these values are representative of the scenarios created in the present study. Results for the quantitative assessment of the dashboard indicators are presented by hectare (Table 5) and detailed in the Supplementary Material C.

Table 5: Quantitative assessment of the DBI for the solution ‘catch crops and biogas production’

Dashboard indicators		**Baseline**	**Solution**
Use of primary resources			
Rock phosphate (kg P_2O_5/ha)	Tier 1	1562.5	0.0
Natural gas (N fertiliser) (L/ha)	Tier 1	138210.0	32926.5
Natural gas (P fertiliser) (L/ha)		27300.0	0.0
Oil (L/ha)	Tier 1	116.7	162.0
Water (m³/ha)	Not assessed	4072.0	4072.0
Nutrients recovered[1] (N-NTK) (kg N/ha)	Tier 1	0.0	857.6
Nutrients recovered[1] (N-NH_4) (kg N/ha)	Tier 1	0.0	108.0
Nutrients recovered[1] (P) (kg P/ha)	Tier 1	0.0	75.4
Emissions to the environment			
Ammonia (air)	Tier 2: fraction of NH^+_4 evaporated on fertiliser application inserted in the DAISY model (Hansen *et al.,* 2000)	0.6	4.5
Nitrous oxide (air)	Tier 3 using the DAISY model (Hansen *et al.,* 2000)	2.8	4.92
Methane (air)	Not assessed.	-	-
Nitrates (water)	Tier 3 using the DAISY model (Hansen *et al.,* 2000)	12.8	4.3
Phosphorus (water)	Tier 2 using SALCA-P	2.5E-03	2.5E-03
Particulate matter (PM_{10})	Tier 1	20.7	32.75
Resilience to climate change			
Carbon footprint	Tier 1	1804.2	1212.1
Soil quality kg/(ha.a)	Tier 1	195.4	187.6
Electricity consumption (kWh/ha)	Tier 3	1244.0	1710.0
Renewable energy production	Tier 3	0.0	3.21E+03

[1] Nutrient recovery was split into N-NTK, N-NH_4 and P.

3.4 Discussion

3.4.1 Set of indicators for environmental assessment in agriculture

Indicators generally simplify a complex reality, and the identification of relevant and valid indicators has considerable potential to guarantee the most effective use of data provided by the systems evaluated (Kosmas et al., 2012).

Viglizzo et al. (2006) used eleven indicators to assess environmental performance, and seven of them are directly related to the DBI in this study: ‘fossil energy use’ with ‘natural gas’, ‘oil (machinery)’ and ‘electricity’; ‘nitrogen balance’ and ‘P balance’ with ‘nutrients recovered’; ‘nitrogen contamination risk’ with ‘nitrates’, ‘phosphorus contamination risk’ with ‘phosphorus (water)’; ‘soil erosion risk’ with ‘soil quality’; and ‘balance of greenhouse gases (GHG)’ with ‘dinitrogen monoxide’, ‘methane’ and ‘carbon footprint’. They also agreed that complex assessments involve an economic and intellectual cost that might make indicators unsuitable for practical users. Therefore, they opted for a simpler assessment that, despite uncertainties around the calculation of the indicators, did not invalidate the set as a useful initial comparison. However, a continuous review is the best way to improve the quality of the indicators.

Toro et al. (2013) used a qualitative dashboard for an environmental impact assessment because it is versatile and easy to apply. In contrast to the present study, they calculated an index for the indicators to reflect the importance of the impact. The Delphi method and questionnaire were also used in Toro et al. (2013) for their qualitative assessment, and consultations were held with experts in each of the activities that require an environmental impact assessment, as in the present study. Finally, they addressed quantitative values for the indicators using the method developed by Dean and Nishry (1965).

3.4.2 Methodologies used to assess environmental sustainability in solutions for nutrient recovery in agriculture

Several methodologies can be used to assess sustainability in agriculture. Although Life Cycle Assessment is the most common method due its robustness and standardised methods, other methodologies have been also applied, requiring less data and concentrating more on the main focus areas of the solutions. It should be noted that despite the technologies having a main focus (e.g., to recover ammonia), it is essential to evaluate other aspects, mainly to avoid a trade-off between impacts.

There has been growing interest in the technology ‘farm-scale anaerobic digestion’ (Aiu et al., 2019). In Styles et al. (2016) and Ramírez-Islas et al., (2020), for instance, LCA was the methodology used to assess the environmental impacts. Styles et al., (2016) focused on potential impacts in global warming, eutrophication, acidification, and fossil resource depletion, while Ramírez-Islas et al. (2020) assessed impacts in photochemical oxidation and abiotic resource depletion. Thus, these studies covered aspects such as manure storage prior to its treatment or handling, NH_3 emissions in storage, composting and drying of digestate and application of composting, the energy produced and the consumption of non-biological resources such as minerals, metals and water. The dashboard indicators selected in the current study covered all the inputs and relevant outputs for this solution except mineral and metal consumption. However, while the LCA provides a full (upstream and downstream) quantitative assessment, the DBI provides a rapid assessment and screening. Finally, Vasco-Correa et al., (2018) stated that odours can be reduced using AD, but this indicator is not covered by the DBI or the LCAs performed on this solution to date.

An LCA performed for catch crops in Montemayor et al., (2019) assessed environmental impacts in terms of global warming (GW), ozone depletion (OD), particulate matter (PM), photochemical ozone formation (POF), air acidification potential (AAP), freshwater eutrophication (FE), marine eutrophication (ME), land use (LU), and mineral, fossil and renewable resource depletion (RRD). Most of the issues covered in Montemayor et al., (2019) relevant to agricultural production and energy-related processes, are covered by the DBI as well, especially the indicators related to emissions and consumption of resources. Using the DBIs, potential hotspots could be addressed in the indicators reported as having a potential harmful effect. In addition, LCAs focus on the damage caused, while the DBI can also provide information on the potential benefits of the technologies.

Precision agriculture features prominently in sustainable development, with precision fertilisation at its core (Jovarauskas et al., 2021). In Jovarauskas et al. (2021), the focus was on an energy assessment of the fertilisation technology, showing that a reduction in mineral fertilisers reduces energy use and GHG emissions. Wang et al. (2019) assessed several indicators for soil (soil organic matter, temperature, moisture, microorganisms, enzymes, fertility and emissions) and water and nitrogen use efficiency and yield, coinciding in several indicators with the DBIs. In the review performed by Bongiovanni & Lowenberg-DeBoer (2004), insecticide and an economic assessment were also included in their set of indicators, but not in the DBI.

The ‘low-temperature ammonium-stripping’ assessed in the current work is used for the valorisation of pig manure. Hou et al. (2015) assessed different technologies for treating manure, focusing on NH_3 volatilisation, GHG emissions, N_2O emissions and nutrient recovery. Similar to the DBI for nutrient recovery, Hou et al. (2015) compared solutions aiming to achieve the same goal but in different ways. In Vázquez-Rowe et al. (2015), eighteen LCA impact categories (climate change, OD, human toxicity, photochemical oxidant formation, PM formation, ionising radiation, terrestrial acidification, FE, ME, terrestrial eco-toxicity, freshwater eco-toxicity, marine eco-toxicity, agricultural land occupation, urban land occupation, natural land transformation, water, metal and fossil depletion) were used to assess digestate treatment technologies, including ammonia stripping. They also highlighted the importance of using a wide range of indicators or impact categories in the LCA to achieve a better understanding of the potential trade-offs between the different technologies. The same reasoning can be applied in the selection of the DBI in the present work, the selection of which also aims to make a rapid comparison of the potential technologies applied in agriculture.

Due to its nutritious properties, the black soldier fly has become an important species in achieving a circular economy, adding value to anthropogenic organic waste by converting it into insect biomass (Klammsteiner et al., 2020). Parodi et al. (2020) assessed the sustainability of black soldier fly larvae-rearing considering the indicators dry matter, carbon and energy balances, nitrogen bioconversion efficiency, phosphorus and potassium balances and CO_2, CH_4 and N_2O emissions. In addition, several LCAs have been performed on the sustainability of black soldier fly-rearing (Smetana et al., 2016; Smetana et al., 2019). As in Vázquez-Rowe et al. (2015), impacts in eighteen categories were assessed in Smetana et al. (2016) to identify a relative sustainability state of insect-based products for food and feed purposes.

The current study focused on the selection of dashboard indicators, the most relevant indicators covering key aspects of resource consumption and emissions to the environment that should be considered in the assessment of technologies for nutrient recovery and enhancement of nutrient efficiency. Despite the limitations and specificity of the cases studies, they revealed that the dashboards indicators covered the important aspects of the technologies. However, further investigation is necessary using other baseline and technology scenarios under different conditions (i.e., climate and system boundaries) for better identification of the potential effects of the technologies and, beyond the nature of the effect, a range for these effects as well.

3.5 Conclusions

In the present work, the dashboard indicators reflect the most relevant environmental aspects and impacts in relation to nutrient recovery and improvements in nutrient efficiency in agriculture. They cover aspects related to natural resource consumption (i.e. land and water), nutrient cycling (i.e. N, P, C) and energy resources (i.e. electricity and fuels), and significant emissions to the air (NH_3, N_2O, CH_4) and water (NO_3^- and P). They also convey relevant information about the environmental performance of potential innovative technologies, as well as being an effective way to benchmark against a baseline (i.e. the current situation).

There is considerable uncertainty around qualitative assessments of future assumptions, but the case studies performed here screened five different technologies, allowed a summary of their potential contributions to reducing or increasing the environmental impacts of agricultural production. Therefore, the DBI covered various aspects in the solutions assessed, but they are not intended to replace the full assessments, required to cover different life cycles related to the system in which the technology could be applied. Therefore, in future studies, the results of the dashboard indicators should be compared with a full LCA, to enable them to be validated, corrected or suggestions made for a better approach to estimating them. Furthermore, economic and social assessments of the technologies are essential if sustainability in agricultural systems is to be achieved.

ACKNOWLEDGEMENTS

We thank the project Nutri2cycle (773682) for the full support during this work and the CERCA Programme/Generalitat de Catalunya.

Special thanks to the anonymous reviewers for their valuable input.

FUNDING INFORMATION

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 713679 and from the Universitat Rovira i Virgili (URV).

AUTHORS’ CONTRIBUTION

Edilene Pereira: Conceptualization, Methodology, Writing-original draft and Investigation. Assumpcio Anton: Conceptualization, Methodology, Supervision and Writing - Review & Editing. August Bonmati: Supervision and Writing - Review & Editing. Sander Brunn, Lars Stoumann Jensen, Erik Meers: Writing - Review & Editing. Laureano Jimenez Esteller: Funding acquisition.

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4. SOCIO ASSESSMENT OF NOVEL TECHNOLOGIES IN AGRICULTURE

This study is available in:

Andrade, E.P., Bonmati, A., Esteller, L.J., Vallejo, A.A., 2022. Assessment of social aspects across Europe resulting from the insertion of technologies for nutrient recovery and recycling in agriculture. Sustain. Prod. Consum. 31, 52–66. https://doi.org/10.1016/j.spc.2022.01.025

4. Assessment of social aspects across Europe resulting from the insertion of technologies for nutrient recovery and recycling in agriculture

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Keywords: S-LCA, agriculture, novel technologies, nutrient recovery, PSILCA.

Abstract:

The potential beneficial and harmful social impacts generated by the introduction of novel technologies, in general, and those concerning nutrient recovery and the improvement of nutrient efficiency in agriculture, in particular, have received little attention, as shown in the literature. This study investigated the current social impacts of agricultural practices in Belgium, Germany and Spain, and the potential social impacts of novel technologies introduced in agriculture to reduce nutrient losses. Based on 65 indicators used in the PSILCA database, the greatest impacts in the baselines are related to fair salaries, biomass consumption, industrial water depletion and public sector corruption. The potential social impacts of the technologies were assessed using 17 midpoint indicators that have a potential to affect social endpoints. The potential benefits of novel agricultural technologies were the creation of more attractive jobs in agriculture, and a better and healthier environment for local communities, workers and society. However, their harmful effects mainly related to workers and local community health, due to the substances used in the technologies and the potential gases emitted. Given the current lack of Social Life Cycle Assessment (S-LCA) studies on novel technologies in agriculture, this study is the first to use the PSILCA database to assess different technologies for nutrient recovery in agriculture in an initial and prospective assessment of their potential social impacts. Further work is required for a site-specific assessment of the technologies when a higher level of social adaptation is achieved.

Nomenclature

CH_4: methane

DALYs: Disability Adjusted Life Years

EC: European Commission

EU: European Union

FAO: Food and agriculture organization

GHG: greenhouse gas

N_2O: nitrous oxide

PSILCA: Product Social Impact Life Cycle Assessment

SRL: Societal Readiness Level

4.1 Introduction

Food and agriculture production systems are facing unprecedented challenges due to the increasing demand for food for a growing population, rising hunger and malnutrition, adverse climate change effects, overexploitation of natural resources, loss of biodiversity, food loss and waste (FAO, 2021b). According to the European Commission (EC, 2021), the European Union (EU) is the world's largest importer and exporter of agri-food products, and the production of commodities are known to have negative environmental and social impacts.

Air pollutant emissions represent a key driver of air quality and ecosystem health, being agriculture responsible for 90% of ammonia emissions mainly from animal manure and fertiliser application (EEA, 2018). In addition, agriculture is one of the main sources of greenhouse gas (GHG) emissions, being responsible for 54% of total methane (CH_4) emitted in EU and approximately 79% of the total nitrous oxide (N_2O) emissions in 2020 (Mielcarek-bocheńska and Rzeźnik, 2021).

To be sustainable, agriculture must meet the needs of present and future generations while ensuring profitability, environmental health, and social and economic equity (Brundtland, 1987). According to the European Nitrogen Assessment (Sutton et al., 2011), ammonia emissions lead to losses of welfare and affect human health. Furthermore, nitrate levels in water resources around the world have increased due to intensive livestock farming and cropping, causing harmful biological effects such as cancer, thyroid disease, infant mortality, and birth defects (Sahoo et al., 2016; Ward et al., 2018). In addition, nitrous oxide emissions can contribute to decreasing lung function, respiratory hospital admissions and cardiovascular outcomes, while nitrogen dioxide has also been associated with adverse respiratory issues, for example coughing or shortness of breath (Levy, 2003).

In a view of the need to improve agriculture and reduce the impacts of nutrient emissions, nutrient recovery technologies will play a pivotal role in achieving these goals. Xia et al. (2020) reviewed current practices and future prospects in control technologies for nitrogen and phosphorous from agricultural runoff, highlighting that tillage practices (i.e., conservation and rotation) can significantly improve surface roughness and reduce surface runoff, also fertilisation management is another effective strategy to control nutrient losses, and process control technologies (i.e., microbial treatment technologies and constructed wetlands) aim to remove pollutants during agricultural runoff transport. In order to mitigate air emissions from agricultural practices, technologies as anaerobic digestion at farm scale, low nitrogen feed and precision farming have been applied (Fellmann et al., 2021).

Innovation in agricultural systems will have several beneficial environmental impacts. However, the associated social impacts may not be immediately apparent, particularly when they are a consequence of environmental benefits. For instance, introducing novel solutions in agriculture to reduce environmental impacts can create opportunities for growth and jobs for local communities, more training for workers, new strategies for the outputs (e.g. biogas production, recirculation of water) on farms, and systems and innovative options involving science, technology and policy. Furthermore, the inclusion of different solutions, some of them with high levels of technology and innovation, presents an opportunity to attract young and skilled workers, making agriculture more interesting to this section of population. However, it is not clear how adaptations and modifications to already established industries might evolve in a sustainable manner (Siebert et al., 2018).

Unfortunately, it is very difficult to obtain specific data to assess the social impacts over a life cycle, i.e. the whole production chain, in agriculture when compared with environmental assessments, leading to an imbalance between the three dimensions of sustainability (Darnhofer et al., 2010). However, there is growing awareness of the need for information on the social costs and opportunities of current activities and their related technological friendly alternatives (Darnhofer et al., 2010). Through the use of life cycle perspective and Life Cycle Assessment (LCA) it is possible to assess environmental loads of a product throughout its entire life cycle and the potential impacts of these loads on the environment (ISO 14040, 2006), being thus a valid tool for addressing the potential shifting of environmental consequences along the whole production chain.

The life cycle of a product involves the extraction of the raw material, the production and distribution of the product, its use and its final deposition, when the product is no longer used. Life Cycle Assessment (LCA) is a tool to investigate the environmental sustainability of the life cycle of products, with the possibility of also providing a social and economic sustainability by including two other tools, Social Life Cycle Assessment (referred to in the present work as S-LCA) and Life Cycle Costing (LCC) (Prasad et al., 2020). S-LCA has been shown to be a relevant methodology for the social evaluation of product systems, processes and services (Chen & Holden, 2017; Pelletier, 2018; UNEP, 2020). S-LCA helps to assess the socioeconomic impacts that directly and indirectly affect stakeholders during a product life cycle, providing short- and long-term information to help organisations better understand their current situation and development over time (Kühnen & Hahn, 2017; Arcese et al., 2018). The Guidelines for Social Life Cycle Assessment of Products and Organizations (UNEP, 2009) were updated in 2020 (UNEP, 2020), and are used to assess social and socio-economic impacts, both positive and negative, of products over their lifecycle.

A socioeconomic assessment may be even harder when it comes to the introduction of novel technologies. Van Haaster et al. (2017) discuss general considerations regarding S-LCA, proposing a framework to explore future potential impacts on social well-being arising from the inclusion of novel technologies, and offer a pioneering prospective S-LCA study. In the present study, an S-LCA using the Likert scale (Albaum, 1997) and expert opinions was used to identify the potential social impacts of the inclusion of solutions to recover nutrients in agricultural systems across Europe.

The objectives of this study were therefore:

- To screen social impacts in agricultural systems using S-LCA and an S-LCA database;
- Identify hotspots in agricultural product systems in Belgium, Germany and Spain using the Product Social Impact Life Cycle Assessment (PSILCA) database;
- To define a set of indicators to assess the social effects of technologies to reduce nutrient losses in agriculture;
- To test and evaluate the effectiveness of prospective assessments in S-LCA, carrying out a case study for three different technologies.

4.2 Methods

A pathway for the S-LCA performed in the present study is detailed in Figure 1 following the Guidelines for Social Life Cycle Assessment of Products and Organizations (UNEP, 2020).

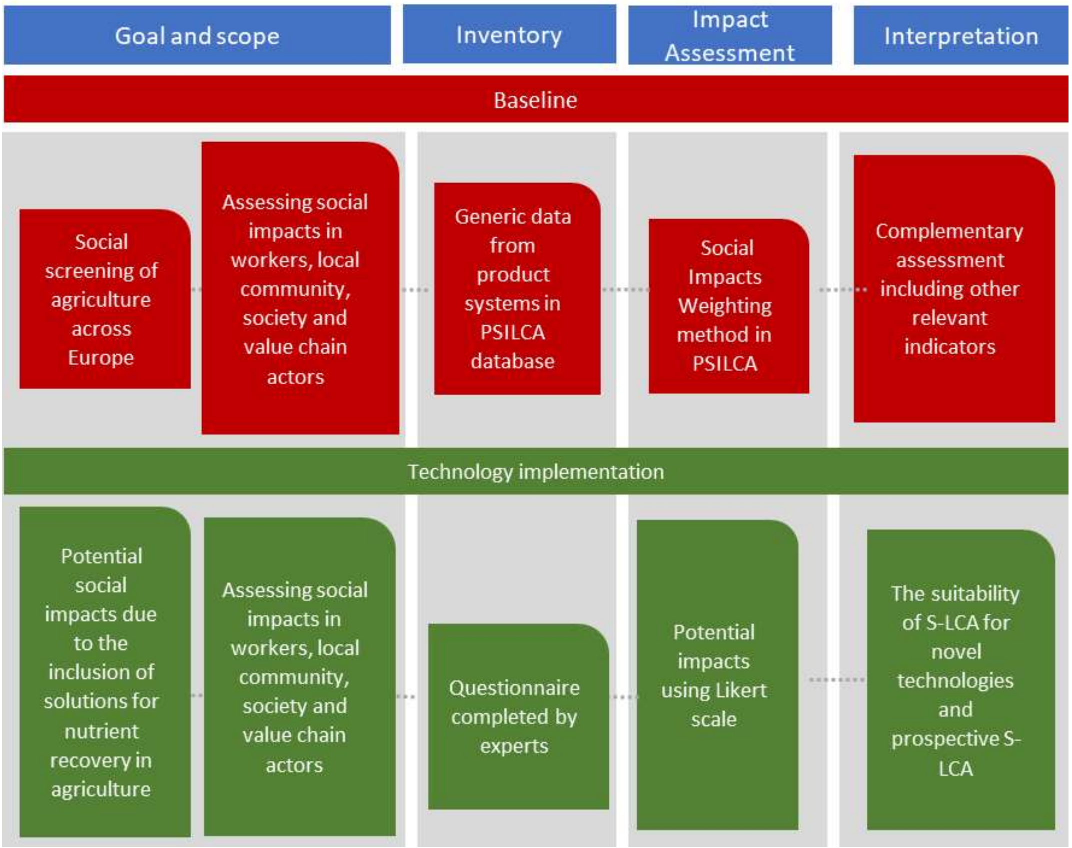

Figure. 1. Path followed to assess a baseline and scenarios created due to the inclusion of a novel technology in an agricultural system.

Scenario analysis has emerged as a way of characterising the future and its uncertainties through structured thinking. In addition, they have been defined as plausible and often simplified descriptions of how the future may develop based on a consistent set of assumptions considering key driving forces and relationships. The qualitative and descriptive assumptions within scenarios are called storylines, and they can describe the consequences or outcomes of a scenario (Rousevell et al., 2010).

4.2.1 Baseline: Agriculture profile using the PSILCA database

The baseline represents a minimum or starting point used for comparisons, that is, a business-as-usual scenario considered to compare with possible changes brought about in the evaluated system. In the current study, the baseline is assumed as to be a 'typical farm', without technologies no technology included to reduce nutrient losses, using the agricultural product system from PSILCA with no changes.

The goal of the first part of the study was to provide a screening analysis taking a country-specific approach using the Product Social Impact Life Cycle Assessment (PSILCA) database. PSILCA version 3 uses the multi-regional input/output database EORA, 2019 version, which covers the entire world economy. As with EORA, PSILCA uses money flows to link processes providing social impacts for around 15,000 sectors in 189 countries (Maister et al., 2020).

The PSILCA database is a global, consistent database, suitable to assess social impacts of products, along product life cycles, providing generic information on social aspects in country-sector combinations and commodities that can be used for screening purposes to identify high-risk regions (Maister et al., 2020; UNEP, 2020). In PSILCA, the sector and country-specific data are obtained from international institutions (e.g., World Bank, OECD, World Health Organization, Walk Free Foundation, ILOSTAT database) and attributed to the selected product systems and indicators. Using PSILCA, it is possible 'to measure' how externalities (e.g. corruption, child labour, trade unionism) affect or can be affected by the product being assessed (Kono et al., 2018; Werker et al., 2019a; Martin & Herlaar et al., 2021).

In the current study, 69 qualitative and quantitative indicators from PSILCA were used to calculate the social impacts of a baseline (current situation) in agriculture and also to identify social hotspots in the product systems (Maister et al., 2020). The indicators address stakeholders such as workers, local community, society and value chain actors. The indicators used in the PSILCA database include those recommend by UNEP-SETAC (Benoit-Norris, 2013).

The system boundaries and life cycle inventory are related to the product systems selected in the PSILCA database: 'Industries - Agriculture, hunting and related service activities' for Belgium, 'Industries - Agriculture and hunting' for Germany, and 'Industries - Agriculture, livestock, and hunting' for Spain. In EORA, each country uses its own classification system and sector names (Lenzen et al., 2013). Therefore, it is assumed that although the names of the products differ slightly, they are comparable in the context of agriculture. Belgium, Germany and Spain were selected because the technologies detailed in section 3.2 have been developed and tested by experts there.

A cut-off of 1E-05 was applied in the impact analysis, which is the maximum detail in the version 'starter' of PSILCA (Maister et al., 2020). The results included all the sectors up to the fifth level of upstream processes, which is sufficient for the current study since the technologies evaluated (section 2.2) have limited capacity to affect the production systems of other countries involved in the main product. No further modification was made to the product systems or indicators values provided by PSILCA.

The functional unit used was 1 USD of output of a generic agricultural product in the respective sectors, since it is intended to assess potential hotspots in the agricultural chain in the countries, and not a specific product. The activity variable was the number of hours required to generate 1

USD of product output, using USD from 2015 as reference. Although it may seem inappropriate to use dollars to assess the impacts for European systems, the dollar is the basis for transactions and is used in major commercial activities in the global economy.

The impact assessment was performed in the free software OpenLCA using the Social Impacts Weighting method from PSILCA, applying characterisation factors to each indicator according to its risk or opportunity created (Table 1). The assignment of risk and opportunity levels was based on international conventions and standards, labour laws, expert opinions and the literature (Maister et al., 2020). The risks represented the potential negative impacts, and the opportunities represented the potential positive impact. The indicator ‘Contribution of the sector to economic development’ was the indicator that assessed opportunities in PSILCA v3.

Nature of indicator	Level	Factor
Risk	Very low	0.01
	Low	0.1
	Medium	1
	High	10
	Very high	100
	No risk	0
Risk/Opportunity	No data	0.1
Opportunity	Low	0.1
	Medium	1
	High	10
	No opportunity	0

Table 1. Characterisation factors for the Social Impacts Weighting method in PSILCA retrieved from Maister et al. (2020)

The total impact on each product system is the summation of the risks subtracted by the opportunities created. In addition, the indicators are also presented separately in Supplementary Material S2 so as not to lose transparency (UNEP, 2020). As explained in Werker et al. (2019b), the metric of medium risk hours (med risk hours) used in PSILCA to present the impact results is not measured on a particular scale (ranges classifying the impacts from very low to very high, for instance), hence it is necessary to compare different supply chains to make the results meaningful. Therefore, the results for this part of the study are presented for each country. Med risk hours represent the total risk involved in producing 1 USD of the output.

4.2.2 Definition of the novel technologies

The metric Societal Readiness Level (SRL) assesses the level of societal adaptation of a novel technology on a scale of 1 (less adapted) to 9 (more adapted) (Bruno et al., 2020). For the technologies included in this study, the SRL was 2. SRL 2 means that the problem is formulated (high environmental impact from agriculture), a solution is proposed (a novel technology to recover nutrients and enhance nutrient efficiency), and the expected societal readiness is defined (social impacts due to the inclusion of the technology in the agricultural scenario) and considers which stakeholders are relevant for the assessment (stakeholders directly and indirectly affected by agriculture and the novel technology developed). The inclusion of the SRL in the presentation of technologies is necessary in order to justify why a qualitative assessment is more suitable for the current study.

The following technologies used in the present study are part of the H2020 Nutri2Cycle[4] project, the focus of which is to close nutrient loops of nitrogen (N), phosphorus (P) and carbon (C) in agriculture.

4.2.2.1 Anaerobic digestion strategies for optimised nutrient and energy recovery from animal manure (farm scale anaerobic digestion)

Residues from agriculture may lead to odour and greenhouse gases (GHG) emissions. Farm scale anaerobic digestion technology produces renewable energy on-site and reduces GHG from manure storage and is a tool to increase energetic self-sufficiency and thus be less dependent on fluctuating energy market prices. In addition, it reduces the need for fossil fuels.

Biogas (main product) and digestate (subproduct) are the final products from the technology. The biogas consists mainly of CO_2 and CH_4, which can be combusted in a combined heat and power (CHP) installation, driving the generator that produces electricity. In addition, the farmer can also use the heat provided by the CHP. The digestate can be used as an organic fertiliser.

This technology was assessed regarding its use in agriculture in Belgium, where it has been developed and tested in the frame of the Nutri2Cycle project.

4.2.2.2 Precision fertilisation of maize using organic fertilisers (Precision fertilisation)

This technology combines precision fertilisation and manure application in a maize crop. To date, manure has been applied as a basal fertilisation, and P variability in the soil is not taken into consideration, which can lead to P accumulation and potential leaching. The technology proposes applying manure as a basal fertilisation based on P requirements established using precision farming tools. By using GPS georeferencing, precision fertilisation can adjust fertiliser application rates according to each specific location in the field. Nowadays, the process of variable-rate fertiliser application, considering the spatial distribution of nutrient content, the creation of fertiliser prescription maps and implementation in the field, is already being put into practice in many farms across Europe (Basso et al., 2016; Vatsanidou et al., 2017).

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[4] https://www.nutri2cycle.eu/

This technology was assessed regarding its use in agriculture in Germany, where it has been developed and tested in the frame of the Nutri2Cycle project.

4.2.2.3 Low-temperature ammonium-stripping using a vacuum (low-temperature stripping)

The aim of this technology is to remove nitrogen from the liquid matrix (manure or thin fraction from digestate). This is done by vacuum stripping and the ammonia is recovered in an absorption system. Absorption can take place using different acids (i.e. sulphuric, nitric or lactic acid), producing ammonia sulphate, ammonia nitrate or ammonia lactate respectively.

Ammonia salt solution can be considered a cleaned form of recuperated nitrogen (N). This ammonia, in the form of an ammonium sulphate, nitrate or lactate salt solution, can be reused as a fertiliser. While the added value of producing the cleaner ammonia water is not proven in the market and as the legislative framework has not been approved yet, the application of the technique will be limited.

This technology was assessed regarding its use in agriculture in Spain, where it has been developed and tested in the frame of the Nutri2Cycle project.

4.2.3 Prospective assessment of novel technologies for nitrogen recovery in agriculture

Social aspects can be firstly assessed applying S-LCA in novel technologies to evaluate potential aspects raised and their associated impacts, qualifying them qualified into positive or negative effects or changes compared to an already existing product, process or service (Burchi et al., 2013). The low adaptation of the solutions is one of the reasons for opting to undertake a prospective and qualitative S-LCA of the technologies.

4.2.3.1 Set of relevant indicators for the S-LCA of novel technologies for nutrient recovery in agriculture

It is important to highlight that most of the technologies that will be incorporated in agricultural systems, making them hard to evaluate as a standalone process due to the low adaptation in the society. Therefore, the prospective assessment undertaken in the present study assessed the potential social impacts due to the inclusion of these technologies considering the life cycle of the product system explored in the baseline.

For a more comprehensive S-LCA method, a limited set of relevant, transparent and easily outlined indicators is required (Siebert et al., 2018). In the current study, the indicators selected prioritised the main issues concerning agriculture and nutrient recovery, both social and environmental indicators (midpoint indicators) with social consequences (endpoint indicators), where the technologies might have an impact. The proposed set of indicators and the assessment carried out aim to present in an easy format to end users and other stakeholders different areas that may be affected by technologies before these stakeholders introduce them into their product systems. For example, by introducing a new technology, stakeholders can contribute to making agriculture more financially attractive for young professionals, safer for workers and local communities, or for a sustainable society in which there is higher level of well-being in the environment, social and economic dimensions (Abad-Segura et al., 2020). The set of indicators is summarised in Table 2, which highlights their relevance for inclusion in the prospective assessment of the novel technologies for nutrient recovery in agriculture. It is important to note that caution should be exercised when carrying out an environmental LCA and a social LCA, using the proposed set of indicators, at the same time to avoid overlaps. It is necessary to clarify how the indicator can have social and environmental consequences or to eliminate the indicator from an assessment, whether environmental or social, as in Werker et al. (2019b).

Midpoint indicator	**Indicator is addressed in…**	**Social endpoint indicators**	**Included because…**
New job position	Hurst et al. (2005)	• Unemployment • Employment in agriculture	• Green innovations introduced in rural areas are expected to create green jobs directly and indirectly • Unemployment and underemployment in rural areas contribute to poverty and low wages • The underestimation of unemployment in rural areas contributes to 'hidden employment' where workers give up searching for jobs or accept working for less time than they would like (Hurst et al., 2005)
High-level skills from workers	van Haaster et al. (2017)	• Hours worked by high-skilled persons engaged • High-skilled labour compensation	• Innovative technologies that require high skills can be associated with decent wages, and safe work conditions, improving agriculture (Kim, 2018)
Training courses for workers	Urbancová & Depoo (2018)	• Extent of staff training	• Several farmers manage their farms by themselves, and training is not a priority in their daily working lives • Employees in agricultural companies are aware of the need to learn and develop due to organisational, technological and social dynamics (Urbancová & Depoo, 2018)
More time in the daily work routine on the farm	Hurst et al. (2005)	• Mean weekly hours worked by employed person by sex and economic activity • Excessive working hours per country	• Adequate working time is a crucial aspect of decent work, providing adequate periods of rest and recuperation • Workers should have access to a minimum desirable number of hours of work to earn an adequate level of monthly remuneration, avoiding involuntary part-time employment and time-related underemployment (Hurst et al., 2005)
Healthy & safety (H&S) of workers regarding regulation for the technology and H&S of workers regarding new source of damage in the farm	van Haaster et al. (2017)	• Existence of labour laws per country • Cases of non-fatal occupational injury in agriculture • Cases of fatal occupational injuries in agriculture	• Agriculture involves dangerous work occupations due to the dangerous machinery used, unsafe electrical wiring and appliances, livestock-transmitted diseases, falls from heights, and exposure to toxic pesticides • Governance or technical instruments intend to protect people and the environment using a technology that is adequately controlled, contributing to sustainable agriculture (Hurst et al., 2005; van Haaster et al., 2017)
Corruption (Potential avoidance of corruption in the substitution of impacting inputs)	PSILCA database (Maister et al., 2020)	• Control of corruption (import of P fertilisers)	• About 85% of P in agriculture comes from processing mined phosphate rock (Cordell et al., 2010), mainly in countries that have a high level of corruption, which both developed and developing countries have been ignoring (Drebee and Abdul-Razak, 2020). When avoiding the

			importation of P, due to the recovery of the nutrient, it has a potential to decrease non-domestic corruption in agricultural products value chain. • An increasing body of literature has provided evidence of the environmental implications of corruption (social aspect).
Ammonia volatilisation (NH_3)	Sustainable Development Goal 2 (SDG 2) 'End hunger, achieve food security and improved nutrition and promote sustainable agriculture' (United Nations, 2022)	• Mean population exposure to particulate matter (PM2.5)	• Agriculture is a major contributor to ammonia emissions, but also has a high potential to mitigate them by implementing beneficial management practices. • The exposure to ammonia volatilised (from a few hours to a few weeks) is associated with small but significant increases in cardiovascular disease-related mortality, and the size of this effect increases with longer-term exposure (Bittman et al., 2013).
Odour on the farm	Wohlenberg et al. (2020) Peters et al. (2014)	• Psychological health effects per organisation, sector and country (number of accidents caused by physical or mental stress)	• Living in proximity to large-scale livestock farms has been linked to symptoms of impaired mental health, as assessed by epidemiologic measures (Donham et al., 2007) • There is evidence that persistent exposure to odours can have adverse effects, for instance, headaches, throat and eye irritation, nausea, sleeplessness, anxiety, stress, or even respiratory problems (D-NOSES consortium, 2019)
Water quality and water consumption	PSILCA database (Maister et al., 2020)	• Use of abiotic and biotic resources and water per sector, area and country	• Water pollution is a global challenge that has increased in both developed and developing countries, undermining economic growth as well as socio-environmental sustainability and health of billions of people (FAO, 2018) • Water quality and water consumption are aligned to the Sustainable Development Goals (SDGs), especially SDG 6 'Ensure access to water and sanitation for all', and target 6.3 '… improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials' • In the last century, water use has doubled the rate of population growth, and in the last 30 years, food production has increased by more than 100%, and agriculture has accounted for approximately 70% of global freshwater withdrawals (FAO, 2017).
Nitrate leaching	SDG 6 'Ensure availability and sustainable management of water and sanitation for all' (United Nations, 2022)	• Pollution of water and groundwater per country	• The Drinking Water Directive (EEC, 1991) defines 50 mg NO_3^-/L as the upper limit for nitrate concentration in water intended for human consumption, and concentrations above 25 mg NO_3^-/L are cause for concern • Some public health studies have estimated elevated risks for subpopulations exposed to chronic levels of nitrate below the regulatory

			standard of 10 ppm nitrate-N, including increased risks of cancer and birth defects (Keeler et al., 2016) •
Phosphorus use (reduction of P importation contributing to reduce local communities' issues)	SDG 12 'Ensure sustainable consumption and production patterns' (United Nations, 2022)	• Nutrient phosphate P_2O_5 (total) used • P fertiliser importation (local communities affected)	• Phosphorus supply disruptions may occur due, for example, to the concentration of production in a small number of countries, political instability, troubled labour and wage relations between workers and phosphate companies (Ridder et al. 2012) • Cadmium accumulation in EU soils due to the use of P fertilisers made with contaminated rock can affect human health, not only causing environmental damage (Ridder et al. 2012) • Some regions that are richest in phosphate reserves are also highly marginalised, with no political voice or economic opportunities
Reduction of external sources of energy	SDG 7 'Ensure access to affordable, reliable, sustainable and modern energy for all' (United Nations, 2022)	• Electricity consumption in agriculture	• The proper usage of renewable energy systems can achieve improvements in local employment, better health, job opportunities, job creation, consumer choice, better life standards, income development, demographic impacts, social bonds creation, and community development (Kumar 2020) • Combining local renewable energy resources with the appropriate technology, self-supply and energy self-sufficiency are possible, generating stable prices and helping to achieve a sustainable model that would help repopulate rural areas (Kumar 2020)
Greenhouse gas emissions (GHG) (regarding health effects on people)	PSILCA database (Maister et al., 2020)	• Burden of disease by country - risk contribution of air pollution (including GHG emissions) in DALYs (Disability-adjusted life year) for 'chronic obstructive pulmonary disease' • Pollution levels by country	• Negative impacts of climate change on crop productivity and livestock will become increasingly serious around the world, having impacts on productivity and consequently on food security (FAO, 2016) • Agriculture, forestry and land-use change are responsible for around 20% of world's total GHG emissions (FAO, 2016) • Climate change threatens society's health, but knowledge and policies linking the reduction of greenhouse gas emissions and potentially large effects on the population's health are not widespread (Haines et al., 2009) • Climate-related health indicators are potentially useful for tracking the adverse public health effects of GHG emissions, enabling more focused interventions (Navi et al., 2017) • Climate change has a huge potential to trigger or aggravate respiratory diseases (D'Amato et al., 2014)

Food production increasing and new knowledge and scientific purpose	SDG 2 ‘End hunger, achieve food security and improved nutrition and promote sustainable agriculture’ (United Nations, 2022)	• Food production index • Expenditure on research and development (% of Gross Domestic Product - GDP)	• Research and development and the proper dissemination of results to agriculturists are crucial to increase agricultural production and achieve food security (Ejeta, 2009)

Table 2. Set of indicators for the S-LCA of novel technologies for nutrient recovery in agriculture

4.2.3.2 Inventory and impact assessment method for qualitative and prospective assessment

Data for S-LCA can be collected from different sources, for instance, scientific publications, generic databases (i.e., PSILCA), interviews, and surveys (UNEP, 2020). For prospective assessments, data sources include expert interviews (Thonemann et al., 2020). The Excel questionnaire featuring the selected indicators was sent to experts in each technology due to the level of detail and the specificity of the assessment (Supplementary material S1). The experts selected in the present study were the researchers responsible for each technology in the Nutri2Cycle project. For each technology, at least two experts were responsible for the answers provided and another expert, the survey leader, was responsible for the review round, resulting in at least three experts for each technology.

The questionnaire was answered using a Likert scale (Albaum, 1997), taking into account the inclusion of a technology in a specific agricultural system. The Likert scale is used to measure attitude and, consist of a series of statements to which a respondent indicates a degree of agreement or disagreement using the following options: strongly agree, agree, neither agree nor disagree, disagree or strongly disagree. The proposed Likert scale was created following the psychometric scale proposed in Likert (1932), specifying the level of agreement with a statement (from totally agree to totally disagree). A detail definition of each potential response for the indicators, and the answers for each technology after two rounds of experts questioning for the indicators selected using the Likert scale are detailed in Supplementary material S3.

In the present study, an adapted version of the approach used in Franze and Ciroth (2011) was applied for the impact assessment, with an assessment method based on interpretation using a simple system with colours and statements. Through this method, results are readily understood and intuitive, and provide a quick overview of the potential impacts of the solutions. Considering the complexity of social phenomena and the difficulty of avoiding ordinal scales completely in S-LCA (Arvidsson, 2019), the scale in Table 3 was used in the impact assessment, ranging from ‘potentially large beneficial effect’ to ‘potentially large harmful effect’. The indicators were not aggregated and the technologies were not ranked.

Level (Likert scale)	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
Impact assessment	High potential of beneficial effect (HPBE)	Potential beneficial effect (PBE)	Indifferent effect (IE)	Potential harmful effect (PHE)	High potential of harmful effect (HPHE)

Table 3. Qualitative assessment of social indicators using Likert scale parameters

Qualitative aspects represent an action from which stakeholders experience the consequences of a product system (Siebert et al., 2018). In the present study, the assessment provided will guide end-users as to the nature of the technologies' potential effect, informing them of what potential effects the technologies may have. The qualitative information obtained from the questionnaires for the midpoint indicators underwent a review round owing to the importance of data triangulation in S-LCA (Ramirez et al., 2016), especially when qualitative data are used since there is no guarantee that the respondents have interpreted the potential effect in the same way (Figure 2). The methodology applied in the review round is presented in the Supplementary material S4.

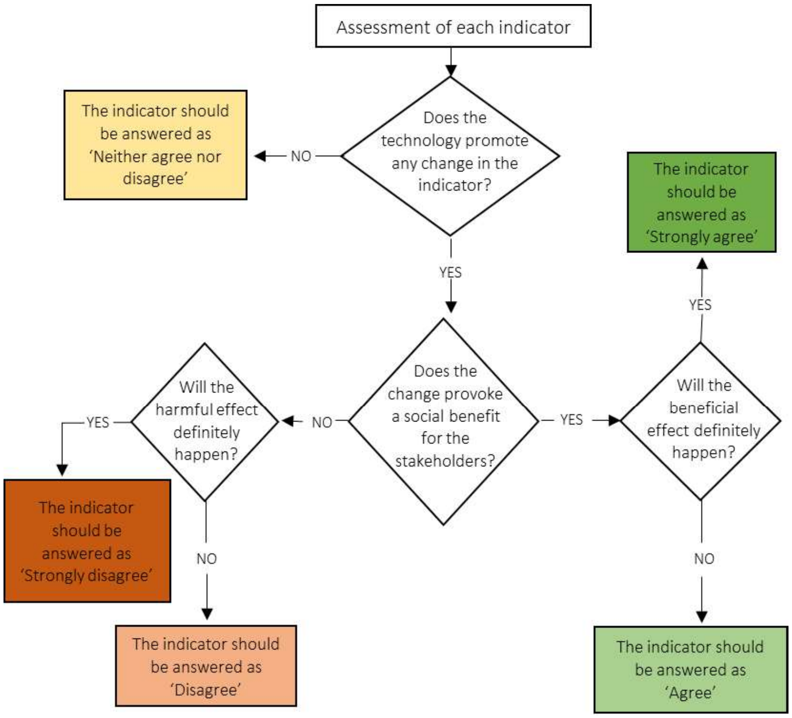

Figure 2. Decision tree for building the social Life Cycle Inventory (S-LCI) through the identification of potential social impacts from solutions for nutrient recovery in agriculture and livestock

4.2.3.2 Comparative analysis using PSILCA

To compare the baseline and the potential changes brought about by the technologies, some indicators in the PSILCA database were selected as having the potential to be affected by the technologies in a potential scenario, with the technologies assessed in a specific analysis (Table 4). Given the difficulty of predicting quantitative data, the complexness of the indicators and the low societal adaptation of the technologies, it was decided to increase or decrease, where it was possible, the indicator's risk level by one level, according to the answers provided in Table 3 and Figure 2, and keeping life cycle inventory as provided by PSILCA for each product system. Thus, for a potential benefit (PBE and HPBE as potential effects of the technology), the risk was reduced in one level in comparison to the risk established in the baseline, but for a potential harmful effect (PHE and HPHE as potential effects of the technology), the risk was increased in one level in comparison to the risk established in the baseline. It is important to note that if the risk is already in the lower boundary or upper boundary of the risk level, it is not possible to decrease or increase the risk, respectively, regardless the effect of the technology.

The baseline is assumed as to be a ‘typical farm’ in the respective country, and the technology scenario was the scenario considering the potential changes in risk due to inclusion of the technology, according to the answers in the questionnaire. The functional unit for both scenarios in the comparison was 1000 USD of a generic agricultural product output.

Ten indicators in PSILCA were associated to the midpoint indicators selected in the present study, meaning that potential benefits or harmful effects of the technologies could change the risks, increasing or lowering them, associated to each indicator in the countries and respective product systems assessed (Table 4). The indicator ‘Presence of sufficient safety measures’ can be improved with more training to use the technology more effectively. ‘DALYs due to indoor and outdoor air and water pollution’ was affected by the reduction (risk decreases) or increase (risk increasing) in GHG emissions. Risks in the ‘Sector average, per month’ can be reduced due to the inclusion of high-skilled workers required to operate the novel technologies. Risks in the ‘rate of non-fatal accidents’ that can be increased due to the insertion of new source of damage in the farm due to the novel technology. The technologies could promote a daily saving of labour, impacting beneficially, regarding H&S and well-being, in ‘weekly hours of work per employee’. The risk in the ‘level of industrial water use’ can be increased or reduced according to the water demanded by the technology. The reduction of external sources of energy (i.e., due to biogas production) can reduce ‘fossil fuel consumption’. Better management of manure (reducing ammonia emissions) can contribute to decrease the risk in the ‘pollution level of the country’, and the creation of new job positions would have a potential beneficial impact reducing risks in ‘unemployment’. Finally, decreasing the dependence on the importation of mineral fertilizers can reduce the risk in the indicator ‘Corruption’.

Stakeholder	Indicator in PSILCA	Midpoint indicator in the present study
Workers	Presence of sufficient safety measures	Training courses for workers
	DALYs due to indoor and outdoor air and water pollution	Greenhouse gas emissions (GHG) (regarding health effects on people)
	Sector average wage, per month	High-level skills from workers
	Rate of non-fatal accidents at workplace	H&S of workers regarding new source of damage in the farm
	Weekly hours of work per employee	More time in the daily work routine on the farm
Local community	Extraction of fossil fuels	Reduction of external sources of energy
	Level of industrial water use (related to total withdrawal)	Water quality and water consumption
	Pollution level of the country	Ammonia volatilisation (NH_3)
	Unemployment rate in the country	New job positions
Value chain actors	Corruption	Corruption (Potential avoidance of corruption in the substitution of impacting inputs)

Table 4. Indicators from PSILCA database affected by the technologies for nutrient recovery and their association to the midpoint indicators selected in this study

4.3 Results

4.3.1 Impact Assessment

4.3.1.1 Social impact assessment of the baseline and identification of hotspots

This section addresses potential social hotspots in the agricultural value chain in Belgium, Germany, and Spain (Figure 3; Supplementary material S2), with indicators assessed according to their impact within the value chain and their respective risk in the subcategories used in PSILCA. The indicators within each subcategory can be checked in Maister et al. (2020). The total impact for the baseline, in med risk hours, using PSILCA, was 10.14 in Belgium, 11.71 in Germany and 12.66 in Spain, representing the estimated total numbers of hours of risk to produce 1 USD output. It is important to bear in mind that for the subcategory ‘contribution of the sector to economic development’ (ECO) this is a positive impact, representing an opportunity of 0.033, 0.027 and 0.039 med risk hours for the sectors, respectively in Belgium, Germany and Spain.

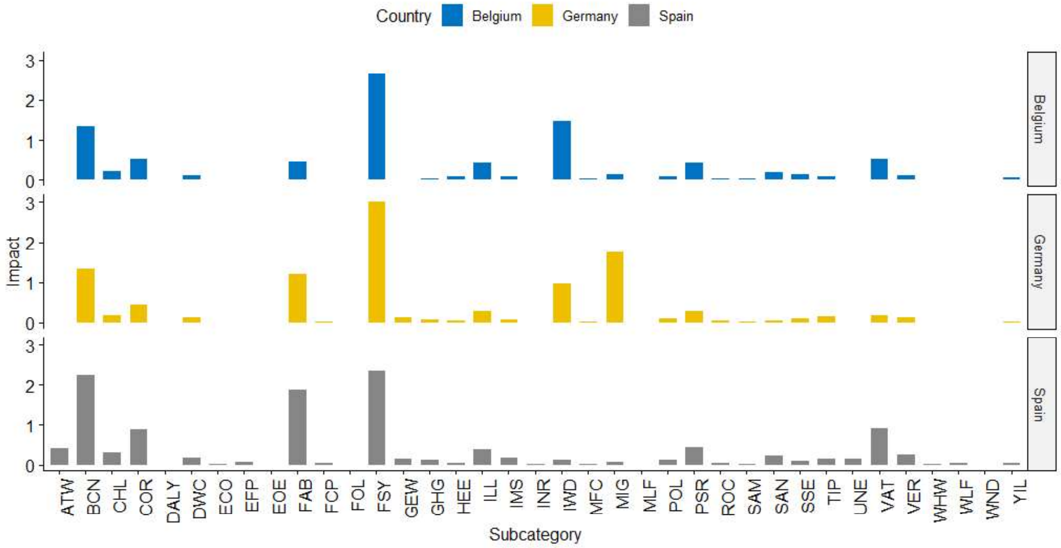

Fig. 3. Impact assessment (med risk hours[5]) of the baseline in agriculture in Belgium, Germany and Spain considering PSILCA database subcategories

Legend: ATW: accidents at work, BCN: biomass consumption, CHL: child labour, COR: public sector corruption, DALY: disability-adjusted life years due to indoor and outdoor air and water pollution, DWC: drinking water coverage, ECO: contribution of the sector to economic development, EFP: embodied footprints, EOE: expenditures on education, FAB: freedom of association and collective bargaining, FCP: fair competition, FOL: forced labour, FSY: fair salary, GEW: gender wage gap, GHG: greenhouse gases footprints, HEE: health expenditure, ILL: illiteracy, IMS: international migrant stock, INR: indigenous rights, IWD: industrial water depletion, MFC: minerals and fossil fuel consumption, MIG: migration, MLF: men in the sectoral labour force, POL: pollution, PSR: promoting social responsibility, ROC: risk of conflicts, SAM: safety measures, SAN: sanitation coverage, SSE: social security expenditures, TIP: trafficking in persons, UNE: unemployment, VAT: value added (total), VER: violations of employment laws and regulations, WHW: weekly hours of work per employee, WLF: women in the sectoral labour force, WND: workers affected by natural disasters, YIL: youth illiteracy

The baseline assessment showed that, considering PSILCA indicators and subcategories, the greater impacts in the value chain of agriculture and potential hotspots in the systems were found in 'fair salary (FSY)' for the three countries assessed. Other important subcategories with large impacts are 'biomass consumption (BCN)', 'industrial water depletion' (IWD), 'value added (total) (VAT)', 'public sector corruption' (COR), 'freedom of association and collective bargaining (FAB)', and 'migration (MIG)'. Therefore, these are the subcategories should be improved in order to contribute to social sustainability in the agricultural sector, i.e. the hotspots in light of the PSILCA results. A detailed explanation for the subcategories with the greatest impacts follows.

'Fair salary' (FSY) is assessed in consideration of the living wage. A living wage is defined as the income needed for a decent living, thus the higher the living wage, the higher the minimum and sector average wages have to be in order to reduce social risks (Maister et al., 2020). In Belgium and Germany, the living wage is more than a thousand dollars per person per month, representing a very high risk, while for Spain it is between 576 and 768 dollars per person per

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[5] Note that the impact produced in the indicator 'contribution of the sector to economic development' represents an opportunity, therefore, a positive impact.

month, representing a high risk. Regarding the sector's average wage, agriculture was found to be a very low risk activity in Germany and Spain, and low risk in Belgium, although agriculture is considered a low-paid sector. It is important to note risk levels for living wage are defined after a combination with the minimum, since the concept of living wage is not necessarily clear, and it is assumed that a very low minimum wage aggravates living conditions in general (Maister et al., 2020).

The 'biomass consumption' (BCN) is assessed as the area used to extract biomass (Maister et al., 2020). Biomass consumption higher than 800 t/km² is considered a very high risk. For Belgium and Germany, biomass consumption was, respectively, 2082 and 1375 t/km² respectively, and for Spain it was 433 t/km², representing a medium risk. The risks were established considering average values across all countries included in the PSILCA database.

'Industrial water depletion' (IWD) was an issue in the agricultural sector in Germany and Belgium, being attributed a very high risk for this subcategory. The risk is related to the indicators addressing water consumed being higher than 40 % of the total withdrawal and more than 13 % of the total renewable water resources in those countries. In Spain, the indicators were classified as low and medium risk respectively.

The indicator 'embodied value-added total' is part of the subcategory 'embodied footprints' (EFP), and it is the result of the difference between inputs (i.e., energy and materials) and outputs (i.e., products and coproducts) of the process divided by the gross output of the sector, obtained from EORA. The indicator embodied value-added total is calculated per 1 dollar of output (Maister et al., 2020). Different processes are higher contributors for very high risks in the agricultural value chain. In Belgium, it was the production of chemicals and chemical products, such as chemical fertilisers used in agriculture. In Germany, was due to the 'wholesale trade, except of motor vehicles and motorcycles' process that includes wholesale trade on its own or on a fee or contract basis related to domestic wholesale trade, as well as international import and export. In Spain, the manufacture of prepared feeds for farm animals represents a very high risk in the indicator.

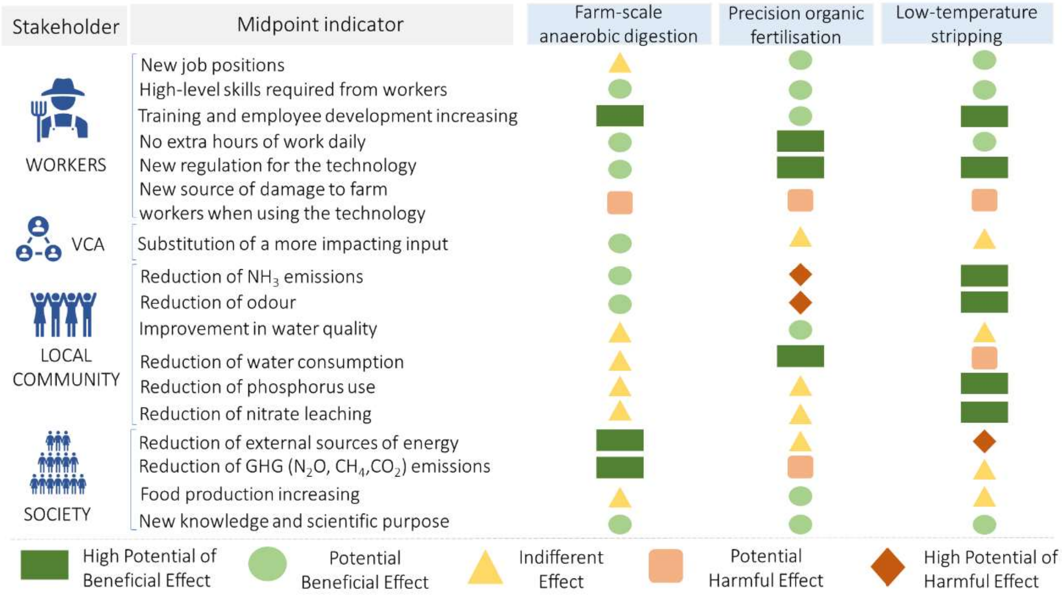
'Public sector corruption' (COR) is a subcategory mainly influenced by the acquisition of imported products in the countries assessed in the present study. The subcategory presented indicators with a very high risk in the Belgian and Spanish agricultural chains, mainly due to agricultural imports from Argentina such as fruits and nuts, and the cultivation of vegetables and other crops. In Germany, it was influenced by mined products imported from China and India, and agricultural products from Argentina. Thus, the greatest impacts were related to non-domestic processes that are intrinsic to the product chain. The same happens for other indicators, for instance the risk of contributing to child labour and youth illiteracy due to agricultural products imported from India, although those processes make a small contribution to the product chains assessed in the current study.

The subcategory ‘Freedom of association and collective bargaining’ (FAB) has indicators with a very high risk in agriculture in Germany and Spain due to the indicator ‘trade union density’, but not in agriculture in Belgium (very low risk). This indicator represents the number of employees who are members of an organised union as a percentage of the total number of employees (Maister et al., 2020). A very high risk is related to the situation where fewer than 20 % of the employees are members of a trade union, and a very low risk is when this value is above than 80 %.

Finally, impacts in ‘migration’ (MIG) have a high value in Germany since the migration rate in the sector is above 15‰ (per mille). Germany is a country that is very open to receiving migrants, which means that issues related to religion, race or discrimination may represent risks if not addressed properly (Maister et al. 2020). In Belgium, the sector has high and medium risk, respectively, and in Spain there is a medium risk.

4.3.3.2 Social Impact Assessment of technologies for nutrient recovery considering experts knowledge

The technologies were prospectively evaluated, bearing in mind that they can vary greatly according to the context (country/farm) in which they are applied or the baseline with which they are compared. In the present study, social impacts were assessed considering where the technology is developed and the midpoint indicators selected in Table 1, and final results after the two rounds of questioning is presented in Figure 4. It is important to highlight that the social assessment provided in this section has no evidence yet due to the low level of adaptation of the technologies, thus, they were assessed as a potential effect.



Stakeholder	Midpoint indicator	Farm-scale anaerobic digestion	Precision organic fertilisation	Low-temperature stripping
WORKERS	New job positions	▲	●	●
	High-level skills required from workers	●	●	●
	Training and employee development increasing	🟩	●	🟩
	No extra hours of work daily	●	🟩	●
	New regulation for the technology	●	🟩	🟩
	New source of damage to farm workers when using the technology	🟧	🟧	🟧
VCA	Substitution of a more impacting input	●	▲	▲
LOCAL COMMUNITY	Reduction of NH_3 emissions	●	◆	🟩
	Reduction of odour	●	◆	🟩
	Improvement in water quality	▲	●	▲
	Reduction of water consumption	▲	🟩	🟧
	Reduction of phosphorus use	▲	▲	🟩
	Reduction of nitrate leaching	▲	▲	🟩
SOCIETY	Reduction of external sources of energy	🟩	▲	◆
	Reduction of GHG (N_2O, CH_4, CO_2) emissions	🟩	🟧	▲
	Food production increasing	▲	●	▲
	New knowledge and scientific purpose	●	●	●

🟩 High Potential of Beneficial Effect
● Potential Beneficial Effect
▲ Indifferent Effect
🟧 Potential Harmful Effect
◆ High Potential of Harmful Effect

Figure 4. Social assessment of the potential impacts of solutions used to recover nutrients from agricultural and livestock practices

Legend: VCA = value chain actors; GHG = Greenhouse gas; N_2O = nitrous oxide; CH_4 = methane; NH_3 = ammonia; CO_2 = carbon dioxide

'Farm-scale anaerobic digestion' technology scored 18 % in HPBE, 41 % in PBE, 35 % in IE, 6 % in PHE and 0 % in HPHE. A technician is recommended for monitoring the biogas installation, and a professional maintenance engineer could be helpful with managing the technology. Although an additional activity is introduced into the system, it is not expected to take much time to do it, thus no extra time of work is necessary and working time could potentially be saved. The biogas produced is inflammable, which can create a harmful effect, making the observation of strict safety rules essential when cleaning the reactor. However, it is expected that with prior adequate training, the risk of damage can be minimised. Since agroresidues will no longer be stored, it is expected a reduction in odour, which is beneficial for workers and to the local community. The production of renewable energy has a potential to contribute to the reduction of fossil-based energy requirements, consequently contributing to decrease GHG emissions.

The use of organic fertilisers in the technology 'precision fertilisation' had 18 % HPBE, 35 % PBE, 24 % IE, 12 % PHE and 12 % HPHE. This technology has the possibility to create a new market, requiring more human resources. In addition, since the use of organic materials as fertilisers is more complex than mineral fertilisers, it is recommended that high-skilled workers to manage this technology, which can be achieved by encouraging more training for workers and hiring skilled labour. Currently, regulations on the use of fertilisers are general and do not promote the use of organic materials, thus suggesting the use of organic fertilisers might press policymakers to create new more specific regulations. In addition, the use of organic materials increases the soil organic matter content, which can have a direct impact on water retention and the potential reduction of water consumption for irrigation. However, it is expected that the technology could contribute to ammonia volatilisation increasing the odour for workers and the local community, although mitigation techniques are available, and has the potential to increase GHG emissions due to the use of organic fertilisers.

‘Low-temperature ammonium-stripping’ scored 35 % in HPBE, 24 % PBE, 24 % IE, 12 % PHE and 6 % in HPHE. It is expected that new job positions will be created since this technology will need technicians for installation and maintenance. Training farmers to operate the technology is important, and technicians must be trained to maintain the plant. This technology was developed to work automatically and remotely controlled, requiring only a brief supervision, which can save some work time, but it is still recommended that a technician operates and checks the proper functioning of the plant. When the technology is correctly used, no air pollution is expected from the reaction of ammonia and sulphur dioxide, but this can be considered a potential source of damage to workers. Proper handling of acidic or basic potential of hydrogen (pH) substances will prevent personal injury. The main aim of this technology is the recovery of ammonia from livestock manure, avoiding manure storage in open pits for long periods, and uncontrolled ammonia emission to atmosphere, consequently reducing odour on the farm.

A summary of the potential social benefits and harmful impacts of the novel technologies for nutrient recovery in agriculture is provided in Table 5. The detailed assessment of the midpoint indicators for the technologies is presented in SM 3.

Farm scale anaerobic digestion	Precision organic fertilisation	Low-temperature stripping
Examples of potential beneficial impacts		
• It is recommended a technician (with high level skills) for biogas installation • It is expected that a potential working time could be saved • It is expected reduction in odour due to lower ammonia emissions • Production of renewable energy as biogas possibly contributing to reduce fossil fuels consumption	• It can contribute to the creation of a new market of organic fertilizers • It is recommended workers with higher skills to operate the technology • It has the potential to contribute to the production of organic fertilisers, and potentially new and more specialised regulations • It has the potential to decrease in water consumption in the crop	• It is recommend technicians (with high level skills) for installation and maintenance of the technology • Some working time saved • No air pollution from the technology is expected • A better management of the manure has a potential to reduce the odour in the farm and surroundings
Examples of harmful impacts		
• Biogas produced is inflammable which is a potential risk to workers and the local community	• It has the potential to Contribute to ammonia volatilisation and GHG emissions, which have an impact on people's health	• Energy consumed in the technology might be a problem, increasing energy demand in the system

Table 5. Summary of potential social benefits and harmful impacts of the novel technologies for nutrient recovery in agriculture

3.1.3 Comparative analysis: baseline x technology

The risk level in the baseline and technologies scenarios (represented in table 6 by their respective countries) are shown in table 6. The required training to work with the technologies represents an improvement of 'presence of sufficient safety measures', thus the risk levels from the technologies in Belgium and Germany were reduced by one level (from low risk to very low risk). There is no data for Spain regarding the indicator. The risk for 'DALYs due to indoor and outdoor air and water pollution' has been raised by one level (from 'very low' to 'low') in Germany due to the potential emission of NH_3 and odour from the use of organic fertilisers. Since the risks 'rate of non-fatal accidents at workplace' and 'extraction of fossil fuels' are already 'very low' for the three countries, no changes were made. As far as 'weekly hours of work per employee' is concerned, the risks were reduced by one level (from 'medium' to 'low') in Belgium and Germany, as the technologies have the potential to save some time during daily work. No changes were attributed to Spain because the lower risk level for this indicator is 'low'. Risk for 'level of industrial water use (related to total withdrawal)' indicator was reduced in Germany (from 'low' to 'very low' risk) since the technology has the potential to reduce water consumption in the crop, but it has been raised in Spain as the technology will consume water, potentially increasing system's water consumption. The risks in 'pollution level of the country' were reduced in Belgium (from 'medium' to 'low') and in Spain (from 'low' to 'very low') since both technologies have the potential to reduce NH_3 emissions. For the indicator 'unemployment rate in the country', the risk was reduced in Germany and Spain since there is potential job positions creation due to the inclusion of the novel technology in the agricultural system. No changes have been made in the indicator 'Corruption' since most of impacts are non-domestic, therefore they low potential to be affected by the technology, although the overall product system impact can be reduced avoiding imports from countries with high level of corruption.

Stakeholder	**Indicator in PSILCA**	**Risk**					
		B	**T**	**B**	**T**	**B**	**T**
		Belgium		**Germany**		**Spain**	
Workers	Presence of sufficient safety measures.	*LR*	*VLR*	*LR*	*VLR*	ND	ND
	DALYs[6] due to indoor and outdoor air and water pollution.	VLR	VLR	*VLR*	*LR*	VLR	VLR
	Sector average wage, per month.	LR	LR	VLR	VLR	VLR	VLR
	Rate of non-fatal accidents at workplace.	VLR	VLR	VLR	VLR	LR	LR
	Weekly hours of work per employee.	*MR*	*LR*	*MR*	*LR*	LR	LR
Local community	Extraction of fossil fuels	VLR	VLR	VLR	VLR	VLR	VLR
	Level of industrial water use (related to total withdrawal)	VHR	VHR	*LR*	*VLR*	*LR*	*MR*
	Pollution level of the country	*MR*	*LR*	ND	ND	*LR*	*VLR*
	Unemployment rate in the country	LR	LR	*LR*	*VLR*	*HR*	*MR*
Value chain actors	Corruption	LR	LR	LR	LR	HR	HR

Table 6. Indicators from PSILCA which have the potential to be affected by the technologies, and their risk level in the baseline (risks from PSILCA) and technology scenario (risks according experts' responses to the questionnaires)

The overall impact of assuming including the technology in each scenario reduced by 0.02 %, 0.04 % and 0.06 %, respectively, in Belgium, Germany, and Spain. The small differences found, from the baseline were due to the potential changes induced by the technologies not affecting the impact categories that have greatest impacts (see section 3.1.1). Furthermore, only a few categories used in PSILCA were able to show potential changes brought about by the technologies (Table 7) (Supplementary material S4). Other indicators that could be affected by the technologies are presented in Supplementary material S6.

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[6] Disability Adjusted Life Years

Indicator	**Typical farm in Belgium**		**Typical farm in Germany**		**Typical farm in Spain**	
	B	*T*	*B*	*T*	*B*	*T*
DALYs due to indoor and outdoor air and water pollution	6.2	6.2	1.8	2.2	10.2	10.2
Industrial water depletion	1497.8	1497.8	976.2	975.8	140.2	143.9
Pollution	111.6	110.5	134.9	134.9	149.7	149.4
Safety measures	53.4	53.3	40.9	40.6	50.4	50.4
Unemployment	10.1	10.1	7.9	7.5	163.0	126.1
Weekly hours of work per employee	28.9	27.8	31.2	27.6	25.0	25.0
*TOTAL IMPACT**	*10144.8*	*10142.5*	*11655.6*	*11651.2*	*12638.6*	*12630.9*

Table 7. Comparative analysis for the S-LCA of novel technologies for nutrient recovery in agriculture considering U$ 1000 output, highlighting impact categories whose results can be changed by the technology

* Total impact considering all impact categories
Legend: B = baseline, T= technology

4.4 Discussion

4.4.1 Interpretation: Complementary assessment

Although scenario storylines attempt to show the different facets of the world, they do not fully reflect the true situation. However, they do achieve a simulation of reality, showing potential situations, and communicate might happen in future (Rounsevell et al., 2010). This section highlights indicators that are covered by the PSILCA database and that have the potential to be affected by the novel technologies (Table 4). Other relevant indicators are presented in the Supplementary material S5.

The 'presence of sufficient safety measures', estimated in PSILCA, was attributed by the 'Severe injury reports 2019' document from the United States. The indicator measures the number of accidents, safety and health incidents per 10,000 employees in the sector. In 2020 in Germany, there were an estimated 582,000 workers in agriculture (Statista, 2021), around 300,000 (Ceicdata, 2021) in Belgium and 765,000 in Spain (Statista, 2021). Thus, to go from 'low' to 'very low' risk, a total of 28.5, 1.47 and 37.5 accidents and incidents (per 100,000 employees) have to be avoided in German, Belgian and Spanish agricultural sectors respectively. According to the ILO (2021), insufficient labour inspections, a lack of hazard training are causes of accidents and incidents in agriculture. Thus, promoting training and development for workers and creating new regulations are essential if accidents and incidents in agriculture are to be avoided following the inclusion of the novel technologies.

'DALYs due to indoor and outdoor air and water pollution' is the most suitable indicator, in PSILCA, for assessing potential social effects with regard to the reduction of emissions in agriculture. However, in this case, the two sources of air and water pollution are accounted for together in the same DALY and the data used were from 2004. DALYs were updated in 2016 (WHO, 2016), and the data for 'ambient air pollution' are divided into lower respiratory infections, tracheal, bronchial and lung cancers, cataracts, ischaemic heart disease, stroke and chronic obstructive pulmonary disease. 'Lower respiratory infections' include GHG emissions, and therefore are related to agricultural emissions (Lee, 2010). According to WHO (2016), the DALYs (per 1,000 population) due to 'lower respiratory infections' are 0.78 (very low risk), 0.44 (very low risk) and 0.30 (very low risk) in Belgium, Germany, and Spain, respectively, representing a very low risk in PSILCA. Unfortunately, data are not provided for workers or specific industry sectors, which would be useful for estimating how much this indicator is affected by agricultural practices and potential effects due to the inclusion of novel technologies in agriculture.

According to Salary Explorer (2021) and the risk scale estimated in PSILCA (Maister et al., 2020), the average wage in the agricultural sector in Belgium is 3,880 €/month but ranges from 1,890 to 8,930 €/month. In Germany, it is 2,290 euros, ranging from 960 to 5,670 €/month. In Spain, this figure is 1,710 euros, ranging from 830 to 3,940 €/month. The risks in PSILCA (Maister et al., 2020) are attributed considering the ratio between average salary and living wage, or average salary and minimum wage. The minimum wage (in euros) in Belgium, Germany and Spain are respectively, 1626, 1585 and 1126 (Country economy, 2021). Thus, the risks for salaries (lowest, average and highest salaries) in agriculture in Belgium are, respectively, high, low and very low. In Germany, the risks are, respectively, very high, high and very low. In Spain, the risks are very high, high and very low. No changes were attributed to this indicator, but if in a near-future it becomes mandatory include technologies to reduce impacts in agriculture, more technicians will be required to deal with the technology. Thus, the average salary in the sector has the potential to be increased, attracting more young and highly skilled professionals to the sector, but the lower salaries, responsible for the higher risks, may not change. Another important point is related to the definition of stakeholders. In the current study as well as in PSILCA, workers fall within the same stakeholder category, but if agricultural workers are divided into different categories (i.e. farm owners, technicians, farm managers, agricultural workers in general) different impacts and hotspots could be addressed. Thus, it is essential to provide ranges for this indicator; however, it is not clear how these should be grouped in a final indicator without losing the potential discrepancies identified.

In 2018, the total number of non-fatal accidents in agriculture in Belgium, Germany and Spain were 398, 47,652 and 29,378, respectively (Eurostat, 2021). In Europe, most of them (66.5 %) (Eurostat, 2021) occurred on the farm or in the forest zone, and 28.3 % were due to agricultural work or work with live animals. Regarding the specific physical activity that was carried at the exact time of the accident, the activity 'handling of objects' represented 27 % of non-fatal accidents in Spain (Eurostat, 2021). This activity could be affected by the inclusion of the novel technologies, either reducing or increasing this number. An increase could be due to the handling of acids or new equipment introduced with the technologies, but with good training this number could be the same or decrease over time. Therefore, for this indicator, more time is needed for a better evaluation, according to the level of implementation of the technologies in agriculture and the data provided. A positive point is the level of specificity in the Eurostat database, although it would be of greater interest if the data for arable and livestock systems were split.

With regards to working time, labour-saving technologies (i.e. precision fertilisation and adoption of other machinery) are in demand due to the complex, highly variable environment in agriculture, and these can led to increased productivity and quality of agricultural output, and reduced dependence on labour, as well as improved environmental control (Gallardo and Sauer 2018). For instance, the time, effort and energy expended in a small family homestead differs significantly from that on a large commercial livestock farm. In farms that are a commercial concern, farm owners are more cautious of employees and interns' work. Thus, full-time employees work a little under 35 hours and part-time workers typically work around 20 hours a week. However, farmers who own their own businesses usually work about 44 hours a week (Bureau of Labor Statistics, 2021). Umstätter et al. (2018) claim that the working hours per person have tended to remain stable with technological progress since the resulting reduction in working time is being used for other activities. Thus, it is hard to make predictions for the indicator on working time since it depends greatly on the farm and work conditions.

It could be argued that there is some overlap between social and environmental indicators; however, their inclusion is deemed important in a social assessment because it results in greater focus on the social consequences of environmental damage, while in environmental LCA the focus is on quantifying the damage.

The exploitation and destruction of natural resources can directly affect local communities whose livelihoods and economies are based on fossil fuels, biomass and ores, for instance (Maister et al., 2020). In 2018, Spain consumed 1,033.5E03 tonnes of nitrogen fertiliser (Eurostat, 2021), and 23.8 % of imports of mixed mineral or chemical fertilisers came from Morocco (OEC, 2021), where there is evidence that rights to health of workers and local communities are being overlooked (Switzer, 2019). In Belgium, 29 % of mixed mineral or chemical fertilisers were imported from Russia, which suffers from a depletion in the source of phosphate fertilisers (Saritas and Kuzminov, 2017). The precise application of nitrogen, the removal of nitrogen pollution from the environment and the use of organic fertilisers will help reduce the consumption of mineral fertilisers, decreasing the pressure on natural resources and specific local communities.

A controversial indicator is the indicator related to water. Results provided by PSILCA can contradict those from other sources. In Belgium, the agricultural sector consumes 1.12 % of total water withdrawal and 0.24 % of total renewable water resources (FAO 2021), both representing a very low impact, although PSILCA identifies a very high risk for both indicators. In Germany, the same divergence was found when comparing PSILCA risk levels and AQUASTAT data (FAO, 2021). A very high risk for agricultural water withdrawal (related to total renewable water resources) was identified in PSILCA, but in AQUASTAT this value was 0.25 %, which represents a very low risk; there was also a low risk for agricultural water withdrawal (related total water withdrawal), while in AQUASTAT this value was 1.4 %, which was a very low risk. For Spain, the opposite was found, with lower risks in PSILCA and higher risks in AQUASTAT. Spain has a very high risk related to agricultural water withdrawal both related to total withdrawal (65 %) and to total renewable water resources (18 %), although in PSILCA it is identified as a low and medium risk respectively. In addition, the AWARE method (Boulay et al., 2018), used in environmental LCAs to assess water scarcity, shows small characterisation factors (for irrigation) for Belgium (2.208) and Germany (1.778), representing a potential low impact, and a high value for Spain (80.760), representing a potential high impact.

The 'pollution level of the country' assesses the overall level of pollution in a country through an index, based on visitors' perceptions, and ranges from 0 to 100, with 100 being the worst result. The index for Belgium and Spain in 2019 was 49.89 and 39.36 respectively (Numbeo, 2019). No data are attributed to Germany in PSILCA, although there is a value of 28.01 in Numbeo (2019). According to Maister et al. (2020), the indicator is suitable for assessing safe and healthy living conditions of local communities. Therefore, since other types of pollution such as noise and waste disposal are included, the inclusion of novel technologies may have the potential to change peoples' perception regarding of pollution. However, to better assess this indicator, it should be assessed in a rural area or in a local community near an agricultural area.

Special attention should be paid to the indicator 'Unemployment rate'. Rotz et al. (2019) highlight that the rapid advance of agricultural technologies has led to different predictions about the future of labour and rurality. For some experts, agricultural technologies can lead to the exploitation of marginalised and racialised labourers by landowners, governments and corporations, resulting in social, economic, and racial inequities in labour, skills development and rural spatiality. However, it has suggested that novel technologies can positively contribute to creating new workplace opportunities in rural communities. Again, the way in which the technology will impact this indicator should be assessed in a specific analysis because it will depend on working conditions applied. For instance, a company could train an employee, not necessarily with high-level skills, to work with the technology or they can hire another worker with experience in that technology. More research and greater maturity of the technologies are needed before a change in the indicator can be confirmed.

Corruption can be measured by the Corruption Perceptions Index (CPI) that ranks countries from 0 to 100, with 100 being the least corrupt (Nedelciu et al., 2020). Usually, one product life cycle affects several countries, and several of the P fertiliser importers into Spain (Jordan, CPI 49) and Belgium (Morocco, CPI 40) have a very high risk of corruption, measured by the Corruption Perceptions Index (CPI) (World Bank, 2019), socially affecting the agricultural products. The situation is similar to Germany, with more than 70 % of P fertilisers imported from Israel, which has a CPI of 60; although it is a high CPI, it is similar index to, for instance, Spain (62) and Portugal (61). Improving nutrient efficiency by increasing the use of organic fertilisers and reducing losses will contribute to a decrease in the import of mineral fertilisers, consequently reducing social impacts in the value chain, but it does not solve the problem corruption.

It is important to highlight that the use of agricultural product systems in PSILCA certainly influences the results, especially related to the flows considered in the selected product system. PSILCA still takes an environmental studies approach and focuses on negative impacts (or risks). In addition, in PSILCA some social indicators can also be environmental indicators, for instance, ‘extraction of biomass’, ‘level of industrial water’ and ‘embodied CO_2 footprint’; therefore, care should be taken in sustainability assessments to avoid double counting of impacts. It is evident that the database will evolve when the data are available, thus, in a near future it is expected that more indicators to assess opportunities will be included in the database.

4.4.2 The diverse use of PSILCA in S-LCA

In the present study, the PSILCA database was used in the S-LCA. However, the representativeness of the data represents a challenging issue for the social LCI in PSILCA due to data availability (Kono et al., 2018). Even though the database covers almost 15,000 different sectors in 189 countries, for a more specific situation in a sector, a complementary assessment is necessary. In the current study, the focus was on strategies for reducing nutrient losses in agriculture, but only a few indicators were available to assess those impacts, making necessary to undertake a complementary assessment to contextualise the results provided.

Werker et al. (2019b) assessed the social impacts on working conditions of a novel technology hydrogen production by advanced alkaline water electrolysis (AEL) from a life cycle perspective when installed in Germany, Austria and Spain. They used a mixed methodology, PSILCA version 2.0, and complemented and compared it with raw data and a qualitative literature analysis.

Although they acknowledge that a greater number of indicators and detailed results are provided, PSILCA excludes important segments of society, such as informal workers, which are relevant for agricultural systems. In addition, the concept of medium risk hours in PSILCA is difficult to understand.

In the current study, PSILCA was used to build a baseline scenario and identify hotspots. Hannouf and Asefa (2018) used the database to evaluate the social performance of background processes in a high-density polyethylene production. With PSILCA, they were able to address the social hotspots areas that require a greater focus from suppliers. In the case of the novel technologies assessed here, hotspots and the potential benefits or harmful effects added into the agricultural system could be identified.

4.4.3 Prospective assessments in social studies, including S-LCA

Prospective assessments in S-LCA are under-investigated due to the difficulty of predicting social impacts since it involves many variables. According to van Haaster et al. (2017), social indicators are difficult to predict since they are time, region and circumstance specific and management dependent.

Haines et al. (2009) uses the DALYs to measure healthy years saved due to the mitigation measures in four sectors (household energy, transport, food and agriculture, and electricity generation) using a ‘comparative risk assessment’ (Wilkinson et al., 2007) to model the potential effects. They recognised that the model has limitations, but they provide important comparative evidence of the possible health effects expected from the adoption of mitigation policies.

In addition, van Haaster et al. (2017) uses S-LCA to develop a framework to assess aspects related to well-being that are potentially affected by novel technologies. The study has a future-oriented approach relying on the construction of scenarios. They selected 11 indicators, including knowledge-intensive jobs and total employment, but they assessed these two indicators quantitatively, unlike the present study. They also address those uncertainties are commonly found in prospective assessments, especially when it comes to the definition of baseline scenarios, which is also highlighted in the current work.

Although the methodologies showed have many limitations, the identification of indicators that could be temporally consistent and cover relevant hotspots, and consistent models or methods to measure or estimate them, are essential to be improved for future research on aggregating prospective and quantitative assessments in S-LCA. Those methods and models and social mechanisms are also relevant for S-LCA using impact pathways[7] (UNEP, 2020) as impact assessment approach.

4.5 Conclusions

The aim of the present study was to select and test indicators in order to perform an S-LCA of novel technologies to be applied in agriculture, undertaking comparison with a baseline in agriculture in Belgium, Germany and Spain. A set of indicators of this kind enables the assessment of social hotspots and opportunities related to novel technologies applied in agriculture to recover nutrients and improve of nutrient efficiency.

Through the questionnaire and expert knowledge, examples of potential impacts of the technologies included the need for highly skilled workers, attracting a highly qualified labour force to agriculture, increasing training and employee development, improving the efficiency of the technologies, in the case of some of them, helping to reduce accidents at work, and the need for new regulations to deal with organic fertilisers more effectively. In addition, novel ways to properly dealing with manure can involve a reduction in odour and other gases for local community and can also contribute to new knowledge and scientific research to improve agriculture. Other indicators, such as new jobs or a reduction in extra hours at the farms, were revealed to be site-dependent and would vary depending on the company or farmer behaviour. However, the inclusion of novel technologies may introduce new sources of damage, for instance, when using acids or working with heavy machinery, although these risks are controllable. Experts were cautious about the potential effects related to N and P emissions since emissions vary according to the conditions in which fertilisers are applied, making a potential effect harder to define.

Using the PSILCA database for the comparative analysis, small difference was seen between the baseline and the potential scenario with the technology included just increasing and decreasing risks of the indicators. A consistent explanation is the fact that the PSILCA is insufficiently sensitive to small changes because it is too generic to show benefits offered by the technologies. Another point is that the indicators for which the technologies have potential to bring about change did not show a high impact in the baseline.

Qualitative assessments for prospective studies in S-LCA may be a starting point for predicting the potential benefits and harmful effects of novel technologies. For future work, also depending on the maturity of the technologies, wherever possible a full S-LCA of technology, either standalone or in the context in which is applied, should be undertaken, in order to provide

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[7] Translation of social activity/stressor into a social damage (Maister et al., 2020).

quantitative ranges for each indicator. The initial screening provided by experts in the technologies should be confirmed using quantitative data for each type of technology and potential scenarios.

Declaration of competing interest

None of the authors are aware of any conflicts of interest.

4.6 Supplementary material

Supplementary material can be accessed in the following link:
https://1drv.ms/x/s!AiM0z1iKRPTCg9BaZ6Bo8xTK0UgNTA?e=ZsoqaD

Acknowledgement

We thank the project Nutri2cycle [grant number: 773682] for the full support during this work and the CERCA Programme/Generalitat de Catalunya.

Funding

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie [grant number: 713679].

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5. SOCIO AND ENVIRONMENTAL LCA OF TECHNOLOGY FOR LIVESTOCK WASTE

This study was submitted to the 13th International Conference on Life Cycle Assessment of Food (LCA food 2022).

5. Integration of socio and environmental LCA: application to novel technologies for nutrient recovery

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Keywords: Agriculture, nitrogen, pig production, S-LCA, E-LCA, sustainability

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5.1 Introduction

Agriculture contributes to 90% of the total ammonia emitted in the world, and 50% of the livestock ammonia emissions in Europe come from cattle, 30% from pigs and 20% from poultry (IIASA, 2017; EEA, 2018). Livestock manure is typically applied to cropland when it is generated in an amount that fits the farm's land nutrient needs. However, when it is produced in excess, livestock manure will need correct management and treatment due to its high organic matter content and concentration of nutrients, especially phosphorus and nitrogen. Aiming to improve sustainability in livestock, several technologies for waste management have been developed to reduce nutrient losses, specially, nitrogen emissions to the air, water and soil (Xia et al., 2020).

Anaerobic digestion is a widely used technology for the treatment of this kind of waste stream, converting organic nitrogen and phosphorus to ammonia and phosphate, but has no impact in modifying the nutrient content. Thus, ammonia still needs to be removed or recovered from digestate, in order to reduce its volatilisation. Unlike ammonia removal, ammonia recovery can produce marketable products, such as fertilisers and close the nutrient loop. However, several inputs (e.g. water, electricity, machinery, acid, infrastructure) and outputs (e.g. air emissions, treated deject) of these technologies have potential to cause environmental and social impacts. Thus, it is essential to assess those impacts, to avoid harmful trade-offs in the system.

Life Cycle Assessment (LCA) is a widely spread tool used to assess social and environmental impacts of several value chains, including, agricultural products and novel technologies (Igos et al., 2019). However, dealing with both aspects, social and environmental, is still a challenge for LCA. Therefore, the goal of this study is to advance on the integration of simultaneous social (S-

LCA) and environmental (E-LCA) life cycle assessments. Thus, in the present study, we have conducted a case study focusing on a novel technology to treat livestock dejections.

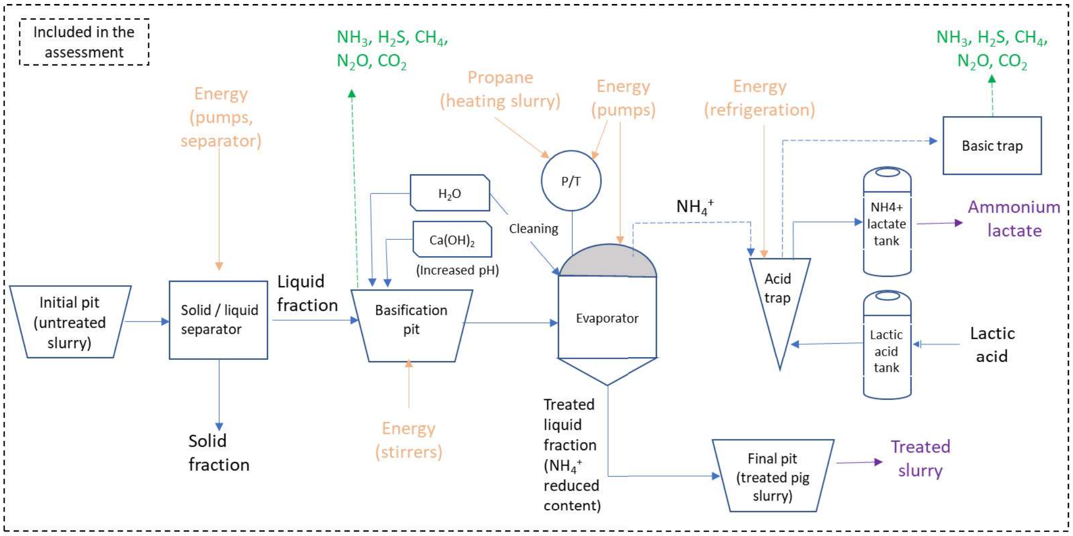
5.2 Methods

5.2.1 Technology ‘Low temperature ammonium-stripping using vacuum’

The technology selected removes nitrogen from pig slurry using vacuum stripping and the final products are ammonia salt solution that can be reused as a fertiliser, and organic fertilizer with less nitrogen content, which in turn improves further management of nutrients, and facilitate final disposal of the treated slurry. When vacuum is applied to an enclosed reactor, boiling point temperature decreases to below normal boiling point, thus reducing energy cost because of lower heating requirement. In addition, gas-phase ammonia mass transfer is boosted by suction effect of the applied vacuum. The recovered ammonia can be in the form of an ammonium sulphate, nitrate or lactate salt solution, among others. This technology can be applied directly to raw livestock manure, to avoid ammonia gas emissions to the atmosphere, or as a subsequent step of an anaerobic digestion process.

A farm scale pilot system (maximum capacity 6.4 m^3) with a treatment capacity of 10 m^3/day is operating in a sow farm of Navàs (Catalonia, Spain). The system is composed of a solid-liquid separator, a closed raft, an evaporator, a vacuum pump, an acidic trap, and a basic trap (Figure 1).

Figure 1. Flow chart of the technology ‘Low temperature ammonium-stripping using vacuum’



Legend: P/T = pressure/temperature

Pig slurry is directed to the solid-liquid separator, which has a filtration particle size of 450 µm and a motor power of 2.5 kW. Then, the liquid fraction is directed to a covered raft, where temperature is increased thanks to solar heating, and pH value is increased up to 11 with $Ca(OH)_2$. $Ca(OH)_2$ is stored in a stainless-steel tank. Gaseous emissions of the covered raft are aspirated and conducted to the evaporator to minimise ammonia loss and atmosphere emissions. The raft is equipped with a mixer to assure the homogeneity of the substrate before entering the evaporator. The evaporator works in batches of 1 ton of liquid fraction of pig slurry, in an operation temperature of approximately of 45 °C and 800 mbar (i.e., small vacuum conditions). The stainless-steel evaporator is equipped with diffusors, internal recirculation and increased internal surface to optimise the evaporation area and boost ammonia evaporation. Due to the low pressure and the basic pH value, ammonium-ammonia equilibrium is displaced to the second species and easily evaporated at this relatively low temperature. Ammonia is absorbed in the acid since the low pH value displaces equilibrium towards ammonium species. As in the case of the evaporator, load cell sensors allow for absorber mass monitoring. Finally, gases exiting the bubbler are directed to a basic trap ($Ca(OH)_2$) to minimise atmosphere hydrogen sulphide (H_2S) emissions.

At the end of the cycle, processed livestock manure is obtained, with lower nitrogen content. On the other hand, an ammonium lactate solution is produced, which can be used as a fertiliser.

The technology will be assessed considering five stages and their respective inputs and outputs (Figure 1):

1. Initial pit (S1) (untreated slurry).
2. Solid/liquid separator (S2).
3. Basification pit (S3) and cleaning operations.
4. Evaporator (S4), acid trap and NH_4^+ lactate and lactic acid tank.
5. Final pit (S5) (treated slurry).

5.2.2 Environmental and social life cycle assessment

The functional unit of the system is 1 m^3 of treated slurry, and the impacts were assessed from cradle-to-gate in both environmental and social assessments. A 10-year life span was used for machinery; a 20-year life span, for the concrete pit. The impacts were using OpenLCA v1.10.3.

Inventory was collected in the field, and costs of the inputs required for the technology and social flows from Product Social Impact Life Cycle Assessment (PSILCA) database (Maister et al., 2020) were used to estimate the social impacts caused by the technology (Table 1). The methodology adapted in the current study is similar to the Serreli et al. (2021), in which the inputs to the system were used in PSILCA as economic values. It is important to highlight that in this work we assess the social impacts of producing and using the technology in a country-level since

PSILCA provides sector and country-level data. Both inventories are available in detail in the supplementary material.

Table 1. Social flows considered used in S-LCA of a novel technology for nutrient recovery in agriculture

Component	Social flow in PSILCA
Reactor 1	Manufacture of machinery and equipment n.e.c - ES
Reactor 2	Manufacture of machinery and equipment n.e.c - ES
Bubbler	Manufacture of glass and glass products - ES
Container 1	Manufacture of fabricated metal products - ES
Automation	Computer and related services - ES
Workforce (infrastructure)	Construction - ES
Cold equipment	Manufacture of machinery and equipment n.e.c - ES
Gas-gas heat exchanger	Manufacture of machinery and equipment n.e.c - ES
Container 2	Manufacture of rubber and plastic products - ES
Separator	Manufacture of machinery and equipment n.e.c - ES
Transportation of equipment	Other land transport; transport via pipelines - ES
Pipes-connections and various	Manufacture of ceramic products - ES
Motor	Manufacture of machinery and equipment n.e.c - ES
Solenoid valves for various fluids	Manufacture of electronic equipment and apparatus - ES
Electricity - 0.316 kWh	Production and distribution of electricity - ES
Lactic acid	Manufacture of chemicals and chemical products - ES
Water	Collection, purification and distribution of water - ES
Mineral oil	Manufacture of other non-metallic mineral products - ES

Environmental footprint (EF) impact categories (EC-JRC, 2012) (Table 2) and EF 3.0 normalization and weighting set (Sala et al., 2018) were used to calculate environmental impacts, and the Social Impacts Weighting Method from PSILCA was used to estimate technology's social risks. 45 social impact subcategories from PSILCA, for the stakeholders workers (WK), society (SO), local community (LC) and value chain actors (VCA), were selected in this study.

Table 2. Environmental footprint impacts categories, indicators and units assessed in the E-LCA retrieved from EC-JRC (2012)

Impact category	Indicator	Unit
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg $CO_{2\ eq}$
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 $_{eq}$
Human toxicity, cancer	Comparative Toxic Unit for humans (CTU_h)	CTUh
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTU_h)	CTUh
Particulate matter	Impact on human health	disease incidence
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	kBq U^{235}_{eq}
Acidification	Accumulated Exceedance (AE)	mol H+ $_{eq}$
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N $_{eq}$
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P $_{eq}$
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N $_{eq}$
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTU_e)	CTUe
Land use	- Soil quality index - Biotic production - Erosion resistance - Mechanical filtration - Groundwater replenishment	- Dimensionless (pt) - kg biotic production - kg soil - m^3 water - m^3 groundwater
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 world $_{eq}$
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb $_{eq}$
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ

Following Werker et al. (2019), since it is provided a detailed account of the environmental implications of the the technology, eleven of the impact categories with a more environmental focus are excluded from this analysis (Table 3). Such exclusion of indicators aims to avoid double-counting effects that can lead to serious errors when large interconnected systems are analyzed or when results are placed into broader contexts (Lenzen, 2008). For instance, ‘industrial water depletion’ is better described with the E-LCA impact category “water use” and the AWARE method (Boulay et al., 2018) that accounts for water depletion and relates it to its regional scarcity. Another example is the ‘pollution level of the country’ which is a qualitative indicator in PSILCA, and in the E-LCA is assessed in the two areas of protection ‘human health’ and ‘ecosystems’ and their associated impact categories covering the diverse types of pollution that can occur in a country (Werker et al. 2019).

Table 3. PSILCA social impact categories excluded of the S-LCA and the related association retrieved from Werker et al. (2019)

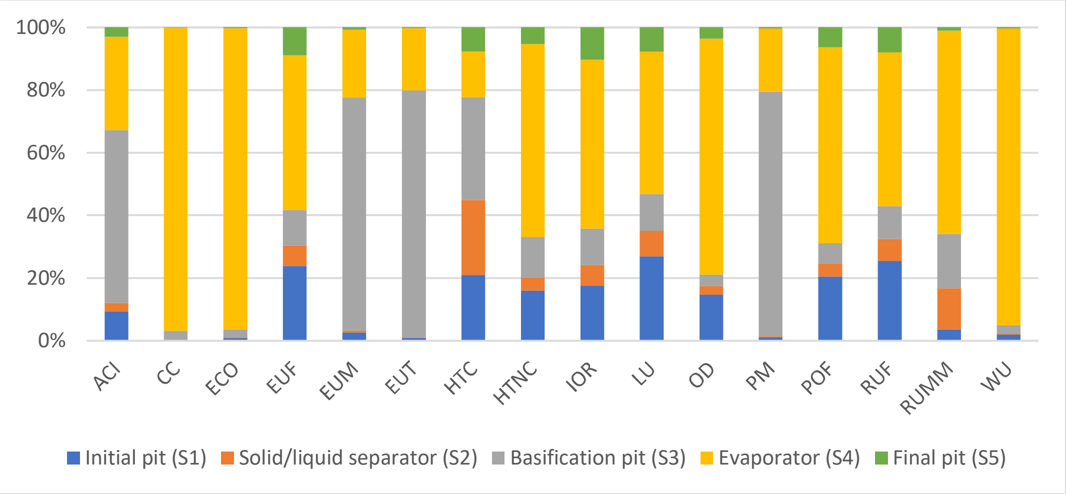
Impact category	Justification (Better described with…)
Biomass consumption	‘Resource use, fossils’ E-LCA impact category.
Embodied agricultural area footprints	‘Climate change’ E-LCA impact category.
Embodied biodiversity footprints	‘Climate change’ E-LCA impact category.
Embodied forest area footprints	‘Acidification’, ‘Climate change’, ‘Ozone depletion’, ‘Particulate matter’ E-LCA impact categories, covering not only different ecological, but also human health problems.
DALYs due to indoor and outdoor air and water pollution	‘Human toxicity, cancer’ and ‘Human toxicity, non-cancer’ E-LCA impact categories.
Industrial water depletion	‘Water use’, which accounts for water depletion and regional scarcity.
Embodied water footprints	‘Water use’, which accounts for water depletion and regional scarcity.
Minerals consumption	‘Resource use, minerals and metals’ E-LCA impact category.
Fossil fuel consumption	‘Resource use, minerals and metals’ and ‘Resource use, fossils’ E-LCA impact categories.
GHG footprints	‘Climate change’ E-LCA impact category.
Pollution level of the country	‘Acidification’, ‘Climate change’, ‘Ozone depletion’, ‘Particulate matter’ E-LCA impact categories.

5.3 Results and discussion

5.3.1 Environmental LCA

Overall environmental impacts of the technology are presented in Figure 3. S4 has higher contribution to eleven out of sixteen impact categories (69%), highlighting more than 90% of the impacts in the impact categories ‘climate change’ – mainly due to the methane emitted -, ‘ecotoxicity, freshwater’ – mainly due to ‘lactic acid production’ and ‘market for steel, chromium steel 18/8’ processes – and ‘water use’ – due to ‘market group for tap water’ and ‘lactic acid production’ processes. Stage 3 has higher contribution of impacts in the impact categories ‘acidification’, ‘eutrophication, marine’, ‘eutrophication, terrestrial’ and ‘particulate matter’ due to ammonia emitted in the stage. The impact category ‘human toxicity, cancer’ has more balanced impacts (21% S1, 24% S2, 33% S3, 15% S4 and 8% S5). The highest contribution to impacts of S1 was in ‘land use’ due to the process ‘market for concrete, normal’; S2 in ‘human toxicity, cancer’ due to the carcinogenic emissions in the process ‘market for concrete, normal’; S5 in ‘ionising radiation’ due to the emissions in the process ‘market for steel. Chromium steel 18/8, hot rolled’.

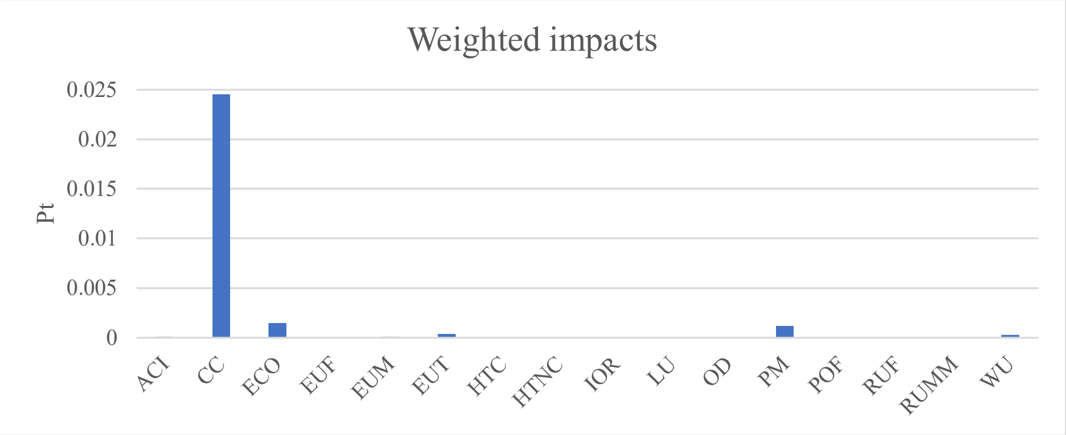
Figure 3. Environmental impacts of the novel technology for ammonia recovery of livestock dejections



Legend: ACI: acidification, CC: climate change, ECO: ecotoxicity freshwater, EUF: eutrophication freshwater, EUM: eutrophication marine, EUT: eutrophication terrestrial, HTC: human toxicity cancer, HTNC: human toxicity non-cancer, IOR: ionising radiation, LU: land use, OD: ozone depletion, PM: particulate matter, POF: photochemical ozone formation, RUF: resource use fossils, RUMM: resource use, minerals and metals, WU: water use

Regarding the E-LCA, 51% of the normalized impacts are attributed to ‘climate change’ (0.12), 33% to ‘ecotoxicity, freshwater’ (0.08) and 6% ‘particulate matter’ (0.01) (Figure 4). As in Van Zelm et al. (2020) several impacts of the process to recover ammonia from digestate came from the acid needed to produce the fertilizer and the direct nutrient emissions during the process.

Figure 4. Weighted environmental impacts (in points - Pt) of the technology for ammonia recovery of livestock dejections

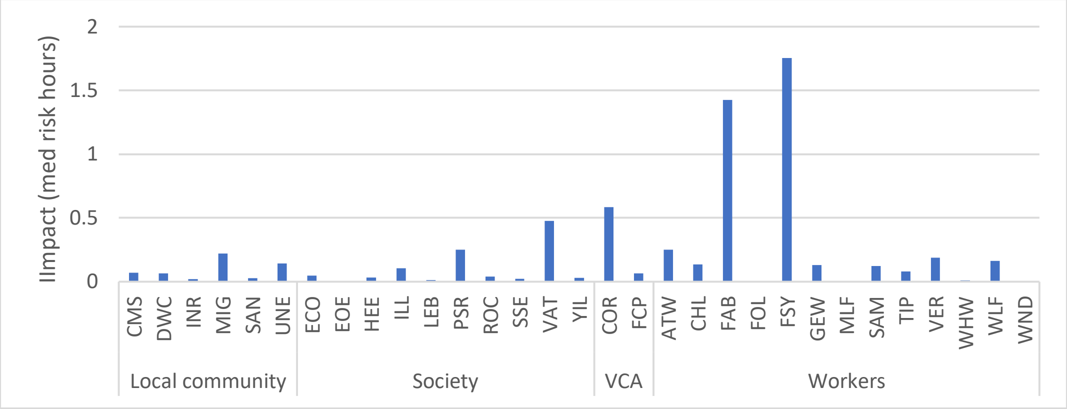


Legend: ACI: acidification, CC: climate change, ECO: ecotoxicity freshwater, EUF: eutrophication freshwater, EUM: eutrophication marine, EUT: eutrophication terrestrial, HTC: human toxicity cancer, HTNC: human toxicity non-cancer, IOR: ionising radiation, LU: land use, OD: ozone depletion, PM: particulate matter, POF: photochemical ozone formation, RUF: resource use fossils, RUMM: resource use, minerals and metals, WU: water use

5.3.2 Social LCA

For the S-LCA, 65% of total impact, measured in medium risk hours, is concentrated in four impact categories, 27% were found in ‘fair salary - WK’ (1.76), 22% in ‘freedom of association and collective bargaining - WK’ (1.42), 9% in ‘corruption - VCA’ (0.58), and 7% ‘value added (total) – VCA’ (0.48) (Figure 5).

Figure 5. Overview of results for stakeholder group and indicators for the novel technology for ammonia recovery from livestock

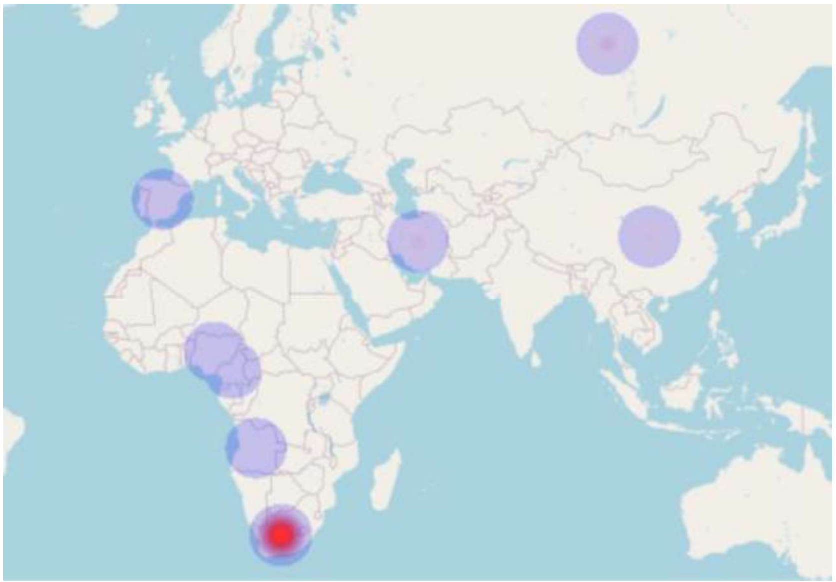


Legend: ATW: accidents at work, CHL: child labour, CMS: Certified environmental management system, COR: public sector corruption, DWC: drinking water coverage, ECO: contribution of the sector to economic development, EOE: expenditures on education, FAB: freedom of association and collective bargaining, FCP: fair competition, FOL: forced labour, FSY: fair salary, GEW: gender wage gap, HEE: health expenditure, ILL: illiteracy, IMS: international migrant stock, INR: indigenous rights, LEB: Life expectance at birth, MIG: migration, MLF: men in the sectoral labour force, POL: pollution, PSR: promoting social responsibility, ROC: risk of conflicts, SAM: safety measures, SAN: sanitation coverage, SSE: social security expenditures, TIP: trafficking in persons, UNE: unemployment, VAT: value added (total), VER: violations of employment laws and regulations, WHW: weekly hours of work per employee, WLF: women in the sectoral labour force, WND: workers affected by natural disasters, YIL: youth illiteracy; VCA : Value chain actors

Main processes responsible for impacts in ‘fair salary’ were related to the high risk of living wage in the flows ‘manufacture of machinery and equipment’ - representing all equipment used in the technology - and ‘computer and related services’ - used to represent plant automation. The impact caused in ‘freedom of association and collective bargaining’ is also mainly due to ‘manufacture of machinery and equipment’ and ‘computer and related services’, in this case, the very high risk is in the trade union density. The impact category ‘Corruption’, represented by the subcategories ‘active involvement of enterprises in corruption and bribery’ and ‘public sector corruption’. In the first, the processes ‘construction’ – used to represent the infrastructure – and ‘other land transport; transport via pipelines’ have a very high risk; in the second, the processes ‘manufacture of machinery and equipment’ and ‘computer and related services’ is the one with a high risk. Finally, the very high risk in the processes ‘metal products’ and ‘metallurgy products’ were the main responsible for the impact category ‘value added (total)’. Lowest impacts (in medium risk hours) were found in 'men in the sectoral labour force - WK' (6.89E-04), 'fatal accidents – WK' (2.90E-04) and 'frequency of forced labour – WK' (2.14E-04).

Various processes allocated all over the world can contribute to the total impact of the product (Figure 6). Thus, for instance, although there is a very low risk of child labour in Spain, there is a contribution in the total impact of the product due to the 'coal and lignite products' processed in South Africa, and to the 'mining and quarrying (energy)' process located in Russia. Those impacts are called non-domestic impacts and only can be seen when considering the whole life cycle of the product.

Figure 7. Domestic and non-domestic impacts (blue circles) in the impact category 'child labour' of the novel technology for ammonia developed in Spain.



5.3 Conclusions and future work

With the methodology adopted, environmental and social aspects of the process could be measured using the same inventory but adapting to the intended conditions, using a sector and country-specific database and monetary flows. The study conducted allowed us to identify the needs and challenges conducting, simultaneously, social and environmental assessments, in our case for a relevant area such as livestock management. However, it is worth to mention that PSILCA provides country-specifics sectors datasets based on country statistics, thus a more detailed regional and sectorial information is probably the cornerstone for the assessment in future studies. To show the real contribution of the novel technology to sustainability in agriculture, it is necessary to compare the results from this technology with other technologies and with no treatment of slurry, also assessing final disposal of the treated slurry and its application. Finally, we would like to encourage to advance on the inclusion of social assessment in sustainability studies, which will help to better improve the databases and methods for such assessments. For future work, further investigation on weighting social and environmental indicators in simultaneous assessments is essential to compare or aggregate results from the two dimensions.

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Supplementary material

1- Environmental life cycle inventory

Process	Inventory flow from Ecoinvent	Value	Unit
	Materials/fuels		
1. Initial pit (S1)	Concrete, normal {CH}| market for | Cut-off, U	0.003845	m3
	Steel, unalloyed {RER}| steel production, converter, unalloyed | Cut-off, U	0.000311	ton
	Organic manure mix (empty process), as N/FR U	1	ton
2. Solid/liquid separator (S2)	Concrete, normal {CH}| market for | Cut-off, U	0.000311	m3
	Clay brick {RER}| production | Cut-off, U	7.73E-05	ton
	Steel, unalloyed {RER}| steel production, converter, unalloyed | Cut-off, U	5.04E-06	ton
	Steel, chromium steel 18/8 {RER}| steel production, converter, chromium steel 18/8 | Cut-off, U	4.20E-05	ton
	Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | Cut-off, U	2.52E-06	ton
	Injection moulding {RER}| processing | Cut-off, U	2.52E-06	ton
3. Basification pit and cleaning (S3)	Concrete, normal {CH}| market for | Cut-off, U	0.000281	m3
	Steel, unalloyed {RER}| steel production, converter, unalloyed | Cut-off, U	3.03E-05	ton
	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U	6.47E-05	ton
	Polymethyl methacrylate, sheet {GLO}| market for | Cut-off, U	8.40E-06	ton
	Cable, three-conductor cable {GLO}| production | Cut-off, U	0.001326	kg
	Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | Cut-off, U	3.78E-06	ton
	Polyethylene, high density, granulate, recycled {Europe without Switzerland}| market for polyethylene, high density, granulate, recycled | Cut-off, U	1.68E-07	ton
	Lime {RER}| market for lime | Cut-off, U	1.2	kg
	Tap water {RER}| market group for | Cut-off, U	20	kg
4. Evaporator (S4)	Concrete, normal {CH}| market for | Cut-off, U	6.83E-04	m3
	Steel, unalloyed {RER}| steel production, converter, unalloyed | Cut-off, U	1.48E-04	ton
	Residual wood, dry {RER}| plywood production, for indoor use | Cut-off, U	2.42E-05	m3
	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U	1.63E-04	ton
	Polymethyl methacrylate, sheet {GLO}| market for | Cut-off, U	1.51E-05	ton
	Cable, three-conductor cable {GLO}| production | Cut-off, U	7.82E-04	m
	Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | Cut-off, U	1.01E-06	ton
	Polyethylene, high density, granulate, recycled {Europe without Switzerland}| market for polyethylene, high density, granulate, recycled | Cut-off, U	8.40E-08	ton
	Tap water {RER}| market group for | Cut-off, U	4.20E+02	kg
	Concrete, normal {CH}| market for | Cut-off, U	1.71E-04	m3
	Steel, unalloyed {RER}| steel production, converter, unalloyed | Cut-off, U	3.7E-05	ton

	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U	4.62E-05	ton
	Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | Cut-off, U	8.40E-07	ton
	Glass fibre reinforced plastic, polyester resin, hand lay-up {RER}| production | Cut-off, U	5.88E-05	ton
	Aluminium, primary, liquid {GLO}| market for | Cut-off, U	8.40E-07	ton
	Copper {RER}| production, primary | Cut-off, U	8.40E-07	ton
	Refrigerant R134a {RER}| production | Cut-off, U	3.78E-04	kg
	Synthetic gas {CH}| market for | Cut-off, U	0.00E+00	m3
	Mineral oil, at plant/RER U (ACYVIA)	2.77E-04	kg
	Lactic acid {RER}| production | Cut-off, U	8.00E+00	kg
	Galvanized steel sheet, at plant/RNA S	3.36E-06	ton
	Polyethylene, high density, granulate {RER}| production | Cut-off, U	1.68E-06	ton
	Injection moulding {RER}| processing | Cut-off, U	1.68E-06	ton
	Tap water {RER}| market group for | Cut-off, U	1.00E+01	kg
	Lime {RER}| market for lime | Cut-off, U	0.00E+00	kg
5. Final pit (S5)	Concrete, normal {CH}| market for | Cut-off, U	0.001714	m3
	Steel, unalloyed {RER}| steel production, converter, unalloyed | Cut-off, U	0.000118	ton
	Electricity/heat		
2. Solid/liquid separator (S2)	Electricity mix/CATALUNYA 2020 U	0.028	kWh
3. Basification pit and cleaning (S3)	Electricity mix/CATALUNYA 2020 U	0.004	kWh
4. Evaporator (S4)	Electricity mix/CATALUNYA 2020 U	0.244	kWh
	Electricity mix/CATALUNYA 2020 U	0.04	kWh
	Emissions to air		
3. Basification pit and cleaning (S3)	Ammonia, ES	0.44	kg
	Hydrogen sulfide	0	kg
	Dinitrogen monoxide	0.03	kg
	Methane	0.29	kg
	Carbon dioxide	8.9	kg
4. Evaporator (S4)	Ammonia, ES	0.1	kg
	Hydrogen sulfide	0.19	kg
	Dinitrogen monoxide	0.02	kg
	Methane	23.8	kg
	Carbon dioxide	9.99	kg

2 – Social life cycle inventory

Component	Cost 1 m^3 of treated slurry (euro)	Cost 1 m^3 of treated slurry (dollar)	Source
Reactor 1	0.009630	0.010818	Direct communication
Reactor 2	0.097347	0.109360	Direct communication
Bubbler	0.026473	0.029740	Direct communication
Container 1	0.018559	0.020849	Direct communication
Automation	0.076687	0.086150	Direct communication
Workforce (infrastructure)	0.066357	0.074546	Direct communication
Cold equipment	0.015828	0.017781	Direct communication
Gas-gas heat exchanger	0.016808	0.018882	Direct communication
Container 2	0.008054	0.009048	Direct communication
Separator	0.050775	0.057040	Direct communication
Transportation of equipment	0.004202	0.004721	Direct communication
Pipes-connections and various	0.020485	0.023013	Direct communication
Motor	0.013482	0.015145	Direct communication
Solenoid valves for various fluids	0.011030	0.012391	Direct communication
Electricity - 0.316 kWh	0.079948	0.089814	Endesa Distribución
Lactic acid	0.00000	0.000000	https://www.efinox.com
Water	0.001206	0.001355	Aigües de Catalunya
Mineral oil	0.0278121	0.031244	https://store.danfoss.com/es

6. GENERAL CONCLUSIONS

6. General conclusions

This thesis is devoted to the development of tools to the assessment of environmental and social impacts due to the inclusion of novel solutions and technologies for nutrient recovery in agriculture. For this, we studied social and environmental of agriculture at different levels (a farm to country-level) to obtain insight into risks and opportunities, also the positive and negative impacts of agricultural systems, especially related to nitrogen emissions. We next provide a set of conclusions that we accomplished in this thesis:

- We proposed methodology that could be used in other work to compare models' suitability for estimating nitrogen or nutrients losses in LCA:
    - The methodology proposed is a useful tool to compare in an easy and initial approach the suitability of the models considering different criteria for different situations (see section 2.3.1 for further results).
    - According to results from the models selected, reliable results were found for NH_3 volatilization and for NO_3 leaching, but not for N_2O emissions. Regarding LCA results, relevant differences in the impact categories analyzed were identified, with a maximum of 56% of difference between the models in the marine eutrophication impact category (see section 2.3.2 for further results).
    - A sensitivity analyses in LCA using different approaches is a relevant strategy to validate the results estimated with models (see section 2.3.3 for further results).
- We proposed a set of dashboard indicators (DBI) that reflect the most relevant environmental aspects and impacts concerning nutrient recovery and improvements in nutrient efficiency in agriculture:
    - This DBI covered aspects related to natural resource consumption, nutrient cycling, energy resources, and significant emissions to the air and water, and provided relevant information about the environmental performance of potential innovative technologies (see sections 3.3.1 and 3.3.2 for further results).
    - There is considerable uncertainty around qualitative assessments of future assumptions, but the case studies performed here screened five different technologies, allowed a summary of their potential contributions to reducing or increasing the environmental impacts of agricultural production (see section 3.3.2 for further results).
    - The DBIs are also useful as an effective way to benchmark the technologies against a baseline (i.e., the current situation), providing different information

related to the life cycle of the technology and the system in which it is applied (see section 3.3.2).

- We also provided a set of indicators that enabled the assessment of social hotspots and opportunities related to novel technologies applied in agriculture to recover nutrients and improving nutrient efficiency:
    - Through the questionnaire and expert knowledge, examples of potential impacts of the technologies included the need for highly skilled workers, attracting a highly qualified labour force to agriculture, increasing training and employee development, improving the efficiency of the technologies, in the case of some of them, helping to reduce accidents at work, and the need (see section 4.3.3.1 for further results).
    - Using the PSILCA database for the comparative analysis, a small difference was seen between the baseline and the potential scenario with the technology included just increasing and decreasing risks of the indicators, mainly because the database is too generic, for the indicators in which the technologies have potential to bring about change did not show a high impact in the baseline (see section 4.3.3.1 for further results).
    - Qualitative assessments for prospective studies in S-LCA may be a starting point for predicting the potential benefits and harmful effects of novel technologies (see sections 4.4.4.2 and 4.4.4.3 for further discussion).

- Finally, with the methodology adopted, putting together environmental and social assessment, it was possible to provide both assessments using the same inventory but adapting to the intended conditions:
    - The use of a sector and country-specific database and monetary flows were essential for the methodology developed (see section 5.3 for further results).
    - The study conducted allowed us to identify the needs and challenges for a relevant area such as livestock management especially related to climate change, ecotoxicity in freshwater and particulate matter (see section 5.3 for further results).
    - The novel technology should be compared to other technologies with similar purpose to verify its real contribution to sustainability in agriculture (see section 5.3 for further results).
    - This study is expected to encourage to advance on the inclusion of social assessment in the different sustainability case studies, which will help to better

improve the databases and methods for such assessments (see section 5.3 for further explanation).

7. FUTURE WORK

7. Future work

Based on the results and conclusions obtained in this thesis, there are some potential research areas to be explored in future works:

- It is not always possible to use mechanist models like Daisy or Animo to estimate nitrogen emissions in LCA, mostly due to the amount of input data and time required for the calculation. However, advantages could be obtained from those models, by modeling different situations, and providing emission factors more adapted and adjusted to particulat climate conditions and management operations (i.e., type and application of fertilizer) in the field. Thus, future work related to a deeper exploration of these models to be applied in a simple way in LCA is necessary.
- Further investigation on N_2O emissions is also relevant since N cycle is very complex and emission fractions (a simple methodology) are usually used to estimate N_2O emissions.
- The dashboard indicators (DBI) provide a qualitative rapid assessment of the technologies, but additional work is needed on their calculation, using different methodologies in order to check for sensitivity, and uncertainty of the values. In addition, providing weights and normalization factors would be relevant, to provide comparable indicators in the rapid assessment, although this aspect is always controversial.
- When the novel technologies achieve a higher level of maturity in the society, having been used in several farms and other agricultural systems, a full S-LCA of the new technology, either standalone or in the context in which is applied, should be undertaken. After that, the initial qualitative screening elaborated using experts' knowledge could be confirmed. Thus, in addition to the nature of the impact caused (benefit or harmful impact), we could have quantitative ranges for each indicator assessed in the current study.
- The results calculated for the technology for ammonia recovery must be compared with results from other technologies to reduce ammonia emissions to the environment and with a situation where there is no treatment of slurry, only storage. By doing that, it is possible to check more trade-offs provoked by the technology, and how they can impact on the environment. In addition, it is essential to include the final destination of the treated slurry and its application on the field, in order to show the real contribution of the novel technology to sustainability in agriculture.

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