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Research article

Environmental prospective of valorizing corn processing effluent to produce ferulic acid grafted chitosan polymer

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ABSTRACT

The food industry requires new production models that include more environmentally friendly waste management practices, considering that the environmental loads of solid waste and wastewater associated with this sector cause damage to the receiving ecosystems. The approach considered in this study focuses on the design and environmental assessment of an enzymatic process for the valorization of ferulic acid present in the effluent of a corn tortilla plant. The ferulic acid can be immobilized on chitosan so that the ferulic acid grafted chitosan can be used as a bioactive film with enhanced antioxidant properties with potential applications in the biotechnology sector.

Its real projection approach requires the evaluation of its environmental and economic performance, trying to identify its benefits and potential in the value chain, using the Techno-Economic Analysis (TEA) as a phase for the conceptual design of the process and the Life Cycle Assessment (LCA) methodology for the environmental evaluation. It should be noted that the TEA indicators are promising, since the values of the financial indicators obtained are representative of the economic profitability, which makes the ferulic acid valorization a viable process. In terms of the environmental impact of the process, the buffer dose and the chitosan production process are identified as the main critical points. This double benefit in environmental and economic terms shows that the valorization of ferulic acid for chitosan functionalization is a promising alternative to improve the sustainability performance of corn processing.

1. Introduction

The food production and processing sectors are essential for food security, but they are also large consumers of water, accounting for more than 66% of global freshwater withdrawals (Bolzonella et al., 2007). The large water consumption is associated with irrigation, animal feed and food processing, with the inevitable consequence of effluents with high organic load, nutrients and suspended solids (Shrivastava et al., 2022). Wastewater from these processes can be treated within the facility or by an external management service, resulting in additional costs and reduced benefits (Lyu et al., 2020). There is a need to propose technologically, economically and environmentally viable processes to close the production cycle and reduce waste production (Ciliberto et al., 2021; Prieto-Sandoval et al., 2018). Beyond end-of-pipe treatment, it is necessary to address the valorization of high-value compounds present in solid waste and wastewater, such as carbohydrates, proteins, fats, and oils (Pulluru et al., 2017).

One of the foods recognized as a staple is corn, whose consumption is growing exponentially, reaching global production values of 1.16 billion tonnes in 2022/2023, according to statistics from the United States Department of Agriculture (USDA). Mexico's position as the most important producer in the Americas stands out, where the corn tortilla is the basis of the diet of more than 129 million inhabitants (Téllez-Pérez et al., 2018). In México, 2,437,552 tons of corn per year are used to produce nixtamalized corn flour (Mexican Ministry of Economy, 2012). The nixtamalization process, whose main rate limiting stage is the cooking and soaking stages, requiring 3–8 h (Holguin-Acuña et al., 2011), generates more than 6 million m^3/year of wastewater (known as nejayote) because at least 2.5 m^3 of water is needed to process 1-ton corn (España-Gamboa et al., 2018). This stream is highly polluted as it is

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characterized by an alkaline pH ($pH > 9.0$), high concentrations of COD: 7,500–30,000 mg/L and solids: 2.4–46.5 g/L (Díaz-Montes et al., 2016; Farooq and Ahmad, 2017; López-Pacheco et al., 2019).

Despite its pollution potential, its valorization potential as a culture medium for probiotics and bacteriocins (Ramírez-Romero et al., 2013), a source of phytochemicals (Castañeda-Ruelas et al., 2021; Castro-Muñoz et al., 2016; Castro-Muñoz et al., 2016), an antioxidant such as ferulic acid with a concentration of around 219 mg/100 g (Acosta-Estrada et al., 2014).

Ferulic acid is a hydroxycinnamic acid with a hydroxyl bond, a carboxyl bond and a carbon double bond in its chemical structure, making it a functional phenolic bioactive compound with multiple applications given its interesting properties (Shivashankara et al., 2015; Kim and Han, 2014). It has antioxidant properties, given the ester derivative forms in its structure (Zheng et al., 2020), anti-inflammatory effects (Li et al., 2021), and antimicrobial activity against *Escherichia coli*, *Pseudomonas aeruginosa*, *Staphylococcus aureus* and Listeria monocytogenes (Borges et al., 2013). In addition, it has also shown anti-cancer effects (Bao et al., 2023), and could be used for UV protection products, as it has an inhibitory effect on the production of melanin, a key element in increasing pigmentation (Islam et al., 2014). It has also shown anti-allergic, hepatoprotective and antiviral potential (Raj and Singh, 2022; Kumar and Pruthi, 2014). Given all these properties, it is widely used in the pharmaceutical, nutraceutical and cosmetic sectors.

Other promising application for ferulic acid in the near future is its use in the preparation of chitosan-ferulic acid conjugates, with applications in the food sector, for example, due to its antimicrobial properties, but also for its ability to prolong the life of vegetables when using the biofilm as a coating (Wang et al., 2021; Dasagrandhi et al., 2018), in the cosmetic sector due to its antioxidant potential (Wang et al., 2018), or in the biomedical sector for the production of more release-effective pharmaceuticals (Li and Li, 2017), among others.

In this context, this research report presents a wastewater treatment model for the sustainable management of nejayote to formulate a biotechnological product based on the grafting of ferulic acid onto chitosan after laccase-catalyzed enzymatic oxidation (García-Zamora et al., 2015).

The development of waste valorization strategies could help to improve resource efficiency as well as to reduce waste production, which would imply a reduction of environmental risks related to its proper management, such as landfilling or illegal incineration. To this end, research on industrial waste recovery could help to achieve the Sustainable Development Goals (SDGs) related to climate action (SDG13), responsible production (SDG12) and innovation in industrial facilities (SDG9).

This proposed valorization scheme is a simple two-step process, where the first step is based on the activation of the ferulic acid with the enzyme and the grafting of the chitosan with the oxidized ferulic acid, while the second step is the downstream process for the recovery of the grafted chitosan, as well as a filtration process for the recovery of the process water. The proposed process results in a grafted chitosan with higher antioxidant capacity than natural chitosan and, at the same time, the enzymatic treatment reduces COD by 70%, which is an important advantage of developing an enzymatic process, achieving a double benefit (Diao et al., 2020; García-Zamora et al., 2015). However, on the other hand, this enzymatic process also implies a reduction in treatment capacity, as it is developed in batch mode, which could be an important aspect to evaluate, both from a technological perspective (given the possible reduction in production efficiency) and an economic one (the reduction in production capacity could imply a reduction in annual profits). Therefore, it is important to develop a technical-economic evaluation, including the modelling of the process using SuperPro Designer® software. On the other hand, enzymatic processes could also have an important effect on the sustainability results, as enzymes usually imply a higher environmental contribution. With this in mind, a Life Cycle Assessment (LCA) has also been developed, following the guidelines of ISO 14040.

To this end, the main objectives of this research report are: (1) large scale modelling of a valorization strategy considering nejayote as raw material for a polymer with improved properties to demonstrate the effectiveness and feasibility of the valorization strategy, (2) to demonstrate the economic viability of the proposed valorization technology and (3) to show the environmental benefits of this waste treatment recovery strategy for the corn processing facilities.

Bearing these objectives in mind, it is hoped that the results of this research report can be used by other researchers and stakeholders in the corn-related industrial sector to reduce the toxic potential of wastewater and move towards more sustainable and circular industrial systems.

2. Methodology

2.1. Process description

In order to make tortillas, tamales or other derived products, corn must undergo a nixtamalization process, which consists of cooking corn in a lime (calcium hydroxide) mixture to remove the pericarp from the kernels (Khatun et al., 2020; Serna-Saldivar, 2015). This process generates a waste product known as nejayote, which is a highly alkaline effluent with high organic load and total solids content (Díaz-Montes et al., 2016; Díaz-Montes and Castro-Muñoz, 2022).

The production process of the grafted chitosan and nejayote treatment was modelled using the SuperPro Designer tool (Fig. 1), considering a processing capacity of 200 L/h of nejayote. As the nixtamalization stage requires a rather high temperature, the nejayote stream is obtained at 70 °C and then pumped to the reactor noted as R-101, where it is mixed with the phosphate buffer solution at pH 6.0 and 34 °C. Subsequently, the *laccase* enzyme is added to oxidize the ferulic acid, at a flow rate of 0.39 g/h to carry out the enzymatic oxidation of the nejayote. The outlet stream from R-101 is pumped to reactor R-102 where chitosan is added, and the reaction process continues for 24 h and under the same temperature and mixing conditions as in reactor R-101. At the end of the reaction, the stream is pumped through PM-104 to the MF-101 filtration unit where phase separation of the stream is carried out to separate the treated nejayote and recover the grafted chitosan. The optimal reaction conditions of temperature, reaction time and pH conditions were taken from the literature (García-Zamora et al., 2015).

2.2. Techno-economic evaluation (TEA)

In order to assess the economic feasibility of the process, it is necessary to develop an economic evaluation based on the calculation of the economic parameters of *Net Present Value (NPV)* and *Payback*, i.e., the time required to recover the initial investment. The first step in the economic evaluation is to define the acquisition costs of all the equipment required in the plant, which must be updated to the year of construction of the plant, i.e., 2023. The assumptions considered for the development of TEA are described on Table 1.

Once the total cost of the equipment purchased has been determined, the *fixed capital investment* (*FCI*) can be calculated. This involves taking into account the construction and installation costs of the equipment. For this purpose, the *FCI* was estimated using the Lang factor, whose values range from 3 to 6, so a value of 5 was considered (Ioannidou et al., 2022; Turton et al., 2008). Another parameter to be defined to perform the TEA is the *Cost of Labor* (*COL*), which should define the number of workers required per shift, which will vary depending on the type of equipment, using the factors available in the research report developed by Ulrich and Vasudevan (1984). To estimate the *COL* item, a total number of 5 workers per shift is assumed, with 3 shifts per day and 8 h per shift. As for the wage, it amounts to 12 $/h. Other costs to be taken into account are those for the purchase of chemicals and raw materials, along with utilities. The costs assumed for these parameters are \$42.30/g for *laccase* enzyme, \$186/kg for NaH_2PO_4, and \$200/kg for

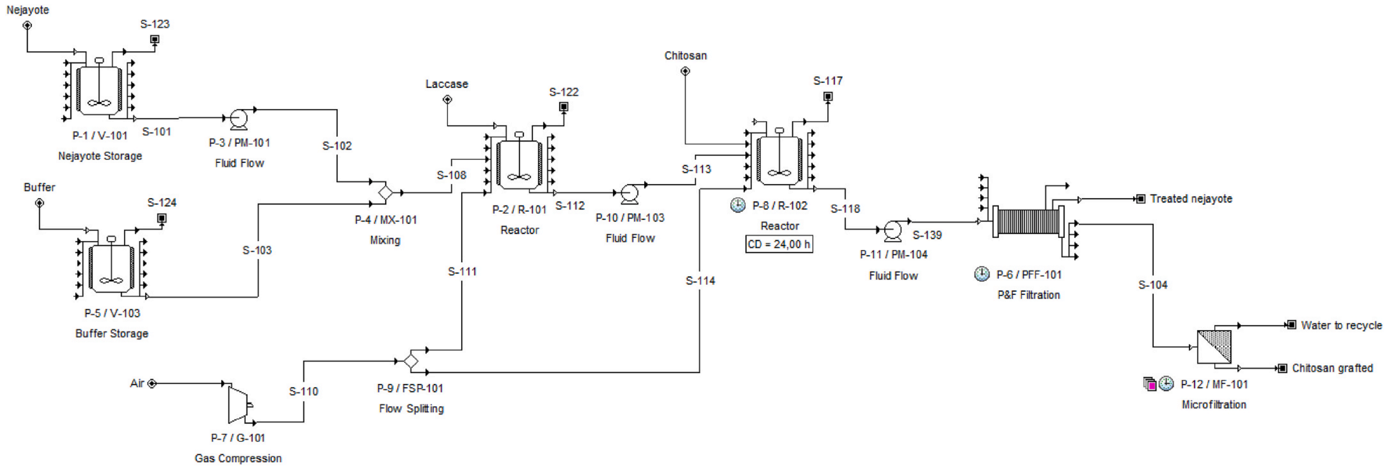

Fig. 1. SuperPro Designer modelling for the Nejayote wastewater treatment and production of graft chitosan.

Table 1
Assumptions considered for the TEA. Acronyms: COL (Cost of Labor), COM (Cost of Materials), LCA (Life Cycle Assessment), LCI (Life Cycle Inventory).

Parameter	Assumption
COL	5 workers per shift 3 shifts per day 8 h per shift
COM	\$42.30/g for *laccase* enzyme \$200/kg for Na_2HPO_4 \$186/kg for NaH_2PO_4
Revenues	1.33 \$/g for grafted chitosan
Other plant parameters	30 years of useful life 3 years for construction
Financial parameters	10% interest rate 7 years of depreciation

Na_2HPO_4. Once the FCI, COL and the cost of utilities and raw materials have been calculated, the *cost of manufacture* (*COM*) can be estimated (Turton et al., 2008).

The last parameter to be defined is the revenues, which will be obtained from the sale of the chitosan graft produced at the facility and considering the avoided costs from the external treatment of the nejayote waste stream. Revenues associated with the sale of the chitosan graft produced have been define. The final parameter to be defined is the revenue generated from the sale of the chitosan graft produced by the plant, taking into account the avoided costs of external treatment of the nejayote waste stream. The revenue associated with the sale of the chitosan was defined at 1.33 \$/g ("Medium DDA - Chitosan, 2023"), based on the data available for the main producers.

To calculate the *NPV* and *Payback* values, it is necessary to develop a discounted cash flow analysis. For this purpose, the parameters described by Humbird et al. (2011) have been considered. The useful life of the plant was assumed to be 30 years, requiring 3 years for plant construction, an interest rate of 10% and 7 years for depreciation, with a working capital estimate of 5% of the FCI.

2.3. *Environmental assessment*

Life Cycle Assessment (LCA) methodology was used to carry out the environmental profile of the nejayote treatment and the production of grafted chitosan. For this purpose, four steps were considered according to the guidelines described in ISO 14040 (Finkbeiner, 2014).

2.3.1. *Goal and scope*

The first step is based on the definition of the goal and scope of the environmental assessment. The objective has been focused on the development of the environmental profile of the treatment of 200 L/h of nejayote from the corn processing facility, which is the functional unit considered for the LCA study. The scope of the analysis has been conducted within a cradle-to-gate approach, including raw material extraction, manufacturing stages, energy requirements and on-site emissions.

2.3.2. *Life cycle inventories (LCI)*

Once all the mass and energy balances have been carried out and the production scheme has been modelled using the *SuperPro Designer* tool, the LCI can be developed based on the selected functional unit. It has been assumed that the effluent treated throughout the process is subsequently handled by an external agent, so this step is not being included in the system boundaries of the assessment. On the other hand, the environmental loads of nejayote have been included in the assessment, considering its background production process from the processing of corn tortilla.

2.3.3. *Environmental profile*

As the LCI has already been defined, the next step is to select the impact assessment method to obtain the environmental profile of the nejayote treatment process. For this purpose, the hierarchical method *ReCiPe 2016 MidPoint V1.03 World (2010)* was selected for the characterization factors within the impact categories available for the estimation of the environmental loads of the process.

Within the MidPoint methodology, the impact categories considered for the assessment are the following: global warming (GW), stratospheric ozone depletion (SOD), ionizing radiation (IR), ozone formation human health (OF, HH), fine particulate matter formation (FPMF), ozone formation, terrestrial ecotoxicity (OF, TE), terrestrial acidification (TA), freshwater/marine eutrophication (FE/ME), terrestrial/freshwater/marine ecotoxicity (TET/FET/MET), human (non-)carcinogenic toxicity (HCNT, HCT), land use (LU), mineral resource scarcity (MRS) and fossil resource scarcity (FRS). On the other hand, the EcoInvent database was used as a secondary data source for all chemical and energy requirements of the plant. In addition, this database does not contain the background information related to the production of nejayote or chitosan, which is necessary to assess the environmental damage caused by this waste stream or input material. For this purpose, bibliographic references were used to include this background information.

2.3.4. *Interpretation of results*

The environmental profile of the process shows the contribution of each LCI input to the overall environmental impact. In this way, it was possible to identify the main process hotspots (the input variables that contribute most to the environmental impact). Taking into account the results obtained, a sensitivity analysis was carried out to improve the profile and evaluate the degree of improvement of the Nejayote treatment process presented.

3. Results and discussions

3.1. *Technoeconomic evaluation*

The techno-economic evaluation of the process was developed considering the above economic parameters, as well as the cost of purchasing the equipment, utilities and raw materials, together with the expected revenues. The values obtained for the purchase of the equipment are shown in Table 2, while the main scores achieved in the economic evaluation of the process are shown in Table 3.

The identification of the equipment required through the process have shown that the centrifugal compressor and the reactors being the ones that have the higher contribution to the total cost of equipment purchase. As far as the “Other costs” section is concerned, the utility costs are related to the cooling water (0.05 $/MT) and electricity (0.1 $/kWh), considering the unit cost values provided by the database of the SuperPro Designer tool, updated until 2023 and adapted to the average values of industrial plants. Regarding the “Materials costs” (laccase enzyme, NaH_2PO_4 and Na_2HPO_4), almost 90% of the total costs of this item are derived from the use of Na_2HPO_4, so that reducing its dose requirements or increasing its recycling in the process is considered a determinant factor in reducing the material costs. In the evaluation of the revenues, these are only from the sale of the grafted chitosan, the effluent treated water has not been considered as an expected revenue of the process.

As can be seen, the *NPV* obtained is positive, which means that the treatment process developed is economically viable and affordable. In addition, the payback period, defined as the time needed to recover all the costs previously required as an investment, is quite low, since the plant starts to make a profit in the fourth year of operation. It can therefore be concluded that the proposed treatment path for the management of the Nejayote waste streams is adequate from both an environmental and a techno-economic point of view. On the other hand, the minimum selling price of chitosan is relevant to determine the threshold at which the treatment plant remains economically viable, since it is the only source of income for the facility. The minimum selling price was found to be $56.42/ton, which is significantly lower to the average value of the market, thus considering this process economically profitable and efficient.

3.2. *Environmental evaluation*

Table 4 shows the summary of the inventory data corresponding to the wastewater treatment, chitosan production and grafted chitosan, while Table 5 includes the EcoInvent database used for performing the environmental assessment.

Table 2

Purchase cost of the equipment required in the facility.

Equipment		Number	Capacity	Purchase cost
R-101	Reactor	1	1.2 m^3	$12,150
R-102	Reactor	1	1.2 m^3	$12,150
V-101	Blending tank	1	0.90 m^3	$6,229
V-103	Blending tank	1	0.20 m^3	$4,068
G-101	Centrifugal compressor	1	3 kW	$2,387
PM-101	Centrifugal pump	1	0.01 HP	$1,213
PM-103	Centrifugal pump	1	0.01 HP	$1,213
PM-104	Centrifugal pump	1	0.01 HP	$1,213
PFF-101	Plate and frame filter	1	80 m^2	$35,000
MF-101	Microfilter	2	122 m^2	$10,000
Total cost				**$85,623.00**

Table 3

Economic values obtained by performing the technoeconomic assessment of the proposed nejayote treatment – chitosan functionality facility.

Direct costs	Factor	Value
Equipment delivered cost	1	$85,623.00
Instrumentation and controls	0.1	$8,562.30
Electrical	0.1	$8,562.30
Utilities	0.2	$17,124.60
Offsites	0.2	$17,124.60
Total capital cost of installed equipment	*1.6*	*$136,996.80*
Indirect costs		
Design, engineering and construction	0.4	$34,249.20
Contingency	0.1	$8,562.30
Total fixed capital costs	*2.1*	*$179,808.30*
Working capital (15% total capital cost)		
Working capital		$26,971.25
Total capital cost		***$206,779.55***
Other costs		
Labor cost	$/year	$160,080.00
Utilities cost	$/year	$2,451.24
Materials cost	$/year	$755,969.32
Net present value (NPV)	**>0**	**Profitable**
Payback	Year	**4**
Minimum selling price (MSP)	$/ton	**56.42**

Table 4

Life Cycle Inventory of the nejayote treatment obtained from the nixtamalization process. Functional unit: 200 L/h of nejayote input.

Inputs from technosphere			Outputs to technosphere		
Material	Amount	Unit	Material	Amount	Unit
Nejayote	200	L/h	Effluent treated	208.75	L/h
Na_2HPO_4	6.33	kg/h	Grafted chitosan	3.38	kg/h
NaH_2PO_4	0.73	kg/h			
Enzyme	0.39	g/h			
Chitosan	2.00	kg/h			
Water	3.07	kg/h			
Energy					
Cooling water	0.19	m^3			
Electricity	3.00	kWh			

The environmental profile obtained using the *ReCiPe MidPoint* methodology is shown in the stacked column plot in Fig. 2.

As can be seen, two main hotspots have been identified (Fig. 2A), related to chitosan and the use of the buffer. Although chitosan is derived from a biotechnological process and biological resources, its extraction from shrimp shells is associated with certain environmental impacts. Recently the environmental assessment of chitosan extraction was developed and the main hotspots identified were sodium hydroxide used for deproteinization of shrimp cells and deacetylation, the last step required to produce chitosan from shrimp shells (Riofrio et al., 2021). Another important factor contributing to the impact identified for the process was the shrimp shells themselves, due to the energy demands of shrimp farming, which requires a large amount of diesel for the machinery. In terms of energy requirements, the most energy intensive equipment corresponds to the air compressor and the reactors, where the enzymatic oxidation and grafting reactions take place respectively, due to the requirement to maintain an agitated and aerated medium. Given this reasoning, and taking into account that the chitosan is functionalized, thanks to the grafting process with ferulic acid, one could think that the environmental impact in this case is assumed to be negligible. The chitosan is not being used by any of the operations in the process, it is only being grafted to increase its functionality, by using the ferulic acid available in the nejayote waste stream.

For this purpose, Fig. 2B is included, in which the chitosan has been discarded, thus showing that the main hotspot of the process is the buffer

Table 5
Ecoinvent database used to assess the scenario under LCA perspective.

Item		Database
Materials		
Nejayote	*Chemicals*	Maize seed, at farm {GLO}| production | Cut-off, U
		Quicklime, milled, packed {RoW}| production | Cut-off, U
		Tap water {RoW}| tap water production, conventional treatment | Cut-off, U
	Energy	Natural gas {RoW}| natural gas production | Cut-off, U
Chitosan	*Chemicals*	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U
		Ethanol, without water, in 95% solution state, from fermentation {RoW}| market for ethanol, without water, in 95% solution state, from fermentation | Cut-off, U
		Urea {RNA}| urea production | Cut-off, U
		Hydrochloric acid, without water, in 30% solution state {RoW}| market for | Cut-off, U
	Energy	Natural gas, high pressure {RoW}| market for | Cut-off, U
		Electricity, medium voltage {MX}| market for | Cut-off, U
Buffer		Sodium hydrogen sulfate {GLO}| sodium hydrogen sulfate production | Cut-off, U
Enzyme		Enzymes {RoW}| enzymes production | Cut-off, U
Water		Tap water {RoW}| tap water production, conventional treatment | Cut-off, U
Energy		
Cooling water		Water, cooling, unspecified natural origin, MX
Electricity		Electricity, medium voltage {MX}| market for | Cut-off, U

and to some extent, the electricity requirement. The buffer solution is composed of sodium dihydrogen phosphate and disodium hydrogen phosphate, so its phosphorus content could contribute to the impact categories of toxicity and eutrophication. The contribution to the FRS and MRS impact categories is based on the energy requirements required for their background production process. Finally, in the case of the FE impact category, the contribution of nejayote is significant, especially due to its high organic matter content.

3.3. *Sensitivity analysis*

In order to consider the scope of environmental improvement, with the aim of achieving even better results with less potential for damage, a sensitivity analysis was carried out around the previously identified hotspots: energy requirements and buffer dosage. The reason for not including a sensitivity assessment for chitosan is based on the fact that this compound is necessary to obtain a benefit from the process, both economically and from a circular economy point of view. The chitosan added to the process is then grafted with ferulic acid, based on the composition of nejayote, to obtain a grafted polymer product with a wide range of potential applications. However, it should be noted that at the end of the process not all of the ferulic acid binds to the fresh chitosan added to the process, so an increase in the productivity and yield of this grafting step should be evaluated to increase both the environmental and economic benefits, as there is a higher percentage of active groups in chitosan according to the stoichiometric estimate corresponding to the amount of ferulic acid present.

Focusing on the buffer and energy requirements, the use of renewable resources was considered, while for the buffer, a 20% reduction in the input dose was evaluated. The reduction is considered reasonable as it is assumed that it could be achieved through process optimisation and efficient use of resources. Furthermore, by improving the productivity of the enzymatic reactions taking place, the processing time, the required buffer dosage and the energy requirements could be reduced. On the other hand, the choice of a different agitator or a more efficient motor could help to reduce the electricity consumption of the process. The results of this sensitivity analysis are shown in Fig. 3.

As the contribution of the buffer demand is higher than that of the electricity demand, the impact on the environmental impact is more significant for the reduction of the dose of buffer needed than for the renewability of the electricity when performing the sensitivity analysis. In the case of buffer dose reduction, the most increased values are obtained for the MRS and TET impact categories; similarly, significant decreases are observed for the impact categories related with ecotoxicity (MET, FET) and human toxicity (HCT, HNCT). With regard to the second sensitivity assessment, related to the use of renewable electricity, although some improvements can be observed, they are not as favorable as those achieved in the analysis of the reduction on buffer dose, since mainly all impact categories show a reduced environmental impact. Therefore, it could be concluded that addressing the amount of buffer needed should be considered as the main objective when evaluating an alternative process scenario.

3.4. *Damage potential*

In order to analyze the damage potential of the proposed treatment scenario, the *ReCiPe EndPoint* calculation methodology has been used, which integrate all the impact categories of the *ReCiPe MidPoint* methodology into three “protection areas”, to give a single final damage potential score. The three areas or categories of harm included in this methodology are human health (HH), ecosystems (E), and resources (R). The HH category includes all *MidPoint* categories that could affect respiratory disease, malnutrition or cancer; the E area refers to damage to species living in freshwater, terrestrial and marine ecosystems; and the R category is primarily based on energy costs and the extraction of fossil and mineral resources. It should be noted that, while the *ReCiPe MidPoint* categories related to human toxicity only apply to the HH protection zone, in the case of GW, it affects both HH and E damage categories. Therefore, the analysis of the final damage score obtained must consider the interrelationship between the *MidPoint* and *EndPoint* calculation methodologies.

The scores obtained for both the base scenario and the scenario considering renewable electricity as an energy source are shown in Table 6. Even though the damage potential could not be avoided at all, as the use of fossil resources for electricity production is an important hotspot, a significant reduction in the damage potential could be obtained when evaluating the “renewable electricity” scenario. Among the protection areas, the highest reduction is achieved in the R category, with 58.97%, while in the HH category the reduction is 39.18% and in the case of the ecosystem it amounts to 39.50%.

4. Future prospects on nejayote valorization

This research report has focused on the valorization of nejayote as a resource for obtaining ferulic acid to be further functionalized with chitosan. However, although this process has been shown to be a techno-economically feasible and potentially sustainable, other alternatives for the valorization of nejayote have also been studied in the literature. However, the references found did not develop an analysis of environmental and/or economic sustainability, so it can be considered a study to be carried out in the future to evaluate which nejayote valorization model is the most appropriate.

An alternative treatment of nejayote would be the recovery of the value-added compounds found in its composition, such as sugars, phenolic compounds or probiotics (Hernández-Pinto et al., 2024). A membrane separation process (specifically microfiltration and ultrafiltration) allowed to obtain a stream rich in calcium and phenolic compounds that could be used in both the food and pharmaceutical sectors (Castro-Muñoz and Yáñez-Fernández, 2015; Castro-Muñoz et al., 2018). However, it is important to consider the energy consumption required for these technologies, as it is usually high, which could imply a reduction of the sustainable potential of the valorization scheme, as well

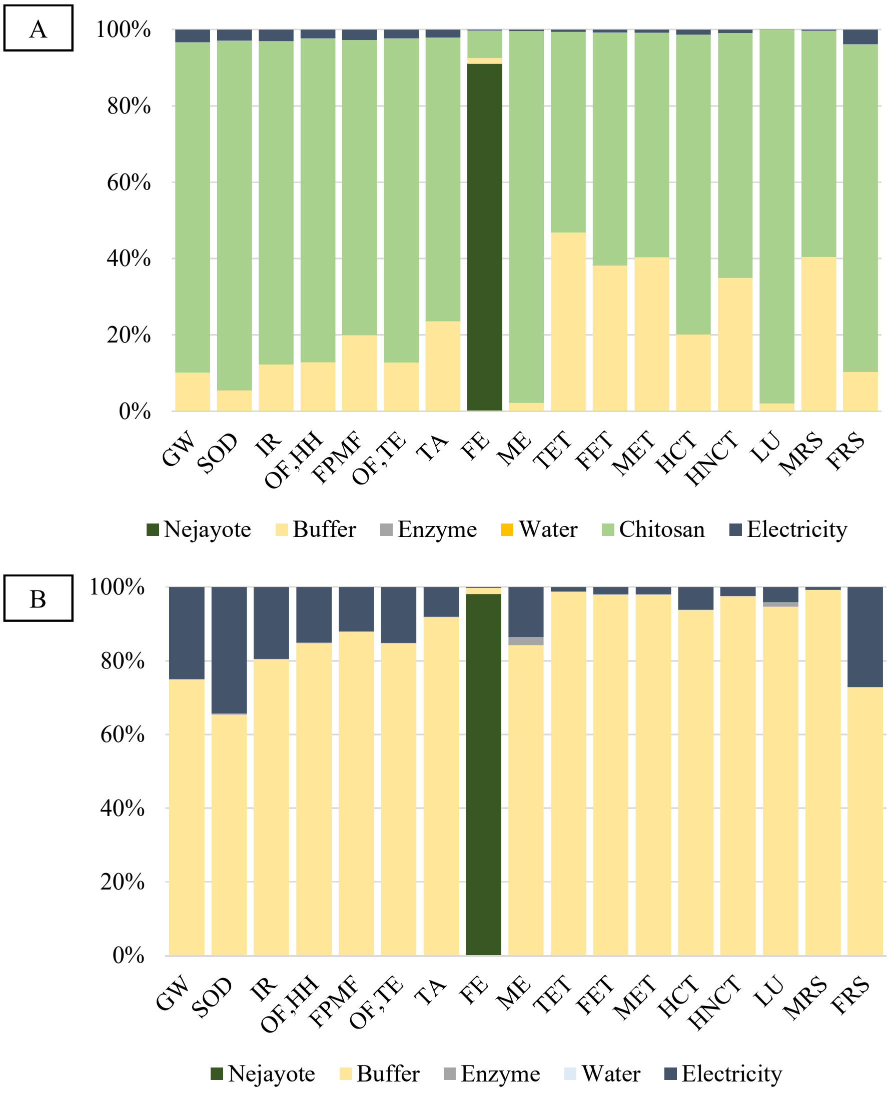

Fig. 2. Environmental profile of the facility for treating the nejayote produced by the nixtamalization process.

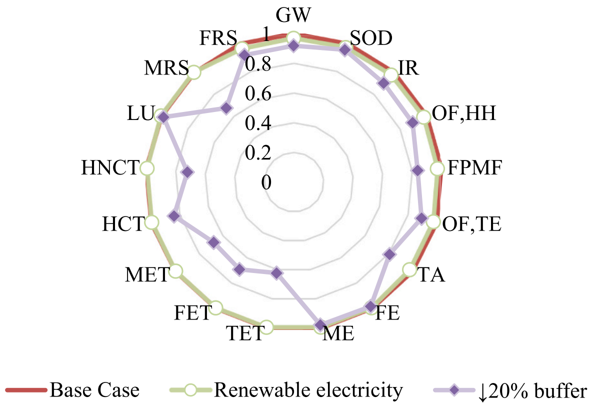

Fig. 3. Sensitivity evaluation considering the use of renewable electricity and the reduction of the buffer required dose.

Table 6
ReCiPe EndPoint methodology values (FU: 200 L/h treated nejayote).

Damage category	Unit	Base Case	Renewable electricity
HH	Pt	3.23	1.96
E	Pt	0.19	0.14
R	Pt	0.08	0.04
Single Score value	Pt	3.50	2.14

as the operation times, which are also high and imply a reduction of the productive capacity (Castro-Muñoz et al., 2020). Therefore, future studies should focus on the modelling of this large-scale membrane valorization model, as well as its evaluation from a life cycle perspective, since it is the most applied technology in the valorization of nejayote (Valenzuela et al., 2023; Valderrama-Bravo et al., 2022; Díaz-Montes and Castro-Muñoz, 2022).

On the other hand, regarding the product, i.e. grafted chitosan, this report has opted for its use as a bioactive film for its enhanced antioxidant properties (Castro-Muñoz et al., 2023a, b; Siddiqui et al., 2022). However, other potential applications have also been addressed. One of them would be the use of grafted chitosan for the preparation of nanocomposite membranes, which have been shown to be efficient for the removal of heavy metals in highly loaded wastewaters (Cosme et al., 2023). Continuing with their application as membrane systems, their effectiveness has also been demonstrated in combination with deep eutectic solvents (DES), avoiding conventional solvents of fossil origin

(Castro-Muñoz et al., 2023a, b). Their effectiveness is due to the high compatibility between chitosan and DES, which is known to increase the separation efficiency, as in the case study developed by Castro-Muñoz et al. (2022), where the separation factor was increased to a factor of 35.

However, as mentioned above, there are no research articles analyzing the case studies from a life cycle analysis perspective, nor an assessment of their suitability to Green Chemistry principles using the Greenness Grid methodology. Therefore, in the future, the aim should be to combine both perspectives, on the one hand, the laboratory development of the valorization model and, on the other hand, its evaluation from the point of view of technological and economic feasibility, as well as its potential impact on the quality of the environment. One potential scenario could be the ferulic acid-chitosan reinforced polymer for its subsequent activation with quercetin from the recovery of onion waste (Santiago et al., 2020).

5. Conclusions

This report evaluated the treatment process of the wastewater stream from corn tortilla and related products, commonly known as “nejayote”. This is a very harmful waste stream which, due to its high organic content, could have a significant impact on the environment. For this purpose, an enzymatic laccase process has been evaluated which, in addition to obtaining a less polluted waste stream, also produces a biotechnological product: a grafted chitosan, thanks to the recovery of the ferulic acid present in the nejayote composition. In this sense, a dual-benefit transformation scheme has been studied, in which the environmental impact has been significantly reduced compared to the discharge of the nejayote stream from the nixtamalization process. From a techno-economic point of view, the modelled scenario is also profitable, as a positive NPV was obtained, together with a low recovery value. In this sense, this system develops the concepts of sustainability and circular economy, while reducing the production of industrial food waste.

CRediT authorship contribution statement

Ana Arias: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Eduardo Torres:** Validation, Supervision, Conceptualization. **José Luis García-Zamora:** Data curation. **Francisco M. Pacheco-Aguirre:** Data curation. **Gumersindo Feijoo:** Writing – review & editing. **Maria Teresa Moreira:** Writing – review & editing, Supervision, Conceptualization.

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.

Data availability

Data will be made available on request.

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