Liquid fertilizer production from organic waste by conventional and microwave-assisted extraction technologies: Techno-economic and environmental assessment

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HIGHLIGHTS

- Recycling of organic waste through the production of liquid fertilizers
- Fertilizer production by alkaline extraction (CSE and MAE) was ten times higher.
- Alkaline extraction reached a competitive minimum fertilizer sale price (1 €/L).
- Alkaline extraction showed lower water and energy consumptions.
- CSE with alkaline solvent is the most feasible process for scaling-up.

GRAPHICAL ABSTRACT
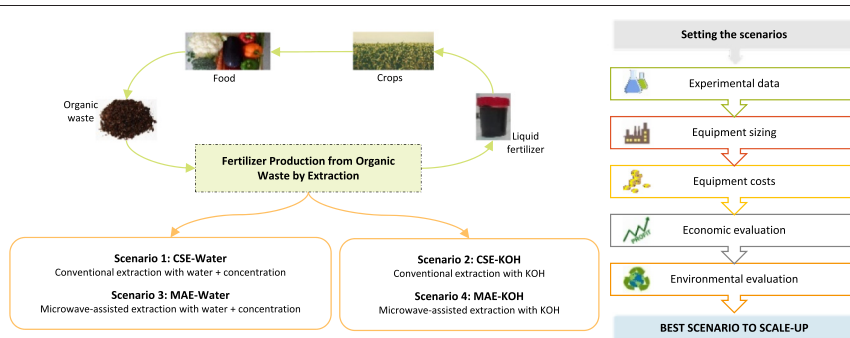
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ABSTRACT

The use of mineral fertilizers in agriculture has significantly increased to support the growing global food demand. Organic fertilizers are produced from renewable waste materials to overcome the drawbacks of inorganic fertilizers. The development of novel production processes of organic fertilizers entails a significant advance towards the circular economy that reincorporates waste materials into the production cycle. In this work, the economic and environmental feasibility of an industrial plant with a treatment capacity of 300 kg/h of organic waste for the production of liquid fertilizers has been performed. Two extraction technologies (conventional and microwave) and two solvents (water and alkaline) have been compared to select the most sustainable and profitable scenario for scaling-up. The extraction process consists of 2 steps: extraction followed by a concentration stage (necessary only if water extraction is applied). The resolution of the mass balances shows that the fertilizer production under alkaline conditions is ten times higher than for water-based extraction. The economic analysis demonstrated that the total investment cost of microwave technology (>3.5 M€) is three times higher compared to the conventional extraction technology (<1.5 M€), mainly due to the higher complexity of the equipment. These facts directly impact the minimum selling price, because the fertilizers obtained by conventional extraction with alkaline solvent would have a lower selling price (about 1 €/L). As for environmental assessment, the indicators show that the environmental impact produced by water-based extraction is higher than alkaline-solvent extraction, mainly due to the necessity of a concentration stage of the liquid extract to meet the requirements of European regulations. In view of the results obtained in the economic and environmental evaluation, it could be concluded that the most favourable scenario for scaling up the production of liquid fertilizers from organic waste is the conventional extraction under alkaline conditions.

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1. Introduction

Inorganic fertilizers have monopolized agriculture. Around 13 million tonnes of inorganic fertilizers were consumed in the European Union (EU) in 2019 (Eurostat, 2020). It has been estimated that 50% of agricultural production uses inorganic nitrogen fertilizers (Chehade and Dincer, 2021). The need for nutrients (nitrogen, phosphorus and potassium, NPK) will increase over time to meet demand. However, inorganic fertilizers harm the environment due to the excessive or inappropriate chemical fertilization of crops. Some adverse effects are greenhouse gas emissions, surface water eutrophication, and excessive fast plant nutrition (Coskun et al., 2017; Liang et al., 2013; Walling and Vaneeckhaute, 2020). In contrast, some advantages of organic fertilizers are the improvement of organic carbon in the soils and the slow release of nutrients that do not harm plants (Sharma et al., 2019). Therefore, the need to replace inorganic fertilizers with organic fertilizers is increasingly pressing.

Nowadays, many studies have demonstrated the possibility of producing organic fertilizers from organic waste, such as the organic fraction of municipal waste (Campuzano and González-Martínez, 2017) and municipal solid waste compost (MMWC) (Fernández-Delgado et al., 2020). These residues should not be applied directly on soils due to the possible presence of pathogens and potentially toxic elements. However, they present a considerably high content of organic carbon and nutrients, which can be recovered through solid/liquid (S/L) extraction within the circular economy framework (Bloem et al., 2017).

In S/L extraction, water or alkaline substances can be used as solvents. In the case of water extraction, a compost tea is produced, which is considered a biostimulant that improves crop quality and corrects the lack of nutrients (Islam et al., 2016). One of the main differences between water extraction and alkaline extraction is that the latter could recover humic substances. Humic substances improve crop development and water retention and reduce diseases and plant pathogens (Amir et al., 2010; Canellas et al., 2015). Under alkaline conditions, the carbon and nutrient content will be higher due to the larger solubilization of organic compounds (Tortosa et al., 2014). On the other hand, the solvents used in alkaline extraction are usually strong bases, such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) dissolved in water at different concentrations (0.05–2 M) (Ait Baddi et al., 2012; Ekpo et al., 2016; Spaccini et al., 2019). However, from an agronomic point of view, it is preferable to use KOH as a solvent since it adds potassium (K) to the fertilizer and, therefore, to the crops (Tortosa et al., 2014).

Regarding the extraction technology, conventional solvent extraction (CSE) is widely known (Monda et al., 2017; Tortosa et al., 2014). However, innovative and greener techniques can replace CSE, such as microwave-assisted extraction (MAE) (Beneroso et al., 2014; Shao et al., 2019). MAE is known as a more environmentally friendly process, with advantages in comparison to conventional extraction methods (Arpia et al., 2021). MAE is based on non-contact heating, since waves penetrate through the walls and heat distribution is more uniform, unlike CSE, which is based on convection and conduction and heat distribution is superficial (Zhang et al., 2020). Moreover, the energy consumption of MAE is lower because operating times are much shorter (minutes vs days) (Tseng et al., 2013). In addition, MAE requires a higher level of temperature and power control during extraction, which can be regulated according to the treatment capacity (Arpia et al., 2021; Picot-Allain et al., 2021). Some limitations of MAE are its dependence on the dielectric properties of the solid material to absorb microwaves (Kostas et al., 2017) and the formation of hot spots (Huang et al., 2016). The recovery of organic matter and other nutrients depends on the substrate and the extraction technology. However, when an alkaline solvent is used, the recoveries are higher (Kuglarz et al., 2013). For example, Monda et al. (2017) extracted 22% of the total organic carbon (TOC) and 1.4% of the total nitrogen (TN) from agricultural compost through CSE with water. In contrast, Tortosa et al. (2014)

showed that 60% of the TOC and 94% of the TN could be extracted from olive solid residue compost by CSE using an alkaline solvent (1 M KOH). Although there are no references concerning the application of MAE for nutrient recovery from organic waste, other studies have shown that MAE can reach the same extraction yields as CSE by reducing the time and increasing the operating temperature (Magnusson et al., 2017; Thu Dao et al., 2021).

To compete with inorganic fertilizers, organic fertilizer production from residues must be feasible from a technical, economic and environmental perspective. Organic fertilizers must comply with the current European regulations (Regulation 2019/1009) regarding organic carbon, nutrients and heavy metals. Adequate investment costs and payback time are necessary to assure the economic feasibility of the production process. Moreover, water and energy consumptions must be reduced, while the contamination of water bodies through eutrophication should be avoided. To this end, the metrics published by The Institution of Chemical Engineers (IChemE) allow sustainability indicators to be calculated and compared.

Although there are many experimental studies about nutrient recovery from organic waste applying CSE and MAE technologies, a comparative analysis of the viability of these technologies from an economic and environmental perspective, to the best of our knowledge, has not previously been reported. The comparison can motivate stakeholders to implement innovative extraction processes from organic waste to produce liquid organic fertilizers that ensure full compliance with EU regulations.

This study aims to evaluate different technologies based on conventional and microwave extraction, using water and alkaline solutions as solvents, to recover carbon and nitrogen from organic waste, such as municipal waste compost, to obtain a liquid organo-mineral fertilizer. The study has taken into account: (i) technical criteria, considering the parameters set by the European Regulation (EU) 2019/1009 in terms of the composition of liquid organo-mineral fertilizers; (ii) economic criteria, checking whether the alternatives comply with a competitive cost-benefit ratio in the current market, through the estimation of investment and production costs and revenue parameters (payback time and minimum selling price); and (iii) environmental criteria, analyzing the environmental impacts of the alternatives using IChemE metrics. The most suitable alternative to recover nutrients from organic waste is selected considering the economic and environmental evaluation results.

2. Materials & methods

2.1. Raw material

The MMWC used in this study is a compost obtained from the organic fraction of municipal mixed solid waste through pile composting in a mechanical-biological treatment (MBT) plant. The MMWC was kindly provided by Resíduos do Nordeste (Mirandela, Portugal). On average, the MMWC had the following composition (% dry weight basis): 488.5 ± 5.0 organic matter, 309.0 ± 4.9 total organic carbon (TOC), 22.6 ± 0.5 total nitrogen (TN), 7.0 ± 0.3 total phosphorus. The MMWC composition can be found elsewhere (Fernández-Delgado et al., 2020).

2.2. Systems and scenarios: definitions

The process to produce an organo-mineral liquid fertilizer according to Regulation (EU) 2019/1009 from MMWC consists of two stages: the first is a solid-liquid extraction, obtaining a liquid rich in nutrients, followed by a subsequent step of vacuum concentration of the liquid extracts (if necessary), in order to obtain a concentrated liquid that can be considered a fertilizer. The concentration step is only necessary if the concentrations of organic carbon and nutrients required by the European Regulation are not reached after the extraction step. Two

extraction technologies have been compared: conventional and microwave-assisted.

Four scenarios have been considered to carry out the economic and environmental study. Scenario 1 (CSE-Water) and Scenario 3 (MAE-Water) consist of S/L extraction using water as the solvent followed by vacuum concentration. Scenario 2 (CSE-KOH) and Scenario 4 (MAE-KOH) are based on S/L extraction using a KOH solution as the solvent without further concentration. The operating conditions set in the four scenarios were selected from previous experimental results (Fernández-Delgado et al., 2019, 2020) and are summarized in Table 1. The process flow diagrams of each scenario are presented in Fig. 1.

In the CSE-Water scenario (Fig. 1.A), the MMWC is mixed with water in the extraction tank (R-101). Then, the mixture obtained is fed to a storage tank (B-101) until centrifugation (S-101), where the waste solid is separated from the nutrient-rich liquid extract. The liquid extract must be concentrated to reach the nutrient requirements and fed to a partial evaporator (D-101). After this step, the concentrated extract can be considered a liquid organo-mineral fertilizer. The steam is also condensed (W-101) and recirculated to reduce total water consumption.

In the CSE-KOH scenario (Fig. 1.B), a preparation tank for the alkaline solution (R-101) is necessary before extraction, mixing water and solid potassium hydroxide (KOH) in appropriate proportions. Once the solution has been prepared, it is mixed with the MMWC in the extraction tank (R-102), and the resulting mixture is fed to the storage tank (B-101) until it is centrifuged (S-101). Once the solid waste and the liquid extract have been separated, a subsequent concentration step is not required. However, a pH adjustment step (R-103) is required and carried out using nitric acid.

The configuration of the MAE-Water scenario (Fig. 1.C) is similar to that of the CSE-Water scenario (Fig. 1.A), whereas the MAE-KOH scenario (Fig. 1.D) is analogous to the MAE-KOH scenario (Fig. 1.B). The difference between them is the extraction equipment used. In scenarios 3 and 4, a microwave-assisted reactor (C-101) is chosen instead of a conventional heated extraction tank (scenarios 1 and 2). In addition, a mill (Z-101) is needed to grind the MMWC to the previously selected particle size ($d_p < 0.5$ mm) before being fed to the microwave-assisted reactor.

2.3. Economic evaluation

As a design basis, a plant with a treatment capacity of 300 kg/h of MMWC with 25% humidity has been considered, corresponding to the average production of MMWC in a mechanical-biological treatment facility currently in operation. The mass flows of raw materials and products have been calculated through a mass balance, considering the lab-scale yields.

The unit costs of the raw materials are as follows: MMWC: 1.32 €/t (Resíduos do Nordeste, 2019), process water: 3.22 €/m^3 (Aquavall, 2017), potassium hydroxide (KOH) 50% w/v: 1.20 €/L, and nitric acid (HNO$_3$): 0.306 €/kg (Sinnott, 2005).

The equipment design was based on the methodology set out in Coulson et al. (2017) and Richardson et al. (2002). The microwave reactor was a commercial model that can operate as a continuous tubular flow reactor (Sairem, 2019a, 2019b). The total equipment cost (TEC) was estimated through CAPCOST software and the methodology described in Sinnott (2005). The Lang factors method was applied to carry out the economic study, since it is a widely known and used method in industrial engineering to estimate the costs of a production plant (Amigun and von Blottnitz, 2009; Elsernagawy et al., 2020; Marouli and Maroulis, 2005; Noor et al., 2020). This method estimates all costs of the plant from TEC and considers the handling of solids, liquids, or both. For the four proposed scenarios, it has been considered that the process involves the management of both solids and liquids. Therefore, the estimated TEC must be multiplied by the corresponding factor to obtain the different plant costs as total physical cost (TPC), fixed capital cost (FCC), and total investment cost (TIC) (Eqs. (1)–(3)) (Sinnott, 2005). On the other hand, the direct and indirect production costs associated with the plant can be calculated to estimate the production cost per litre of the product obtained.

$$TPC = TEC * (1 + f_1 + f_2 + \ldots + f_9) = TEC * 3.15 \qquad (1)$$

$$FCC = TPC * (1 + f_{10} + f_{11} + f_{12}) = TPC * 1.40 \qquad (2)$$

$$TIC = FCC * (1 + f_{13}) = FCC * 1.05 \qquad (3)$$

The profitability of each scenario and the minimum selling price were estimated considering the following assumptions:

- All scenarios had a plant lifetime of 10 years.
- Equipment amortization was estimated in 20 years.
- Operation hours were estimated at 8000 h/y.
- The heating and cooling utilities used were cooling water and steam (CSE-Water: 3 barg, MAE-Water: 6.5 barg), respectively.
- The income tax was set at 20% to calculate the annual profit.

The selling price was calculated considering the net present value (NPV) of the plant to be 0 € and the internal rate of return (IRR) equal to the discount rate (10%). Once the minimum selling price had been set, the payback time could then be calculated.

2.4. Environmental evaluation

IChemE metrics (IChemE, 2002) can be applied to compare any industrial process from an environmental perspective. In this case, the four proposed scenarios were compared in terms of water consumption, energy consumption, global warming, and eutrophication. The metrics were chosen based on previous studies (Estrada et al., 2010; Pérez et al., 2020).

Table 1
Operating conditions of the different scenarios proposed to produce liquid fertilizers from municipal waste compost.

Scenario	CSE-Water[a]	CSE-KOH[b]	MAE-Water[a]	MAE-KOH[c]
Type of extraction	Conventional	Conventional	Microwave	Microwave
Solvent	H$_2$O	KOH 1 M	H$_2$O	KOH 0.87 M
Optimal operating conditions				
S/L ratio (% w/v)	40	40	40	30
Time (min)	1440	1440	2,5	5
Temperature (°C)	45	45	80	157
Agitation (rpm)	200	200	–	–
Particle size	No grinding, no sieving	No grinding, no sieving	Grinding ($d_p < 0.5$ mm), no sieving	Grinding ($d_p < 0.5$ mm), no sieving
Concentration ratio	1/10	–	1/8	–

[a] Fernández-Delgado et al. (2019).
[b] Fernández-Delgado et al. (2020).
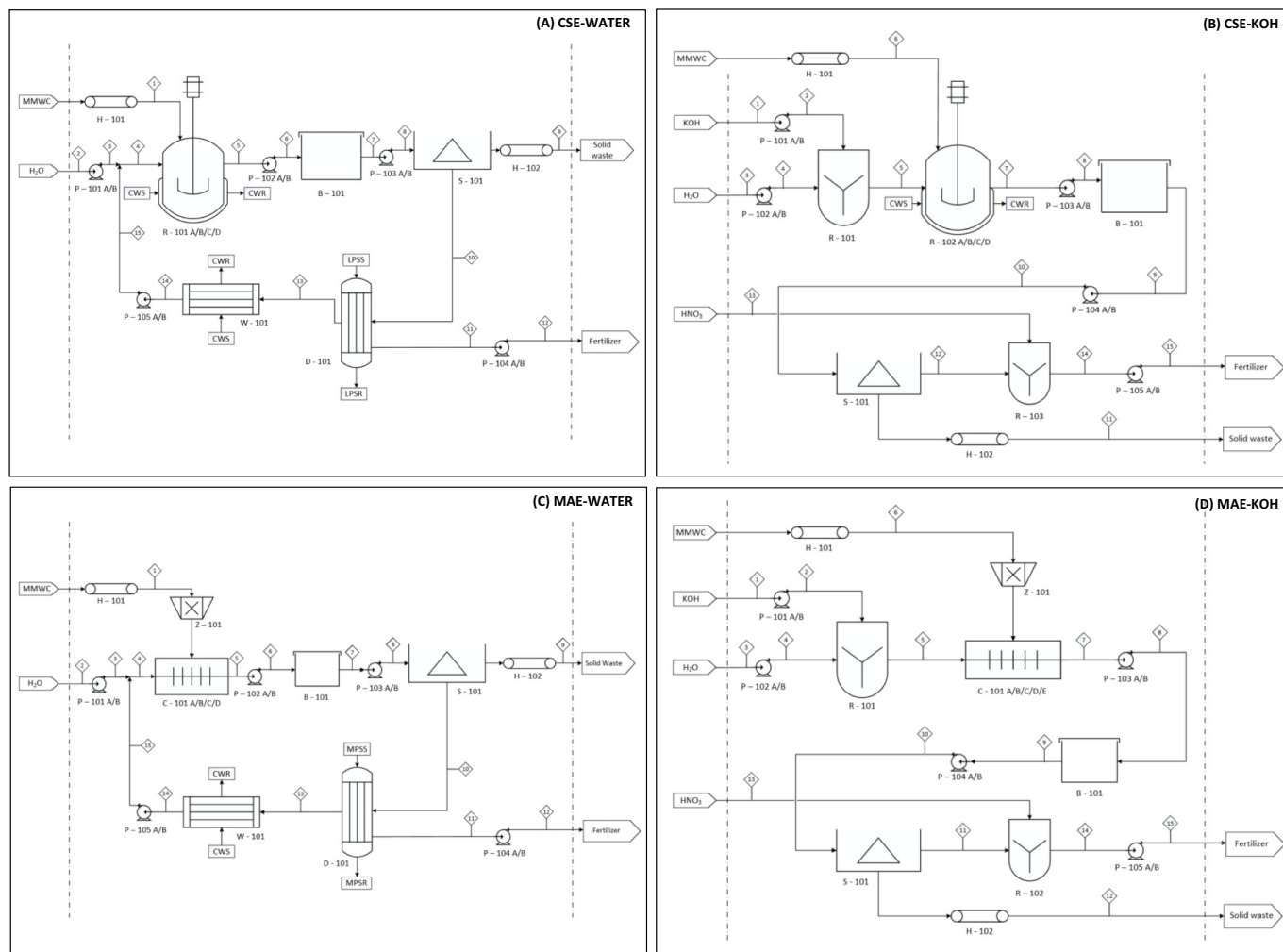[c] Data not previously published.

Fig. 1. Flow diagram of each of the proposed scenarios. Flow diagrams elaborated according to UNE ISO 10628:2015. Scenario A: Conventional extraction with water (CSE-Water); Scenario B: Conventional extraction with KOH (CSE-KOH); Scenario C: Microwave-assisted extraction with water (MAE-Water); Scenario D: Microwave-assisted extraction with KOH (MAE-Water). CWS: Cooling Water Service; CWR: Cooling Water Return; LPSS: Low-Pressure Steam Service; LPSR: Low-Pressure Steam Return.

2.4.1. Energy consumption

All the scenarios required electrical power. Therefore, the required electrical energy was calculated considering the necessary electrical power of the equipment. On the other hand, the CSE-Water and MAE-Water scenarios also used steam to concentrate the liquid extracts and cooling water to condense water after extraction and reuse it in the production process. Therefore, the energy coming from the steam and cooling water must also be considered in the total energy calculation. Once all the energy resources had been identified, the indicator associated with the energy consumption could be determined as the total net use of primary energy per kg of product (kJ/kg product).

2.4.2. Water consumption

All the scenarios proposed used water in the fertilizer production due to the use of aqueous solvents to extract the nutrients from the MMWC. The amount of water used in the process could be calculated from the resolution of the mass balances. Similarly, all the scenarios, except MAE-KOH, require cooling water during the fertilizer production process. The CSE-Water and CSE-KOH scenarios need the extraction tank to be cooled to maintain the temperature, and the CSE-Water and MAE-Water scenarios require cooling water in the total condenser after the concentration step. Furthermore, in the CSE-Water and MAE-Water scenarios, water recirculated to the process has been considered. The net water consumption can be calculated as the water used minus

the water reused annually. Thus, the water consumption indicator per product can be obtained (kg water used/kg product).

2.4.3. Global warming

Another indicator to calculate is global warming, measured considering the equivalent carbon dioxide (CO_2) produced. This factor must consider the greenhouse gases emitted that directly or indirectly affect the environment. This factor is expressed as the CO_2 equivalent per added value of the product (kg CO_2 eq./€).

2.4.4. Eutrophication

Finally, the fact that the composition of organic carbon and nutrients in the liquid extracts can cause eutrophication of marine areas should be considered. The eutrophication parameter was calculated from the equivalent phosphate mass flow and the added value of the fertilizer produced annually (g PO_4^{3-} eq./€).

3. Results and discussion

3.1. Composition of the liquids obtained in the different scenarios

The composition of the liquid products obtained in each scenario after the extraction processes (conventional or microwave-assisted) is compared in Table 2.

Table 2
Composition of the liquid extracts obtained in the different scenarios.

Parameters	Units	Scenario				Regulation 2019/1009
		CSE-Water[a]	CSE-KOH[b]	MAE-Water[a]	MAE-KOH[c]	
Physical properties						
pH		6.04	6.51	7.63	6.73	–
Conductivity	mS/cm	21.1	71.9	19.9	74.4	–
Density	kg/m^3	1034	1102	1028	1074	–
Viscosity	10^3 Pa·s	1.71	2.65	1.70	2.58	–
Carbon compounds						
TOC	% w/v	17.8	6.9	9.0	3.9	3
Humic acids	% TOC/TOC$_{total}$	10.1	47.6	13.9	61.3	–
Fulvic fraction[d]	% TOC/TOC$_{total}$	89.9	52.4	86.1	38.7	–
Principal nutrients						
TN	% w/v	2.1	3.8	2.3	3.4	2
NO	% w/v	1.2	0.7	0.7	0.3	0.5
P as P$_2$O$_5$	% w/v	0.04	0.2	0.03	0.1	2
K as K$_2$O	% w/v	4.2	8.3	3.1	8.2	2
Secondary nutrients						
Ca	g/L	21.8	4.8	8.5	0.2	–
Mg	g/L	6.6	0.8	3.1	0.2	–
Na	g/L	21.7	2.4	14.5	1.4	–
Micronutrients						
Fe	mg/L	342	1300	167	3000	–
Mn	mg/L	115	43.8	30	12	–
Heavy metals						
Cu	mg/L	31.6	16.8	18.4	10.4	600
Zn	mg/L	132	108.4	40.7	33.1	1500
As	mg/L	1.8	1.3	1.5	0.7	40
Cd	mg/L	0.2	0.4	0.08	0.1	3
Hg	mg/L	0.001	0.02	0.001	0.03	1
Ni	mg/L	12.9	9.2	5.8	4.5	50
Pb	mg/L	0.3	6.6	1.6	2.2	120
Cr	mg/L	4.8	5.3	1.9	1.5	–

n.d.: no determined.
Note: Data were shown as the mean value with less than 5% of relative error.
 [a] Fernández-Delgado et al. (2019).
 [b] Fernández-Delgado et al. (2019).
 [c] Data not previous published.
 [d] Fulvic fraction is composed of fulvic acids and non-humified fraction.

All liquid products comply with the Regulation (EU) 2019/1009 regarding the composition of liquid organo-mineral fertilizers, although some differences could be observed. One of the most notable differences is the composition of organic carbon, since the liquids obtained in the CSE-Water and MAE-Water scenarios present a higher TOC concentration due to the concentration step. However, the amount of humic acids is less than in the CSE-KOH and MAE-KOH scenarios. Previous studies have shown that the concentration of humic acids is higher when the extraction is performed under alkaline conditions (Fernández-Delgado et al., 2020; Raposo et al., 2016). The presence of humic substances in organic fertilizers enhances plant growth and water holding capacity (Özkaynak Kanmaz, 2019). If the principal nutrients are compared, the alkaline extracts (CE-KOH and MAE-KOH) have higher TN and K concentrations than the water extracts (CSE-Water and MAE-Water). It should be considered that, under alkaline conditions, K is also provided by the solvent; whereas the pH adjustment step can also contribute to the N content. Regarding the secondary nutrients and micronutrients, the differences could be due to the extraction conditions (solvent and temperature) and the variability in the raw material composition. It should be noted that none of the liquids exceeds the maximum concentrations of heavy metals set by Regulation 2019/1009 (Table 2). Therefore, the liquids comply with the European regulation requirements to be applied on agricultural land if their industrial production proved to be economically and environmentally feasible.

3.2. Economic evaluation

3.2.1. Investment costs

The TIC was estimated when the flow diagrams (Fig. 1) had been drawn, the mass balances solved and the main equipment designed. Table S.1 summarizes the cost of equipment and the corresponding code used in the flow diagram.

As shown in Table S.1, the CSE-Water and CSE-KOH scenarios have a CTE 2 to 3 times less than the MAE-Water and MAE-KOH scenarios, mainly due to the cost of the extraction equipment. In the CSE-Water and CSE-KOH scenarios, the equipment has a price ranging between 37,400 € and 122,500 €. On the other hand, in the MAE-Water and MAE-KOH scenarios, the microwave equipment price was between 580,000 € and 725,000 €. The price of the microwave equipment is higher due to the necessity of having five reactors in the MAE-KOH scenario compared to the four required in the MAE-Water scenario. This is because of the configuration of the selected microwave reactor, which can treat 200 kg/h (Sairem, 2019a; Sairem, 2019b). Considering the S/L ratio of the MAE scenarios, the mass flow treated in the MAE-KOH scenario (30% w/v) was higher than in the MAE-Water scenario (40% w/v). Therefore, the MAE-KOH scenario needs more microwave reactors to process the same mass flow used in the MAE-Water scenario, increasing the total equipment price.

On the other hand, if microwave technology is compared to conventional extraction, the MAE technology requires more complex equipment with a higher instrumentation and operation control level, which is due to the different energy transfer mechanisms. In the MAE

extractor, the heating depends on the electromagnetic field and the dielectric properties of the material to absorb microwaves (Arpia et al., 2021; Chan et al., 2015; Kostas et al., 2017). As a result, the heating is seldom uniform, causing unheated or very overheated spots (Chemat and Cravotto, 2012). Therefore, a greater control of the heat distribution is necessary, depending on the mass and volume treated in the reactor. However, CSE is based on heating the mixture through conduction and convection, so temperature control, although necessary, requires more straightforward control equipment. Moreover, the energy transfer in CSE is slower and non-uniform, causing hot spots within the reactor (Al-Ghouti et al., 2021). Hence, the microwave-assisted reactor can reach a price up to 20 times higher than the conventional reactor.

The TIC was calculated from the equipment cost using Lang's factorial method. Fig. 2 shows the different costs considered to estimate the TIC. As shown in Fig. 2, the investment costs associated with the CSE scenarios (CSE-Water and CSE-KOH) are three to four times lower than the MAE scenarios because the TIC was calculated from the equipment cost. Thus, the TIC of CSE plants ranges between 1.1 M€–1.4 M€ (CTE: 232–276.8 thousand €). When microwave technology is applied (MAE plants), the TIC ranges between 3.7 M€ and 4.2 M€ (CTE: 807.3–909.2 thousand €). On the other hand, scenarios that use water as a solvent have a lower TIC than those that use an alkaline solvent, although the difference is less than 15%. The difference could be due to the stirred tanks required to prepare the alkaline solvent before extraction and to adjust the liquid fertilizer's pH after extraction in the KOH scenarios.

3.2.2. Production costs

The summary of the production costs is shown in Table 3. The annual production costs for CSE scenarios (876–1867 thousand €) are between 20% and 75% lower than for MAE scenarios (2307–3542 thousand €). Furthermore, the costs of the scenarios that use water as a solvent are lower than the equivalent scenarios using an alkaline solvent (Table 3).

Regarding cost contribution, the direct cost of production represents around 60% of the total annual cost in the four scenarios (Table 3). As can be seen, the most significant costs associated with the CSE-Water and MAE-Water scenarios are related to utilities, maintenance and capital charges, representing between 60%–75% of the direct cost of production. However, in the CSE-KOH and MAE-KOH scenarios, the cost of raw materials is the predominant contribution to the direct cost of production (30%–50%), followed by the cost of utilities, maintenance and capital charges (total contribution: 34%–55%). This is because the CSE-

Table 3
Production costs items and sub-items.

Production costs ($\times10^3$ €)	CSE-Water	CSE-KOH	MAE-Water	MAE-KOH
Variable costs				
Raw materials	34	559	34	650
Miscellaneous materials	10	13	36	40
Utilities	106	133	363	409
Fixed costs				
Maintenance	102	130	356	401
Operating labour	80	80	80	80
Laboratory costs	16	16	16	16
Supervision	16	16	16	16
Plan overheads	40	40	40	40
Capital charges	102	130	356	401
Insurance	10	13	36	40
Local taxes	20	26	71	80
Royalties	10	12	36	40
Total direct production cost	**546**	**1168**	**1440**	**2213**
Indirect production cost				
Sales expense	110	233	289	443
General overheads	110	233	289	443
Research and development	110	233	289	443
Total indirect production cost	**330**	**699**	**867**	**1329**
Annual production cost	**876**	**1867**	**2307**	**3542**

Data in bold represent "total direct cost", "total indirect cost" and "total annual production cost" (data in bold represent the sum of previous data).

Water and MAE-Water scenarios only use MMWC and water as raw materials. However, the CSE-KOH and MAE-KOH scenarios require potassium hydroxide to perform the extraction under alkaline conditions and nitric acid to adjust the pH of the final liquid product. In addition, in the CSE-Water and MAE-Water scenarios, the water stream from the concentration step can be reused, thus reducing water consumption. Therefore, using chemicals such as nitric acid and potassium hydroxide with a higher water consumption leads to a higher cost of raw materials in the CSE-KOH and MAE-KOH scenarios. On the other hand, MMWC is an abundant waste available the entire year, obtained from composting the organic fraction of municipal solid waste. The European Union produced 250 Mt of municipal waste in 2018 (Eurostat, 2019). Considering current regulations, the direct agricultural use of MMWC is restricted (European Commission, 2018), so the surplus must be allocated to other applications. The selling price of the MMWC is around 10–15 €/t (Resíduos do Nordeste, 2019), an affordable and competitive price in the market with a low impact on production costs.
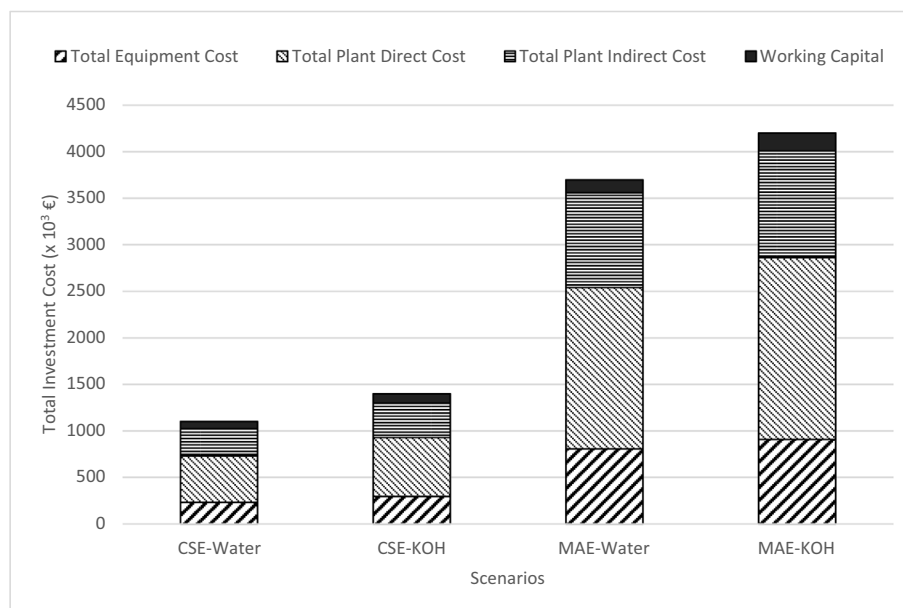

Fig. 2. Estimation of investment costs.

Table 4
Economic evaluation of the proposed scenarios.

Scenario	Fertilizer produced	TIC	Production cost	Minimum selling price	Maximum payback time
Units	L/h	M€	€/L	€/L	years
CSE-Water	46.1	1.1	2.4	4.0	7.1
CSE-KOH	515.0	1.4	0.5	0.7	7.0
MAE-Water	57.7	3.7	5.0	9.1	7.1
MAE-KOH	648.8	4.2	0.7	1.1	7.1

3.2.3. Profitability analysis

The plant's income comes from the sale of the fertilizer produced, so it is necessary to determine the production cost of the fertilizer and the minimum selling price per litre of product for each scenario. Once the minimum selling price had been calculated, the payback time could be estimated and the economic profitability of the scenarios on an industrial scale could be evaluated (Sganzerla et al., 2021). Table 4 summarizes the most important parameters associated with the economic evaluation of the plant.

Liquid fertilizer production in the CSE-Water and MAE-Water scenarios is approximately ten times lower than in the CSE-KOH and MAE-KOH scenarios (Table 4). This is because of the concentration step necessary to reach the minimum concentrations established by the European Regulation. So, this step directly impacts the production cost and the minimum selling price. On the other hand, comparing the technology, the scenarios based on CSE have a selling price and a production cost of up to 10 times lower than the scenarios based on MAE. Although fertilizer production is higher in the MAE scenarios, the TIC

and the annual production costs in microwave-assisted scenarios are also much higher than in the CSE scenarios, increasing the selling price and production cost. It should be noted that some studies have demonstrated the economic viability of the MAE technology for other applications (Ciriminna et al., 2016; Nguyen and Zhang, 2020; Wang et al., 2015).

The four scenarios could recover the investment in a maximum payback time of 7 years if the fertilizer is sold at the minimum selling price. At this point, the plant would have an NPV of 0 € and an IRR equal to the fixed discount rate (10%). Therefore, if the fertilizer is sold above the minimum selling price, the plant could produce benefits (NPV > 0 € and IRR > 10%), and the return time could be lower than 7 years. Therefore, the results have shown that the product must be sold at a price higher than the minimum selling price, ranging between 1 and 9 €/L (Table 4). Therefore, the scenarios could be economically feasible considering these conditions. Furthermore, considering the prices of commercial liquid organo-mineral fertilizers, usually in the range of 0.5–10 €/L (Fernández-Delgado et al., 2020), the minimum selling prices shown in Table 4 can be competitive. In this way, fertilizers produced in the CSE-Water and MAE-Water scenarios could achieve a lower profit margin because the minimum selling price is higher (4–9 €/L) in comparison to the minimum selling price of the CSE-KOH and MAE-KOH scenarios (0.7–1.1 €/L).

Considering the results, the fertilizers produced in the CSE-KOH and MAE-KOH scenarios could be competitive with commercial fertilizers, obtaining benefits from the production through the margin between the minimum selling price and the market price.

3.2.4. Sensitivity analysis

Based on the economic evaluation, a sensitivity analysis was performed to analyze the influence of the most critical parameters, which could affect the NPV (Fig. 3). For the scenarios evaluated, the key
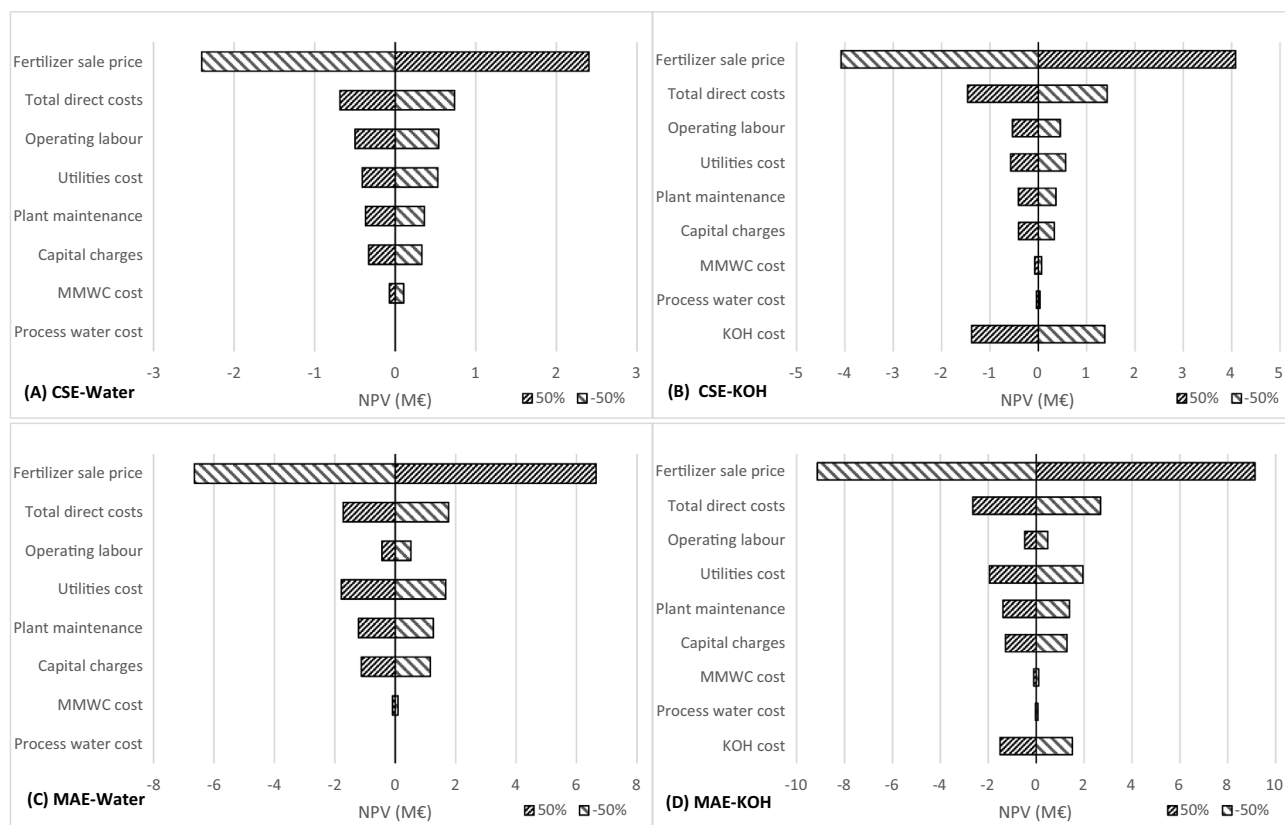

Fig. 3. Sensitivity analysis for the proposed scenarios. Scenario A: Conventional extraction with water (CSE-Water); Scenario B: Conventional extraction with KOH (CSE-KOH); Scenario C: Microwave-assisted extraction with water (MAE-Water); Scenario D: Microwave-assisted extraction with KOH (MAE-Water).

parameters that significantly affect the NPV are the fertilizer selling price, the total direct costs and utilities in the CSE-Water and MAE-Water scenarios. Similarly, in the CSE-KOH and MAE-KOH scenarios, the most significant parameters are the fertilizer selling price, the total direct costs and the KOH price.

Among the variable costs, the cost of utilities significantly affects the feasibility of the water-based extraction scenarios (Fig. 4.A–C). The optimization of the utilities cost, reducing their contribution by 50%, could increase the NPV of these scenarios by 0.5 and 1.7 M€. In contrast, in the KOH scenarios (Fig. 4.B–D), a 50% decrease in the KOH cost could raise the NPV to 1.5 M€. Finally, it should be noted that a variation in the MMWC cost does not involve significant changes in the NPV in any of the scenarios evaluated.

Concerning the plant profits, the only income is generated from selling the liquid fertilizer. As shown in the previous section, the KOH scenarios resulted in lower minimum selling prices ($\approx$1 €/L) in comparison to the water scenarios (>4 €/L). Therefore, a 50% increase in the fertilizer selling price can increase the NPV by 2.5 to 4 € for CSE scenarios (Fig. 4.A–B) and by 6.5 to 9 M€ for MAE extraction (Fig. 4.C–D). It is necessary to compare the minimum selling prices with the prices of commercial liquid organo-mineral fertilizers to establish whether the scenarios could give benefits. Fernández-Delgado et al. (2020) estimated that the market prices ranged between 1 and 10 €/L. Tortosa et al. (2014) estimated the economic cost for organo-mineral fertilizer production from olive residue compost using a conventional extraction. They concluded that production costs could be less than 0.4 €/L, without considering the initial investment for the extraction and filtration equipment. Therefore, concerning the KOH scenarios, an increase in the selling price of 50% could be acceptable as it is within the price range of commercial fertilizers ($\approx$1.5 €/L). However, the minimum selling price for the water scenarios is higher (4–9 €/L). Consequently, increasing it by 50% (6–13.5 €/L) might not be viable because prices will be higher than those of the market and the fertilizer would not be sold.

Thus, the most beneficial scenarios to produce fertilizers are the CSE-KOH and MAE-KOH scenarios. The CSE-KOH scenario could be the most favourable as it requires a lower CTI for construction and production, with lower production costs and a more significant margin between the minimum selling price and the market price.

3.3. Environmental evaluation

Environmental indicators from the IChemE sustainability metrics (IChemE, 2002) were calculated to compare the environmental impact of the scenarios. The parameters calculated were energy consumption, water consumption, global warming and eutrophication of aquatic areas. The results for each scenario are compared in Fig. 4.

Regarding energy consumption, Fig. 4.A shows that the CSE-Water and MAE-Water scenarios present higher energy consumptions (9.4–14.2 kW·h/kg$_{product}$) compared to the CSE-KOH and MAE-KOH scenarios (0.5–1.2 kW·h/kg$_{product}$) due to two fundamental causes. First, the concentration step comprises a partial evaporator and a total condenser, which consume a high energy power (>550 kW) to concentrate the liquid extracts. The second reason is that the indicators were calculated based on the production of the fertilizers (Table 4), which is lower for water-based extraction. Comparing both technologies, Fig. 4.A shows that the MAE scenarios have higher energy consumptions per kg of the product than the CSE scenarios. This fact indicates that microwave technology requires a higher energy consumption than CSE technologies, mainly due to the different operating temperatures. In our study, CSE operates at moderate temperatures (45 °C), considerably lower than those required when microwave technology was applied (80–160 °C), indicating that CSE requires less energy than MAE per kg of fertilizer produced. However, it must be considered that MAE uses energy more efficiently than CSE because water can absorb microwaves better than conventional heat (Yu et al., 2020, 2021).
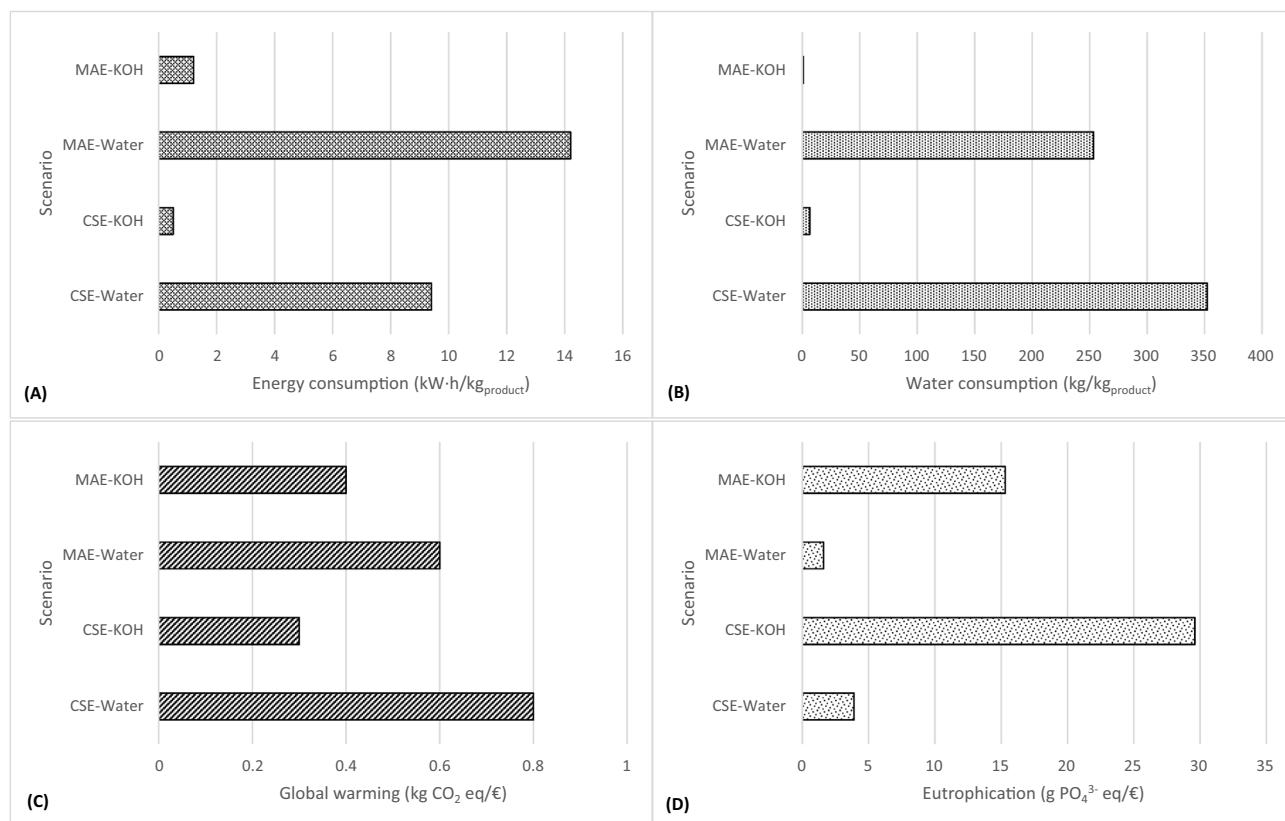

Fig. 4. Comparison of the environmental indicators for the proposed scenarios. (A) Energy consumption (kW·h/kg$_{product}$). (B) Water consumption (kg/kg$_{product}$). (C) Global warming (kg CO$_2$ eq/€). (D) Eutrophication (g PO$_4^{3-}$ eq/€).

A similar trend was observed for the water consumption indicator (Fig. 4.B), which considers the water used for cooling, the process water and the recirculated water. Hence, in the CSE-Water and MAE-Water scenarios, the indicator reaches 250 and 350 kg of water per kg of fertilizer produced. The concentration step and the lower production of fertilizers in these scenarios considerably increase the indicator value compared to the CSE-KOH and MAE-KOH scenarios. Under alkaline extraction conditions, water consumption reached values below 10 kg of water per kg of product. By comparing the extraction technologies, the CSE scenarios led to values higher than the MAE scenarios. One probable reason is that the conventional technology needs cooling water to maintain the operating temperature during extraction. In addition, the fact that the fertilizer production is lower in CSE than in MAE scenarios causes the water consumption indicator to be slightly higher.

Once the energy consumption had been determined, the contribution to global warming could be estimated (Fig. 4.C). In all cases, the parameters were below 1 kg CO_2 eq./€. However, it should be noted that global warming for the CSE-KOH and MAE-KOH scenarios is approximately half that of the CSE-Water and MAE-Water scenarios due to the lower energy consumption and higher fertilizer production. On the other hand, no significant differences were observed between conventional and microwave technology regarding global warming.

It is also necessary to consider the possible eutrophication of aquatic areas due to the fertilizers' direct and indirect discharge (Fig. 4.D). Eutrophication is produced by excess nutrients in water, such as organic carbon, nitrogen and phosphorus. In this case, the CSE-KOH and MAE-KOH scenarios show the highest values of eutrophication because the production of fertilizers is much higher than the production in the CSE-Water and MAE-Water scenarios. The eutrophication indicator relative to alkaline extraction was between 15 and 30 PO_4^{3-} eq./€. On the other hand, in the CSE-Water and MAE-Water scenarios, the indicator only reached values lower than 5 g PO_4^{3-} eq./€. Therefore, the eutrophication risk is lower for the fertilizers obtained when water is used as a solvent. Considering both the fertilizer production and the IChemE environmental indicators, the CSE-KOH and MAE-KOH scenarios present a lower environmental impact, especially regarding water consumption and global warming.

4. Conclusions

This study presents a comparative economic and environmental assessment to produce liquid fertilizers from organic waste such as MMWC. The scenarios are based on conventional and microwave-assisted extraction technologies using water or an alkaline solution as solvents.

Considering the technical, economic and environmental perspectives, the most favourable for scaling up is the CSE scenario with alkaline solvent. From the technical perspective, the fertilizer production by alkaline extraction is ten times higher than when water is used as a solvent. The economic evaluation concluded that the total investment cost of CSE is 4 times less compared to MAE, mainly due to the higher complexity of the microwave equipment. The sensitivity analysis shows that the minimum selling price corresponding to alkaline extraction (≈1 €/L) is more competitive than the price of water-based extraction (>4 €/L). Regarding the environmental assessment, alkaline extraction has a less notable environmental impact than water-based extraction, especially considering water and energy consumption due to the necessity of a concentration step. Regarding water consumption, water-based extraction reached a higher indicator (253–352 kg water/ kg fertilizer) than alkaline extraction (0.9–6.5 kg water/kg fertilizer). For energy consumption, the parameters corresponding to water extraction were between 12 and 18 times higher than alkaline extraction. More work is required to scale up the process to a pilot plant to validate the technology, verify the quality of the fertilizer produced, and check if other organic residues could be used as raw materials. Therefore, this study is a starting point in recycling organic waste that demonstrates the potential viability of producing organic fertilizers from these wastes.

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CRediT authorship contribution statement

Marina Fernández-Delgado: Methodology, Investigation, Writing – original draft. **Esther del Amo-Mateos:** Methodology, Investigation. **Susana Lucas:** Conceptualization, Supervision, Writing – review & editing, Funding acquisition. **M. Teresa García-Cubero:** Methodology, Funding acquisition, Writing – review & editing. **Mónica Coca:** Conceptualization, Supervision, Writing – review & editing, Project administration, Funding acquisition.

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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