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Environmental and social sustainability assessment of a circular process for the valorisation of sewage sludge ash and mining by-products into bio-based fertilisers

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HIGHLIGHTS

- Raw material supply covered 55% – 98% of total environmental impacts.
- LG-MgO-based formulations improved environmental performance in CE scenario.
- Raw material supply showed medium-high social risk in the assessed categories.
- CE solution potentially improves the social performance of fertiliser manufacturing.

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ABSTRACT

Phosphorus (P) recovery from sewage sludge ash (SSA) represents an interesting solution to P supply concerns. While techno-economic assessments show promising outcomes, the environmental and social performance of these recovery processes remains insufficiently explored, hindering the market uptake of recovered P in bio-based fertilisers. This work investigates the environmental impacts of producing four commercial granular fertilisers representative of the Italian fertilizer market in 2024 (i.e., ENERGEO CV, ENERGEO CV TOP, LITHOZINC and PHEOSCOR). Furthermore, a social hotspot analysis (SHA) was conducted to account for the social implications of raw materials supply (e.g., P, Mg, S, Ca, Cl) in fertiliser manufacturing. Impacts were evaluated for a Business-As-Usual (BAU) scenario, in which fertilisers are based on mineral P (i.e., phosphorite), and a Circular Economy scenario (CE), in which phosphorite is partially replaced with P recovered from SSA via wet chemical extraction and co-precipitated with calcium hydroxide or low-grade magnesium oxide mining by-product (LG-MgO). Raw material supply covered from 56% to 98% of total environmental impacts across all fertilisers, except for ENERGEO CV – BAU and ENERGEO CV TOP – BAU, where core processes were the main contributors to specific sub-categories. LITHOZINC – CE and PHEOSCOR – CE showed similar or enhanced performances compared to the corresponding BAU formulations, indicating potential benefits in employing LG-MgO as precipitant. The supply chains of raw materials exhibited a medium-high social risk in the assessed categories, with Egyptian phosphorite extraction posing the greatest concerns for workers and local communities, and the innovative solution potentially improving the social performance of the fertiliser manufacturing process.

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Abbreviations

ADPf	Abiotic depletion potential for fossil resources
ADPm	Abiotic depletion potential for minerals and metals
AP	Acidification Potential
BAU	Business-As-Usual scenario
CE	Circular Economy scenario
E-LCA	Environmental Life Cycle Assessment
ENERGEO CV	fertilizer formulation from TIMAC AGRO Italia S.p.A.
ENERGEO CV TOP	fertilizer formulation from TIMAC AGRO Italia S.p.A.
EPD	Environmental Product Declaration
EPfw	Eutrophication Potential – freshwater
Epma	Eutrophication Potential – marine
EPte	Eutrophication Potential – terrestrial
ET	Eco-toxicity (freshwater)
FW	Net use of fresh water
GWPbio	Global Warming Potential biogenic
GWPfos	Global Warming Potential fossil
GWPlul	Global Warming Potential land use and land use change
GWPtot	Global Warming Potential total
HTc	Human toxicity (cancer effects)
HTnc	Human toxicity (non -cancer effects)
HWD	Hazardous waste disposed
IR	Ionizing radiation, human health
LG-MgO	low-grade magnesium oxide mining by-product
LITHOZINC	fertilizer formulation from TIMAC AGRO Italia S.p.A.
LU	Land use related impacts
NHWD	Non-hazardous waste disposed
NRSF	Non-renewable secondary fuels
ODP	Depletion Potential of the stratospheric ozone layer
PCR	Product Category Rule
PENRE	Non-renewable primary resources used as an energy carrier (fuel)
PENRM	Non-renewable primary resources with energy content used as material
PENRT	Total use of non-renewable primary energy resource
PERE	Renewable primary resources used as energy carrier (fuel)
PERM	Renewable primary resources with energy content used as material
PERT	Total use of renewable primary energy
PHEOSCOR	fertilizer formulation from TIMAC AGRO Italia S.p.A.
PM	Particulate matter emissions
POCP	Photochemical ozone creation potential
PR	phosphate rocks
RSF	Renewable secondary fuels
RWD	Radioactive waste disposed
SHA	Social Hotspot Analysis
SHDB	social hotspots database
SM	Secondary materials
SS	Sewage Sludge
SSA	Sewage Sludge Ash
WDP	Water deprivation potential

1. Introduction

Phosphorus (P) plays a pivotal role in human society, with around 89% of the global P production being dedicated to agricultural applications, primarily for fertiliser manufacturing (Jupp et al., 2021; Meng et al., 2019). However, the increasing demand for phosphate rocks (PR), driven by intensive agriculture practices, population growth and rapid urbanisation caused the overexploitation and quality decline of available PR reserves (Bacelo et al., 2020; Ryszko et al., 2023). Given this context, recovering P from secondary and renewable sources became crucial to meet the future demand and face the rising social and environmental challenges (Carrillo et al., 2024).

A promising category of secondary and renewable P sources includes P-rich waste streams, such as food waste, crop residues, slaughterhouse waste, livestock manure and municipal wastewater (Meng et al., 2019; Witek-Krowiak et al., 2022). Among them, municipal wastewater treatment by-products – such as aqueous phases (i.e., municipal wastewater treatment effluent, sewage sludge (SS) digestion supernatants and thickening/dewatering liquors), SS (i.e., digested SS, dewatered/dried SS) and sewage sludge ash (SSA) – are particularly significant due to the large volumes produced worldwide (Canziani et al., 2023). Nowadays, more than thirty P recovery technologies exist globally, reflecting the differences in national contexts and drivers in terms of regulations and/or presence of industrial stakeholders interested in recovered products (Canziani et al., 2023; Desmidt et al., 2015).

Despite the wide availability of technologies, recovered P still accounts for a small fraction of the fertiliser market. Economic viability remains a major barrier, with the cost of P-based recovered products ranging from 3 €/kg P (wet chemical and thermochemical recovery from SSA) to 28 €/kg P (recovery from SS), exceeding the average price of PR (1.1 €/kg P) and conventional P-based fertilisers (i.e., triple superphosphate, 2.2 €/kg P (Businessanalytiq, 2025a; Businessanalytiq, 2025b; Egle et al., 2016). Beyond economic challenges, a growing attention is being paid to assessing the environmental impacts of P recovery scenarios. In this context, Life Cycle Assessment (LCA) is a well-recognised methodology to quantify the environmental sustainability of products and technologies in the circular economy framework (Del Borghi et al., 2020; Moreschi et al., 2024).

Recently, the environmental performance of P recovery technologies was compared with the production of PR-based fertilisers (i.e., triple superphosphate) or conventional SS management strategies (i.e., incineration, landfilling, direct land application). For instance, Amann et al. (2018) evaluated the overall environmental performances of 18 P recovery technologies, identifying SSA thermochemical treatment as the best trade-off option in terms of heavy metal decontamination, emissions and energy demand, P recovery efficiency and total absence of organic micropollutants in the recovered product. Similarly, Lam et al. (2022) outlined that replacing half of conventional PR-based fertilisers with P-based products derived from municipal wastewater could reduce the environmental impact of the assessed crop production systems, particularly for recovery pathways involving struvite precipitation from digester supernatants and SSA thermochemical treatment. On the contrary, Pradel and Aissani (2019) found substantially higher environmental impacts for SS-based fertiliser production compared to triple superphosphate, mainly due to lower P concentration, higher chemical, energy and infrastructures requirements, lower fertilizing value of the recovered product and higher gaseous emissions compared to the reference system. Other studies highlighted the potential environmental benefits of alternative sludge valorisation routes, such as energy recovery from hydrochar from hydrothermal carbonisation instead of its direct agricultural application or chemical P recovery (Behjat et al., 2024; Mannarino et al., 2022). Despite several trials to identify the environmental impact and benefits of existing P recovery technologies, the obtained findings remain difficult to compare, due to the lack of robust and reliable data inventories and the discrepancy in system boundaries, functional units and selected impact characterisation methodologies (Lam et al., 2022).

Looking at a comprehensive sustainability assessment, research on the social and socio-economic implications of P-recovered products across their entire life cycle remains very limited. Indeed, existing works mostly address social aspects within broader and integrated economic, environmental, social and technical assessments of different SS management strategies. For example, Ronda et al. (2023) combined technical, socio-economic and envi-ronmental indicators to assess the sustainability of SS thermal valorisation routes (i.e.: flash and slow pyrolysis, gasification and combustion), identifying scalability and heavy metals content in SS treatment by-products as key limiting factors of such strategies. Similarly, Law & Pagilla (2021) applied a Triple Bottom Line (TBL) framework based on economic, social, and environmental factors to compare different P recovery options in the Chicago metropolitan area, concluding that P recovery from SSA as calcium phosphate (LEACHPhos process) and subsequent resource storage in dedicated monofils could offer long-term sustainability benefits, safer sludge disposal option, reduced Operating Expense and an improved recovery efficiency compared with other recovery routes. Furthermore, only a limited number of studies have explicitly focused on social sustainability. For instance, Teah et al. (2017) evaluated the social performances of fertilisers production and consumption in Japan using mineral (i.e.: imported PR) or secondary sources (municipal wastewater-derived struvite and hydroxyapatite), demonstrating that PR substitution with recovered P could reduce social impacts of Japanese fertilisers' supply chain, albeit with limitations given by national recycling capacity. To the best of our knowledge, no studies specifically evaluated the combined environmental and social implications of introducing recovered P into existing and market-ready fertiliser formulations. Specifically, the social impacts associated with the extraction and supply of both primary and secondary raw materials remain largely unexplored within a life cycle perspective.

Based on the aforementioned research gaps, this study aims to evaluate the environmental impacts related to the production of four commercial granular fertilisers used in the agricultural sector through Environmental Life Cycle Assessment (E-LCA).

Specifically, the environmental performance of a conventional production process, based on non-renewable mineral P sources (i.e., phosphorite) was compared with an innovative P recovery technology developed within the ERA-MIN3 EU PHOSTER project. In this innovative P recovery technology, a fraction of the mineral source is substituted with P-based products recovered via a wet chemical P recovery process from SSA. To account for the social impacts associated with PR extraction and refinement and with the supply of key elements for fertiliser production (i.e., Mg, S, Ca, Cl), a Social Hotspot Analysis (SHA) was conducted for specific stakeholders.

By integrating environmental impact assessment and SHA, this work provides a comprehensive evaluation of P recovery sustainability, offering novel insights to decision-makers for the transition toward circular and sustainable P management and guiding future research on impact reduction strategies for P recovery technologies.

2. Materials and methods

This section describes the phosphorous recovery process from sewage sludge ash, the analysed scenarios, and the methodological framework employed for E-LCA and SHA.

2.1. Phosphorus recovery from sewage sludge ash: the PHOSTER project

The PHOSTER project delivered a sustainable circular economy solution for the recovery of secondary minerals and metals from SSA and mining industry by-products to substitute critical raw materials (i.e., P, Mg) in fertiliser manufacturing. Within the project, a wet chemical P recovery process from SSA was developed, comprising SSA wet acid leaching by H_2SO_4 or HCl, leachate coagulation and filtration, and P alkaline precipitation from the P-rich solution by $Ca(OH)_2$ or a low-grade MgO by-product of magnesite calcination (LG-MgO). Process parameters, material and energy inputs, and output flows were directly derived from experimental pilot-scale data reported in Esposito et al. (2024). In that study, the SSA sample used for process optimisation corresponds to sample S5 previously characterised in Boniardi et al. (2021). Therefore, SSA properties, leaching behaviour and P recovery performance adopted in the present study are based on laboratory-verified and experimentally characterised material, ensuring full consistency between the recovery process modelling and the underlying ash characteristics.

A simplified process scheme is reported in Fig. 1.

2.2. Production of fertilisers and description of analysed scenarios

The four considered fertilisers, named as ENERGEO CV, ENERGEO CV TOP, LITHOZINC and PHEOSCOR, are produced at the Ripalta Arpina plant (Cremona, Italy) of TIMAC AGRO Italia S.p.A., which produces and packages different products, as simple phosphate mineral fertilisers, NPK compound minerals and NPK organo-minerals. The four fertilizers were selected based on their extensive use in Italian professional agriculture for arable and fruit crops, representing approximately 10% of the total granular fertiliser production in Italy in 2024 by the company (Table S1 in Supplementary Material (SM)**)**. The manufacturing of such products takes distinctly place in a superphosphate production plant (semifinished product), a nitrogen melting plant (semifinished product) and a granulation plant. The superphosphate production plant comprises a H_2SO_4 storage and mixing unit, a raw phosphorite grinding unit and a diluted H_2SO_4 and ground phosphorite mixing unit. The latter is paired to a wet washing unit, to abate gases generated by the exothermic reaction, and two drying plants, equipped with bag filtration. More details about the discussed plant operation are provided in El Chami et al. (2023). Two main scenarios were outlined: a Business-As-Usual (BAU) scenario, in which fertilisers are solely based on imported PR (i.e., phosphorite), and a Circular Economy (CE) scenario, in which a fraction of PR is replaced with P-based products recovered via the wet chemical P recovery process from SSA developed within the PHOSTER project. Specifically, in CE scenario, ENERGEO CV, ENERGEO CV TOP, LITHOZINC and PHEOSCOR were respectively integrated with P-based products recovered from the following process configurations, expressed as “leaching agent - precipitating agent”: HCl – $Ca(OH)_2$, H_2SO_4 – $Ca(OH)_2$, HCl – Lg-MgO, H_2SO_4 – Lg-MgO. A detailed description of the CE scenario is reported in Table S2–S4 (SM).

2.3. Environmental Life Cycle Assessment and social hotspot analysis

The methodological framework adopted for this study is an integrated assessment of the four granular fertilisers. The analysis combines an Environmental Life Cycle Assessment (E-LCA) to quantify environmental impacts with a Social Hotspot Analysis (SHA) aimed at screening potential social risks in the upstream supply chain.

2.3.1. Goal and scope definition

The E-LCA was conducted to evaluate the environmental impacts related to the production of four granular fertilisers (ENERGEO CV, ENERGEO CV TOP, LITHOZINC, PHEOSCOR). The analysed product systems, defined as the production of granular NPK fertilisers via granulation process, falls under the UNSD Central Product Classification group 346 (Fertilisers and pesticides) and class 1611 (Natural calcium phosphates, natural aluminium calcium phosphates and phosphatic chalk). The product system function comprises P production via a conventional mining or innovative recovery process from SSA. The software employed in this study was SimaPro version 10.2, relying on the Ecoinvent database version 3.11 (Ecoinvent v. 3.11). The E-LCA was conducted based on the ISO 14040:2006 and ISO 14044:2006 standards (ISO, 2006a; ISO, 2006b). The product-specific requirements indicated in Product Category Rule (PCR) 2010:20 Version 2.21 (Mineral or chemical fertilisers) were followed. The functional unit was 1 ton of produced fertiliser, including the packaging of the final product. Based on the product life-cycle subdivision proposed in the reference Central

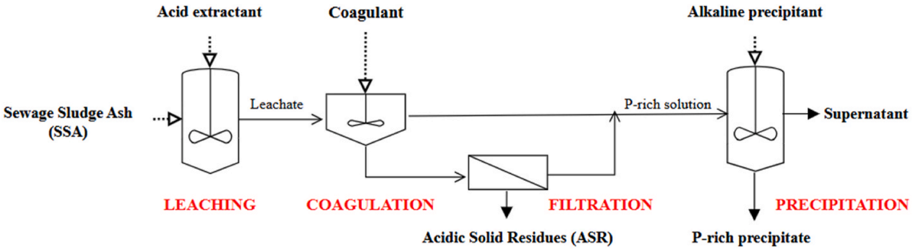

Fig. 1. Wet chemical P recovery process from SSA as developed within the PHOSTER project (modified from Esposito et al. (2024)).

Product Classification, only upstream processes (from cradle-to-gate) and core processes (from gate-to-gate) were considered, therefore a “cradle-to-gate” analysis was performed.

Upstream processes cover:

- the production and transport of raw materials for granulation,
- the production of primary and secondary packaging of fertilisers,
- the production of fossil fuels for the manufacturing plant.

Conversely, core processes encompass:

- the transport of primary and secondary packaging transport,
- fertiliser manufacturing,
- water consumption,
- thermal and electric energy generation,
- waste management.

However, the production of raw material packaging and bag filters was not considered.

SHA was conducted to evaluate the social impacts of P extraction and refinement from phosphorite rocks and those of key raw materials supply for fertiliser production (i.e., Mg, S, Ca, Cl), then preliminary investigation of representative companies illustrates how the generic risk profiles manifest in actual operations. Conversely to E-LCA, the social assessment was framed as an exploratory hotspot analysis focused on the upstream phase (raw material supply), with the primary aim of identifying and illustrating the most critical social risks along the raw materials supply chains (Mancini et al., 2023). This methodological choice is in agreement with relevant scientific literature, which highlights that raw material extraction and upstream processes typically represent major social hotspots in agri-food and fertilizer supply chains, while the downstream production stages can substantially influence final social outcomes, depending on location-specific labor conditions and manufacturing practices (Tsalidis et al., 2020).

2.3.2. *Life cycle inventory*

The Environmental-Life Cycle Inventory is the LCA step involving the collection of data and the application of calculation procedures to quantify inputs and outputs from a product system (EC, 2010). Data for fertiliser manufacturing were derived from the environmental product declaration (EPD) released to TIMAC AGRO Italia S.p.A. in 2018 (EPD - TIMAC AGRO Italia S.p.A., 2018). The EPD was conducted according to the reference PCR, as mentioned in the previous subsection, and data contributing less than 1% of the total mass and energy flows were excluded from the Environmental-Life Cycle Inventory.

Whenever possible, the production system was divided into subprocesses with directly collected data. Where specific sub-metering was not feasible (e.g., for shared site-level energy), flows were allocated to the co-produced fertilisers based on their relative mass outputs, consistent with the underlying EPD/PCR approach. The collected data were divided into input ones, referred to materials, transport and energy, and output ones, referred to generated products and polluting streams released in the receiving compartments (i.e., air, water and soil). Data were also classified as specific data, collected from direct measurements or obtained from target literature, generic data, obtained from specific databases, and proxy data, based on estimations or average values. Whenever possible, specific data were employed. Upstream processes primarily relied on specific data. For the BAU scenario, information on fertiliser manufacturing, energy consumption and gaseous emissions was sourced collected from company reports of 2024. Specifically, for products already covered by EPD (i.e., LITHOZINC NPK 6-12-16 Bulk), data from the preparatory E-LCA to the EPD were used. Data for the formulations related to the CE scenario were provided by the Department of Civil and Environmental Engineering of Politecnico di Milano, as deliverables of the PHOSTER project, and refer to recovery configurations and products whose chemical composition and regulatory compliance were previously experimentally validated. Data related to raw materials transportation were calculated based on the means of transport and the supposed distance between raw-materials supplier sites and fertiliser manufacturing plant. Other data related to raw materials, fuels and electricity were collected from the Ecoinvent database (v. 3.11). Proxy data were employed for a limited number of raw materials and did not significantly contribute ($\leq$10%) to the total impact in each considered sub-category. All data were geographically referred to Europe.

As previously mentioned, upstream processes primarily include the manufacturing and transport of raw materials for granulation, generation of primary and secondary packaging of fertilisers and of fossil fuels for the production plant. The type and quantity of required raw materials to produce the four fertilisers under both scenarios are reported in Table S4 and S5 (SM). It should be noticed that the total fraction of raw materials in each formulation exceeds 100%, as part of the mineral wastes are recirculated within the production process.

Primary and secondary packaging data are provided in Table S6 (SM), assuming identical quantities required in BAU and CE scenarios. Plant electric and thermal energy demands are satisfied through four boilers and one cogeneration units fed with natural gas, whose annual consumption is reported in Table S7 (SM). In addition, an annual diesel consumption of 124,149 L for transport was estimated.

Core processes cover the transport of primary and secondary packaging, fertiliser manufacturing, plant water consumption, thermal and electric energy generation and waste management. Truck transport was assumed for the shipment of primary and secondary packaging. Natural gas consumption was converted to primary energy values using a lower heating value of 9.7925 kWh/Std m^3. A thermal efficiency of 42.4% was assumed for the cogeneration unit. This unit provides only part of the plant electricity demand, while the rest is purchased from the grid. Data of electricity purchase, sale and production are provided in Table S8 (SM). An electric efficiency of 36.9% was calculated based on the net electricity production. 22.5% of the plant total energy consumption is related to superphosphate and super-calcium-nitrogen powdering, while the remaining fraction is associated to granulation.

Emissions from the cogeneration unit were allocated between electric (65.2%) and thermal energy production (34.8%), following the PCR 2007:08 (Electricity, steam and hot/cold water generation and distribution) and applying the allocation factors listed in Table S9 (SM). Process-specific electricity uses of 12 kWh/tonne for powdered products (superphosphate, super-calcium-nitrogen) and 23 kWh/tonne for granular fertilisers were provided by TIMAC AGRO Italia S.p.A. Moreover, the company registered a groundwater consumption of 8529 m^3 and 22526 m^3 for superphosphate and NPK-fertiliser production, respectively. Process water was supposed to totally disperse as vapor, since the moisture of final products and raw materials is comparable. No water discharges were recorded in the reference EPD. Plant diesel consumption was estimated assuming a diesel density of 0.84 kg/L and a lower heating value of 42.877 MJ/kg, resulting into a total thermal energy consumption of 4,471,435 MJ. Plant gaseous emissions and waste streams are reported in Table S10 and S11 (SM), respectively. No wastes are generated by the production process, as mineral wastes are recirculated back to the production process.

The SHA followed the ISO 14075:2024 standard by employing the Social Hotspots Database (SHDB) as the primary data source, providing standardized characterization factors derived from multi-regional input-output analysis across 140+ countries and 57 economic sectors (Benoit-Norris et al., 2012). This approach ensures consistent assessment of direct, indirect, and induced social impacts across the entire supply chain. Quantity and criticality of raw materials, as defined by the European Commission, were used as cut-off criteria to detect main potential impacts and social hotspots. Whenever possible, the system was divided into sub-processes and data were directly acquired for each sub-process. Whenever not possible, no allocation rule was applied, and the same social performance factors were attributed to each product. Specific data were gathered from scientific publications and reports of main raw material suppliers and main producing countries (e.g.: USGS Mineral Commodity Summaries, 2024; USGS, 2024).

Firstly, to identify the main social hotspots, the analysis was extended to the main producing countries of the raw materials under investigation, such as P (China, USA, Morocco, Egypt), Mg (Brazil, China, Israel, Kazakhstan), S (China, Russia, Saudi Arabia, USA), Ca (Germany, Malaysia, UK, Zambia) and Cl (Canada, France, Thailand, USA). By comparing the social risk index of different countries, the geographic areas with major social criticises associated to raw material supply were identified. In case the social conditions of assessed countries were unknown, the world's largest producers for the specific material were considered. Data obtained from the SHDB (expressed in mrh-eq) per country and raw material supply chain were computed as production-weighted averages across considered countries (Traverso et al., 2022). Subsequently, the weighted average values were divided into 4 classes using a risk rating scale: from 1 (low risk) to 4 (very high), to highlight the most critical social hotspots.

2.3.3. *Life cycle impact assessment*

This phase translates the elementary flows gathered in the inventory into impact indicators related to human health, natural environment and resource depletion. For the E-LCA, in accordance with ISO 14040-14044 standards and in agreement with the existing literature, environmental impacts were assessed using the impact assessment methodology from the Environmental Footprint 3.1. Specifically, a subset of relevant impact categories was selected according to their importance on the contribution to the overall normalised single-scores in Environmental Footprint 3.1. The impact categories and sub-categories, related acronyms and units of measures are listed in Table 1, where the chosen subset are highlighted in bold.

Lastly, to strengthen the discussion of the results and provide a broader perspective, comparisons were made with relevant scientific literature in the field (El Chami et al., 2023).

The SHA focused on key social themes considered as the most directly affected groups along upstream extraction and refining stages of the key raw materials under investigation (e.g., P, Mg, S, Ca, Cl). The assessed indicators were grouped into five main categories: Right to decent work, Health and safety, Society, Governance, and Community. Regarding the work framework. The selected sub-categories covered wage assessment, forced labor, and freedom of association, alongside workplace accidents for health and safety. Broader societal impacts were assessed through gender equality and poverty/inequality indicators. Furthermore, the analysis included corruption as a proxy for governance issues, while community impacts were evaluated through access to safe drinking water, sanitary facilities, and property rights. Social impact categories and sub-categories are listed in Table 2.

Representative supplier companies were selected to illustrate how the sector level social risk profiles identified in the SHA can materialise

Table 1

Impact categories and related sub-categories accounted in the E-LCA. The chosen subset of relevant impact categories is highlighted in bold. The three waste indicators are sourced from the EDIP 2003 set.

Impact category and sub-category	Acronym	U.M.
Environmental impact potentials		
Global Warming Potential fossil	GWPfos	[kg CO_2 eq]
Global Warming Potential biogenic	GWPbio	[kg CO_2 eq]
Global Warming Potential land use and land use change	GWPlul	[kg CO_2 eq]
Global Warming Potential total	GWPtot	[kg CO_2 eq]
Depletion Potential of the stratospheric ozone layer	ODP	[kg CFC-11 eq]
Acidification Potential	AP	[mol H^+ eq]
Eutrophication Potential – freshwater	EPfw	[kg P eq]
Eutrophication Potential – marine	EPma	[kg N eq]
Eutrophication Potential – terrestrial	EPte	[mol N eq]
Photochemical ozone creation potential	POCP	[kg NMVOC eq]
Abiotic depletion potential for minerals and metals	ADPm	[kg Sb eq]
Abiotic depletion potential for fossil resources	ADPf	[MJ - net calorific value]
Water deprivation potential	WDP	[m^3depriv]
Resource use		
Renewable primary resources used as energy carrier (fuel)	PERE	[MJ]
Renewable primary resources with energy content used as material	PERM	[MJ]
Total use of renewable primary energy	PERT	[MJ]
Non-renewable primary resources used as an energy carrier (fuel)	PENRE	[MJ]
Non-renewable primary resources with energy content used as material	PENRM	[MJ]
Total use of non-renewable primary energy resource	PENRT	[MJ]
Secondary materials	SM	[kg]
Renewable secondary fuels	RSF	[MJ]
Non-renewable secondary fuels	NRSF	[MJ]
Net use of fresh water	FW	[m^3]
Land use related impacts	LU	[-]
Wastes disposal		
Hazardous waste disposed	HWD	[kg]
Non-hazardous waste disposed	NHWD	[kg]
Radioactive waste disposed	RWD	[kg]
Human health		
Particulate matter emissions	PM	[disease inc.]
Ionizing radiation, human health	IR	[kBq U235 eq]
Eco-toxicity (freshwater)	ET	[CTUh]
Human toxicity (cancer effects)	HTc	[CTUh]
Human toxicity (non -cancer effects)	HTnc	[CTUh]

Table 2

Selected social impact categories (bold) and sub-categories accounted in the SHA.

Right to decent work	Wage assessment Forced labor Freedom of association
Health and safety	Workplace accidents
Society	Gender equality Poorness and inequality
Governance	Corruption
Community	Access to safe drinking water Access to sanitary facilities Property rights

at the facility level in concrete operational settings. The suppliers' selection was based on available information (e.g., actual suppliers, project partners) representing leading companies with state-of-the-art practices, substantial market share, and technological leadership in the sector. In this way, company specific information on policies, certifications and reported practices complements the aggregated database results, providing qualitative insight into how generic country–sector risks translate into actual working conditions and community interactions for key suppliers in the fertiliser value chain. Consequently, a semi-quantitative approach was adopted using a reference-scale scoring based on available evidence and SHDB risk information. This approach converts social inventory outcomes into a score based on established reference scales defined according to national/international standards or best practices. This approach is in line with the Guidelines for Social Life Cycle Assessment of Products and Organisations (UNEP, 2020) and provides social performance results. Specifically, reference scale typically ranges from – 2 to +2, where the score +2 indicates an “Ideal Performance” (a positive output is achieved and accurately reported). For instance, a score of +2 cn be achieved in case of compliance with ideal conditions for a specific subcategory, according to the International Labour Organisation (ILO) conventions (such as Freedom of Association and Protection of the Right to Organise Convention (1948/87), Right to Organise and Collective Bargaining Convention (1949/98), Forced Labour Convention (1930/29), Equal Remuneration Convention (1951/100), Discrimination (Employment and Occupation) Convention (1958/111), Occupational Safety and Health Convention (1981/155)). Conversely, a value of −2 indicates a “non-compliance” in a subcategory where a high-risk social issue is detected and no action taken (where explicitly mentioned, a score of −2 may also indicate lack of data). A score of +1 indicates a “progress beyond compliance”, in ther words company proactive behaviour positively exceeds the regulatory compliance, while a value of - 1 indicates “slightly below compliance level”, with one or more non-conformities in a social category, although it does not represent a social hotspot for a specific sub-category. Lastly, the score 0 represents “Compliance” with local international laws.

This methodological approach allows linking sector level social risk profiles to actual industrial actors in the investigated value chain, using publicly available information on certifications, policies and reported practices to illustrate how generic country-sector risks can manifest – or be mitigated – at specific sites. It should be noted that the companies are not intended to represent the full variability of their sectors, but rather to exemplify “better practice” suppliers within BAU and CE scenarios. Consequently, the aggregated SHA based on the social database and input–output information remains the primary tool to identify and compare social hotspots across materials and countries, while the analysis of representative companies is explicitly framed as a qualitative, illustrative step that helps interpret how the macrolevel risk patterns may translate into concrete working and community conditions for key suppliers.

2.4. Limitations

Some limitations need to be accounted when interpreting findings from this work (chapter 3). The E-LCA employs a cradle-to-gate boundary and uses secondary data sources (e.g., generic database processes for energy), which may not fully reflect site-specific operational conditions or regional supply chain variations. The social evaluation, scoped as an upstream SHA leveraging the SHDB, does not imply plant-level inventory data for fertilisers production and end-use phases; a comprehensive Social Life Cycle Assessment (encompassing SLCPA and SLCIA) would necessitate detailed primary data from individual facilities. Moreover, the P recovery process modelling draws from pilot-scale data with conservative assumptions regarding chemical inputs and energy demands, likely overstating impacts compared to prospective industrial implementations. Finally, agronomic performance and long-term soil accumulation effects from substituting mineral P with SSA-derived alternatives fall outside this study's scope and need to be further investigated.

3. Results and discussion

This section presents the comprehensive findings of the study. First, the E-LCA results are detailed (section 3.1), covering total impacts and hotspot identification, and then compared with relevant literature (section 3.2). Subsequently, SHA results are reported (section 3.3).

3.1. Environmental life cycle impact assessment

Fig. 2 reports the set of impact categories (GWPtot, ODP, AP, EPfw, EPma, EPte, POCP, ADPf and WDP) as highlighted in section 2.3.3. For clarity and brevity, each fertiliser assessed in a specific scenario is referred to as “fertiliser – scenario” and, throughout the manuscript, the fertilisers are identified using the following abbreviations: F1 (ENERGEO CV), F2 (ENERGEO CV TOP), F3 (LITHOZINC) and F4 (PHEOSCOR). Detailed numerical results for all assessed impact categories are reported in Table S12–S15 (Supplementary Material).

Overall, the environmental benefit of CE formulations remained limited when considering the subset of impact categories reported in Fig. 2, with CE generally underperforming BAU for AP, EPma, EPte, POCP and WDP across the four fertilisers. While literature generally indicates environmental benefits for P-recovery (Lam et al., 2022), the results from the present study show that only LGMgO-based fertilisers improved climate performance, whereas $Ca(OH)_2$-based formulations generally underperformed compared to the conventional scenario. This behaviour is consistent with previous work showing increased burdens for several air and water related categories when comparing P recovery routes from SSA with conventional triple superphosphate production through the PolFerAsh process (Smol et al., 2020). These results confirm the potential environmental advantage of replacing conventional $Ca(OH)_2$ with waste-derived LGMgO in wet chemical P recovery processes, although trade-offs among impact categories remain.

The comparison between HCl- and H_2SO_4-based configurations indicates that H_2SO_4-based formulations (F2, F4) tend to reduce some of the reported impact categories relative to their HCl-based counterparts (F1, F3), suggesting an influence of the acid extractant on the overall environmental performance of the fertilisers.

The higher burdens observed for CE formulations in several impact categories are primarily driven by the additional chemicals and energy required by the SSA-based P recovery process (e.g. production of H_2SO_4/HCl and $Ca(OH)_2$ or LG-MgO, thermal treatments, pumping and mixing), which offset the credits from mineral P substitution under the current efficiency levels. In particular, the contribution analysis shows that acid production, alkali supply and electricity for the recovery line are key hotspots in CE configurations, consistent with previous LCA studies on P recovery from SSA and sludge-derived streams.

Conversely, the reduced impacts of LG-MgO-based formulations in climate- and resource-related categories suggest that using waste-derived precipitants with lower embodied energy and fossil resource demand can partially compensate the additional burdens from the recovery process. These patterns highlight that improving the environmental performance of CE options is less a matter of “using SSA-derived P per se” (Lam et al., 2022) than of optimising the specific recovery route (chemicals, energy and integration with existing plants), which aligns with recent findings on the sensitivity of P recovery systems to reagent origin and process energy efficiency (Witek-Krowiak et al., 2022).

In order to deepen the analysis, Fig. 3 compares the environmental profiles of the four P-recovery configurations alone, exploring the influence of the extraction process on the environmental sustainability of the final formulations. The analysis shows that LG-MgO-based configurations generally outperformed $Ca(OH)_2$-based ones, except for EPma, EPte and WDP. This evidence might be attributed to the absence of $Ca(OH)_2$, whose production represented one of the highest contributors to

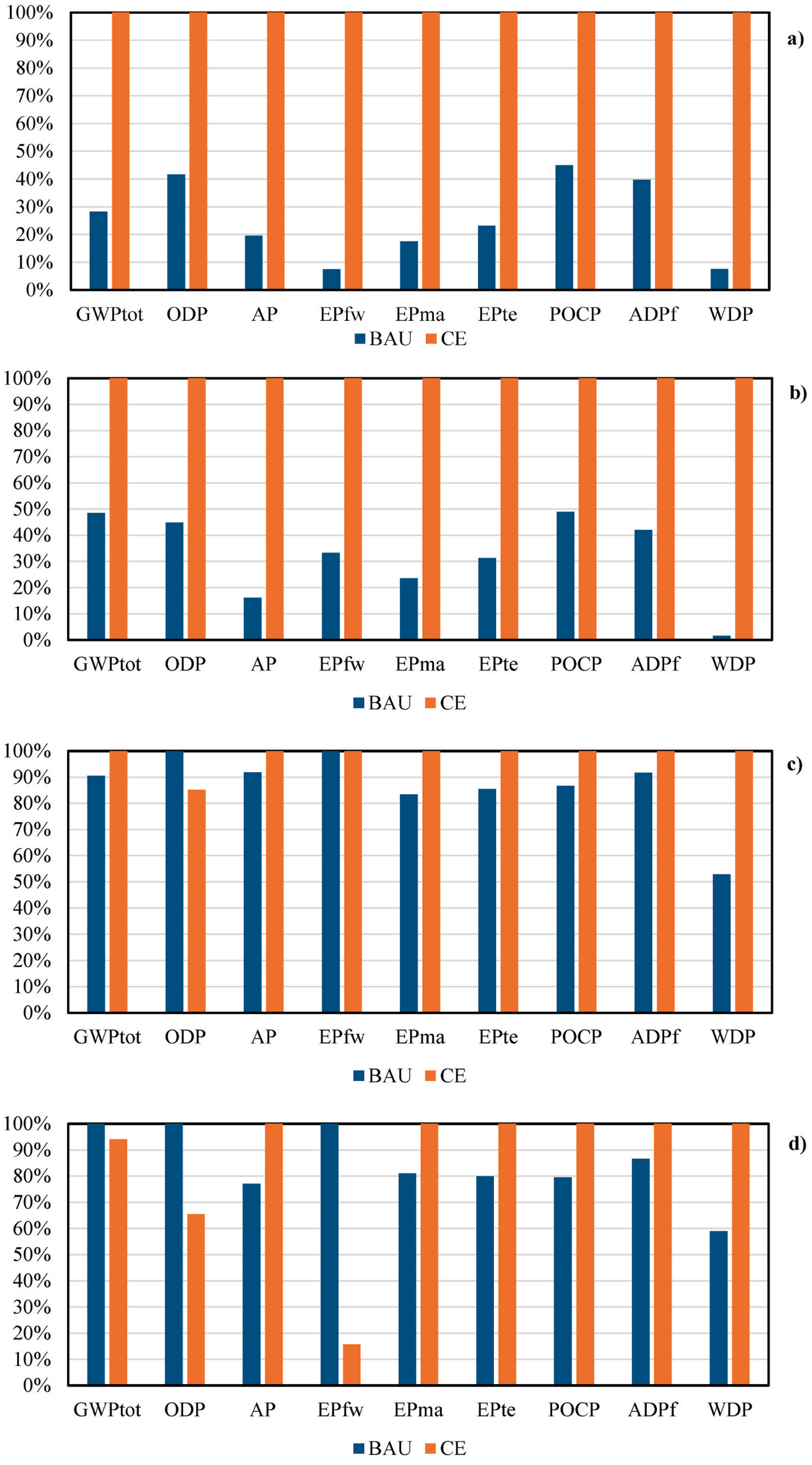

Fig. 2. Total environmental impacts associated with F1 (a), F2 (b), F3 (c) and F4 (d) production assessed in BAU and CE scenarios. Values are individually normalised to the higher impact between BAU and CE scenarios. Note: GWPtot: Global Warming Potential total; ODP: Ozone Depletion Potential; AP: Acidification Potential; EPfw: Eutrophication Potential freshwater; EPma: Eutrophication Potential marine; EPte: Eutrophication Potential terrestrial: POCP: Photochemical Ozone Creation Potential; ADPf: Abiotic Depletion fossil and WDP: Water Depletion Potential.

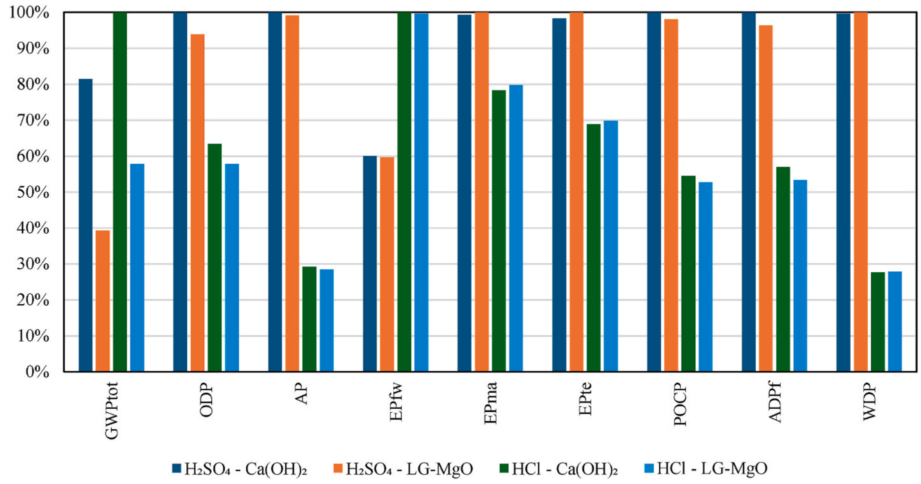

Fig. 3. Total environmental impacts of the four assessed configurations of P recovery from SSA. Impacts are individually normalised to the higher value of each sub-category. (Note: GWPtot: Global Warming Potential total; ODP: Ozone Depletion Potential; AP: Acidification Potential; EPfw: Eutrophication Potential freshwater; EPma: Eutrophication Potential marine; EPte: Eutrophication Potential terrestrial: POCP: Photochemical Ozone Creation Potential; ADPf: Abiotic Depletion fossil and WDP: Water Depletion Potential).

GWPtot. No significative differences were noticed between the environmental performances of HCl- and H_2SO_4-based configurations (Table S16 in SM).

Figure S1 (SM) displays total impacts distribution across upstream and core phases for each fertiliser and all investigated scenarios. Upstream phase always exhibited a major impact contribution on the production of each analysed fertiliser, except for F1 – BAU and F2 – BAU. Specifically, the environmental impacts from raw materials production ranged between +55% and +98% for almost all sub-categories. Exceptions were noticed for specific sub-categories in case of F1 – BAU (GWPfos, GWPtot, EPma, EPte, POCP and HWD), F2 – BAU (EPma, POCP and HWD), F3 – CE (HWD) and F4 – CE (HWD), with core contributions ranging between +60% and +72% of total impacts.

Focusing on GWPtot, the major upstream contributions across each scenario derived from phosphorite mining, P-based products manufacturing (e.g.: SSP complex, DAP, TOP PHOS) and P recovery from SSA (i.e., production of HCl (7% – 22%), H_2SO_4 (8% – 11%) and $Ca(OH)_2$ (28% – 32%). Conversely, the main core contributions were represented by thermal (35% – 47%) and electric (13% – 17%) energy generation. In line with these findings, previous studies identified raw material manufacturing as the major environmental hotspot for fertilisers containing recovered P, with significant impacts deriving from the production of chemicals used in P recovery from SSA (H_2SO_4, HCl, HNO_3, CaO, $CaCO_3$, NaOH) or from aqueous phases (NaOH, $MgCl_2$, NH_4Cl) (Amann et al., 2018; El Chami et al., 2023). Other relevant contributors to the environmental footprint, as reported in the scientific literature, include water consumption and thermal and electric energy use (Behjat et al., 2024; Mannarino et al., 2022; Pradel and Aissani, 2019).

When examining changes in impact distribution between upstream and core phases, a shift from $Ca(OH)_2$-based to LG-MgO-based fertilisers in BAU scenario generally increased upstream contribution to total impacts (+10%), whereas marginal variations were ascribed to this change in CE scenario. Furthermore, no relevant displacements were noticed in upstream or core phases relevance when changing the acid extractant. Overall, the transition from BAU to CE scenario increased (+10% – +15%) upstream phase relevance for F1 and F2, while no significant changes were observed for F3 and F4 in the analysed sub-categories.

3.2. *Comparison between E-LCA and scientific literature outcomes*

To enhance the discussion of the present findings, a comparison with the E-LCA study recently performed by El Chami et al. (2023) was conducted, assessing the environmental impacts of producing four different fertilisers (named as TIMATECH, EUROCOD, PRIME, MAGNIFIQUE) under two scenarios: a baseline scenario (BASE), where fertilisers are solely based on commercial-grade inputs, and a circular scenario (CIR), where conventional N source (i.e., Egyptian urea) was partially replaced with $(NH_4)_2SO_4$ recovered from by-products of plastic industry (i.e., SO_2).

The study from El Chami et al. (2023) was selected for comparison due to its close alignment with the objectives of the present work, namely assessing the environmental impact assessment of the partial substitution of mineral-based resources with secondary products in market-ready fertiliser formulations. Despite this, it is important to acknowledge that the two studies differ in key methodological aspects and system boundary definitions. Specifically, El Chami et al. (2023) adopted the Environmental Footprint 3.0 method and included the use phase of the fertilisers within the system boundaries (downstream phase), while the present study relies on the Environmental Footprint 3.1 method and is limited to upstream and core phases. Such differences are known to considerably influence E-LCA outcomes and, in turn, limit the possibility to drawn unbiased quantitative comparisons. For this reason, the comparison presented in this section is intended to be qualitative rather than conclusive, aiming to relate the present findings within the existing literature while explicitly accounting for methodological heterogeneity.

For consistency with the labelling approach adopted in sub-section 3.1, each fertiliser assessed in a specific scenario is referred to as "fertiliser – scenario" and, throughout the manuscript, the fertilisers are identified using the following abbreviations: C1 (TIMATECH), C2 (EUROCOD), C3 (PRIME) and C4 (MAGNIFIQUE).

Fig. S2 (SM) show the variations in specific impact sub-categories (GWPtot, AP, EPfw, ET, LU, WDP, ADPf) in response to a change from conventional (BAU or BASE) to innovative (CE or CIR) formulations. The partial substitution of N source resulted in different outcomes, depending on the considered impact sub-category and fertiliser. C1 was the only fertiliser proving environmental benefits across each impact sub-category investigated, with the most significant reduction in WDP (−16.1%). This could be attributed to the lower N content in both C1 – BASE and C1 – CIR compared to other formulations (Table S17 in SM). GWPtot (−4.4% to −9.2%) and EPfw (−2.9% to −5.5%) were consistently reduced across all fertilisers. These reductions were attributed to the shorter transport distance between the new N recovery location (i.e., Milan, Italy) and the fertiliser manufacturing plant (i.e., Ripalta Arpina, Cremona, Italy), which potentially reduce GHGs emissions, and to the reduced N content in CIR formulations, which may decrease N emissions from fertiliser application. The innovative formulations investigated in this work showed less significant environmental benefits compared to that of El Chami et al. (2023), with CE formulations underperforming BAU formulations across every fertiliser for AP, Epma, Epte, WDP and ADPf.

Specifically, $Ca(OH)_2$-based fertilisers (F1 and F2; Fig. 2a and b) showed higher impacts in the CE scenario than in the BAU scenario for most of the displayed categories, whereas LGMgO-based fertilisers (F3, F4; Fig. 2c and d) exhibited a more favourable pattern, with the CE scenario leading to reduced impacts in several climate- and resource-related categories (e.g. GWPtot, ODP, EPfw) while still performing worse for AP, EPma, EPte and POCP. The environmental impact sub-categories proving impact reduction were GWPtot (F4, -5.8%), EPfw (F3 and F4, -17.7% and −84.3%, respectively) and ET (F4, -27.4%). Conversely, significant increases were noticed for WDP, especially for F1 and F2 (+1226% and +6340%, respectively), indicating the need for further P recovery process optimisation, as already indicated by Boniardi et al. (2024).

On the contrary, other studies (Amann et al., 2018; Lam et al., 2022) indicated improvements in specific impact sub-categories when P recovery scenarios were compared to scenarios comprising SS conventional management (i.e., incineration, landfilling and direct land application) or mineral-based fertiliser production. Amann et al. (2018) revealed that SSA-based recovery technologies achieved comparable or reduced impacts in cumulative energy demand, GWPtot and AP relative to the adopted reference system. These benefits were attributed to credits for mineral-P substitution and high P recovery efficiency (70% – 90% of influent P in municipal wastewater treatment plant), which offset the increase in energy and chemicals inputs due to P recovery process. Similarly, Lam et al. (2022) reported that SSA thermochemical treatment (RP3) and wet acid extraction (RP6) generally reduced EPfw and AP, while potential benefits in ET depend on the trade-off between heavy metals content in the final product and credits from biogas production.

Examining upstream and core impacts related to GWPtot (Fig. S3 and SM), CIR formulations showed a significant decrease in upstream contribution, potentially due to the abovementioned reduction in transport distance. Conversely, no significant variations were noticed in core contribution, as energy management was already optimised through cogeneration (El Chami et al., 2023). In the present work, changing from BAU to CE formulations significantly increased upstream contribution for F1 (+299.6 kg CO_2 eq) and F2 (+182.7 kg CO_2 eq), while a less relevant increase (+53 kg CO_2 eq) and a slight decrease (−12 kg CO_2 eq) were noticed in case of F3 and F4, respectively. As discussed in sub-section 3.1, the upstream improvement in F4 – CE could be related to the absence of $Ca(OH)_2$, whose production significantly contributed to GWPtot, and to the substitution of HCl with H_2SO_4, whose supply generates fewer gaseous emissions.

3.3. *Social hotspot analysis (SHA)*

Fig. 4 presents the outcomes from the SHA conducted and expressed in terms of average social risk score. As previously mentioned, the average social risk values associated with the supply chains of each raw material were weighted based on the production data of each considered country.

Most of the social risk values ranged between 2 and 4, indicating a medium-high risk for raw material supply chains across the selected social impact sub-categories. Moreover, elevated social risks were identified for phosphorite production in the considered stakeholder categories.

Subsequently, a more detailed analysis of the social performance of main raw materials and chemicals used in BAU (Egyptian phosphorite) and CE (H_2SO_4, HCl, $Ca(OH)_2$, LG-MgO) scenarios, as well as of a hypothetical P recovery plant, was carried on based on available data from the raw materials suppliers' official websites. The relevant data are summarised in Table S18 (SM), while the derived social impact scores are displayed in Table 3.

An Egyptian phosphorite supplier with an annual production of around 5 million tonnes of concentrated PR was assumed as representative supplier. According to its official website, the company declares an explicit commitment to improve freedom of association, reduce workplace accidents and reject forced labour. Therefore, these sub-categories were assigned the social performance value of +1. Despite the supplier specifically affirmed to reject any discrimination form, a value of 0 was assigned to the "gender equality" sub-category, as no explicit mention was found in the company website. A score of +2 was not assigned to any sub-category, due to the absence of third-party verification of company commitments. An Italian H_2SO_4 supplier with an annual output of around 560 ktonnes/year of H_2SO_4 was chosen as sector representative. Since the supplier is certified with SA8000® (SAI, 2014) and ISO 45001:2018 certifications (ISO, 2018), a score of +2 was assigned to the related sub-categories. Despite the environmental and

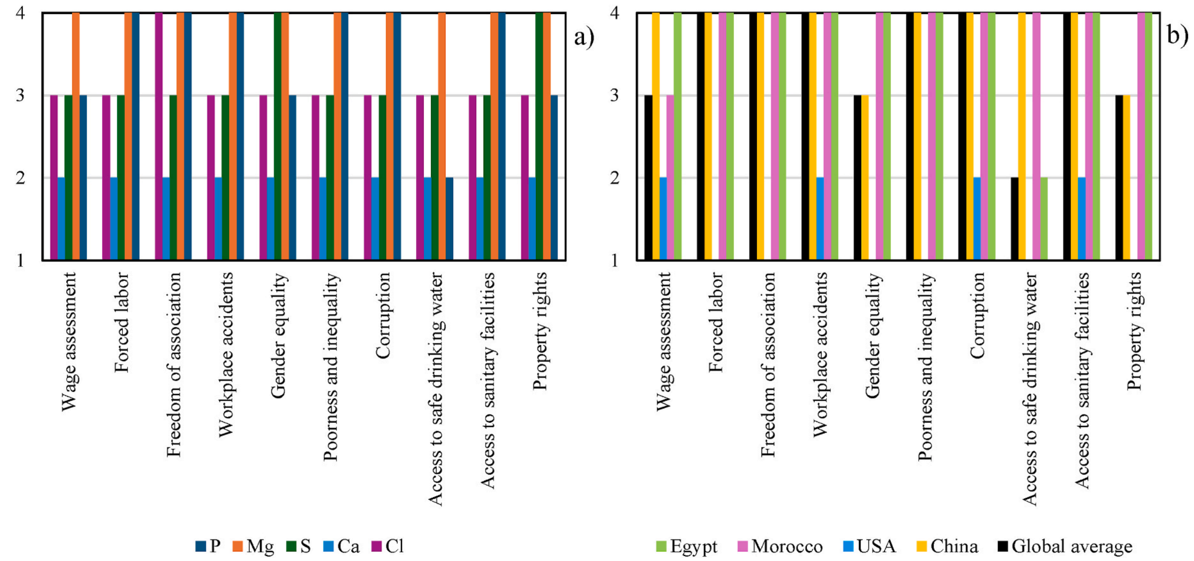

Fig. 4. Average social risk scores for the supply chains of P, Mg, S, Ca and Cl (a) and focus on P extraction and refinement in China, USA, Morocco and Egypt (b). (1 = low, 2 = medium, 3 = high, 4 = very high).

Table 3
Social impact scores for the main P-based raw materials employed in BAU and CE scenarios across every assessed social impact sub-category. The scores are visually represented with a colour scale ranging between red (−2) and green (+2).

		Phosphorite supplier	H_2SO_4 supplier	HCl supplier	$Ca(OH)_2$ supplier	LG-MgO supplier	P recovery plant
Right to decent work	Wage assessment	0	0	0	0	+1	0
	Forced labour	+1	0	0	0	0	0
	Freedom of association	+1	0	0	0	0	0
Health and safety	Workplace accidents	+1	+2	+2	+2	+2	+1
Society	Gender equality	0	+1	+1	0	0	+1
	Poorness and inequality	0	+1	+1	0	+1	0
Governance	Corruption	0	0	0	0	0	0
Community	Access to safe drinking water	0	0	0	0	0	0
	Access to sanitary facilities	0	0	0	0	0	0
	Property rights	0	0	0	0	0	0

health risks typically associated with sulfuric acid production, a score of 0 was assigned to remaining sub-categories, as the collected data refers only to official information. The HCl supplier was selected as representative for the HCl production sector in Italy. Since the supplier is certified with the ISO 45001:2018 certification, a value of +2 was assigned to the related sub-categories. Moreover, a score of +1 was assigned to sub-categories reflecting company commitment to avoid any discrimination based on age, gender, sexual orientation, health status, ethnicity, nationality, political opinions and religious beliefs. The LG-MgO is supplied by the private mining company Magnesitas Navarras (Navarre, Spain), partner of the PHOSTER project. Since the company holds a third-party certification in occupational health and safety, a score of +2 was assigned to the "work accidents" sub-category. A leading Italian producer of calcic lime, dolomitic lime and derived products, with a capacity exceeding 2 million tonnes/year of calcic lime, was selected as representative for $Ca(OH)_2$ supplier. Since the supplier holds an ISO 45001:2018 certification, a value of +2 was assigned to the related sub-categories. The P recovery plant was assumed to be located in Italy. The overall performance of the Italian chemical sector was considered for the analysis, assigning a value of +1 to the sub-categories in which this sector performs better than the national average. Given its upstream focus, the SHA does not capture potential social risks or benefits associated with downstream fertiliser production and use; a cradle-to-gate SLCA could in principle lead to different overall social patterns.

4. Recommendations and practical implications

As discussed in the previous chapter, the environmental benefit of CE formulations remains limited across several of the assessed impact categories, with main hotspots related to raw materials supply, energy use and water consumption. Within this framework, process optimisation emerges as the most effective strategy to mitigate these trade-offs and improve the environmental performance of SSA-derived fertilisers. Process optimisation should be supported by integrated modelling approaches capable of simulating process performance over a wide range of configurations, accounting for key parameters such as SSA chemical composition, reagent type, and dosage (Boniardi et al., 2024a; 2024b). These modelling efforts should be complemented by case-specific assessments that consider local raw material availability, infrastructure, regulatory frameworks and market drivers. At the same, targeted research should investigate innovative process configurations, including the partial reuse of P-rich leachates (Esposito et al., 2025), the adoption of less environmentally and economically intensive reagents, as industrial by-products industrial by-products (Boniardi et al., 2024a; Esposito et al., 2025) and the valorisation of process residues, such as the integration of leaching solid residues into cementitious mortars (Ottosen et al., 2022).

Despite the modest environmental gains, P recovery strategies directly address several structural concerns of mineral P supply, including the non-renewable nature of PR, with estimated depletion times ranging between 100 and 400 years (Desmidt et al., 2015; Ohtake and Tsuneda, 2019), the market volatility and geopolitical risks arising from the uneven global distribution of mineral reserves, and the environmental impacts of conventional P extraction and use, such as land degradation from mining activities and eutrophication of water bodies. From this perspective, recovered-P-based fertilisers could contribute to long-term resource security, even when short-term environmental gains are limited.

In parallel with technological optimisation, policy and societal measures are required to effectively support the deployment of P recovery technologies at an industrial scale, with particular attention to the recommendations discussed in the following sections.

4.1. Legislation and policy frameworks

When the economic viability of P recycling routes is not ensured, public policies, regulatory instruments and targeted subsidies become crucial enablers. Government interventions should ensure a fair P price that reflects health and environmental impacts from P mining (Bianchini and Rossi, 2020). Several countries have already introduced binding regulatory measures: Switzerland made P recovery from SS mandatory from 2026 (ADWO, 2015); Austria aims to recover up to 85% of P from the municipal SS up by 2030 (BAWP, 2017); Germany will mandate P recovery for municipal wastewater treatment plants with exceeding specific size and P-load thresholds from 2029 (BMUV, 2017). At the European level, PR (2014) and P (2017) were included in the EU list of Critical Raw Materials, while the Waste Framework Directive (2018) and the Fertilizing Products Regulation (2019) were revised to expand the range of secondary raw materials allowed in fertiliser production (Jupp et al., 2021). To translate these frameworks into effective action, consistent implementation at both national and local levels is essential, including clear technical guidelines, harmonised requirements, and transparent criteria for prioritising recovery technologies and investment pathways.

4.2. Social acceptance and awareness

Public perception represents another key factor influencing the diffusion of P recovery initiatives. Increasing societal acceptance of waste-derived resources requires targeted communication strategies aimed at farmers, consumers, and local communities (Ohtake and Tsuneda, 2019), with marketing campaigns, sector-specific workshops, demonstration projects, and pilot applications proving decisive in building social trust. A successful example is the calcium phosphate fertiliser produced via alkaline leaching of SSA in Gifu (Japan), where a dedicated outreach strategy – including advertisements, briefing sessions, free sample offerings and leaflet distribution – led to growing market acceptance and increasing sale volumes (Canziani et al., 2023; Ohtake and Tsuneda, 2019). Social initiatives should also highlight the co-benefits of P recovery processes beyond nutrient recovery itself, such as energy recovery from hot flue gases and pathogen and organic pollutant destruction in case of SS incineration (Law and Pagilla, 2021; Swann et al., 2017). Therefore, strengthening social acceptance is an essential step to support the market uptake of SSA-derived fertilisers and the wider implementation of P recovery pathways.

5. Conclusions and future perspectives

This study assessed the environmental and social impacts of substituting mineral phosphorus (P) with sewage sludge ash (SSA)-derived P in market-ready granular fertilisers under Business-As-Usual (BAU) and Circular Economy (CE) scenarios. The hey findings are related to CE options and social implications. CE formulations generally provided limited environmental benefits, frequently underperforming BAU formulations across key air- and water-related impact categories, such as acidification potential (AP), marine eutrophication (EPma), terrestrial eutrophication (EPte), photochemical ozone creation (POCP), and water deprivation (WDP). CE options employing low-grade magnesium oxide (LG-MgO) demonstrate reduced climate- and resource-related burdens compared to $Ca(OH)_2$-based configurations, highlighting the critical influence of precipitant selection in the recovery process. The upstream Social Hotspot Analysis (SHA) identified medium-to-high social risks with Egyptian phosphorite extraction, while indicating that partial substitution with recovered P could diversify supply chains and reduce risks.

Future perspectives are mainly related to improving the environmental performance of CE formulations will require recovery process optimisation, primarily in terms of reagents selection and dosage, energy intensity and water consumption. Also, advancing social sustainability assessment will require stakeholder collaboration to gather facility-specific social inventories, facilitating progression from screening-level SHA to robust cradle-to-gate Social Life Cycle Assessment. Future studies should include the use phase within the system boundaries, investigating potential differences in fertiliser efficiency and nutrient bioavailability between different scenarios. Future research should assess the robustness of P recovery performance and regulatory compliance across a wider range of SSA typologies, exploring the influence of wastewater treatment and incineration configurations.

CRediT authorship contribution statement

Lorenzo Esposito: Writing – original draft, Visualization, Investigation, Formal analysis. **Erica Gagliano:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Valeria Tacchino:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Stefano Spotorno:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation. **Roberto Canziani:** Writing – review & editing, Supervision, Resources. **Daniel El Chami:** Writing – review & editing, Supervision, Resources. **Michela Gallo:** Writing – review & editing, Methodology. **Adriana Del Borghi:** Writing – review & editing, Methodology, Conceptualization. **Andrea Turolla:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the Writing process

During the preparation of this work the author used correction tools based on generative AI to improve text fluency. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.148080.

Data availability

Data will be made available on request.

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