Uptake of circular fertilisers: multi-assessment of impacts, trade-offs and framework conditions

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement N° 101060426.

List of Acronyms

CAP	Common Agricultural Policy
CF	Circular Fertiliser
IWW	Industrial wastewater
LCSA	Life Cycle Sustainability Assessment
NIMBY	Not In My Backyard
NGO	Non-Governmental organization
PSILCA	Product Social Impact for Life Cycle Assessment
UWW	Urban wastewater

Keywords list

- Alternative fertilisers
- Resource efficiency
- Alternative fertilisers value chains
- Agriculture, life cycle assessment
- Sewage sludge
- Bio-waste
- Organic by-products
- Waste water

Disclaimer

Table of Contents

Introducing FER-PLAY

FER-PLAY is a Horizon Europe project working to **protect ecosystems**, **decrease EU dependence** on fertiliser imports, and **improve resource efficiency** through the **promotion of circular fertilisers**[1]. The project maps and assesses circular fertilisers made from waste, waste water and by-products, and highlights and disseminates their multiple benefits to foster their wide-scale production and application.

The present report presents a summary of the **results of the multi-assessment conducted on seven value chains** selected among 61 that were mapped in a preliminary phase and are available on the FER-PLAY database. The multi-assessment includes environmental, economic, and social issues (through Life Cycle Sustainability Assessment, LCSA), social acceptance, the regulatory framework, and the technical conditions for upscaling. Extended versions of the social acceptance, regulatory framework and technical conditions are provided as separate documents.

This report is addressed to fertiliser producers, policymakers, and farmers. Although it contains highly technical information, usually addressed to experts, technicians, and scientists (e.g., the results of the life cycle assessments), relevant efforts have been put in place to make them understandable and straightforward for the intended audience, without neglecting the richness of the details and findings of the study.

[1] Nutrient-providing products that are produced from a waste stream. It includes organic (i.e., compost) and inorganic (i.e., struvite) fertilisers.

Report objectives

Four objectives set the route followed in the report:

1. **Assess the advantages and lagging aspects** of the selected circular fertilisers compared to their non-renewable counterparts considering environmental performance.
2. **Evaluate social and economic aspects** of circular fertilisers value chains, alongside the **overarching regulatory framework and industrial upscaling conditions.**
3. Significantly **contribute to the scientific knowledge and practice of life cycle assessment** of circular fertiliser production and use.
4. Present **recommendations** and shed light on **how to conduct the sustainable agriculture transition through the replacement of non-renewable fertilisers with circular ones**.

Methodology

The multi-assessment consists of a group of analyses that, presented altogether, convey a comprehensive understanding of circular fertilisers. Such analyses are:

- **Regulatory framework assessment**, aiming at spotting regulatory barriers and proposing new drivers for the uptake of circular fertilisers. It was done by identifying 46 policy experts, with whom 24 interviews and 20 surveys were carried out. Based on the inputs provided by the experts, and matching them with the project's co-creation tasks, and literature review, a regulatory map was built at the international, European and national levels. The mapping stresses both the regulatory constraints, enhancers, and opportunities for the uptake of circular fertilisers.

- **Social acceptance assessment,** surveying three key stakeholders: farmers, fertiliser producers, and local administrations. A descriptive analysis was carried out with the collected data from the surveys. To wrap the social acceptance assessment up, different hypotheses were developed, materialised in questions that were evaluated to develop qualitative conclusions about the stakeholders' behaviour toward circular fertilisers. Complete social acceptance assessment is provided in a separate document; this report only highlights its most relevant conclusions and recommendations.

- **Life Cycle Sustainability Assessment** (LCSA), accounting for the environmental impacts of producing and using circular fertilisers, as well as the life cycle costs, and the social risks associated with it. It builds the core of the assessment by addressing the three sustainability dimensions (environment, economics, and social) of the seven target value chains. Each value chain was assessed in its entire life cycle (production and use phases), including regional differences among three climate-based European regions (northern, central and Mediterranean). The **functional unit was set to the supply of a specific amount of nutrients (NPK) and carbon to agricultural soils**, with the reference flow being 1 tonne of circular fertiliser applied to the soil. That functional unit was set with the intention of **comparing each circular fertiliser to an equivalent non-renewable nutrient mix regarding their environmental impacts.**

  The **system boundaries were set to cradle-to-gate-to-grave**, accounting for all the processes from the sourcing of raw materials up until the application of fertilisers on soil, but splitting the results between production and use phase, allowing to better pinpoint environmental hotspots. With this general framework, some specific adaptations had to be made regarding particular characteristics of certain value chains.

Life Cycle Impact Assessment was conducted following the guidelines of the **Product Environmental Footprint (PEF 3.1)**. In-depth analysis was only conducted for impact categories representing more than 5% of total impacts, after normalising and weighting the results.

Life Cycle Assessment results were obtained using different software applications for the value chains, namely **GaBi** (composted bio-waste, solid fraction of digestate and spent mushroom substrate), **SimaPro** (urban waste water struvite and stabilised sludge), and **OpenLCA** (industrial waste water struvite and feather meal). **Ecoinvent 9.3.1** dataset was used for modelling background processes and, in particular, the **non-renewable baseline**. It was set to an Ecoinvent-available mix of market available fertilisers, segmenting them by nitrogen, phosphorus, and potassium content, and peat as a non-renewable carbon provider.

For the economic assessment, the **environmental Life Cycle Costing** approach was followed. It allowed to match the system boundaries with the environmental assessment, but merged in a single result all the costs incurred by a varied group of stakeholders involved all along each value chain.

For social aspects, Social Life Cycle Assessment (S-LCA) methodology was followed, focusing on the associated social risk points of each value chain. Through a hotspot analysis, high and very-high risk items were identified, which resulted in the highlighting of six social risk indicators: **fair salary, frequency of forced labour, international migrant stock, non-fatal accident, public sector corruption and trade union density.**

When conducting the life cycle assessment, several **methodology limitations** were found, which affected in a significant way the results of the study. An important number of nuances and specificities could not be included in the study because of the lack or scarcity of means to do so. Some of the more relevant limitations are mentioned below:

- **Lack of differentiated emission factors** for circular and non-renewable fertilisers. Because of this, for example, eutrophication impacts resulted in the same values, because both compared products contain the same amount of nutrients, and the software is not able to differentiate between different molecule types and their specific form-dependant nutrient dynamics.

- **Climate- and soil-dependent variables** could not be sufficiently assessed because of the diversity of soils and climate under study and the lack of specific information for all of them coming from recognised sources.
- Even though LCA methodologies state that the "Land use" impact category accounts for effects on soil, results obtained only targeted land occupation. Given that the main advantage of most circular fertilisers lies in their **ability to improve soil health**, this limitation caused that significant positive environmental impacts went unnoticed. **Overall effects on soil could not be assessed** because of the lack of data and dedicated impact categories.
- The approach of **assessing regional industrial** practices entails significant challenges as compared to the common practice of assessing specific production facilities and processes. It implies having to **average variable data** and having to make an important number of **assumptions**, most of the time having to select the system for which more data is available at the expense of attaining actual representativeness.
- Social indicators were selected using a hotspot analysis, which provided **only 6 out of 70 high and very high probability risks indicators**. The selected indicators, described above, were assessed in FER-PLAY. During the course of the project, several limitations were found in the social data extracted from the **PSILCA database**. Examples are scarce information regarding fertilising industry or difficult representativity among European countries. For these reasons, the writers of the present study encourage the reader to understand the discussed social risks as a probability or trend and therefore, not representative or quantitative.

- **Technical assessment,** conducted to identify key technical aspects for effective non-renewable fertilisers replacement. To do so, four aspects were taken into consideration: physical characterisation (e.g., particle size distribution, bulk density, flowability, moisture content, hygroscopic properties, etc.), compatibility testing (e.g., spreading patterns, dissolution rates, potential for equipment clogging or corrosion, etc.), combination with other circular substrates (e.g., nutrient profiling, blending, etc.), and market demand and benchmarking. Additionally, production technologies were also subjected to a benchmarking analysis, conducted by the study of scales and technological comparison. Technical assessment included the estimation of **Environmental impacts prevention and control costs,** estimated by using the eco-costs methodology, which assigns monetary values to LCA's environmental impact results based on a damage or avoidance logic.

Regulatory framework

Regarding the **regulatory framework**, several "**soft law**" instruments were identified at the **international level**, which although providing guidance, have no binding power (e.g., UN's Sustainable Development Goals, FAO's International Code of Conduct for the Sustainable Use and Management of Fertilisers, etc.).

At the **European level**, three types of regulation have been identified: (1) **hindering regulations**, such as the Waste Framework Directive, and the Fertilising Products regulation, which puts in place significant barriers to circular fertilisers adoption, (2) **regulatory instruments with opportunities for improvement** and that could be refined to better support circular fertilisers uptake such as the Nitrates Directive, the Sewage Sludge Directive, and the Organic Farming Regulation, and (3) **enabling regulations**, such as the Carbon Removal and Carbon Farming Certification Framework, and the Soil Monitoring Law, which are supportive of circular fertilisers use.

At the **national level**, on the other hand, several **implementation challenges have been identified**, due to inconsistencies, delays, excessive strictness, and even lack of ambition.

Therefore, the recommendations emerging from the analysis propose to **tackle regulatory barriers** at European and national levels. It is much needed then to **align the different European regulations**, **improve the national implementation**, and **increase the policy ambition**.

At European level, it is necessary to **introduce new regulatory drivers**, including:

- Revitalising the Integrated Nutrient Management Action Plan.
- Establishing a European Nutrients Recycling and Organic Matter Target.
- Implementing fiscal tools for sustainable nutrient management.
- Considering the integration of agriculture into the Emissions Trading System.
- Enhancing research and innovation in sustainable nutrient management.

Life Cycle Sustainability Assessment

LCSA results for each one of the seven circular fertilisers targeted are presented below, with their environmental, economic, and social analyses.

Struvite from urban waste water

Upon the environmental assessment of **struvite from urban waste water (UWW)**, no regional differences were found, attributable to the scarcity of region-specific information. The four more relevant impact categories for UWW struvite, accounting for over 60% of impacts, are **freshwater eutrophication, mineral and metal resource use, acidification, and climate change**. UWW struvite performed better (had less impacts) in freshwater eutrophication and climate change, while having slightly higher impacts in acidification, and significantly higher impacts in mineral and metal resource use.

From an economic point of view, UWW struvite **life cycle costs are concentrated mainly (99%) in the variable operating costs of the production stage**. This is caused by using chemicals to promote the crystallisation of struvite, which adds significant costs to the system. It is important to bear in mind that struvite production has not been developed striving for profitability, but for solving the problem that struvite crystallisation poses for waste water treatment facilities. With the transition of wastewater treatment plants towards the eco-factory paradigm, economies of scale are expected to take over, making the recovery of struvite more cost-efficient.

Regarding social impacts, the struvite value chain exposes different degrees of social impacts among the three studied regions. Specifically, the northern regions reveal small probabilities of suffering social impacts, in contrast with central and Mediterranean countries, where the probability of public corruption and forced labour are worrisome. However, the authors postulate that an on-site assessment will show an improvement in those social indicators.

Three **recommendations** have been derived from the assessment: (1) find **more sustainable means of producing chemicals** (i.e., $MgCl_2$), (2) promote the **transformation of urban waste water treatment facilities into eco-factories**, and (3) continue **researching into the benefits of struvite as a slow-release circular fertiliser**.

Struvite from industrial waste water

Struvite from industrial waste water (IWW) was found to be **less harmful to the environment** than its non-renewable counterpart considering all impact categories. The most relevant impact categories, accounting for over 60% of the total impact, were **freshwater eutrophication, climate change, acidification, and particulate matter**. The only case where IWW struvite had a higher impact than its non-renewable counterpart was for climate change in the central European region, probably as a result of the energy matrix of the region. Overall, the most impact-contributing item was the consumption of $MgCl_2$, which could anyway be lowered using 'virgin' magnesium chloride with recovery-sourced options. IWW struvite had lower impacts both during the production and use phases, the latter because of the advantages of struvite being a slow-release fertiliser, which prevents leaching occurrence.

With regard to the economic dimension, as happens with UWW struvite, life cycle **costs of IWW struvite are mostly concentrated in the production stage** (as a result of the cost of chemical supplies, and also other inputs such as electricity, heat, transportation, packaging, etc.). Variable operating costs and capital expenses of the production stage account for 76% and 18% of total life cycle costs respectively.

The **chemical industry was the dominant contributor sector to probability of social risks** along the three studied regions. Authors argue that, this is due to big economical expenses on chemical feedstock. Among the six studied social risk indicators, the international migrant stock was also pointed in each one of the three European regions, highlighting the cross-border nature of this risk. The results suggest that **the operations linked to the chemical sector need closer scrutiny and better regulation** to mitigate these risks, especially **in relation to labour practices and government interactions**.

The **recommendations** arising from the assessment are: (1) determine and enforce **appropriate application rates and timing**, (2) carry out **long-term emission measurements** and record them, (3) consider the **use of recovered $MgCl_2$** in the production stage, substituting virgin options, (4) strive for **reducing chemical supply costs**, and (5) consider putting in place **subsidies** both for struvite production and demand stimulation.

Stabilised sludge

The use of **stabilised sludge** presents, in general, **environmental advantages** in contrast with the non-renewable option. The most environmental-impact-contributing categories, accounting for over 75% of the total impact, were **freshwater eutrophication, climate change, and marine eutrophication**. For both types of eutrophication, the results of SS were slightly lower, but because of the limitations of the use phase assessment, the actual advantages may have gone unnoticed. In contrast, stabilised sludge resulted in **notably lower impacts on climate change**. In this value chain, the technology selection is paramount, anaerobic digestion being superior because of its associated electricity generation which attains energy self-sufficiency.

From the economic point of view, significant differences were identified among on the regions (depending on the sludge-stabilising technologies used in each region). While in central and Mediterranean regions variable **operating costs during the production stage** concentrate 84 and 69% of the total life cycle cost, respectively, in the northern region, production variable operating costs account for 13% of total life cycle cost, fixed operating costs for 14%, and capital costs for 19%. The northern region was found to be the one with the lowest costs because of not using aerobic digestion (the most energy-intensive method) as a sludge stabilisation technique.

On **the social dimension**, the production of stabilised sludge **is strongly influenced by the energy sector**, posing significant challenges across all six studied indicators. These industries are often **associated with hazardous work conditions, regulatory complexity and labour issues**, particularly in regions where governance and labour protections may be weaker. In addition, the **linkage between trade union density and public sector corruption** might suggest that weak labour representation may contribute to higher corruption risks, further complicating the social landscape in these industries.

Three **recommendations** emerged from the analysis: (1) **identify the most suitable stabilisation technology**, (2) **move towards a more energy-neutral process**, and (3) **reinforce measures to control gaseous emissions** during anaerobic digestion.

Composted bio-waste

Composted bio-waste production process was modelled as having an anaerobic digestion stage that is then followed by the composting (instead of going straight ahead to composting). With this configuration, compost was found to **outperform its non-renewable counterpart in the environmental impact categories** which represent 93% of total environmental impacts, namely land use, freshwater ecotoxicity, and mineral and metal resource use. Regarding climate change (1.83% of total impact), if not taking into consideration biogenic CO_2 eq. emissions (pertaining to the short carbon cycle), composted bio-waste also has a significant advantage over its counterpart.

LCC results shed light on the importance of the involvement of both private and public sectors in the rendering of compost production and consumption. **Capital costs account for 68% of total life cycle costs**. The calculation was conducted through a model where capital costs were covered by local public administrations which then assigned the operation of the composting facilities through public tenders. Other exploitation configurations are also possible.

Probability of social risks are mainly located in fossil and nuclear fuel processes in the northern regions of Europe. This industry involves hazardous work environments and big economic influence, leading to high rates of probability of non-fatal accidents and public sector corruption. The geopolitical significance of energy resources, particularly linked to Russia, further complicates the issues related to forced labour, making this sector a critical driver of various social risks in the northern and central Europe regions. **Another highlighted sector in the central and Mediterranean regions was the chemical manufacturing sector** due to their global operations and economic significance. These sector global dependence and its high stakes in financial and regulatory matters might drive the observed probability of social risks in the Mediterranean regions in the same way as mentioned in other value chains.

Four **recommendations** are presented as results of the multi-assessment: (1) **improve composting conditions** (e.g., temperature, moisture, ventilation, etc.), (2) enhance composting systems by **incorporating the stage of anaerobic digestion**, (3) reinforce measures to **control gaseous emissions** during compost production, and (4) **keep enforcing selective food waste collection**, as it allows the composting of organic matter and thus, harnessing environmental advantages of using compost in agricultural soils.

Feather meal

The use of **feather meal** as a circular fertiliser was found to have **overall significant environmental burdens** when compared to its non-renewable counterpart. For both products, **acidification** (26%) and **particulate matter** (25%) have the highest impacts, followed by terrestrial (21%) and marine (13%) eutrophication (caveat: the modelling lacks the capacity to differentiate most of the eutrophication impacts between a circular and a non-renewable fertiliser); and climate change (9%) is the lowest-contributing impact category for both feather meal and its counterpart. Feather meal's climate change impacts come mainly from the rendering stage and its high energy consumption, together with the several transportation stages all along the value chain.

In contrast to hitherto analysed products, feather meal concentrates **most of its life cycle costs during the use stage** (53%). Production (comprised of rendering and fertiliser production) has a lower cost structure thanks to its integration into industrial processes, and also contains significant revenues from the sale of other co-products obtained during manufacturing.

The **rubber and plastic manufacturing** sector, as classified in the NACE list, **was detected as a risky sector** as a result of its presence in the value chain, even though it did not seem obvious. In the northern states the living wage risks are cardinal in the plastic and the energy sectors, probably driven by global economic pressures. Central Europe and Mediterranean countries attach high probability risk of non-fatal workplace accidents. This might be caused by their **large-scale operations and complex financing arrangements, which is common for each Member State**.

Four **recommendations** emerged from the assessment: (1) apply technologies to **reduce energy and water consumption**, (2) **improve logistics** where possible, (3) **explore alternative more environmentally friendly treatment methods** and technological advancements of raw feathers to produce organic fertilisers, and (4) put in place a **consistent and long-term record of emission measurements** across different conditions.

Solid fraction of digestate

Solid fraction of digestate (SFD) assessment took into consideration three different feedstocks: **food waste, sewage sludge, and manure**, and weighted average results were analysed as an effort to capture the reality of the average product available in the three target European regions. Solid fraction of digestate results evidence a **considerable environmental advantage** compared to the non-renewable option. The most relevant categories, accumulating over 99% of total environmental impact, were land use, fossil resource use, and freshwater ecotoxicity. In all the cases, SFD not only resulted in having fewer impacts but also avoiding them. The main driver of this is the substitution of grid power thanks to the valorisation of biogas obtained during anaerobic digestion. Another aspect contributing to SFD's superb environmental performance is the assumption that the liquid fraction is also valorised as a fertiliser. This value chain shows **significant regional variations**, caused by the weight each feedstock has in each region.

When addressing economic aspects, fixed and variable **operating costs during the production stage** accumulated most of the total life cycle costs, followed by capital costs. This was the common result among the three feedstocks assessed within the three addressed regions.

In the northern regions, the **high probability of social risks provided by motor vehicle services** could suggest that sectors with extensive supply chains and interactions with public services might be prone to corruption. In the central countries, the contribution of the motor vehicles and mining sectors points to wider industrial challenges in ensuring fair labour practices and mitigating corruption. In summary, these results suggest that greater oversight and regulation might be needed in these sectors to address the identified risks. **In the Mediterranean case, lot of countries were intertwined in the value chain**. However, their contributions were very small, **reflecting Mediterranean countries' interconnectedness with the European labour markets**.

Two recommendations were extracted from the analysis: (1) **leverage biogas production** as long as it displaces more polluting sources of electricity, and (2) **harness both liquid and solid fractions of digestate as fertilising options**.

Spent mushroom substrate

Lastly, **spent mushroom substrate outperforms its non-renewable counterpart in the environmental impact** categories accounting for 86% of total environmental impacts (i.e., land use, fossil resources use, freshwater eutrophication, and mineral and metal resource use). Regarding climate change (6.55%), if biogenic carbon emissions (pertaining to the short carbon cycle) are not accounted for, SMS has a considerable advantage also in this category. There are **significant regional differences**, mostly because of the starting 'recipe' of the mushroom substrate, as well as the production facilities size.

LCC provided remarkable insights, namely on the **key role of mushroom production and sales** in the value chain. Also, the **fresh substrate 'recipe' efficiency and economies of scale** turned out to be decisive in the economic performance. **Mushroom production is a labour-intensive activity; thus, its fixed operation costs are the biggest** all along the assessed value chain, followed by variable operating costs. In all cases, capital costs of the mushroom cultivation stage were roughly half of both types of operating costs.

Speaking about social considerations, **the manufacture of food and beverages and the chemical sectors were the main contributors**. The large-scale operations and its significant energy dependencies may boost the social risks found. Northern EU-countries presents a high probability risk of non-fatal accident in addition to low-wage workers, who are vulnerable to exploitation. Central ones, like Poland, exposes high risk of a low coverage of collective bargaining due to a low or inefficient trade union density. In the Mediterranean regions, high-risk industries such as mining and food manufacturing consistently appear across different indicators, reflecting their complexity and often challenging working conditions.

Three recommendations emerged from the analysis: (1) **strengthen emission-avoiding strategies** put in place during the entire SMS value chain, (2) **assess the feasibility of modifying fresh substrate 'recipes'** in the central and northern regions, and (3) **target mushroom production** in neighbouring agricultural areas.

Technical assessment

Technical assessment addressed **technical aspects for industrialisation**, **fertiliser benchmarking**, and **production technology benchmarking**. The most relevant advantage of circular fertilisers found through those analyses –specifically for struvite– is the **fitness of production processes to scale up**, having also the key driver of high raw material availability.

On the other hand, a couple of lagging aspects could be highlighted based on the technical assessment results. There is an important need for **additional efforts toward scaling up circular fertiliser production facilities** –especially for SFD and SMS–. Items such as solid-liquid separation techniques (e.g., centrifugation and screw press), drying, pelletising, nutrients concentration and storage, and the potential combinations of each target fertiliser with other organic options are also unsolved aspects that require **more research, investment, and large-scale deployment**.

Market barriers were also identified by the technical assessment, focusing mainly on the **immatureness of the market**, and the **early-stage demand**, which may require a series of stimuli to expand considerably.

The technical assessment also included the **assessment of environmental impacts prevention and control costs**. It spotted that, following the eco-costs[2] methodology, **most damage costs** are related to **particulate matter and climate change** impacts for most of the studied value chains. Other prominent categories were **marine eutrophication, fossil resources use, and non-cancer human toxicity**.

[2] Eco-costs is a framework that assigns a monetary value to environmental impact category results. The conversion factors (€/impact unit) are calculated based on how much would it cost to prevent the environmental damage from occurring.

Take aways

Advantages of circular fertilisers

Summing up the multi-assessment, the report asserts that **most of the analysed circular fertilisers offer advantages in their environmental performance compared to their non-renewable counterparts**. The most frequent advantages were spotted in the acidification, terrestrial eutrophication, and land use impact categories, as well as in climate change, mineral and metals resource use, and freshwater eutrophication. For several value chains and impact categories the results even had negative values (< 0), meaning that those **value chains contribute to reducing the pressure on planetary boundaries**.

It is relevant to emphasise that **it is likely that the most important advantages of circular fertilisers are precisely the positive effects caused on soil as a result of adding organic matter**, which because of methodology constraints are not accounted for in this report.

In the social aspects, S-LCA results show disparity in the seven value chains. Nevertheless, the **impacts in the northern regions drift to be lower** in circular fertilisers instead of its counterpart. This trend of heterogeneous results suggests that value chains incorporating other key processes, such as spent mushroom substrate and the food industry, carry significant probabilities of social risks. These findings highlight that the concept of circular economy, as exemplified by **CF, integrates diverse sectors and processes**. **This integration reduces social risks associated with additional** waste treatment **steps** by repurposing waste as by-products within the circular system.

As a result of the social acceptance assessment, which can be found in a separate document, some advantages were identified:

- Small and medium enterprises are the most interested ones in answering the fertiliser producers survey. This, in addition to the fact that those business are increasing their number of workers in the last 10 years leads to the idea that **this sector might be a prosperous growing one**, according to the surveys. Most of the fertiliser producer companies develop their own R&D strategy plans, concluding that **fertiliser producers hold updated businesses** that will include state-of-the-art strategies.

- Young farmers answered the end-users' surveys. This fact reflects the **interest of youth in CF** and therefore matches the guidelines of the Common Agricultural Policy that is applying pressure to engage young farmers in European farms. Most surveyors understand that circular fertilisers play a key role in the improvement of soils quality. This assumption can be used to improve farmers' acceptance of circular alternatives to current non-renewable fertilisers. There has been a **cumulative decrease in** the past years in **mineral fertilisers' consumption. Further decreases can be obtained by promoting circular ones**. The majority of surveyors do not consider the disruption linked to the presence of nearby fertilisers' factories to be significant. **A small NIMBY effect is detected**. This fact shows framers' positive behaviour towards fertiliser companies that manage waste by-products.

Lagging aspects of circular fertilisers

But **any advantage 'comes at a price'**, and important trade-offs were also identified. Regarding environmental impacts, climate change, terrestrial eutrophication, and acidification were also the most frequent **categories where circular fertilisers underperformed** compared to their non-renewable equivalents.

On the economic side, **non-renewable fertilisers**, with their established position, production efficiencies, automatisation, and scales, still have a market price advantage**. Currently, non-renewable fertilisers industry also does not internalise harmful environmental externalities** in their cost structures, adding up more (unfair) advantages. **Circular fertilisers, on the other hand, rely mostly on public waste management facilities or private small- or medium-scale businesses**, which is a huge difference in the way fertiliser production is conducted. The assessment shed light on the most capital-consuming stages of each production process.

The **role of the public sector** when it comes to investment was also identified as paramount to circular fertilisers market feasibility. Also, **circular fertiliser value chains tend to have much more complex stakeholder networks** than that of their non-renewable equivalents.

Social laggings are not well studied, neither by scholars nor enterprises. For this reason, is tough to argue the results compared to other published documents. **The present study confirms that CF needs extra research investment**. Feather meal production might be a promising technology in the future, taking into account that it is a new product, and therefore its information was strenuous to collect. For ending, UWW struvite, IWW struvite and stabilised sludge are the most socially favourable products. The former product, stabilised sludge, is an exception in the central region of Europe, where it is very unfavourable for the social dimension of sustainability. **All these results must be understood within the established project boundaries**.

As a result of the social acceptance assessment, which can be found in a separate document, the following lagging aspects were identified:

- **Farmers do not trust fertiliser producers**, according to the surveys performed. Therefore, most fertilising producing businesses are hiring outsourced salespersons to interact with end-users. CF production companies perceived the **acceptance procedure of subsidies as lengthy and complex**. **Most of companies do not follow standardised methods**. If this fact keeps constant, in the future those businesses will produce products that might not accomplish the regulations in the future.

- **Public administration perceives the regulatory environment** of their country as **complex** and with hurdles in regulatory and approval processes.

- **Not many technical farmers answer the surve**y. This fact is disheartening due to the necessity of having extra experience in agrarian sciences to use properly organic fertilisers. Currently, Spain has the 2nd largest organic area, behind France, but can lose its seat in the oncoming years. **Farmers are reporting difficulties finding stock of circular** fertilisers nearby. Only 34% of the contestants find this task really or extremely easy. **NGOs** are not perceived as a neutral stakeholder. **Fertiliser producers** and **salespersons are not perceived as a fair communication channel** among farmers.

Regarding technical aspects, the **need to put additional efforts toward scaling up circular fertiliser production facilities** was identified. Further advancements regarding **energy consumption** are needed as well.

Technical analysis also found additional **market barriers for circular fertilisers**, namely their immature market development. To overcome them, **stimulating demand for circular fertilisers was deemed necessary**.

Methodological annotations

With the aim of contributing to the **knowledge and practice of circular fertilisers sustainability assessments**, several methodological conclusions were elaborated. The exercise of compiling for the first time –to the best of the authors' knowledge– this amount of information shed light on the **scarcity of available data**, specifically process-specific and region-segregated information.

In particular, the **lack of specific emission factors** for the application of different types of circular fertilisers was deemed to be one of the main weaknesses of the assessment. Thus, **field tests and experiments are needed** to obtain more robust data.

Data that allows accounting for the effects on soil physic-chemical conditions after the application of different types of fertilisers is not available in a way that matches LCA methods. Such values would have to be incorporated into new or revised impact categories through the proposal of emission factors. For that reason, perhaps **the most relevant advantage of organic circular fertilisers (the improvement of soil health) fell out of the scope of this study**.

The Product Social Impact LCA (PSILCA) database was chosen one for conducting the S-LCA. Several decisions were necessary for modelling each value chain (using the OpenLCA software). The most crucial one was the process that will represent the NRF. **Only one process related to fertiliser production was available in Europe**, making difficult its differentiation between regions and value chains. The authors conclude that **this database is not suitable for comparison studies of fertilisers**. We hypothesise that **a Reference Scale S-LCA based on surveys of key stakeholders might be better for this specific sector**. The **PSILCA database might be used only for an initial risk mapping stage**, helping to point out the most important indicator desirable to be assessed.

To conclude with the S-LCA considerations, there are three **sensitive points that may lead to deviations and errors**. Firstly, the price of the inputs. Those **economic expenses determine the background processes**, and the number of risk hours proportionally increases. Expensive starting products guide to high risks (i.e., spent mushroom substrate scenario). Secondly, the price of the final product**. Expensive final products lead to high** activity variables (in the project, working hours) which determine the **weight of the social indicators**. Thirdly, the country's dependence on the PSILCA database is also worth noting. **This particular database defines its processes not in the sector information but in the country-related information**. Those three factors create a bias in the FERPLAY modelling process. This selection bias can significantly impact the validity and reliability of the exposed results.

Recommendations for promoting circular fertilisers uptake

The research conducted enabled the proposition of the following **recommendations:**

Improving the environmental performance of circular fertilisers

- Reinforce measures to control gaseous emissions during circular fertiliser production.
- Look for greener options for feedstock (e.g., mushroom substrate mixes or anaerobic digestion inputs), chemical supplies (e.g., $MgCl_2$), and manufacturing technologies (e.g., sludge stabilisation options).
- Foster energy efficiency.
- Harness circular fertiliser production potential in nearby agricultural areas and improve logistics.
- Guarantee a high-quality source-separated collection model for bio-waste that minimises pollution with non-compostable materials that are later rejected within the process and sent to landfill or incineration.
- Transform waste water treatment facilities into eco-factories.
- Determine and enforce appropriate application rates and timing to mitigate leaching, run-off and gaseous emission impacts.

Lowering the obstacles for circular fertilisers cost efficiency

- Look for more cost-efficient chemical supplies and strive to reduce operational costs.
- Put in place a policy mix that helps circular fertiliser production attain competitiveness.
- Develop both voluntary and mandatory carbon markets.

Social recommendations

- Put in place policy tools to mitigate highlighted social risks on the circular fertilisers' production stage, and on its supporting activities.
- Strengthen surveillance and risk-mitigation strategies regarding non-fatal accidents in the workplace in processes involving the food industry.
- Ensure regional and national institutions are in charge of distributing subsidies in order to maximize the number of applicants to these funds.
- Offer economically appealing subsidies to attract new adopters to these new products.
- Foster clusters, technical advisors' associations, and online learning academies, ensuring sufficient access to key information to promote a trustable and clear environment around circular fertilisers.

Aligning policy instruments with the goal of widespread adoption of circular fertilisers

- Tackle regulatory barriers at the European and national level.
- Introduce new regulatory drivers at the European level.

Widening available knowledge on circular fertilisers

- Develop a consistent and long-term record of fertiliser-application-related atmospheric emission measurements.
- Develop local and region-level emission factors linked to the application of fertilisers to soils (emissions to air, water and soil).
- Deepen the understanding of nutrient release dynamics and its differences depending on specific molecules.
- Innovate further to enable the incorporation of effects on soil in future environmental sustainability studies.

"This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement N° 101060426."

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.