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METHOD ARTICLE

REVISED Application of a practical methodology for the selection of suitable value chains to produce circular fertilisers from secondary raw materials

[version 2; peer review: 2 approved, 1 approved with reservations]

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Abstract

Background

The growing demand for food products, driven by a growing world population, has increased Europe's dependence on conventional fertilisers, which have a high impact on the environment. In the last decade, new circular fertiliser value chains have appeared as promising alternatives to conventional fertilisers.

Methods

Because of the huge number of alternatives, this study aimed to develop a practical methodology that facilitates the analysis of data related to each value chain to identify and select the most promising circular fertiliser value chains to promote their wide-scale production and use in agriculture, replacing the dependence on conventional fertilisers in Europe. This methodology is based on two stages (funnelling process and scoring system) and considers the 16 criteria (e.g. technical viability, nutrient content, among others) defined in the

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study. The methodology was tested for 48 value chains identified during the mapping of secondary raw materials in Europe with the potential to be used as circular fertilisers, classifying them into seven different raw materials: urban wastewater (UWW), industrial wastewater (IWW), sewage sludge (SS), biowaste (BW), biological by-products (BBP), treated manure (TM), and digestate (DIG). The funnelling process is based on a GO/NO-GO approach that meets six criteria and allows the discarding of 18 value chains, from 30 to the second stage. The scoring system was a more complete analysis, including ten new scoring criteria.

Results

This system allowed the identification of the potential of the value chains analysed, concluding that struvite from UWW, struvite from IWW, stabilized sludge from SS, composted biowaste from BW, feather meal from BBP, solid fraction from DIG, and spent mushroom substrate from TM are the most promising options for agriculture.

Conclusions

The develop methodology was used to evaluate 48 different value chains with the potential to generate promising circular fertlizers. Seven value chains were finally selected.

Keywords
Agriculture, bio-waste, circular fertilisers, compost, organic by-products, resource efficiency, sewage sludge, wastewater

article can be found at the end of the article.

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REVISED **Amendments from Version 1**

In this revised version, several improvements have been made based on reviewers' feedback. The abstract has been refined adding a brief mention of what aspects the selection methodology covers. Changes in the introduction have been made to shift the focus from the conventional fertilisers use to why the uptake of circular fertilisers is important.

Word spelling has been checked and unified and some typos were corrected in the results and discussion section.

Any further responses from the reviewers can be found at the end of the article

1. Introduction

The application of fertilisers in agricultural fields is essential to ensure food production and safety. With the world's population projected to increase food demand by over 50% by 2050, sustainable fertilizer solutions are needed to maintain agricultural productivity while minimizing environmental impact. Fertiliser products contain primary macronutrients such as nitrogen (N), phosphorus (P), and potassium (K); secondary macronutrients such as calcium (Ca), magnesium (Mg), and sulfur (S); or a combination of both, which are required to provide the nutrients that plants need and to increase soil fertility and crop productivity.

Conventional fertilizers are produced through synthetic and manufacturing processes from raw materials such as air, natural gas, and mined ores. The application of conventional fertilizers is very extended in the European Union (EU) since they are used on 75% of agricultural land, and their application is expected to increase globally at a rate of +2% in the next few years (European Commission, 2019a). The EU is largely dependent on imports of most conventional fertilizers and their main macronutrients (N, P, K), which come from finite and non-renewable sources located in third countries. Additionally, the use of conventional fertilizers has associated harmful environmental impacts due to the methods used for the extraction of nutrients, manufacturing processes, and significant CO_2 emissions associated with the transport of fertilizer products to other countries different from the production regions (Basosi *et al.*, 2014).

To promote sustainability in agriculture, the European Union (EU) has prioritized the transition toward circular fertilizers produced from secondary raw materials such as wastewater and biowaste. This shift is reinforced by policies like the new EU Fertilising Products Regulation (Regulation EU 2019/1009), which facilitates the use of recycled and organic materials in fertilizing products (European Commission, 2019b). According to estimates, recycled biowaste could replace up to 30% of fertilizers currently in use, and phosphorus recovery from sewage sludge, biodegradable waste, and other sources could offset two million tons of phosphate rock imports annually (European Commission, 2016). Circular fertilizers also offer environmental benefits, such as improving soil health, enhancing carbon storage, and reducing the carbon footprint associated with fertilizer production and transportation (Culas *et al.*, 2025; Lam *et al.*, 2020).

Multiple value chains for circular fertilisers have appeared in the last decade as promising alternatives to replace the use of conventional fertilisers. These value chains differ in the input secondary raw materials (e.g., wastewater, biowaste, manure), production processes based on nutrient recovery technologies (e.g., composting, anaerobic digestion, precipitation, stripping), and output circular fertilisers (e.g., compost, struvite, ammonium sulfate, phosphates, etc.). Nevertheless, all of them allow the matching of the availability of valuable nutrients contained in the different secondary raw materials with the necessity of using circular fertilisers to replace the conventional ones, to boost the circular economy concept, and to increase the sustainability of industrial processes. Some of these value chains are already well established and the circular fertilisers market-available (e.g., compost production from biowaste) (Czekała *et al.*, 2017; Toledo *et al.*, 2020), whereas others are still under research because of low technology readiness level (TRL) (e.g., vivianite production from urban wastewater) (Wilfert *et al.*, 2018; Wu *et al.*, 2019) or their commercialization is hindered due to legal barriers (e.g., struvite production from urban wastewater) (de Boer *et al.*, 2018). Despite the huge number of options found in the literature related to circular fertiliser value chains, no specific methodologies have been identified in other studies that can contribute to identifying and selecting the most promising circular fertilisers to replace the use of conventional fertilisers in the EU.

In this sense, in the framework of the FER-PLAY project (a Horizon Europe funded project), a database was created to gather and harmonize the existing knowledge on key circular fertiliser value chains produced in the EU from seven secondary raw materials (urban wastewater (UWW), industrial wastewater (IWW), sewage sludge (SS), biowaste (BW), biological by-products (BBP), treated manure (TM), and digestate (DIG), and a practical methodology based on two stages (funnelling process and scoring system) was developed to identify and select the most promising ones for promoting their wide-scale production and use in agricultural fields, taking into consideration 16 criteria defined in this study, which include, among others, secondary raw material availability, technical viability, nutrient content, type of transport and ease, and type of storage and ease.

2. Methods

2.1. Mapping and selection of circular fertiliser value chains

A complete database (freely accessible online, https://doi.org/10.5281/zenodo.11060654) was created, including the most important characteristics of several circular fertiliser value chains, classifying all of them into seven different raw secondary materials: urban wastewater (UWW), industrial wastewater (IWW), sewage sludge (SS), biowaste (BW), biological by-products (BBP), digestate (DIG) and treated

manure (TM). The list of output products (Table 1) includes struvite, vivianite, K-struvite, phosphates, stabilized sludge, compost, P-rich ashes, ammonium sulfate, ammonium nitrate, biochar, hydrochar, mineral concentrate, spent mushroom substrate, liquid fraction of digestate, solid fraction of digestate, hair powder pellets, and horngrits/homchips. At the time of the selection process, 48 value chains were mapped, but the database is constantly updated and currently includes 51 value chains. The value chains were selected based on a mapping conducted by the partners of the FER-PLAY project, which integrates circular fertiliser producers, farmer associations, and R&D centers with experience in circular bioeconomy. The following sources were considered for the mapping: the selection of circular fertiliser value chains and data collection related to each value chain: i) know-how of partners' and partners' extensive networks; ii) peer-reviewed scientific publications; iii) past and current projects and initiatives developed under the EU funding programs relevant to the topic; iv) databases; v) statistics and market studies; and vi) external stakeholders linked to each value chain.

For each value chain selected, the FER-PLAY database (freely accessible online, https://doi.org/10.5281/zenodo.11060654) includes information related to: i) production (including process description, raw material availability, volume produced, number of production plants, Technology Readiness Level

Table 1. Preselection of the main circular fertiliser value chains from secondary raw materials.

Raw material	Fertiliser	References
Urban wastewater (UWW)	Struvite	Arcas-Pilz *et al.* (2021)
	Vivianite	Wilfert *et al.* (2018)
	K-struvite	Data not published
	Phosphates	Eureau (2021)
	Stabilized sludge	Zilio *et al.* (2022)
Industrial wastewater (IWW)	Struvite	Ylmén *et al.* (2018)
	Vivianite	Wu *et al.* (2019)
	K-struvite	Data not published
Sewage sludge (SS)	Struvite	Ferraro *et al.* (2023)
	Vivianite	Wijdeveld *et al.* (2022)
	Phosphates	Data not published
	Composted sewage sludge	Bożym & Siemiątkowski (2018)
Biowaste (BW)	Composted biowaste (green compost)	Anceschi *et al.* (2018)
	Composted biowaste (food waste and green compost)	Torrijos *et al.* (2021)
	Struvite	Siciliano (2016)
	P-rich ashes	Luyckx & Van Caneghem (2022)
	Biochar	Nisticò *et al.* (2019)
	Hydrochar	Taskin *et al.* (2019)
Biological by-products (BBP)	Composted biological by-products	Toledo *et al.* (2020)
	Hair powered pellets	Data not published
	Feather meal	Gerber *et al.* (1999)
	Horngrit/homchips	Data not published
	Meat-, Meatbonemeal	Bøen & Haraldsen (2013)

Raw material	Fertiliser	References
Digestate (DIG)	Untreated (raw) digestate with animal manure	Samoraj *et al.* (2022)
	Untreated (raw) digestate without animal manure (plant-based)	Van Puffelen *et al.* (2022)
	Liquid fraction of digestate	Tambone *et al.* (2017)
	Solid fraction of digestate	Tambone *et al.* (2017)
	Composted digestate	Czekała *et al.* (2017)
	Struvite	Szymanska *et al.* (2019)
	Vivianite	Wilfert *et al.* (2018)
	K-struvite	European Commission: Joint Research Centre *et al.* (2019)
	Phosphates	European Commission: Joint Research Centre *et al.* (2019)
	P-rich ashes	Hämäläinen *et al.* (2021)
	Enriched biosolids with struvite	Data not published
	Tenebrio molitor frass	Houben *et al.* (2021)
Treated manure (TM)	Composted animal manure	Vukobratović *et al.* (2018)
	Ammonium nitrate	Samanta *et al.* (2022)
	Ammonium sulphate	Menkveld & Broeders (2017)
	Mineral concentrate	Cempa *et al.* (2022)
	Vivianite	European Commission: Joint Research Centre *et al.* (2019)
	Phosphates	European Commission: Joint Research Centre *et al.* (2019)
	Biochar	Data not published
	Hydrochar	Fu *et al.* (2022)
	Solid fraction of manure	Fernández-Rodríguez *et al.* (2021)
	Liquid fraction of manure	Sigurnjak *et al.* (2017)
	K-struvite	Company *et al.* (2022)
	Spent mushroom substrate	Tuhy *et al.* (2015)
	Manure-processing effluent	Data not published

(TRL)), ii) distribution/trade (including national/international demand, transport area, transport ease, import, export), iii) storage and application (storage ease, storage necessities, storage emissions, pH, uptake speed, application form, application type, application timing, application dose, application emissions), iv) product content (including nitrogen, phosphorus, potassium, organic matter, sulphur, moisture content, calcium, magnesium, other micronutrients, heavy metals, pharmaceuticals, pathogens, microplastics), v) cost (including CAPEX, OPEX and market price) and vi) legislation (including applicability in organic farming, possibility of application in nitrate vulnerable zones (NVZ), national regulatory framework, product function category (PFC) and component material category (CMC) according to the Regulation EU 1009/2019)).

2.2. Funnelling process

Several circular fertilisers are available in the market or are close to being marketed. To ensure geographic representativity,

coverage, and replicability multi-assessment, it was crucial to assess only those value chains that are well characterized and represent the variability of agricultural applications and practices. To this end, a funnelling process based on a GO/NO-GO approach was applied. The funnelling process facilitates:

- The selection of relevant circular fertiliser value chains from a multitude of existing value chains so that further impact assessment is feasible and resource effective.
- Quickly disregard those value chains that are not properly characterized or not viable for industrialization and/or their application due to various problems (e.g., low nutrient content, toxicity, technical nonviability), not considering them for the assessment phase.

The GO/NO GO approach (Figure 1) is based on the application of a set of six predefined criteria. Every value chain was examined against the first criterion, and if the result was positive (GO), it was analyzed against the following and so on: Only those value chains that passed all stages obtained the "GO" label and were considered as promising and subjected to further assessment through the scoring system. After applying the funnelling process to the 48 circular fertiliser value chains, the obtained results were reviewed to ensure consistency. The value chains that seemed promising and received the "NO GO" label were scrutinized in detail. To accept the inclusion of these circular fertilisers, they must be widely used in Europe because their use demonstrates their capacity as a circular fertiliser in addition to their advanced development of production technology.

Six criteria were considered during the funnelling process to classify the GO/NO GO. These criteria cover different aspects of circular fertiliser value chains. Their definitions are as follows:

- **C1**. Data availability. At least three different studies have characterized the value chain.
- **C2**. Nutrient and organic carbon content. C2 was split into two categories: 2(A)-Nutrient content and 2(B)-Soil improvement capacity. On the one hand, the circular fertiliser (linked to category 2(A)) presented the minimum NPK content established by one of the possible PFC according to Regulation EU 2019/1009. On the other hand, the circular soil improver (linked to category 2(B)) presents the minimum organic carbon (C_{org}) content established by one of the possible PFC from the classification according to Regulation EU 2019/1009.
- **C3**. Toxicity. The circular fertiliser does not exceed the maximum permissible limits for contaminants (e.g., heavy metals, such as cadmium, arsenic, chromium, and mercury; microorganisms, such as *Salmonella spp* and *Escherichia coli*; and pharmaceuticals) established in Regulation EU 2019/1009.
- **C4**. Technical viability. The technology used for the recovery of nutrients in the value chain achieved a Technology Readiness Level (TRL) of at least five.
- **C5**. Versatility. The circular fertiliser can or could be used in more than five countries according to their national legislation and/or comply with Regulation EU 2019/1009. Due to the difficulty of accessing and interpreting the national/regional laws of the different countries, this criterion mainly uses Regulation EU 2019/1009 as a reference.

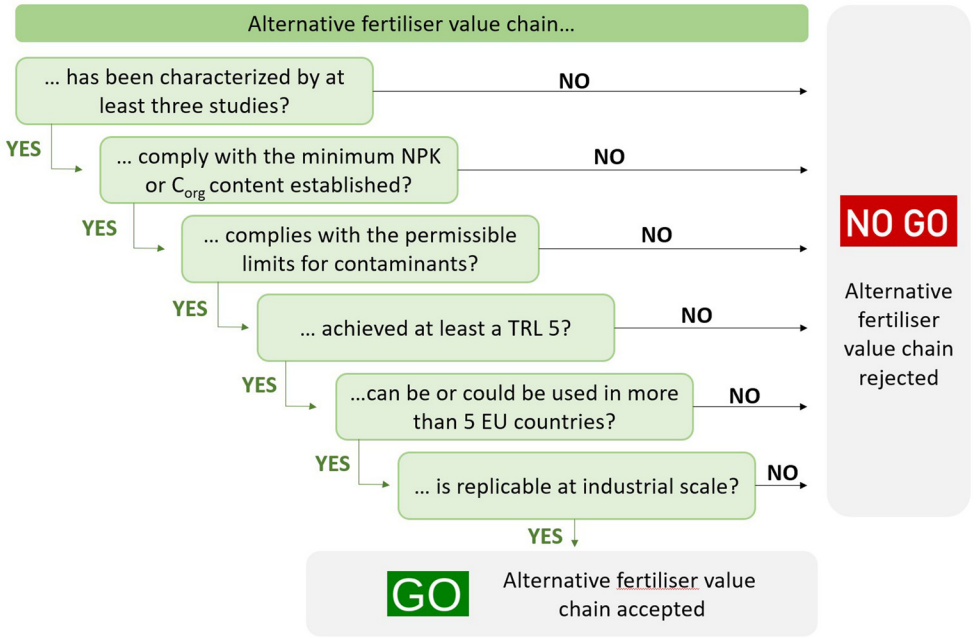

Figure 1. GO/NO GO approach for the evaluation of each value chain.

- **C6**. Industrialization. The circular fertiliser value chain is replicable at the industrial level around the EU, that is, feedstocks that are common in the EU.

For the evaluation of the criteria based on the European Fertilizing Regulation (C2, C3, and C5), at least one PFC was designed for each of the analyzed circular fertiliser value chains. For this classification, the NPK and C_{org} contents assigned in the FER-PLAY database for each fertiliser were considered since they are the main parameters linked to the nutrient content and soil amendment capacity. Compliance with the requirements of any of the CMC for the raw materials from which the fertiliser was produced was excluded from the study. The absence of a PFC assignment directly indicates that C2 has not been fulfilled. Table 2 summarizes the PFC classifications related to the 48 value chains evaluated during the funnelling process.

2.3. Scoring system

Once the GO/NO-GO approach was applied, the circular fertiliser value chains that obtained the "GO" label were validated using a scoring system. The scoring system was based on the assignment of points under a set of ten defined categories. The scores ranged from 1 to 5, with 1 indicating "poor compliance" with the criteria, and 5 showing "excellent" compliance. The criteria defined for the application of the scoring system are described below. Table 3 summarizes the requirements established for the assignment of values from 1 to 5 corresponding to each scoring criterion.

- **SC1**. The secondary raw material is abundant across Europe. The abundances of the seven raw materials in Europe were classified based on the available information included in the FER-PLAY database. The raw material with the highest amount of annual production in Europe received a score of 5, whereas the other raw materials received a score based on the percentage of abundance compared to the most abundant raw material (Table 3). In the case of the production of biological by-products, only production data from Germany was available because of the inaccessibility of the data.

- **SC2**. References on nutrient recovery technology across Europe. To determine the level of study and knowledge of the technology and fertiliser evaluated, a bibliographic search was conducted using Scopus (https://www.scopus.com). A bibliographic search was carried out for each fertiliser evaluated according to their keywords. The search was limited to studies conducted in Europe over the last ten years in Europe. A total of 641 scientific articles were found on the 30 circular fertilisers evaluated at this stage. The fertiliser with the highest number of references received a score of 5, whereas the others received a score based on the percentage of the number of references compared to the most referenced (Table 3).

- **SC3**. Production maturity across Europe. The scoring for this criterion was based on the TRL established by the EU (TRL EU). The TRL varied from 5 (1 point) (the minimum requirement to reach this scoring

Table 2. Product Function Category (PFC) classification for circular fertiliser value chains evaluated during the funnelling process.

Raw material	Fertiliser	PFC
Urban wastewater (UWW)	Struvite	1.C.I.a.i
	Vivianite	1.C.I.a.i
	K-struvite	-
	Phosphates	-
	Stabilized sludge	3.A
Industrial wastewater (IWW)	Struvite	1.C.I.a.i
	Vivianite	1.C.I.a.i
	K-struvite	1.C.I.a.i
Sewage sludge (SS)	Struvite	1.C.I.a.i
	Vivianite	1.C.I.a.i
	Phosphates	1.C.I.a.i
	Composted sewage sludge	3.A
Biowaste (BW)	Composted biowaste (green compost)	3.A
	Composted biowaste (food waste and green compost)	3.A
	Struvite	1.C.I.a.i
	P-rich ashes	1.C.I.a.i
	Biochar	1.A.I./3.A/3.B
	Hydrochar	1.A.I./3.A/3.B
Biological by-products (BBP)	Composted biological by-products	3.A
	Hair powered pellets	1.A.I/1.C.I.a.i/3.A
	Feather meal	1.A.I/1.C.I.a.i/3.A
	Horngrit/homchips	1.A.I/1.C.I.a.i/3.A
	Meat-, Meatbonemeal	1.A.I
Digestate (DIG)	Untreated (raw) digestate with animal manure	-
	Untreated (raw) digestate without animal manure (plant-based)	-
	Liquid fraction of digestate	-
	Solid fraction of digestate	3.A
	Composted digestate	3.A
	Struvite	1.C.I.a.i
	Vivianite	1.C.I.a.i
	K-struvite	-
	Phosphates	-
	P-rich ashes	1.C.I.a.i
	Enriched biosolids with struvite	-
	Tenebrio molitor frass	1.A.I

Raw material	Fertiliser	PFC
Treated manure (TM)	Composted animal manure	3.A
	Ammonium nitrate	1.C.I.b.i
	Ammonium sulphate	1.C.I.b.i
	Mineral concentrate	1.C.I.b.i
	Vivianite	1.C.I.a.i
	Phosphates	-
	Biochar	3.A
	Hydrochar	3.A
	Solid fraction of manure	3.A
	Liquid fraction of manure	-
	K-struvite	1.C.I.a.i
	Spent mushroom substrate	3.A
	Manure-processing effluent	-

*The symbol **(-)** indicates that the parameters to establish PFC are not fulfilled.*

stage) to 9, the maximum existing TRL, and therefore, the maximum score (5 points). The TRL data for each fertiliser were defined based on the information gathered during the creation of the FER-PLAY database.

- **SC4**. The forecasted volume of circular fertiliser is significant across Europe. This criterion is based on the expected volume of production for each fertiliser included in the FER-PLAY database. Considering that there is not an expected production value for Europe for all circular fertilisers, the available data corresponding to each country were extrapolated to the European area based on the national production and area of each country. The fertiliser with the highest forecasted volume of annual production received a score of 5, whereas the other fertilisers received a score based on the percentage of the forecasted volume compared to the most abundant (Table 3).
- **SC5**. Marketability of circular fertilisers across Europe. This criterion is based on the EU Fertilizing Products Regulation (Regulation EU 2019/1009). This regulation establishes rules for placing EU fertilizing

Table 3. Criteria for the scoring system of circular fertiliser value chains.

Criteria	1	2	3	4	5
SC1	The lower abundancy	75% less ref	50% less ref	25% less ref	The highest abundane (ref)
SC2	The lower references	75% less ref	50% less ref	25% less ref	The highest references (ref)
SC3	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
SC4	The lower production	75% less ref	50% less ref	25% less ref	The highest production (ref)
SC5	-	Not marketable	-	Marketable	-
SC6	Liquid or frozen or solid, flammable and toxic	Liquid or frozen or solid, flammable or toxic	Liquid or frozen, no chemical hazards	Solid, refrigerated	Solid, no temperature requirements
SC7	Liquid or frozen or solid, flammable and toxic	Liquid or frozen or solid, flammable or toxic or emissions	Liquid or frozen, no chemical hazards	Solid, refrigerated	Solid, no temperature requirements
SC8	Manually	Mechanically located	Mechanically (located and random)	Compatible with existing technologies or possible of automation-mechanically	Compatible with existing technologies and possibility of automation
SC9	-	Use not allowed	-	Use allowed	-
SC10	-	Manure content	-	No manure content	-

The abbreviation (ref) is referred to the list of references used for the creation of the database.

products on the market. Therefore, those products that fulfilled the requirements of this legislation received a score of 4 points, whereas those that did not fulfil them received a score of only 2 points.

- **SC6**. Circular fertiliser transport and ease. The characteristics of the fertiliser for its transport in terms of the state of the fertiliser (liquid, frozen, or solid), chemical risks (flammable or toxic), and temperature requirements were evaluated, as shown in Table 3.
- **SC7**. Circular fertiliser type of storage and ease. The characteristics of the fertiliser for its storage in terms of the state of the matter (solid, liquid, or frozen), chemical risks (flammable, toxic, or emissions), and temperature requirements are shown in Table 3.
- **SC8**. Circular fertiliser application in agricultural fields. The ease of fertiliser application was evaluated using this criterion. Fertilisers that must be applied manually received the lowest score (1 point), whereas those with existing machinery with the possibility of mechanical automation received the highest score (5 points). Intermediate scores are presented in Table 3.
- **SC9**. Circular fertiliser is used for organic production. This criterion is based on EU Regulation EU 2021/1165, which authorizes certain products and substances for their use in organic production. Therefore, all fertilisers in the list received a score of 4 points, whereas those not in the list received only two points.
- **SC10**. Nitrogen content in circular fertilisers. The NVZ are geographical areas designated by governments to protect water resources from nitrogen pollution. Excess nitrogen from agricultural sources is one of the main causes of water pollution in Europe. The designation of NVZ is intended to prevent the overapplication of nitrogen-based fertilisers, which can result in excessive nutrient runoff and leaching. In EU countries, farmers within designated NVZ are required to fulfil national regulations regarding the application of nitrogen as fertiliser from manure (such as limits on the amount that can be applied and the timing). Due to the great difficulty in accessing these national regulations as well as the variety of conditions depending on the categorization of the areas, it was considered to "penalize" fertilisers obtained from manure. Consequently, all fertilisers that contained or came from animal manure were scored with two points since their application in the NVZ will always be limited (either by quantity or by season). The other fertilisers obtained a score of three points.

3. Results and discussion

3.1. Classification based on the funnelling process

Out of a total of 48 circular fertiliser value chains evaluated during the funnelling process (Table 1), 27 obtained a favourable classification of "GO" (Figure 2). Consequently, they passed directly to the second stage of assessment through the scoring system. In contrast, 23 were classified as "NO GO" and were initially discarded. Table 4 summarizes the circular



Figure 2. Value chains classified with the "GO" label after the funnelling process.

Table 4. Value chains classified with the "NO GO" label after the funnelling process.

Raw material	Fertiliser	Critical criteria	Reasons
Urban wastewater (UWW)	Vivianite	C3-Toxicity	No qualitative data found
		C4-Technical viability	TRL 3 (TRL < 5)
		C6-Industrialization	More development is needed
	K-struvite	C2(A)-Nutrient content	P2O5 < 12%
		C3-Toxicity	No qualitative data found
		C4-Technical viability	TRL 4 (TRL < 5)
		C5-Versatility	Does not comply with EU regulation and could not be classified under any PFC
		C6-Industrialization	More development is needed
	Phosphates	C2(A)-Nutrient content	No qualitative data found
		C3-Toxicity	No qualitative data found
		C4-Technical viability	TRL 3–4 (TRL < 5)
		C5-Versatility	No qualitative data found
		C6-Industrialization	More development is needed
Industrial wastewater (IWW)	Vivianite	C3-Toxicity	No qualitative data found
		C4-Technical viability	TRL 4 (TRL < 5)
		C6-Industrialization	More development is needed
	K-struvite	C6-Industrialization	More development is needed
Sewage sludge (SS)	Vivianite	C3-Toxicity	No qualitative data found
		C6-Industrialization	More development is needed
	Phosphates	C4-Technical viability	TRL 3–4 (TRL < 5)
		C6-Industrialization	More development is needed
Biological by-products (BBP)	Meat-, Meat bone meal	C1-Data availability	Not enough data in studies
Digestate (DIG)	Untreated (raw) digestate with animal manure	C2(A)-Nutrient content or C2(B)-Soil improvement capacity	Cannot be classified under any PFC. Does not comply with any NPK & C_{org} requirements
	Untreated (raw) digestate without animal manure (plant-based)	C2(A)-Nutrient content or C2(B)-Soil improvement capacity	Cannot be classified under any PFC. Does not comply with any NPK & C_{org} requirements
	Liquid fraction of digestate	C2(A)-Nutrient content or C2(B)-Soil improvement capacity	Cannot be classified under any PFC. Does not comply with any NPK & C_{org} requirements
	Vivianite	C3-Toxicity	High potential of iron toxicity
		C6-Industrialization	More development is needed
	K-struvite	C2(A)-Nutrient content	No qualitative data found
	Phosphates	C2(A)-Nutrient content	No qualitative data found
	Enriched biosolids with struvite	C2(A)-Nutrient content	Cannot be classified under any PFC
		C5-Versatility	Not complied and do not have PFC classification

Raw material	Fertiliser	Critical criteria	Reasons
Treated manure (TM)	Vivianite	C3-Toxicity	High potential of iron toxicity
		C6-Industrialization	More development is needed
	Phosphates	C2(A)-Nutrient content	No qualitative data found
		C3-Toxicity	No qualitative data found
	Biochar	C3-Toxicity	No qualitative data found
	Hydrochar	C3-Toxicity	High potential of zinc and cadmium toxicity
	Liquid fraction of manure	C2(B)-Soil improvement capacity	Corg < 5%. Cannot be classified under any PFC. Does not comply with any NPK & Corg requirements
		C3-Toxicity	No data found in the database
		C5-Versatility	It could not comply with any PFC classification
	Manure-processing effluent	C2(B)-Soil improvement capacity	Corg < 5%. Cannot be classified under any PFC. Does not comply with any NPK & Corg requirements

fertiliser value chains initially discarded, as well as the criteria and reasons for which they were discarded.

Among the value chains that obtained the "GO" label, only struvite passed the funnelling process for fertilisers produced from IWW. Consequently, struvite obtained from industrial wastewater did not compete with other fertilisers within its own category during the application of the scoring system. For other secondary raw materials, such as UWW and SS, only two circular fertilisers passed favourably the funnelling process, whereas for the rest of the raw materials (BW, BBP, DIG and TM), the "GO" label was obtained for four to seven circular fertiliser value chains.

For the UWW raw material, the value chains that received the "NO GO" label were vivianite, K-struvite, and phosphates. They were discarded based on criterion C4 because the TRL did not exceed 4 for any of them. This low TRL directly leads to a lack of data that prevents the determination of their toxicity (C3) and, in some cases, their nutrient content (C2). Unfortunately, their low level of technological maturity means that their versatility (C5) and industrialization (C6) are not possible. In the specific case of vivianite, different bibliographic references have concluded that phosphorus recovery as vivianite is an innovative practice that is still in its infancy (Wu *et al.*, 2019). The same pattern related to the level of immaturity of the nutrient recovery technology was detected for vivianite, K-struvite, and phosphates produced from IWW and SS.

Regarding the discarded value chain for BBP, meat bone-meal is a specific fertiliser produced in Germany. Although it was included within the 48 value chains initially selected because it is a promising option according to the literature (Bøen & Haraldsen, 2013; Sica *et al.*, 2025), not enough data are available at the European level to properly assess it as a promising circular fertiliser.

DIG was the raw material with the most "NO GO" labels, discarding seven value chains from the initial 12. The main reason for discarding was criterion C2. Untreated (raw) digestate with animal manure, untreated (raw) digestate without animal manure (plant-based), liquid fraction of digestate, K-struvite, phosphates, and enriched biosolids with struvite did not comply with any NPK and C_{org} requirements established for these fertilisers in Regulation EU 2019/1009. Therefore, they could not be classified within any PFC. Consequently, versatility (C5) was affected as well. In the case of vivianite, this value chain is discarded due to its high potential for iron toxicity (C3) (European Commission: Joint Research Centre *et al.*, 2019).

In the case of TM, six circular fertiliser value chains were classified with the "NO GO" label. For vivianite and phosphates, the reasons are consistent with those described for DIG. In the case of biochar and hydrochar, the "NO GO" label was due to the toxicity criterion (C3). For biochar, no quantitative data were found, whereas for hydrochar, the values for zinc and cadmium content exceeded those established in the legislation. The liquid fraction of manure and manure-processing effluents could not be classified under any PFC because they did not comply with the NPK and C_{org} requirements established for C2.

Even though untreated (raw) digestate with animal manure, untreated (raw) digestate without animal manure, and the liquid fraction of digestate were classified as "NO GO" during the funnelling process, there are important reasons to consider their evaluation in the second assessment stage based on

the scoring system. By one hand, according to data provided by the European Biogas Association (EBA, 2024), the direct application of digestate as a circular fertiliser in agriculture is the most frequent destination for digestate in Europe (73%), followed by the use of upgraded digestate as a biofertiliser (15%). Some European countries, such as Sweden, have already designed voluntary schemes and guidelines for the application of digestates in soil. On the other hand, anaerobic digestion is booming in Europe owing to the demand for renewable gas, and digestate will be produced in increasing quantities in the upcoming years (Bumharter *et al.*, 2023; EBA, 2024a). Therefore, this is considered a favourable context to take advantage of the potential use of digestate as a fertiliser. Additionally, several studies have demonstrated the advantages of using digestate as a circular fertiliser in agricultural fields. Long-term fertilization with digestate helps maintain soil fertility and support soil life, ensuring that high-yield agricultural lands can be sustainably utilized (Karimi *et al.*, 2022). Several other benefits of digestate as an organic fertiliser are also worth highlighting. Compared to the same organic material in its raw form, digestate contains a higher percentage of readily available minerals, such as nitrogen, which enhances its fertilizing value. In addition to providing essential nutrients to plants, digestate offers further advantages over conventional agricultural fertilisers (Czekała *et al.*, 2020).

3.2. Classification based on the scoring system

In total, 30 circular fertiliser value chains passed the funnelling process (Section 3.1) and were evaluated through the application of the scoring system. Considering the criteria SC1-SC10 for each value chain and the corresponding score detailed in Table 3, Table 5 summarizes the score obtained for each fertiliser evaluated. The maximum score was obtained for the struvite produced from SS at 37 points.

For raw materials related to wastewater (UWW, IWW, and SS), the fertiliser with the highest score was struvite (36–37 points). Considering the triplicate representation of struvite in these categories, stabilized sludge was selected as one of the seven most promising fertilisers instead of struvite, as there were only three points of difference in their score for UWW (33 vs. 36). Additionally, considering that SS comes from urban wastewater, it was decided to consider the production of stabilized sludge from the SS raw material.

For fertilisers produced from BW, the composted biowaste (food waste and green compost) obtained the highest score with 33 points compared with the other five value chains evaluated.

The fertilisers produced from BBP raw materials obtained the lowest score compared to the rest of the value chains because of the lack of data for criterion SC4. Even though composted biological by-products were the fertiliser that achieved the highest score (28), considering that the composted BW was already selected as one of the seven most promising value chains to be assessed in the future based on a multi-assessment analysis, considering that there is only one point of difference with the other value chains evaluated for BBP, feather meal was selected as a promising option to be included in the list of the seven most promising value chains, taking into account its advantages compared with the other three value chains with the same score: i) this organic fertiliser is produced through controlled physical hydrolysis of fresh feathers, ii) its nitrogen content is equivalent to that of blood meal, but the nutrient release is slower, which is better for organic crops, and iii) higher availability of data for this value chain.

Regarding DIG raw material, struvite obtained the highest score of 34 points. Considering that struvite has already been represented previously as a promising fertiliser from UWW and IWW, solid fraction of digestate with a score of 31 points was selected as a promising fertiliser from DIG to be assessed in the future under a multi-assessment analysis. In the case of fertilisers produced from TM raw material, spent mushroom substrate obtained the highest score of 34 points.

The selection of the seven most promising fertilisers based on the FER-PLAY methodology are: struvite from UWW, struvite from IWW, stabilized sludge from SS, composted biowaste from BW, feather meal from BBP, solid fraction from DIG, and spent mushroom substrate from TM. This selection was conducted to ensure i) geographical representativeness, ii) availability of all raw materials and technologies in Europe, and iii) existence of the necessary machine for the application of each fertiliser in agriculture.

4. Conclusions

The practical methodology, developed in the framework of the FER-PLAY project and based on two stages (funnelling process and scoring system), allowed the identification and selection of the most promising circular fertiliser value chains out of a total of 48 included in the database created during the mapping of circular fertilisers in Europe, demonstrating that it is a useful tool that facilitates the analysis of data associated with the huge number of circular fertilisers that have appeared in the last decade as promising alternatives to conventional fertilisers.

The funnelling process, which is the first stage of the selection process, was used as a GO/NO GO approach to evaluate the 48 value chains based on six criteria that covered different aspects of the fertilisers, such as the composition, maturity of the production technology, and industrial replicability in different EU countries.

The scoring system, the second stage of the selection process, allowed the assessment of 30 circular fertiliser value chains based on the assignment of points under a set of ten defined categories covering different characteristics of the fertilisers, such as the availability of secondary raw materials across Europe, the marketability of the circular fertilisers across Europe, as well as practical aspects such as transport and storage of the fertiliser products and ease of use.

Table 5. Scores obtained for each value chain after the assessment with the scoring system. In bold are the circular fertilisers with the higher score.

Raw material	Fertiliser	Score
UWW	**Struvite**	**36**
	Stabilized sludge	33
IWW	**Struvite**	**36**
SS	**Struvite**	**37**
	Composted sewage sludge	31
BW	Composted biowaste (green compost)	31
	Composted biowaste (food waste and green compost)	**33**
	Struvite	32
	P-rich ashes	24
	Biochar	26
	Hydrochar	27
BBP	**Composted biological by-products**	**28**
	Hair powered pellets	27
	Feather meal	27
	Horngrit/homchips	27
DIG	Untreated (raw) digestate with animal manure	28
	Untreated (raw) digestate without animal manure	27
	Liquid fraction of digestate	28
	Solid fraction of digestate	31
	Composted digestate	31
	Struvite	**34**
	P-rich ashes	26
	Tenebrio molitor frass	25
TM	Composted animal manure	33
	Ammonium nitrate	23
	Ammonium sulphate	23
	Mineral concentrate	24
	Solid fraction of manure	30
	K-struvite	21
	Spent mushroom substrate	**34**

Combining the methodology developed in the framework of the FER-PLAY project with the specific interests of the stakeholders involved in the fertiliser value chain allowed the selection of one value chain for each raw material evaluated, with the seven most promising circular fertiliser value chains for Europe: struvite from UWW, struvite from IWW, stabilized sludge from SS, composted biowaste from BW, feather meal from BBP, solid fraction of digestate, and spent

mushroom substrate from TM. The evaluation of the selected value chains in this study will be complemented through a multi-assessment analysis of their environmental, social, and economic impacts to promote their wide-scale production and use in agricultural fields in Europe.

Data availability statement

Underlying data

The FER-PLAY database is freely accessible online on Zenodo (https://doi.org/10.5281/zenodo.11060654). (Inagro (Belgium) *et al.*, 2024)

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Additional data for this article consists of bibliographic references, which are included in the References section.

Author contribution

Investigation, Elisa Gambuzzi, Rita Gentili, Jessica Pérez-García, Ambrogio Pigoli, Inès Verleden, Pedro Villanueva-Rey, Werner Vogt-Kaute, Wim Moerman and Lucía González-Monjardin; methodology, Elisa Gambuzzi, Rita Gentili, Jessica Pérez-García, Ambrogio Pigoli, Inès Verleden, Pedro Villanueva-Rey, Werner Vogt-Kaute, Wim Moerman and Lucía González-Monjardin; writing – original draft preparation, Lidia Paredes; writing – review & editing, Elisa Gambuzzi, Rita Gentili, Ambrogio Pigoli, Inès Verleden, Werner Vogt-Kaute, Wim Moerman and Lucía González-Monjardin.

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References

Anceschi A, Guerretta F, Magnacca G, *et al.*: **Sustainable N-containing biochars obtained at low temperatures as sorbing materials for environmental application: municipal biowaste-derived substances and nanosponges case studies.** *J Anal Appl Pyrolysis.* 2018; **134**: 606–613.
Publisher Full Text

Arcas-Pilz V, Rufí-Salís M, Parada F, *et al.*: **Recovered phosphorus for a more resilient Urban Agriculture: assessment of the fertiliser potential of struvite in hydroponics.** *Sci Total Environ.* 2021; **799**: 149424.
PubMed Abstract | **Publisher Full Text**

Basosi R, Spinelli D, Fierro A, *et al.*: **Mineral nitrogen fertilisers: environmental impact of production and use.** Academia. EduR Basosi, D Spinelli, A Fierro, S JezFertil. *Compon Uses Agric Environ Impacts.* •academia.Edu, 2014.
Reference Source

Bøen A, Haraldsen TK: **Meat and bone meal and biosolids as slow-release phosphorus fertilisers.** *Agricultural and Food Science.* 2013; **22**(2): 235–246.
Publisher Full Text

Bożym M, Siemiątkowski G: **Characterization of composted sewage sludge during the maturation process: a pilot scale study.** *Environ Sci Pollut Res Int.* 2018; **25**(34): 34332–34342.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

Bumharter C, Bolonio D, Amez I, *et al.*: **New opportunities for the European Biogas industry: a review on current installation development, production potentials and yield improvements for manure and agricultural waste mixtures.** *J Clean Prod*. 2023; **388**(14): 135867.
Publisher Full Text

Cempa M, Olszewski P, Wierzchowski K, *et al.*: **Ash from poultry manure incineration as a substitute for phosphorus fertiliser.** *Materials (Basel).* 2022; **15**(9): 3023.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

Company E, Farrés M, Colprim J, *et al.*: **Exploring the recovery of potassium-rich struvite after a nitrification-denitrification process in pig slurry treatment.** *Sci Total Environ.* 2022; **847**: 157574.
PubMed Abstract | **Publisher Full Text**

Culas RJ, Anwar MR, Maraseni TN: **A framework for evaluating benefits of organic fertiliser use in agriculture.** *J Agric Food Res.* 2025; **19**: 101576.
Publisher Full Text

Czekała W, Dach J, Dong R, *et al.*: **Composting potential of the solid fraction of digested pulp produced by a biogas plant.** *Biosyst Eng.* 2017; **160**: 25–29.
Publisher Full Text

Czekała W, Lewicki A, Pochwatka P, *et al.*: **Digestate management in polish farms as an element of the nutrient cycle.** *J Clean Prod.* 2020; **242**: 118454.
Publisher Full Text

de Boer MA, Romeo-Hall AG, Rooimans TM, *et al.*: **An assessment of the drivers and barriers for the deployment of urban phosphorus recovery technologies: a case study of the Netherlands.** *Sustain.* 2018; **10**(6): 1790.
Publisher Full Text

EBA: **Exploring digestate's contribution to healthy soils.** 2024.
Reference Source

EBA: **European Biomethane Map 2024.** 2024a.
Reference Source

Eureau: **Wastewater treatment-sludge management - Briefing Note.** 2021.
Reference Source

European Commission: **Circular economy: new regulation to boost the use of organic and waste-based fertilisers.** 2016.
Reference Source

European Commission: **Fertilisers in the EU Prices, trade and use.** EU Agricultural Markets Briefs, 2019a.
Reference Source

European Commission: **Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003.** 2019b.
Reference Source

European Commission: Joint Research Centre, Delgado Sancho L, Eder P, *et al.*: **Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009): process and quality criteria, and assessment of environmental and market impacts for precipitated phosphate salts & derivates, thermal oxidation materials & derivates and pyrolysis & gasification materials.** Publications Office of the European Union, 2019.
Reference Source

Fernández-Rodríguez MJ, Mancilla-Leytón JM, Jiménez-Rodríguez A, *et al.*: **Reuse of the digestate obtained from the biomethanization of Olive Mill Solid Waste (OMSW) as soil amendment or fertiliser for the cultivation of forage grass (*Lolium rigidum* var. *Wimmera*).** *Sci Total Environ.* 2021; **792**: 148465.
PubMed Abstract | **Publisher Full Text**

Ferraro A, de Sario S, Attanasio A, *et al.*: **Phosphorus recovery as struvite and hydroxyapatite from the liquid fraction of municipal sewage sludge with limited magnesium addition.** *J Environ Qual.* 2023; **52**(3): 584–595.
PubMed Abstract | **Publisher Full Text**

Fu H, Wang B, Wang H, *et al.*: **Assessment of livestock manure-derived hydrochar as cleaner products: insights into basic properties, nutrient composition, and heavy metal content.** *J Clean Prod.* 2022; **330**: 129820.
Publisher Full Text

Gerber T, Steinbacher F, Hauser B: **Holzfasersubstrat zur kultur von pelargonium-zonale-hybriden - Biophysikalische und pflanzenbauliche untersuchung.** *J Appl Bot.* 1999; **73**(5–6): 217–221.
Reference Source

Hämäläinen A, Kokko M, Kinnunen V, *et al.*: **Hydrothermal Carbonisation of mechanically dewatered digested sewage sludge—Energy and nutrient recovery in centralised biogas plant.** *Water Res.* 2021; **201**: 117284.
PubMed Abstract | **Publisher Full Text**

Houben D, Daoulas G, Dulaurent AM: **Assessment of the short-term fertiliser potential of mealworm frass using a pot experiment.** *Front Sustain Food Syst.* 2021; **5**: 714596.
Publisher Full Text

Inagro (Belgium), Consorzio Italiano Compostatori (https://www.compost.it/), Centro Tecnológico del Agua, *et al.*: **FER-PLAY database.** [Dataset], Zenodo. 2024.
http://www.doi.org/10.5281/zenodo.11060654

Karimi B, Sadet-Bourgeteau S, Cannavacciuolo M, *et al.*: **Impact of biogas digestates on soil microbiota in agriculture: a review.** *Environ Chem Lett.* 2022; **20**(5): 3265–3288.
Publisher Full Text

Lam KL, Zlatanović L, van der Hoek JP: **Life Cycle Assessment of nutrient recycling from wastewater: a critical review.** *Water Res.* 2020; **173**: 115519.
PubMed Abstract | **Publisher Full Text**

Luyckx L, Van Caneghem J: **Recovery of phosphorus from Sewage Sludge Ash: influence of chemical addition prior to incineration on ash mineralogy and related phosphorus and heavy metal extraction.** *J Environ Chem Eng.* 2022; **10**(4): 108117.
Publisher Full Text

Menkveld HWH, Broeders E: **Recovery of ammonium from digestate as fertiliser.** *Water Pract Technol.* 2017; **12**(3): 514–519.
Publisher Full Text

Nisticò R, Guerretta F, Benzi P, *et al.*: **Thermal conversion of municipal biowaste anaerobic digestate to valuable char.** *Resources.* 2019; **8**(1): 24.
Publisher Full Text

Samanta P, von Ungern-Sternberg Schwark L, Horn H, *et al.*: **Nutrient recovery and ammonia-water production by MF-vacuum evaporation treatment of pig manure.** *J Environ Chem Eng.* 2022; **10**(1): 106929.
Publisher Full Text

Samoraj M, Mironiuk M, Izydorczyk G, *et al.*: **The challenges and perspectives for anaerobic digestion of animal waste and fertiliser application of the digestate.** *Chemosphere.* 2022; **295**: 133799.
PubMed Abstract | **Publisher Full Text**

Sica P, Müller-Stöver D, Magid J: **Enhancing the fertiliser value of recycled phosphorus for horticulture crops through Acidification and placement.** *J Soil Sci Plant Nutr.* 2025.
Publisher Full Text

Siciliano A: **Assessment of fertiliser potential of the struvite produced from the treatment of methanogenic landfill leachate using low-cost reagents.** *Environ Sci Pollut Res Int.* 2016; **23**(6): 5949–5959.
PubMed Abstract | **Publisher Full Text**

Sigurnjak I, Vaneeckhaute C, Michels E, *et al.*: **Fertiliser performance of Liquid Fraction of digestate as synthetic nitrogen substitute in silage maize cultivation for three consecutive years.** *Sci Total Environ.* 2017; **599–600**: 1885–1894.
PubMed Abstract | **Publisher Full Text**

Szymanska M, Szara E, Was A, *et al.*: **Struvite—an Innovative fertiliser from anaerobic digestate produced in a bio-refinery.** *Energies.* 2019; **12**(2): 296.
Publisher Full Text

Tambone F, Orzi V, D'Imporzano G, *et al.*: **Solid and Liquid Fractionation of digestate: mass balance, chemical characterization, and agronomic and environmental value.** *Bioresour Technol.* 2017; **243**: 1251–1256.
PubMed Abstract | **Publisher Full Text**

Taskin E, de Castro Bueno C, Allegretta I, *et al.*: **Multianalytical characterization of Biochar and Hydrochar produced from waste biomasses for environmental and agricultural applications.** *Chemosphere.* 2019; **233**: 422–430.
PubMed Abstract | **Publisher Full Text**

Toledo M, Gutiérrez MC, Peña A, *et al.*: **Co-composting of Chicken Manure, Alperujo, Olive Leaves/Pruning and Cereal Straw at full-scale: compost quality assessment and odour emission.** *Process Saf Environ Prot.* 2020; **139**: 362–370.
Publisher Full Text

Torrijos V, Calvo Dopico D, Soto M: **Integration of food waste composting and vegetable gardens in a university campus.** *J Clean Prod.* 2021; **315**: 128175.
Publisher Full Text

Tuhy Ł, Samoraj M, Witkowska Z, *et al.*: **Conversion of spent mushroom substrate into micronutrient fertiliser via biosorption in a pilot plant.** *Ecol Eng.* 2015; **84**: 370–374.
Publisher Full Text

Van Puffelen JL, Brienza C, Regelink IC, *et al.*: **Performance of a full-scale processing cascade that separates agricultural digestate and its nutrients for agronomic reuse.** *Sep Purif Technol.* 2022; **297**: 121501.
Publisher Full Text

Vukobratović M, Lončarić Z, Vukobratović M, *et al.*: **Use of composted manure as substrate for lettuce and cucumber seedlings.** *Waste Biomass Valor.* 2018; **9**(1): 25–31.
Publisher Full Text

Wijdeveld WK, Prot T, Sudintas G, *et al.*: **Pilot-scale magnetic recovery of vivianite from digested sewage sludge.** *Water Res.* 2022; **212**: 118131.
PubMed Abstract | **Publisher Full Text**

Wilfert P, Dugulan AI, Goubitz K, *et al.*: **Vivianite as the main phosphate mineral in digested sewage sludge and its role for phosphate recovery.** *Water Res.* 2018; **144**: 312–321.
PubMed Abstract | **Publisher Full Text**

Wu Y, Luo J, Zhang Q, *et al.*: **Potentials and challenges of phosphorus recovery as vivianite from wastewater: a review.** *Chemosphere.* 2019; **226**: 246–258.
PubMed Abstract | **Publisher Full Text**

Ylmén R, Gustafsson AMK, Camerani-Pinzani C, *et al.*: **Recovery of phosphorous from industrial waste water by oxidation and precipitation.** *Environ Technol.* 2018; **39**(15): 1886–1897.
PubMed Abstract | **Publisher Full Text**

Zilio M, Pigoli A, Rizzi B, *et al.*: **Using highly stabilized digestate and digestate-derived ammonium sulphate to replace Synthetic Fertilisers: the effects on soil, environment, and crop production.** *Sci Total Environ.* 2022; **815**: 152919.
PubMed Abstract | **Publisher Full Text**

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Eduarda Fraga Olivo
Universidade do Extremo Sul Catarinense (UNESC), Criciúma, Brazil

Review Summary
The article presents a solid and innovative methodological proposal for the selection of suitable value chains for the production of circular fertilizers from secondary raw materials. The study addresses a highly relevant topic within the current context of the transition to a circular economy and more sustainable food systems. The methodology is well-structured and illustrated through empirical applications, which strengthens its practical replicability.

Strengths
The proposed methodology is clearly described, with well-defined steps and comprehensive evaluation criteria (economic, environmental, social, and regulatory);
The focus on waste valorisation and the production of circular fertilizers contributes directly to sustainability goals and the circular economy agenda;
The practical application of the methodology to real-world case studies adds consistency to the proposal and demonstrates the feasibility of the approach in concrete scenarios.

Weaknesses and Suggestions for Improvement
It is recommended to include a sensitivity analysis to assess the impact of varying the weights assigned to the evaluation criteria, which would enhance the robustness of the results;
Although stakeholder involvement is mentioned, the extent to which their inputs influenced the evaluation and final selection of value chains could be described in more detail, including quantitative aspects;
The economic analysis, although present, could be more thoroughly developed. The inclusion of financial indicators such as cost-benefit assessments of the prioritized solutions would strengthen the evaluation;
I also suggest reviewing the English language in specific instances, particularly the use of “fertiliser” versus “fertilizer,” depending on whether the journal follows British or American English conventions.

Is the rationale for developing the new method (or application) clearly explained?

Partly

Is the description of the method technically sound?
Yes

Are sufficient details provided to allow replication of the method development and its use by others?
Yes

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: As a graduate in Biological Sciences and a current Master's student in Materials Science and Engineering at UNESC, with a dual degree program in Mechanical Engineering, Energy and Materials at the Polytechnic Institute of Viana do Castelo (Portugal), my academic background and ongoing research focus on solid waste valorization and circular economy strategies. I work on sustainable solutions for the agro-industrial sector, particularly the transformation of waste streams into value-added products.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 04 April 2025

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Alev Kir
Olive Research Institute (ORI), Izmir, Turkey

I confirm that I have no other comment for the article.

Is the rationale for developing the new method (or application) clearly explained?
Partly

Is the description of the method technically sound?
Partly

Are sufficient details provided to allow replication of the method development and its use by others?
Partly

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Conducts research in Agronomy on Organic annual and Olive in certified experimental open field of Institute's and farmers' conditions. Involved a project (ORGANIC-PLUS-774340) funded by EU H2020 in 2018 and 'Coordinating Organic Plant Breeding Activities for Diversity' (COBRA-Core Organic II-Eranet) between 2013 and 2016. In 1990 has graduated from Ege Uni., Faculty of Agriculture, Soil Science and Plant Nutrition Dept. (Izmir, Turkey) and received MSc, PhD on Plant Nutrition and soil fertility. Researcher at MoAF (1994-continuing) and was head of the Organic Farming (OF) Department of Aegean Agricultural Research Institute (AARI, Izmir-Turkey) (2006-2017). Led three vegetable and legume research projects in the national organic farming program of Turkey. Currently works at the Department of Soil Science and Plant Nutrition at Olive Research Institute (ORI)(Izmir Turkey) and leaded 21 research projects and tasks.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 19 March 2025

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Ramisah Mohd Shah
Universiti Malaysia Terengganu, Terengganu, Malaysia

Review:

Abstract:
1. The methodology is briefly described, but the selection criteria (16) are not explained. A brief mention of what aspects they cover (e.g., environmental impact, cost, availability) would help.
2. "Promising circular fertilizers"—It would be helpful to clarify whether the selected options have already been tested in agriculture or are just theoretically promising.

Introduction:
1. Introduction is well-structured, informative, and logically flows from the importance of fertilizers to the need for circular alternatives.
2. The description on why conventional fertilizers is problematic was included, but it would help to contrast their environmental impact with the benefits of circular fertilizers in a separate sentence for better emphasis.
3. Standardized the use of the word ‘fertilizers’ or ‘fertilisers’ throughout the article because they are mixed up.

Methods:
Methodology is well-structured and provides a clear approach for mapping and selecting circular fertilizer value chains.

Results and Discussion:
Minor Typos of citation: Bøen & Haraldsen,, 2013” → Extra comma and (Karimi et al., 2022) appeared 2 times (at the beginning and end of sentence).

Conclusion
The conclusion is comprehensive and well-structured, effectively summarizing the FER-PLAY methodology and its key findings.

Is the rationale for developing the new method (or application) clearly explained?

Yes

Is the description of the method technically sound?

Yes

Are sufficient details provided to allow replication of the method development and its use by others?

Yes

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Agronomy, Plant genetic resources

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 11 March 2025

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Alev Kir
Olive Research Institute (ORI), Izmir, Turkey

The important points I would like to draw attention to regarding the article are listed below. Accordingly;

1. In the Abstract and Introduction sections, the article particularly emphasizes the overwhelming dominance of conventional fertilizers in use. Can we say that this information really carries an importance and necessity that serves the purpose of the article? Since my opinion is to the contrary, I suggest that this issue be considered.

2. I have criticisms of the terminology generally used in the article. For example, the term fertilizer used does not match the materials examined. There is a tendency to use the term "fertilizer" mostly in chemical products containing a high percentage of plant nutrients. The targeted and studied materials are not evaluated in this sense. I suggest that this issue be considered.

3. The evaluation of risky and toxic materials in the article in the same order as materials that do not pose a risk in terms of environmental health has resulted in the evaluation of completely different issues by subjecting them to a ranking.

4. I present to your attention the evaluation of materials such as bio-waste compost and manure under independent subheadings.

Is the rationale for developing the new method (or application) clearly explained?
Partly

Is the description of the method technically sound?
Yes

Are sufficient details provided to allow replication of the method development and its use by others?

Yes

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Conducts research in Agronomy on Organic annual and Olive in certified experimental open field of Institute's and farmers' conditions. Involved a project (ORGANIC-PLUS-774340) funded by EU H2020 in 2018 and 'Coordinating Organic Plant Breeding Activities for Diversity' (COBRA-Core Organic II-Eranet) between 2013 and 2016. In 1990 has graduated from Ege Uni., Faculty of Agriculture, Soil Science and Plant Nutrition Dept. (Izmir, Turkey) and received MSc, PhD on Plant Nutrition and soil fertility. Researcher at MoAF (1994-continuing) and was head of the Organic Farming (OF) Department of Aegean Agricultural Research Institute (AARI, Izmir-Turkey) (2006-2017). Led three vegetable and legume research projects in the national organic farming program of Turkey. Currently works at the Department of Soil Science and Plant Nutrition at Olive Research Institute (ORI)(Izmir Turkey) and leaded 21 research projects and tasks.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 28 Mar 2025

Lucía González

Thank you for reviewing our article and giving valuable feedback. We will address each comment by the number you presented.

1. We have changed the introduction section to shift the focus away from the use of conventional fertiliser and more into why circular alternatives are important.
2. Since this article is part of the outputs of the public funded project FER-PLAY the terminology used is the same that was agreed by the consortium and advisory board of this project. We added the word "circular" to try and clarify that the focus is on the recovery of resources.
3. Both the exclusionary and evaluative criteria presented in this article were agreed upon based on a series of interactions with stakeholders of the projects such as fertilisers producers and farmers associations, academic and policy experts. As the most relevant aspect to consider when evaluating value chains to produce circular fertilisers.
4. The focus of this project was on resource recovery. Using existing secondary materials and giving them further use. Because of this, the classifications used are

based on the origin and type of secondary raw material and not on the characteristics of the final circular fertiliser produced (such as being organic or mineral).

Competing Interests: No competing interests were disclosed.