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[Jessica Pérez-García](#)\*, [Pedro Villanueva-Rey](#), Leticia Rodríguez-Hernández, [Teresa Alvarino](#), [Lucía González-Monjardin](#)

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Article

# From House to Farm: LCA of Sewage Sludge as a Circular Fertiliser in Three European Regions

Jessica Pérez-García <sup>1,\*</sup>, Pedro Villanueva-Rey <sup>1</sup>, Leticia Rodríguez-Hernández <sup>2</sup>,  
Teresa Alvarino <sup>1</sup> and Lucía González-Monjardin <sup>1</sup>

<sup>1</sup> Galician Water Research Center Foundation (Cetaqua Galicia), AquaHub - A Vila da Auga, Rúa José Villar Granjel 33, 15890 Santiago de Compostela, Spain

<sup>2</sup> VIAQUA, Gestión Integral de Aguas de Galicia, A Vila da Auga, José Villar Granjel 33, E-15890, Santiago de Compostela, Spain

\* Correspondence: jessica.perez.ext@cetaqua.com

**Abstract:** This study evaluates the environmental performance of stabilised sewage sludge used as a circular fertiliser (CF) across three European regions: Central, Mediterranean, and Northern Europe, comparing its performance against non-renewable fertilisers (NRF). The research applies a life cycle assessment (LCA) approach, considering a mix of the most used stabilisation technologies in each region such as anaerobic digestion, chemical treatment, thermal drying, composting, and aerobic digestion. Environmental impacts were assessed based on key categories including climate change, acidification, eutrophication, and resource use. The environmental performance of CF production outperformed NRF in all assessed categories, showcasing its potential as a sustainable alternative. Findings reveal that the choice of stabilisation process is key to the overall environmental performance of the region. High energy driven technologies, such as thermal drying present the bigger impacts. Regional disparities highlight the need for context-specific technology selection to optimise environmental outcomes. The study underscores the importance of integrating energy recovery and nutrient recycling in sludge management practices. These findings advocate for the promotion of circular fertilisers within a sustainable agricultural framework, emphasising technology adaptation based on local conditions to enhance ecological and economic benefits.

**Keywords:** sewage sludge; circular fertilisers; regionalisation; life cycle assessment; resource recovery; waste valorisation; circular economy

## 1. Introduction

Wastewater treatment plants (WWTP) generate large amounts of sludge as a byproduct of the water treatment process. This sludge is rich in essential nutrients such as nitrogen (N) and phosphorus (P), and contains significant levels of organic matter, making it a valuable resource for agricultural applications as waste-based fertiliser [1,2].

The use of sewage sludge for agricultural purposes is a widespread practice around the world. In the European Union (EU), it is regulated under Directive 86/278/EEC, which establishes standards to minimise environmental risks by promoting safe application practices and setting limits on contaminants to protect soil quality and ecosystems [3]. However, to maximise benefits and mitigate associated risks, it is essential to ensure proper treatment of sludge prior to its land application [4]. In line with regulatory frameworks, most EU Member States require sewage sludge to undergo stabilisation—through biological, chemical, or thermal processes [5]. However, treatment technologies across the EU 27 vary significantly based on factors such as final disposal methods and the size of the WWTP, which influence the selection of appropriate stabilisation processes [6]. Moreover, significant differences are observed not only between Member States but also within regions of the same country [7].

Transitioning to a circular economy is essential for a sustainable agriculture, as it can significantly reduce dependence on finite resources. Currently, mineral fertilisers are heavily reliant

on non-renewable resources like phosphate rock and nitrogen, which are extracted through energy-intensive processes such as the Haber-Bosch method, resulting in significant environmental impacts [8]. Alternatively, replacing mineral fertilisers with circular fertilisers (CF) derived from waste streams offers several advantages. These alternatives not only supply essential nutrients but also enhance soil structure through their organic matter content [1]. Additionally, the slow nutrient release fosters long-term soil fertility, reducing the need for frequent fertilisation [9]. This contributes to a more sustainable agricultural system and supports the transition toward a circular economy [10].

In this context, FER-PLAY project aims to facilitate the uptake of alternative fertilisers, to protect ecosystems, decrease EU dependence on fertiliser imports, foster circularity and improve soil health. The project mapped and assessed alternative fertilisers made from secondary raw materials and highlighted their multiple benefits to promote their wide-scale production and use on field. In this sense, Life Cycle Assessment (LCA) is an appropriate tool used to assess the environmental performance of different products or services (ISO 14040, 2006), and particularly of the management of sewage sludge or biofertiliser [11,12]. LCA can support decision-making by guiding the adoption of circular economy practices and ensuring agricultural sustainability through the evaluation of environmental impacts of different alternatives.

This research focuses on the analysis of regionalised sludge stabilisation technologies to enhance representation for specific geographic areas, particularly Europe. The study aims to demonstrate the importance of identifying the technologies used in each region.

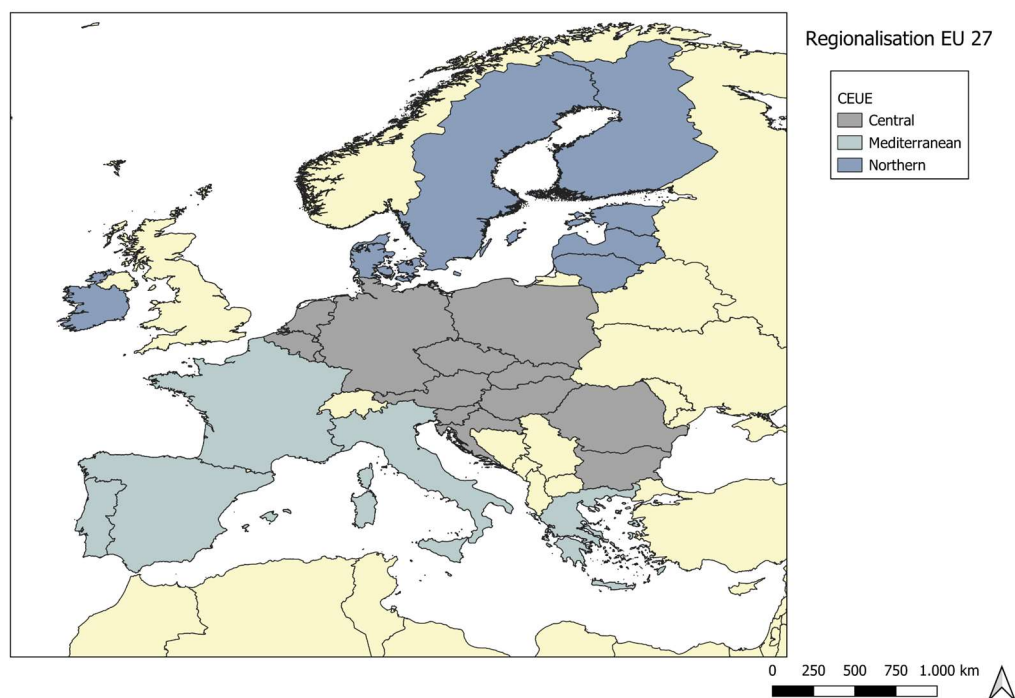
To achieve this, the research assesses the environmental performance of circular fertilisers production from sewage sludge using the most common stabilisation technologies in Europe. This evaluation is conducted through a LCA approach, considering three different climatic regions for agricultural applications. The analysis addresses CF production and allows its comparison with its non-renewable fertiliser (NRF) counterpart. Finally, a life cycle impact assessment is performed to point out environmental hotspots and trade-offs to identify sustainable practices in sludge management across different regions.

## 2. Materials and Methods

This research conducts an environmental LCA to evaluate the different technologies used for sludge stabilisation in three European regions. The aim is to facilitate the adoption of CF derived from secondary raw materials, promote their wide-scale production, and improve soil health. LCA was performed according to ISO 14040 and ISO 14044 standards [13,14]. The following sections outline the four interrelated stages of the assessment: i) goal and scope definition, ii) life cycle inventory (LCI), iii) life cycle impact assessment (LCIA), and iv) interpretation of results.

### 2.1. Goal and Scope Definitions

The main goal of the study is to compare the impacts of producing CF from sewage sludge, excluding its application to soil, in a European context. The regions—Central, Mediterranean, and Northern Europe—were selected based on climatic conditions to ensure comprehensive geographical representation and encompass the diversity of agricultural practices. The countries within each region were selected by the FER-PLAY's advisory board (Figure 1). Hence, the purpose is to analyse the environmental performance of CF by identifying the most commonly used stabilisation technologies across the three selected regions.



**Figure 1.** Map showing the EU 27 countries included in the three considered regions (Central, Mediterranean, and Northern).

The selection of stabilisation technology is influenced by various factors such as the size of the treatment plant, influent characteristics, and geographical location [6]. However, although some stabilisation methods are widely adopted, significant variation exists in the technologies used across European countries, with notable differences observed between them. Five sludge treatments were considered:

- **Anaerobic digestion** aims at reducing, stabilising, and partially disinfecting sludge. It consists of confining the sludge in a reactor at a temperature of about 35 °C for a period of time. During this process, biogas (mixture of methane and carbon dioxide) is generated as a by-product and usually used to maintain the temperature of the vessel [15].
- **Chemical treatment** refers mostly to lime treatment, meaning the addition of lime to sludge in order to raise its pH to 12, destroying or inhibiting the biomass responsible for the degradation of the organic compounds. The treatment also helps disinfecting sludge, increasing its dry matter content, and making handling easier [15].
- **Thermal drying** implies delivering energy to the system to evaporate the water resulting in its densification. A dry matter content of at least 45% is necessary to inhibit the re-growth of bacteria [15].
- **Composting** is an aerobic process consisting of aerating sludge mixed with a co-product such as sawdust or animal manure. Composting produces excess heat, which can be used to raise the temperature of the composting mass. The mix then evolves for several weeks. Composted sludge reaches a good level of disinfection, and is stabilised, reducing therefore the arising of odours. The final dry matter content in composted sludge can reach over 60% making it easy to handle [15].
- **Aerobic digestion** stabilises sludge by degrading the organic matter by microorganisms under aerobic conditions (i.e., in the presence of oxygen). Although a simpler process than anaerobic

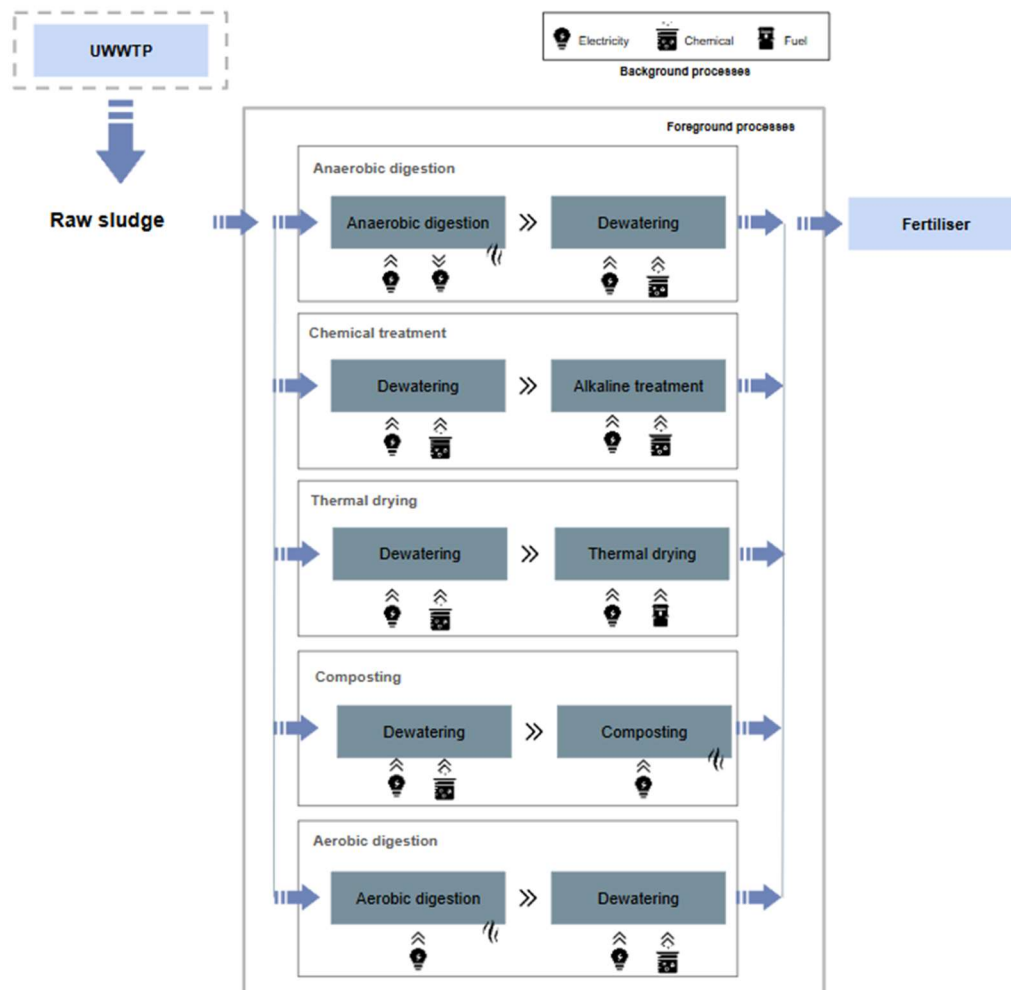
digestion, it requires a significant amount of energy (from 5 to 10 times more than anaerobic digestion) [15]. As a result, it is mostly used in smaller wastewater treatment plants [6].

The functional unit (FU) has a significant influence on the LCA results; therefore, it is essential to define a suitable FU as a reference unit to which the input and output data are referred [13]. In reviewed studies, such as Lam et al. (2020) and Yoshida et al. (2013), the most common FU selected was the volume of treated water, the amount of sludge disposal or the amount of recovered nutrients. However, this study focuses on comparing the production of a CF with its non-renewable counterpart. Therefore, the selected FU was based on the supply of a specific amount of nutrients to agricultural soils [12]. Specific nutrients supply values for the value chain are presented in Table 1.

**Table 1.** Stabilised sludge nutrient content [15].

<b>Dry matter (%DM)</b>	20.00
<b>Nitrogen content (% DM)</b>	4.11
<b>Phosphorus content (% DM)</b>	2.90
<b>Potassium content (% DM)</b>	0.30

The system boundaries considered in the present work were limited to fertiliser production, starting with the sludge generation (originated from primary clarifier and biological reactor from Urban wastewater treatment (UWWT)), excluding upstream wastewater treatment processes as depicted in Figure 2. For each stabilisation technology, chemical consumption, energy consumption (i.e., electricity and fuel), and the derived emissions were included. Infrastructure was not considered in the assessment because it was demonstrated in previous studies that only 4% of environmental impacts are attributable to the construction phase [17].



**Figure 2.** System boundaries considered in the study. Urban wastewater treatment was excluded from system limits (dashed lines).

## 2.2. Data acquisition and life cycle inventory

LCI was collected for the three European regions. As previously mentioned, the three geographical regions share the same objective and scope, with the unit processes identical across all scenarios. However, the distribution of stabilisation technologies utilised and the composition of the raw sewage sludge exhibit differences across countries, requiring specific modelling for each case [6]. Therefore, each region has a different LCI. Table 2 presents the distribution of the technological mix, compiled based on the most common stabilisation methods employed in the respective countries of each European region, as outlined in Section 2.1. Further information is provided in Section 1 of Supplementary material.

**Table 2.** Stabilisation method distribution per European region.

Region	Anaerobic digestion	Chemical treatment	Thermal drying	Composting	Aerobic digestion
Northern	10.8	36.1	39.7	11.6	1.8
Central	39.4	5.3	5.3	15.9	34.0
Mediterranean	68.2	6.0	6.0	6.0	13.7

Primary data at the industrial level was mostly obtained from stakeholders and partners involved in the FER-PLAY project. These data encompassed a wide range of inputs for sludge stabilisation processes, including energy consumption, chemical use, fuel consumption, and waste generation. Conversely, energy and chemical consumption for the necessary unit processes were obtained from secondary sources such as technical handbooks [18]. For the chemical treatment of sludge (i.e., alkaline treatment), the required amount of lime was sourced from the literature [19].

Concerning anaerobic digestion, the production of biogas and digestate, including fugitive CH<sub>4</sub> emissions, were modelled based on the study by Huygens et al. (2022). Direct emissions linked to biogas combustion were estimated based on the emission factors proposed by the EMEP/EEA air pollutant emissions inventory guidebook [20], taking into account the TIER 1 emission factor. In addition, the composition of the final product and air emissions generated during the compost production process were also modelled based on Huygens et al. (2022). It was assumed in the composting process that cellulose-rich bulking agents, necessary to combine with sludge during this process, are waste products from other processes and therefore have no associated environmental impact [15].

Secondary data related to energy and chemical production, or waste treatment were obtained from Ecoinvent v3.9 database [21] by following a “cut off” approach. Meanwhile, electricity production of each country was obtained from Eurostat database considering each country's contribution to represent the electrical grid of each group of countries. These processes were modelled using background processes for the electricity market. Similarly, NRF were modelled using a “market” approach representative of Europe. The nutrient supply from these processes were equivalent amounts provided by stabilised sludge, enabling a comparative analysis of their life-cycle impacts.

Table 3 presents the input/output inventories for stabilised sewage sludge for the UWWT value chain, per functional unit, for the Central, Mediterranean, and Northern regions of Europe, respectively.

**Table 3.** Inventory data for the sludge stabilisation technology mix across the three regions (per FU).

	Central	Mediterranean	Northern	
<b>Inputs from the technosphere</b>				
<b>Materials</b>	<b>Amount</b>	<b>Amount</b>	<b>Amount</b>	<b>units</b>
Raw sludge	3.61	50.57	40.93	t (wet basis)
Electricity	5290.40	2113.62	2136.07	kWh
Polymer (dewatering)	0.23	0.190	0.25	kg
Lime, CaO (chemical treatment)	8.89	9.71	41.30	kg
Fuel (thermal drying)	4.45	4.85	22.71	L
Transportation supplier by truck	0.030	0.025	0.032	tkm
Transportation supplier by train	0.056	0.046	0.060	tkm
Transportation supplier by ship (dewatering)	0.063	0.051	0.067	tkm
<b>Outputs to the technosphere</b>				
<b>Products and co-products</b>	<b>Amount</b>	<b>Amount</b>	<b>Amount</b>	<b>units</b>
Stabilised sludge	1.00	1.00	1.00	t (wet basis)
Electricity	22.30	260.95	29.38	kWh
<b>Waste</b>	<b>Amount</b>	<b>Amount</b>	<b>Amount</b>	<b>units</b>

Wastewater	7,830.00	7,700.00	4.96	m <sup>3</sup>
<b>Emissions</b>				
<b>To air</b>	<b>Amount</b>	<b>Amount</b>	<b>Amount</b>	<b>units</b>
CH <sub>4</sub>	1.01	0.17	0.16	kg
NO <sub>x</sub>	111.09	188.28	27.27	g
CO	87.53	146.55	18.16	g
NMVOC	5.61	9.39	1.06	g
SO <sub>x</sub> (biogas combustion)	6.06	10.15	1.14	g
NH <sub>3</sub>	0.13	0.22	0.024	g
Pb (biogas combustion)	0.0028	0.00050	0.00050	mg
Cd (biogas combustion)	0.0011	0.00020	0.00020	mg
Hg (biogas combustion)	0.067	0.11	0.013	mg
As (biogas combustion)	0.024	0.0340	0.0044	mg
Cr (biogas combustion)	0.10	0.169	0.019	mg
Cu (biogas combustion)	0.17	0.29	0.033	mg
Ni (biogas combustion)	0.13	0.212	0.024	mg
Se (biogas combustion)	0.12	0.20	0.022	mg
Zn (biogas combustion)	2.24	3.76	0.42	mg
PCDD/F (biogas combustion)	0.54	0.90	0.10	ng
Water vapour (thermal drying)	0.050	0.050	0.23	m <sup>3</sup>
N <sub>2</sub> O	22.64	8.641	11.37	g
H <sub>2</sub> S (composting)	0.010	0.0036	0.0036	g
N (composting)	2.06	0.76	1.03	g
Terpenes (composting)	0.05	0.02	0.02	g

#### 2.4. Assumptions

Sludge generation was considered to have no environmental burdens, aligning with a zero-burden approach. Specifically, all environmental impacts from the wastewater treatment process were attributed exclusively to the main product, treated wastewater, as sewage sludge is considered a waste [22,23]. Consequently, no upstream impacts were assigned to the sludge as mentioned earlier in Section 2.1.

Aerobic digestion is predominantly used as a stabilisation method in small WWTP, and it is not frequently used even [6]. For this reason, this technology was disregarded from the study. Regarding the electricity generated from the biogas produced in anaerobic digestion, it is considered a co-product of the system. Therefore, all the environmental impacts of the process, including the direct emissions from the combustion of biogas, are allocated to the sludge. It is assumed that the electricity generated and leaving the system is free from environmental burdens.

#### 2.5. Life Cycle Impact Assessment

The Environmental Footprint (EF) 3.1. (adapted) method, developed by the Joint Research Centre of the European Commission, was selected to carry out the LCIA. This analysis followed a

midpoint approach and included 16 impact categories [24]. However, toxicity-related categories (ecotoxicity freshwater, human toxicity cancer, and human toxicity non-cancer), were not considered in this study due to the lack of robustness and reliability in the characterisation factors [25]. The most relevant categories selected were Acidification (A) in mol H<sup>+</sup> eq.; Climate change (CC) in kg CO<sub>2</sub> eq.; Marine eutrophication (MEP) in kg N eq.; Freshwater eutrophication (FEP) in kg P eq.; Photochemical ozone formation (POF) in NMVOC eq.; Resource use, fossils (RUf) in MJ; Resource use, minerals and metals (RUm) in kg Sb eq; and, Water use (WU) in m<sup>3</sup> deprived. These categories were chosen based on previous LCA studies in fertiliser production [11], and they cover environmental burdens on various protection areas, as recommended by PEFRC guideline [25]. SimaPro 9.6 [26] was the software used to perform the impact assessment. In this study, normalisation and weighting steps were not carried out.

### 3. Results

This section presents the results of the environmental assessment of CF production across the three regions under study, focusing on the contribution analysis.

#### 3.1. Environmental Performance

Contribution analysis of CF production is shown in Figure 3. The analysis reveals a different environmental profile for each region, with environmental burdens being unequally distributed among the different technologies. Differences can be attributed to various factors, such as variations in the composition of raw materials or differing sludge management practices.

In the Central region, the technology based on Anaerobic digestion presents the highest contribution in all evaluated categories, except for RUm and RUf, with the following contributions: acidification (50%), climate change (52%), marine eutrophication (67%), freshwater eutrophication (38%), photochemical ozone formation (65%), fossil resource use (20%), and water use (-64%). In contrast, chemical treatment demonstrates a significantly lower contribution across all categories, with contributions not exceeding 17%. Similarly, thermal drying predominantly contributes to the RUf category (37%), while in the other categories, its contributions do not exceed 15%. Composting is mainly responsible for impact categories A (34%), FEP (47%), RUf (31%) and RUm (42%).

When looking at Figure 3, it is observed that the Mediterranean region exhibits environmental benefits in some categories associated with anaerobic digestion, with the following contributions - 13%, -74%, -77%, -87% and -83% for A, FEP, RUf, RUm and WU respectively. Anaerobic digestion shows significant impacts in the MEP category; however, its contribution to CC is relatively low (8%).

Regarding the Northern region, Anaerobic digestion presents environmental benefits in some categories such as FEP (-4%), RUf (-9%), RUf (-28%), WU (-13%). Chemical treatment is the technology with the highest contribution to CC, with an average of 31% in the remaining categories. However, thermal drying dominates all categories, with contributions ranging from 41% to 66%. Finally, the remaining technology exhibits negligible impacts in most categories, except for A, MEP, FEP, and RUm, where its contributions are 16%, 10%, 14%, and 17%, respectively.

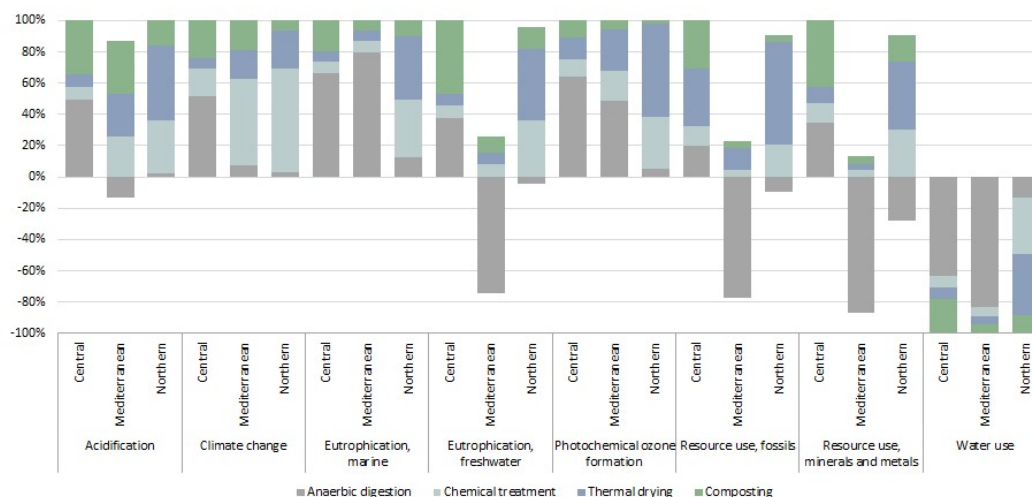


Figure 3. Contribution analysis of circular fertiliser for each European region.

## 4. Discussion

This section identifies the environmental hotspots of the CF value chain, compares them across regions and, with its non-renewable counterpart.

### 4.1. Identification of the Environmental Hotspots

The environmental assessment identified the hotspots across the life cycle stages for each evaluated scenario. Emissions resulting from combustion of biogas, associated with anaerobic digestion, represent the main hotspot in A, CC, MEP and POF for the Central region. These environmental burdens are due to NO<sub>x</sub> and sulphur dioxides in A, while methane fugitive emissions contribute significantly to CC and POF. Furthermore, NO<sub>x</sub> and CH<sub>4</sub> were significant contributors to MEP and POF, respectively, in the Mediterranean region. Lime consumption during chemical treatment processes also contributed substantially to the environmental burdens in CC for both the Mediterranean and Northern regions. In contrast, fuel consumption in thermal drying is the main carrier across almost all categories for the Northern region.

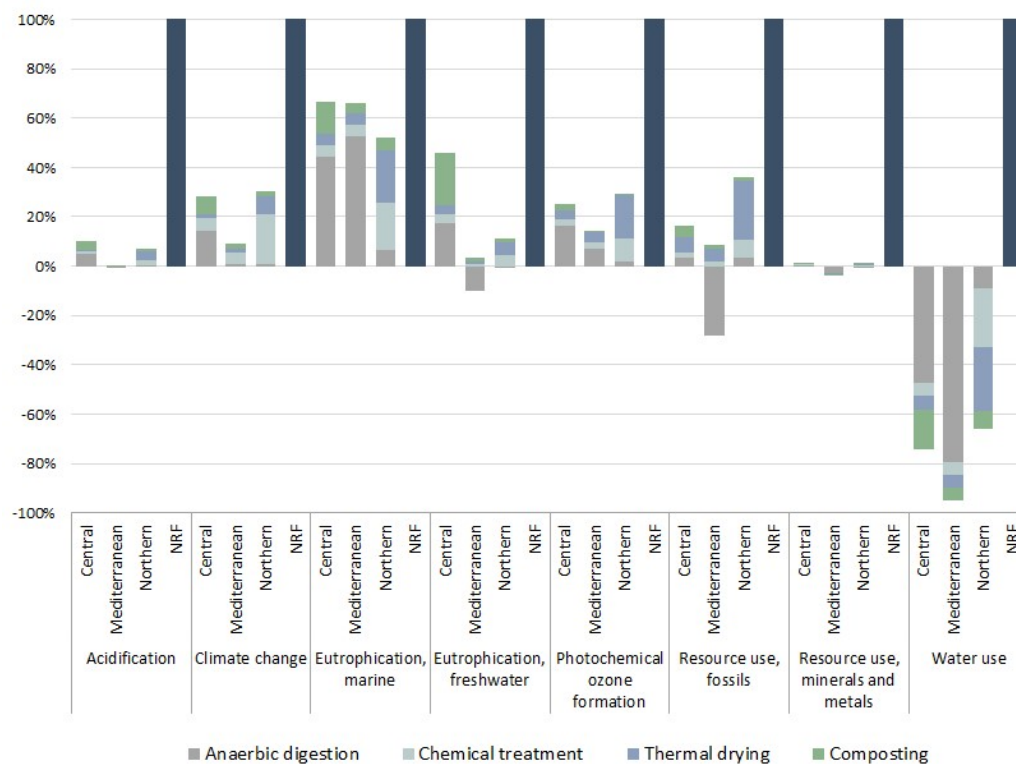
When comparing the results of this study to previous research, similar environmental hotspots are identified across technologies. For anaerobic digestion, biogas combustion emissions, particularly fugitive methane, are the primary contributors, consistent with the findings of [27,28], especially in terms of global warming. Biogas also provides environmental benefits by replacing grid electricity, reducing fossil fuel consumption, and associated SO<sub>2</sub> and NO<sub>2</sub> emissions, thus generating environmental credits for electricity production [29]. Additionally, Houllion and Joliet (2004) highlighted the significant impact of fuel use for heating, which is also reported in the present study. Similarly, lime has been identified as another key environmental hotspot in chemical treatment processes, emphasising its relevance in impact categories such as CC and POF [31].

### 4.2. Comparative Analysis of the Scenarios

Figure 4 shows the comparative environmental analysis of the evaluated scenarios among CF production in the three regions with its non-renewable counterpart (absolute values per category are reported in Table S4 of Supplementary Material). NRF shows the worst performance for all the impact categories assessed due to their high energy consumption during production and the significant environmental impacts associated with the extraction of raw materials.

A lot of LCA studies focused on CF production from sewage sludge. However, when compared to other studies, it is observed that different approaches have been established in the environmental assessment of CF from sewage sludge. Allocation in the production of these fertilisers remains a

controversial discussion [32]. Some studies, such as Pradel et al. (2016, 2019) and Sfez et al., (2019), include wastewater treatment within their scope, while others consider not only the production of CF but also their application to soil [35,36]. Despite the differences in approaches, assumptions, and methodologies, to the best of the authors' knowledge, studies have consistently shown better environmental performance of CF. This highlights the benefits of using sewage sludge as a fertiliser, as well as its potential due to its inherent fertilising properties.



**Figure 4.** Normalised life cycle impact characterisation results for circular fertiliser production for each European region and its non-renewable counterpart.

When comparing fertiliser production across regions, as illustrated in Figure 5, the technological mix implemented in the Central region shows the best environmental performance across all categories. This is mainly attributed to the dominant use of anaerobic digestion technology, where energy recovery is essential in enhancing the overall environmental outcomes.

The Central region exhibits the highest environmental impacts in categories such as A, MEP, and FEP. This is primarily due to the predominant use of anaerobic and aerobic digestion technologies. However, as noted in previous sections, aerobic digestion was not considered in the study, and thus, the impacts are mostly attributed to anaerobic digestion. In contrast, for categories CC, POF, and RUF, the Northern region shows the worst environmental performance, which can be attributed to the use of chemical treatment and thermal drying technologies, both of which are equally prevalent. These findings highlight that the results are significantly influenced by the choice of technology implemented in each region.

## 5. Conclusion

As far as we know, this research is the first environmental analysis of a CF taking into account a regional approach. The results have shown that fertilisers from stabilised sludge have a better environmental performance than their NRF counterparts, highlighting their potential as a sustainable alternative to mineral fertiliser. However, the renewable origin of CF does not automatically ensure their environmental sustainability, so further studies are needed. Interestingly, the regional approach

provides valuable insights. Thus, differences were found among the studied regions, showing that one-size-fits-all solutions are not always the best choice and, therefore, the particularities and nuances of the countries need to be considered before applying a circular solution. The analysis underscores the influence of stabilisation technologies on life cycle impacts, showing the importance of the technology used based on the specific conditions of each region. Stabilisation technologies with resource and energy recovery (such as anaerobic digestion) lead to environmental burden reductions derived from self-generated electricity. Furthermore, the intrinsic properties of CF, such as slow nutrient release and improved adsorption capacity, contribute to reduced impacts during the use phase, promoting soil health and long-term agricultural sustainability. These findings stress the importance of adopting holistic LCA approaches to guide technology prioritisation and support the integration of CF into sustainable agricultural systems.

**Supplementary Materials:** The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

**Author Contributions:** Conceptualization, Jessica Pérez-García, Pedro Villanueva-Rey and Lucía González-Monjardin; methodology, Jessica Pérez-García, Pedro Villanueva-Rey and Lucía González-Monjardin; formal analysis, Jessica Pérez-García.; investigation, Jessica Pérez-García and Lucía González-Monjardin.; resources, Leticia Rodríguez-Hernández.; data curation, Teresa Alvarino and Leticia Rodríguez-Hernández.; writing—original draft preparation, Jessica Pérez-García.; writing—review and editing, Lucía González-Monjardin, Pedro Villanueva-Rey, Leticia Rodríguez-Hernández and Teresa Alvarino.; visualization, Jessica Pérez-García. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The original contributions presented in this study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

A	Acidification
CC	Climate change
CF	Circular fertiliser
EU	European Union
FEP	Freshwater eutrophication
FU	Functional unit
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
MEP	Marine eutrophication
N	Nitrogen

<b>NRF</b>	Non-renewable fertiliser
<b>P</b>	Phosphorus
<b>POF</b>	Photochemical ozone formation
<b>RUf</b>	Resource use, fossils
<b>RUm</b>	Resource use, minerals, and metals
<b>UWWTP</b>	Urban wastewater treatment
<b>WU</b>	Water use
<b>WWTP</b>	Wastewater treatment plant

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