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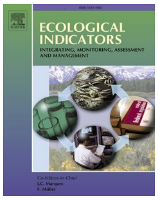

Original Articles

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

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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.

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

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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., 2020) and indicator-based methods (Van de Werf et al., 2002; Binder et al., 2010; Acosta-Alba and 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 et al., 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.

2. Methodology

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.

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.

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.

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.

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-stripping using a vacuum)	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 ammonium sulphate or nitrate salt solution and can easily be transported to distant croplands.	Pig manure management without processing, where surplus livestock manure is exported to distant croplands	D	4
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

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 and 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.

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

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., 2015), 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 / 1 kg 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 and Samaras (2019)).

[3] EMEP-EEA guidebook 3.d Crop production and agricultural soils (ANNEX 1 in Ntziachristos and 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′ (European Commission, 2018).

[6] Richner et al. (2014)

[7] Prasuhn (2006).

[8] Ten Hoeve et al. (2017).

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

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.

3. Results

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 and Kulshreshtha (2013) (eleven), Kasztelan and Nowak (2021) (nine), Wheaton and 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.

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 and 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.

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 and 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 and 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).

- 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

3.2.1. 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 and 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 and Nadeu, 2016). Nutrient recovery contributes to the indicator AEI 5 ‘Mineral fertiliser consumption’ and EGD 2.2.3 ‘Mobilising research and fostering innovation’.

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, 2020).

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. *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.

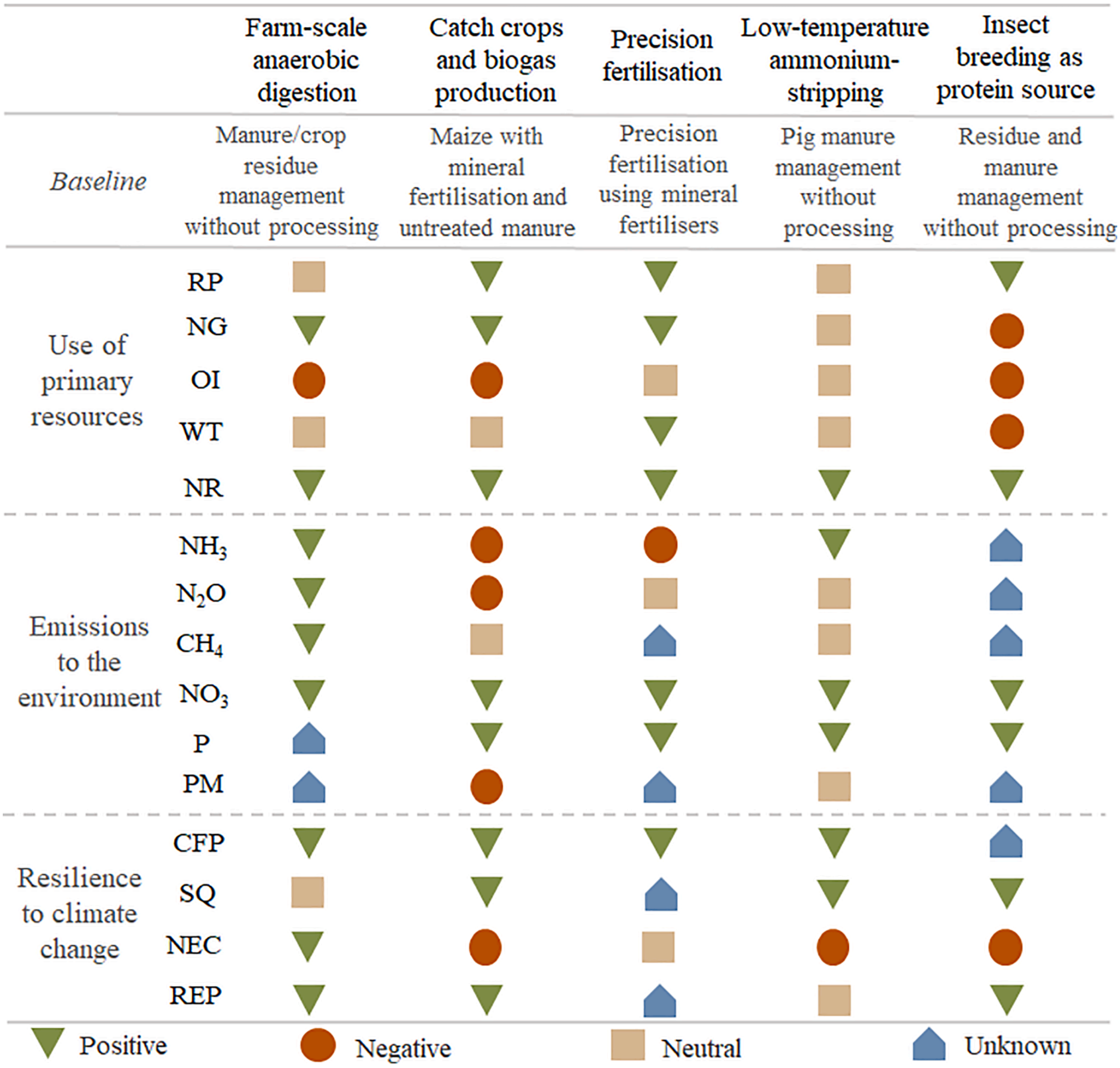
Overall, compared with the baseline established by the experts, all the solutions have the potential to have a positive impact on the indicators ‘nutrients recovered’ and ‘nitrate leaching’. ‘Farm-scale anaerobic digestion’ was the technology that had the most positive impact potential (63%), followed 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.

3.3.1. *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



		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

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

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 and 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.

3.3.2. *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. 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.

3.3.4. 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 and 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).

3.4. 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.

4. Discussion

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., 2014).

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

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 (m^3/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, 2000)	0.6	4.5
Nitrous oxide (air)	Tier 3 using the DAISY model (Hansen, 2000)	2.8	4.92
Methane (air)	Not assessed.	–	–
Nitrates (water)	Tier 3 using the DAISY model (Hansen, 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.

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).

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’ (Aui 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. (2018) 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 and 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.

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.

CRediT authorship contribution statement

Edilene Pereira Andrade: Conceptualization, Methodology, Writing – original draft, Investigation. **August Bonmati:** Supervision, Writing – review & editing. **Laureano Jimenez Esteller:** Funding acquisition. **Sander Brunn:** Writing – review & editing. **Lars Stoumann Jensen:** Writing – review & editing. **Erik Meers:** Writing – review & editing. **Assumpcio Anton Vallejo:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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