Environmental and Exergetic Analysis of Large-Scale Production of Citric Acid-Coated Magnetite Nanoparticles via Computer-Aided Process Engineering Tools

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Abstract: Considering that functional magnetite (Fe₃O₄) nanoparticles with exceptional physicochemical properties can be highly applicable in different fields, scaling-up strategies are becoming important for their large-scale production. This study reports simulations of scaled-up production of citric acid-coated magnetite nanoparticles (Fe₃O₄-cit), aiming to evaluate the potential environmental impacts (PEIs) and the exergetic efficiency. The simulations were performed using the waste reduction algorithm and the Aspen Plus software. PEI and energy/exergy performance are calculated and quantified. The inlet and outlet streams are estimated by expanding the mass and energy flow, setting operating parameters of processing units, and defining a thermodynamic model for properties estimation. The high environmental performance of the production process is attributed to the low outlet rate of PEI compared to the inlet rate. The product streams generate low PEI contribution (−3.2 × 10³ PEI/y) because of the generation of environmentally friendlier substances. The highest results in human toxicity potential (3.2 × 10³ PEI/y), terrestrial toxicity potential (3.2 × 10³ PEI/y), and photochemical oxidation potential (2.6 × 10⁴ PEI/y) are attributed to the ethanol within the waste streams. The energy source contribution is considerably low with 27 PEI/y in the acidification potential ascribed to the elevated levels of hydrogen ions into the atmosphere. The global exergy of 1.38% is attributed to the high irreversibilities (1.7 × 10⁵ MJ/h) in the separation stage, especially, to the centrifuge CF-2 (5.07%). The sensitivity analysis establishes that the global exergy efficiency increases when the performance of the centrifuge CF-2 is improved, suggesting to address enhancements toward low disposal of ethanol in the wastewater.

Introduction

Globalization has increased the emerging technologies and processes to cover the consumption demands of societies, market competitions, and future innovations. The major challenges for the industries are related to resource depletion, ozone depletion, ecosystem damage, and human health. These are critical factors for the green engineering design of new technologies and processes considering the economic, environmental, and social development. Accordingly, the process design needs to incorporate the sustainability concept toward the creation of new production routes and the optimization of the existing process technologies. The sustainability concept integrates material and energy efficiency, water conservation, greenhouse emissions, and zero-discharge wastes. Several techniques have been extensively applied to evaluate the environmental sustainability of new technologies and processes, allowing to quantify sustainability indicators and to determine the environmental impacts and performance. Environmental sustainability is highlighted because of its wide participation in manufacturing, nanotechnological, water treatment, and energetic processes, representing a challenge in the development of green engineering designs.

Currently, nanotechnology plays an important role in the development of green materials, technologies, and processes, influencing environmental sustainability, economic stability, and human health. One of the major contributions of nanotechnology is to provide an efficient use of the available resources in the industry and academy considering the reduction in the nonrenewable materials and energy requirements. Therefore, nanotechnology has been demonstrated to

Received: October 24, 2020
Accepted: December 24, 2020
Published: January 27, 2021
be useful, providing new and innovative frontiers for a wide number of possible industrial applications. Different types of innovative materials in the nanoscale are being developed based on market demand, covering several industrial fields such as textiles, food, health, and the environment. The major advantages offered by nanomaterials are the shape, surface area, and particle size, which confer unique optical, mechanical, electrical, and physicochemical properties. These advantages also provide a high reactivity for the modification with organic and inorganic molecules, allowing the synthesis of engineered nanomaterials for an extended range of applications, including a more efficient environmental remediation. The engineered nanomaterials bring a double benefit to the environment because many are considered greener and safer, and the synthesis methods can follow the environmental sustainability approach.

Among the most explored engineered nanomaterials, iron-based nanoparticles have attracted great attention because of the potential application following an environmental sustainability approach. Magnetite (Fe₃O₄) nanoparticles, the most common oxidation state of iron, is a promising nanomaterial attributed to their exceptional physicochemical properties, such as nontoxicity, superparamagnetism, adsorption strength, and electrical capacity. This allows that Fe₃O₄ nanoparticles can be applied in an extensive number of applications related to environmental remediation. Although these nanoparticles are synthesized using different physical, chemical, and biological methods, the principle of engineering design following the sustainability concept needs to be addressed. The coprecipitation of iron(II) and iron(III) to grow the Fe₃O₄ nanoparticles is one of the most implemented methods because of its simplicity and low cost. Additionally, coprecipitation is considered environmentally friendlier than other methods because of the less use of energy and hazardous compounds. Moreover, performing in situ modification of Fe₃O₄ nanoparticles in one approach promotes physicochemical improvements, which includes the agglomeration reduction. The Fe₃O₄ nanoparticles tend to form agglomerates because of the strong dipolar interaction between particles, leading to a reduction in the spin coordination and the magnetic moment. Therefore, this can be avoided with surface modification using carboxyl groups contained in organic compounds, such as citric acid, which enhances the stability, functionality, chemical resistance, and surface area. Accordingly, these considerations need to be analyzed to determine if the coprecipitation method and the in situ modification contribute to environmental sustainability.

The scaling-up of emerging processes from the laboratory to the industrial scale is a challenge for the increasing manufacture of products. Different aspects have to be considered including the equipment design and the optimization of critical stages of the process. The large-scale production of nanomaterials can be addressed using computer-aided tools for the modeling and scaling-up of the process, allowing to establish the operating requirements and environmental sustainability. Moreover, the environmental impacts of emerging technologies and processes have to be studied to establish whether large-scale production is feasible or requires improvements. Among the novelty, safety issues also represent an important factor for the development and scaling-up of such technologies and processes. However, the scaling-up of relevant nanoparticle-related processes is partially limited by a lack of information related to the environmental and safety risks, especially the exposure which is a field scarcely explored. Possible effects of the exposure to nanomaterials require a deep evaluation considering properties, such as surface area, reactivity, and particle size, because of the generation of potential atmospheric and toxicological impacts at an industrial-scale production. Accordingly, preventive and protective parameters are necessary to establish the risk levels of nanomaterials’ production, including the risks posed by the chemicals utilized during the production process. The United States Environmental Protection Agency (U.S. EPA) and the National Institute for Occupational Safety and Health (NIOSH) have established some parameters regarding the potential risks of nanomaterials. However, the regulations are not accurate with an existing degree of uncertainty, likely underestimating the potential hazards during the production and application of nanomaterials.

The environmental sustainability and safety risks of emerging technologies and processes can be studied using different computer-aided simulation tools, such as the waste reduction algorithm (WAR), prefeasibility analysis, life cycle assessment, market uncertainty, and sensitivity analysis, among others. The WAR is a free-access tool developed by the National Risk Management Research Laboratory from the U.S. EPA. A complete environmental assessment can be performed with WAR because of the robust database, providing a diagnosis and quantification of the potential environmental impacts (PEI). The PEI contribution can be calculated based on the time (PEI/γ) and the mass and energy streams (PEI/kg of product), in which it is possible to incorporate different components for a more complete analysis. Accordingly, a scaled-up and simulation process for the novel production of iron oxide nanoparticles modified with citric acid (Fe₃O₄-cit) nanoparticles can be achieved using WAR, following environmental, economic, and technical approaches. The quantification of the PEI using WAR is addressed at the early phase of the industrial process, allowing to determine improvements through an environmental decision-making approach. However, a lack of knowledge in the existing computer-aided tools makes the simulation and the category disaggregation more limited and complex. These limitations require excessive resources for the environmental assessment of a large-scale process, which also makes the scope and results of such studies harder to achieve. Currently, limited studies have been reported in the literature related to the environmental assessment in emerging technologies and processes using WAR. Meramo-Hurtado et al. performed an environmental assessment of large-scale production of chitosan microbeads modified with titanium dioxide nanoparticles. Vargas-Mira et al. reported a comparative and sensitivity analysis of six different routes for the production of hydrogen from oil palm residual biomass, including three gasification methods and two purification technologies. Ortiz-Sanchez et al. applied the WAR tool to determine the environmental impacts of a production process of muccic acid using orange peel wastes, considering biorefinery concepts. Petrescu and Cormos used WAR combined with CAPE-OPEN to evaluate the environmental sustainability of an integrated gasification combined cycle with/without carbon capture and storage. In general, the WAR can be extensively applied to emerging technologies and processes with different nature, allowing to establish and analyze the environmental sustainability for scaling up to industrial levels.
Exergy analysis is a diagnosis tool that allows determining the performance and sustainability of emerging processes at an industrial scale. This is also a decision-making tool for the technology selection and the improvement of the process stages from energy and thermal perspectives. The exergy analysis is defined using the second law of thermodynamics, which describes the maximum amount of work produced during the process that brings the system into equilibrium with the environment. This analysis identifies the energy losses within the process through the quantification of parameters, such as irreversibilities, destroyed exergy, exergy efficiency, the exergy of waste, and exergy of utilities. In contrast with the energy, the exergy does not follow the mass conservation law and can be destroyed attributed to the irreversibilities, as in the case of the loss of heat in the process to the environment. Recently, authors have reported the exergy analysis of processes and technologies, aiming to determine the magnitude and location of the inefficiencies among various process stages. Meramo-Hurtado et al. performed the exergy analysis of a production process of chitosan microbeads modified with TiO₂ nanoparticles. The exergy efficiency of around 0.04% was attributed to the high waste and water flows in the outlet rates. Accordingly, a sensitivity analysis allowed to determine the inadequacies of the system, locating the inefficiencies in the separation or purification stage. Sharshir et al. performed a comparative study related to exergy efficiencies of solar stills composed of micro-/nanoparticles. Exergy destruction was identified and attributed to the basin of the solar still, suggesting the selection criteria of a suitable material for basin liners. Ehyaei et al. evaluated the performance of a parabolic trough collector using fluid and metal oxide nanofluids. The authors concluded that a slight decrease in the exergy efficiency was attributed to the addition of metal oxide nanoparticles into the fluids. Similarly, other studies have been also addressed to evaluate the thermal performance of copper oxide nanosuspensions in heat transfer systems, which highlights the importance of nanomaterials for different applications.

This study reports the simulation of large-scale production of Fe₃O₄-cit nanoparticles synthesized via the coprecipitation method with an in situ modification using citric acid. The scaling-up is performed using WAR to evaluate the PEI contribution (including eight toxicological and atmospheric categories) by extending the mass and energy balances, and thus, to determine the environmental sustainability of the process. This environmental analysis has been scarcely applied in the nanotechnology field, and to the authors’ knowledge, no studies are exploring and reporting the implementation of WAR for the production of Fe₃O₄-cit. Additionally, an exergetic sensitivity evaluation is also performed for the first time in the production process of this type of engineered nanomaterial, which allowed establishing the required improvements in the different stages. It is found that consumption of PEI occurred during the process because of the transformation of the raw materials into compounds with less global impacts and that the separation stage was inadequate according to the exergy analysis. A novel approach was addressed from an environmental and exergetic sustainability approach for a potential large-scale production of Fe₃O₄-cit, contributing to the engineering design of new technologies and processes.

**RESULTS AND DISCUSSION**

Transmission electron microscopy (TEM) images of the as-synthesized Fe₃O₄-cit are shown in Figure 1. Enhanced dispersion is observed, indicating better stability compared to those Fe₃O₄ synthesized without in situ functionalization, as reported in the literature. The enhanced dispersion is mainly attributed to a decrease in the dipolar–dipolar interaction between nanoparticles, avoiding the formation of large agglomerations. The carboxyl layer on the Fe₃O₄ surface is evidenced, which grew to an average thickness of 2.2 nm. Additionally, the presence of a carboxyl layer improves the functionality of the Fe₃O₄ allowing them to be used as a promising nanomaterial for environmental applications. The carboxyl layer protects the nanoparticles against corrosive environments and increase the interaction with different types of molecules during adsorption processes. Patiño-Ruiz reported a complete characterization of functional and superparamagnetic Fe₃O₄-cit, which were used for the preparation of core–shell nanostructures in the remediation of water polluted with heavy metals. Accordingly, environmental assessment and exergetic analysis need to be addressed, aiming to scale-up the synthesis of Fe₃O₄-cit to an industrial level and to supply the demand for environmental applications.

**Environmental Analysis.** WAR was used as a computer-aided tool to establish the environmental performance of largescale production of Fe₃O₄-cit, aiming to determine potential improvements within the process. The mass flows of the main streams of the production process are listed in Table 1. The main operating units comprised a mixer with inlet streams containing the raw materials, a reactor for the coprecipitation reaction and in situ modification, and centrifuges with the final product stream. These were the operation units with the major changes in the mass balances, providing the highest PEI contribution within the entire process. On the other hand, the physicochemical properties of the final product (Fe₃O₄-cit) were validated to support the simulation. The properties were estimated using Aspen Plus and compared with those calculated experimentally, as summarized in Table 2. According to the results, the simulated average molecular weight, mass density, Gibbs free energy, and production yield presented accuracy values above 99% regarding the experimental calculations.
The total output and generation rates of the as-established scenarios are displayed in Figure 2a,b. In general, the PEI per year (PEI/y) and per ton of the product (PEI/t) showed similar contributions for all scenarios. The negative generation rate values suggest that the reduction of PEI within the process is attributed to the transformation of the raw materials into environmentally friendlier substances. These results prove a good environmental performance for the large-scale production of Fe₃O₄-cit. Additionally, output rates were equal for scenarios 1 and 3, as well as for scenarios 2 and 4, indicating a similar global environmental performance for energy and product streams. Although the output rates were similar for all scenarios, a slightly higher contribution of PEI is observed for scenarios 2 and 4. This contribution is attributed to major environmental impacts generated by the product streams rather than energy consumption, considering that natural gas was assumed as the energy source for the production process. It is worth noting that this design presents a convenient output rate of PEI (3.3 × 10⁴ PEI/y). This result is lower compared to those values reported by Arteaga-Díaz et al.,⁵ which determined an output rate of PEI (5.3 × 10⁶ PEI/y) much higher for the production of Fe₃O₄ nanoparticles via coprecipitation.

**Potential Toxicological Impacts.** Human toxicity potential by ingestion (HTPI), human toxicity potential by exposure both dermal and inhalation (HTPE), terrestrial toxicity potential (TTP), and aquatic toxicity potential (ATP) were evaluated considering the generation of PEI/y in the output and generation rates. Figure 3a shows negative values for the generation rates, indicating the reduction of compounds with high toxicity and corrosive effects on the ecosystems. However, PEI contribution in the output rates were observed with considerably higher values for HTPI and TTP compared to those for HTPE and ATP. The contributions in HTPI and TTP are attributed to the generation of solid and liquid organic wastes in the outlet.

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### Table 1. Properties of the Main Streams within the Production Process of Fe₃O₄-Cit, Considering Mixer, Reactor, and Centrifuges, as the Main Operating Units

| stream | 2 | 9 | 10 | 11 | 14 | 15 | 16 | 17 | 21 | 22 | 23 | 26 | 29 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mass flow \((\times 10^4, \text{t/y})\) | 3.59 | 3.89 | 0.18 | 6.27 | 4.66 | 0.02 | 1.81 | 10.38 | 0.16 | 2.12 | 8.13 | 0.50 | 0.10 |
| \(\Delta H\) \((\text{kJ/kg})\) | −59 | −61 | −1 | −103 | −75 | −0.2 | −30 | −164 | −1 | −34 | −75 | −4 | −0.6 |
| \(T\) \((\text{°C})\) | 28 | 80 | 28 | 28 | 28 | 28 | 80 | 28 | 28 | 28 | 28 | 28 |
| \(P\) \((\text{atm})\) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| water | 1.0 | 0.92 | 1.0 | 0.96 | 0.0 | 0.99 | 0.97 | 0.33 | 0.95 | 0.30 | 0.24 | 0.0 |
| iron(II) | 0.0 | 0.02 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| iron(III) | 0.0 | 0.06 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| NaOH | 0.0 | 0.0 | 1.0 | 0.0 | 0.04 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Fe₃O₄-cit | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.53 | 0.04 | 0.01 | 0.16 | 0.80 |
| Cit. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 0.01 | 0.0 | 0.13 | 0.01 | 0.04 | 0.20 |
| ethanol | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| NaCl | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.02 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

**ΔH** is the enthalpy, \(T\) is the temperature, and iron(II) and iron(III) are the FeCl₂·4H₂O and FeCl₃·6H₂O salt precursors, respectively, and Cit. is citric acid.

### Table 2. Physicochemical Properties of Fe₃O₄-Cit Simulated Using Aspen Plus

| property | experimental | simulation | accuracy (%) |
|---|---|---|---|
| average molecular weight \((\text{g/mol})\) | 233.55 | 231.54 | 99.14 |
| mass density \((\text{kg/m}^3)\) | 5180.00 | 5200.31 | 99.61 |
| Gibbs free energy \((\text{kJ/mol})\) | −1012.6 | −1010.0 | 99.74 |
| production yield \((\text{product mass flow/main feedstock flow})\) | 0.3118 | 0.3105 | 99.58 |

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Figure 2. Total generation and output rates of all scenarios and their contribution in (a) PEI/y and (b) PEI/t of product.
streams, which represent a hazard of ingestion of high doses to humans and terrestrial organisms. On the other hand, the low values in HTPE suggest the nonuse of highly volatile and corrosive compounds, such as acids, avoiding possible damage by contact or inhalation in humans. In the case of ATP, the contributions were near zero, indicating that none of the scenarios represent a contamination source of aquatic ecosystems. These contributions in the toxicological categories are in agreement with those shown in Figure 2, where scenarios 1 and 3 have better environmental performances compared to scenarios 2 and 4. Although the potential toxicological impacts show no negative side effects in aquatic systems, a production plant should be located away from areas with a dense population of humans, animals, and flora.

Potential Atmospheric Impacts. The contributions in the atmospheric categories are shown in Figure 3b, including the global warming potential (GWP), ozone depletion potential (ODP), photochemical oxidation potential (PCOP), and acidification potential (AP). The GWP and ODP are analyzed from a global perspective, whereas the PCOP and AP from a regional viewpoint. The GWP, ODP, and AP showed no contribution (approaching zero) in terms of PEI/y for all scenarios, suggesting the large-scale production of Fe₃O₄-cit to be environmentally friendly. These results are attributed to the oxidation of raw materials to compounds that are not emitted or are less persistent in the atmosphere, avoiding the formation of acid rains. However, a high contribution of PCOP (26,200 PEI/y) in all scenarios was evident because of a large amount of ethanol that was used during the purification stage, which promotes the formation of smog through photochemical reactions of hydroxyl radicals (OH•). Accordingly, the contribution in the PCOP category in all scenarios is directly related to the product streams rather than energy consumption. The atmospheric categories results were consistent with the reported literature, considering performance obtained by similar systems (titanium dioxide nanoparticles production), in which the PCOP category presented the highest PEI, while the other atmospheric variables trended to zero.

Energy Source Contribution. The energy source contribution in the toxicological and atmospheric categories was evaluated considering three types of fuels, including natural gas, oil, and coal. The environmental performance of large-scale production is also analyzed using the potential effects of the energy source. Although natural gas was used for the global environmental analysis in this study, oil and coal were included to establish the energy source contribution of scenario 3 (only energy consumption). Figure 4 shows slight contributions for HTPI, TTP, ATP, and GWP, whereas AP exhibited the highest contribution with PEI/y values of 4.6, 17.2, and 27.4 for natural gas, oil, and coal, respectively. These results for AP suggest a negative impact regionally, in which oil and coal usage, especially, promotes acidification by releasing hydrogen ions (H+) to the atmosphere. However, the PEI contribution of the energy source was considerably lower compared with those in the toxicological and atmospheric impacts, providing high performance from an environmental and energetic viewpoint. Additionally, the natural gas usage showed to be promising as the main energy source because of the lowest contribution in the PEI/y. The above statement (and the initial assumption made in this study) is supported by...
of the main streams, in which numbers 23 and 26 showed the highest value of 173226 and 8791 MJ/h, respectively. These streams are located in the purification stage and contain mainly ethanol. A large amount of ethanol was exclusively used to wash the Fe₃O₄-cit, resulting in a waste of useful energy of this valuable compound in the production process. On the other hand, the other streams exhibited considerably lower total mass exergy values because of the consumption of useful energy offered by the raw materials such as iron salt precursors, NaOH, and citric acid. The consumption of these raw materials was carried out during the coprecipitation reaction in the RX-1 unit, involving the streams 9, 14, and 17 with total mass exergies of 599.56, 641.12, and 1114.6 MJ/h, respectively. These results are explained by the formation of nanoparticles using surface energy, which is produced from the useful work offered by the raw materials during the reaction.⁷⁶

The exergy analysis of the raw material preparation, reaction, and separation stages, including the exergy efficiency, destroyed exergy, and irreversibilities are shown in Figure 5a. The raw material preparation stage presented a high exergy efficiency attributed to the useful energy provided by the raw materials in the mixer units. Moreover, no destroyed energy and irreversibilities were exhibited because the useful energy of the raw materials are not used in this stage. In the case of the reaction stage, the exergy efficiency decreased, whereas the destroyed exergy and irreversibilities increased. This occurs because of the conversion of the raw materials during the coprecipitation reaction, which is also considered to be the high temperature (80 °C) required for the reactor unit, leading to a loss of heat to the environment⁶⁶ and higher power consumption.⁶⁸ Although the destroyed exergy and irreversibilities were low, using thermal isolation promoted the reduction of the exergy losses.⁶⁹

In the separation stage, very low exergy efficiency of 0.08% was observed, but it also high destroyed exergy and irreversibilities up to 98.37% and 1.74 × 10⁵ MJ/h, respectively. These results are related to the waste leaving the process, which contains large amounts of water and ethanol used for the purification of Fe₃O₄-cit, and unreacted chemicals and other impurities. The loss of valuable compounds, such as water and ethanol, affects the performance of the separation stage, attributed mainly to the negative impacts reflected in the exergy loss. Ethanol is a valuable fuel with high specific chemical exergy that enters the process and remains in the production process, and other impurities. These results are explained by the formation of nanoparticles using surface energy, which is produced from the useful work offered by the raw materials during the reaction.⁷⁵

Although the optimized separation stage is suggested, aiming to improve the performance through the recovery, recycle, and further use of the water and ethanol mass flows.⁵²

Global exergy analysis is shown in Figure 5b. Total irreversibilities, the exergy of waste, and the exergy of utilities were 1.7 × 10⁵, 1.7 × 10⁵, and 2.9 × 10⁵ MJ/h, respectively. The high values in irreversibilities and exergy of waste were attributed to the use and final disposition of a large amount of water and ethanol with no further recovery and reuse. Although ethanol was used for the purification of Fe₃O₄-cit, it was also considered as a fuel that was consumed through a chemical reaction within the system boundary. Hence, a high exergy loss is expected because of the waste of the useful chemical exergy, which in turn generates irreversibilities in the production process.⁷⁷

In the case of the exergy of utilities, the low value is related to the required utilities for recycle, recovery, and treatments of

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**Table 3. Specific Chemical Exergy of Each Compound Used in the Production Process**

| compound | enthalpy (kJ/kg) | entropy (kJ/kg K) | specific chemical exergy (kJ/kg) |
|----------|------------------|-------------------|---------------------------------|
| water    | −15,852          | −9.0              | 50.0                            |
| iron(II) | −7792.0          | −26.1             | 843.9                           |
| iron(III)| −8226.8          | −27.6             | 983.3                           |
| NaOH     | −10,648.3        | 1.63              | 1872.6                          |
| Fe₃O₄-cit| −4828.6          | −1.50             | 502.3                           |
| Cit.     | −8012.1          | 5.57              | 4011.4                          |
| ethanol  | −6016.2          | 7.50              | 27,154                          |
| NaCl     | −7034.9          | 0.45              | 244.9                           |

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**Table 4. Total Mass Exergy of the Main Streams**

| stream | physical exergy (MJ/h) | chemical exergy (MJ/h) | total mass exergy (MJ/h) |
|--------|------------------------|------------------------|-------------------------|
| 2      | 0.233                  | 205.39                 | 205.63                  |
| 9      | 70.682                 | 528.87                 | 599.56                  |
| 10     | 1.433                  | 383.45                 | 384.88                  |
| 11     | 0.407                  | 358.33                 | 358.74                  |
| 14     | 1.723                  | 639.40                 | 641.12                  |
| 15     | 0.000                  | 102.68                 | 102.68                  |
| 16     | 0.117                  | 205.06                 | 205.17                  |
| 17     | 215.4                  | 899.18                 | 1114.6                  |
| 21     | 0.005                  | 147.37                 | 147.37                  |
| 22     | 0.131                  | 266.31                 | 266.44                  |
| 23     | 0.681                  | 173224                 | 173226                  |
| 26     | 0.035                  | 8791.1                 | 8791.2                  |
| 29     | 0.001                  | 137.12                 | 137.12                  |

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**Figure 4.** Contribution in the PEI/y of each energy source considered in scenario 3 (only energy consumption).
resources, which were considered to be supplied by external industrial facilities. Accordingly, the global exergy efficiency was calculated, and a value of 1.38% suggests the need for process intensification and improvements in the separation stage through mass and energy integrations. In a similar study, the global exergy efficiency of a green production process of TiO2 nanoparticles has been significantly low. The global exergy efficiency of 0.27% was attributed to a high contribution of the separation unit, including centrifuges for the purification of the final product, which was similar to the separation stage implemented in this study.

Considering the separation stage as critical, the exergy analysis of each unit (CF-1, CF-2, and MX-6) in this stage was performed and is shown in Table 5. Here, CF-2 was the unit with the lowest exergy efficiency. CF-1 exhibited the same exergy loss compared to CF-2 because its stream contains the major impurities and unreacted chemicals after the washing of the final product. However, the exergy efficiency was considerably higher for CF-1, considering that CF-2 possesses the outlet stream containing the ethanol that leaves the process with the same exergetic value, which can be supported with the high irreversibilities value. Accordingly, a sensitivity analysis was performed for the CF-1 and CF-2 units to establish the variation of the global exergy efficiency of the production process.

Figure 6a,b shows a clear improvement of the global exergy efficiency up to 91.3%, which occurs with the increase of the CF-2 efficiency of around 84.6%. This improvement is attributed to the reduction of the exergy of waste in CF-2, suggesting that the performance of the production process can be increased through the lower generation of wastewater and further recovery of ethanol. Meanwhile, the sensitivity analysis for CF-1 shows no significant changes in the global exergy (1.46%) of the process, even when there is an exergy of waste attributed to the impurities and unreacted chemicals. Therefore, the optimization of large-scale production of Fe3O4-cit can be achieved with the use of alternative technologies, aiming to recover and reuse valuable compounds and decreasing the wastewater effluents in the separation stage.

| Table 5. Exergy Analysis of Each Unit Involved in the Separation Stage (Critical Stage) |
|-----------------|-----------------|-----------------|-----------------|
| parameter       | CF-1            | MX-6            | CF-2            |
| exergy efficiency (%) | 99.9            | 100             | 5.07            |
| destroyed exergy (%)       | 0.0             | 0.0             | 92.8            |
| irreversibilities (MJ/h)   | 0.3             | 0.5             | 1.6 × 10^5      |
| exergy of waste (MJ/h)     | 1.6 × 10^5      | 0.0             | 1.6 × 10^5      |
| exergy of utilities (MJ/h) | 13.8            | 0.5             | 13.8            |

Figure 5. (a) Exergy analysis of the three main stages and (b) global exergy analysis of the production process.
CONCLUSIONS

The WAR algorithm allowed estimating the PEI contribution extended to eight toxicological and atmospheric categories and considering four scenarios for the large-scale production of Fe₃O₄-cit. The contributions in scenarios 2 and 4 with values up to $3.3 \times 10^3$ PEI/y and $3.3 \times 10^1$ PEI/t of the product indicate that product streams promoted major environmental impacts compared to the energy streams. HTPI and TTP suggested a large generation of waste, representing a hazard in humans and terrestrial organisms, whereas HTEP and ATP showed better environmental performances. This is related to the nonuse of volatile and corrosive compounds and a reduction of negative impacts in aquatic ecosystems. A similar performance for GWP, ODP, and AP was observed because of the transformation of the raw materials into others environmentally friendlier. However, high PCOP ($2.6 \times 10^4$ PEI/y) contribution suggested the formation of smog ascribed to the use and disposal of a large amount of ethanol.

The global exergy efficiency (1.38%) was considerably low attributed to the high destroyed exergy and irreversibilities in the separation stage (centrifuges CF-1 and CF-2). In this stage, CF-2 was ascribed as the most critical unit with high destroyed exergy (92.8%) and high irreversibilities ($1.6 \times 10^5$ MJ/h), which were related to a large amount of ethanol contained in the wastewater. After the sensitivity analysis of this unit, the global exergy efficiency (84.6%) increased substantially, indicating the optimization of CF-2 to promote higher performance. Therefore, the recovery of water and ethanol using an intensification process approach leads to a more promising, efficient, sustainable, and flexible production of Fe₃O₄-cit. The implementation of further concepts can provide an extended vision of this study, such as the “Circular Economy”, uncertainty and economic analysis, systematic design tools for process integration and intensification, and business model innovation.

Experimental Methods. The general scheme for modeling and scaling-up the production of citric acid-coated magnetite (Fe₃O₄-cit) nanoparticles is shown in Scheme 1. Sustainable design was performed using computer-aided tools, including a rigorous process simulation. The methodology considered the PEI of the process streams. Additionally, an exergetic analysis was performed to identify inadequacies in the main process stages, allowing to perform improvements through the decision-making process. The experimental data collected at the laboratory scale was used to calculate and simulate the large-scale production, including mass and energy balances, as well as toxicological and atmospheric effects.

Modeling of the Laboratory Protocol. General Process Description. The production of Fe₃O₄-cit at the laboratory
scale consisted of a coprecipitation reaction of two iron salt precursors, in which citric acid was used in situ to lead the formation of a carboxyl layer. Scheme 2a–d shows the laboratory protocol in brief, including the main stages of the synthesis. First, a 2:1 molar ratio of ferric chloride hexahydrate (FeCl₃·6H₂O) and ferrous chloride tetrahydrate (FeCl₂·4H₂O) were mixed (see Scheme 2a). The solution was poured into a three-neck flask and heated up to 80 °C. Then, a 1 M sodium hydroxide (NaOH) solution was added dropwise to adjust the pH to 12. The NaOH solution plays an important role, allowing the growth and precipitation of the nanoparticles. After 30 min, 0.5 g of citric acid in 50 mL of distilled water was added dropwise, leading to the hydrolyzation of the carboxyl groups to form the layer (see Scheme 2b). The Fe₃O₄-cit particles were collected using magnetic separation and cooled down at 25 °C (see Scheme 2c). Further, a purification stage allowed for the elimination of unreacted chemicals and impurities. The purification consisted of several washes using distilled water (three times) and ethanol (once), including centrifugation between washes under vacuum for 20 min, controlling the temperature around 25 °C (see Scheme 2c). Finally, the Fe₃O₄-cit particles were dried at 70 °C overnight and then cooled down at 25 °C (see Scheme 2d).

The large-scale production of Fe₃O₄-cit is described in Scheme 3. This is a screening of the scaling-up to an industrial level, using the general description of the synthesis at a laboratory scale. The production process consisted of five mixing units containing the main raw materials. The coprecipitation reaction and the in situ modification were performed in a reactor unit, in which two heat exchangers were used to increase and reduce the temperature before and after the reaction, respectively. Finally, the separation stage involved two centrifuges, one mixing unit, one dryer, and one heat exchanger. This stage allowed the purification of the final product with a yield of 1000 t/y of Fe₃O₄-cit.

**Computer-Aided Process Simulation and Scaling Up.** The scaling-up of the laboratory protocol consisted of the documentation of all stages, including the quantification of raw materials and other procedure details. This information allowed designing the main process flowsheet, in which the required operation units were specified. Table 6 displays the typical process steps and the homologation to this study. The experimental parameter setting to process the plant scaling-up process is a crucial step for analyzing nanotechnology-based topologies. Thus, the task involved apply some steps under a comprehensive framework that includes the following:

1. The lab or experimental procedure serves as an opening point for process layout generation.

**Scheme 3. Process Flow Diagram Describing the Different Units Used for the Large-Scale Production of Fe₃O₄-Cit**

![Scheme 3](image)

**Table 6. Scaling-Up of the Main Units Process from the Laboratory to an Industrial Scale**

| lab-scale process | scaled-up process |
|-------------------|-------------------|
| reaction with heating | batch reactor isolated with an in-tank stirrer |
| a magnetic stirrer or mechanical rotor | in-tank stirrer |
| ultracentrifugation | ultracentrifugation |
| drying | dryer |
| heat transfer equipment | heat exchangers for heat recovery |

II From the above, the most suitable plant flow diagram with all processing units included is designed (it may include reactors, downstream processing units, and others).

III All units are scaled-up individually based on estimation procedures, equations, and averages considered in the approach.

IV Processing units are then interconnected considering reaction engineering, mass transference, heat exchange, and recovery technologies.

V The generated data from previous stages are also used to perform rigorous process simulation that allows representing under in silico framework how the scaled-up topology would perform at an industrial scale (or defined scale approach).

VI Data from process simulation (extended mass/energy balances, property estimation, mixing properties, reaction yields, among others) is used to perform any life cycle-based methodology or technical/efficiency analysis approach.

The described approach involves estimating process variables under a conservative approach linked with the scale-up framework. Thus, representativeness is somewhat overestimated, but the proposed approach guaranteed that underestimating technical variables (such as environmental burdens, irreversibilities, and others) are necessarily prevented, making this a straightforward way to avoid confusing conclusions. The above can be taken as a path to provide comprehensive benchmarks and orientations toward industrial-scale performance that can be realistically accomplished. Meaningfully, the possible change of process phases contributions between lab- and industrial-scale can be noteworthy regarding process design framework, even when talking about emerging transformation technologies.

The formulation of preliminary mass and energy balances were obtained from the interprocess connection, using the consolidation of input and output streams. Accordingly, the resulting process data was used for the simulation of large-scale...
production, including simplifications and considerations in the calculations and the simulation. Average data of the process and equipment were collected using the expertise from the laboratory scale procedure, as well as from the literature and information of the products reported in the market.

The simulation flowsheet is displayed in Scheme 4. The raw materials included the iron salt precursors, pH stabilizer (NaOH), and citric acid. Energy input was considered because of the reaction, which needs to be heated up to 80 °C. The output streams contain the co- and by-products, final product, wastewater, and other emissions. Mass and energy input and output streams within the separation stages are important for the simulation and further environmental and exergy analysis.

The production capacity was adjusted with a yield of 1000 t/y of Fe₃O₄–cit. The process simulation was divided and performed according to the chemical reagents selection, thermodynamics and state equations, production capacity, parameters for mass and energy flows, operational conditions, and reaction stoichiometry. Aspen Plus software was used to model and simulate the large-scale production.

Mathematical Formulations. Environmental Analysis.

The waste reduction algorithm (WAR) was used as a computer-aided tool to estimate environmental performance, estimating the materials and energy quantities. Accordingly, the system boundary was established only for chemical reactions occurring in the manufacturing process, considering energy consumption. The calculations of the PEI (generated and accumulated in the process) were estimated using the mass flows in the inlet and output streams, according to measurable quantities obtained from the main mass balance. The PEI contribution of the production process was calculated using eq 1 in Figure 7, where \( I \) is the total PEI contribution in the process (including chemical reactions and energy consumption), \( I_{\text{in}}^{(p)} \) and \( I_{\text{out}}^{(p)} \) are the input and output rates of PEI for chemical reactions, respectively, \( I_{\text{gen}}^{(p)} \) and \( I_{\text{con}}^{(p)} \) are those PEI for energy generation, \( I_{\text{w}}^{(p)} \) and \( I_{\text{q}}^{(p)} \) are for waste energy emissions from chemical reactions and energy consumption, and \( I_{\text{gen}}^{(p)} \) is the consumption of PEI. The waste energy emissions were neglected in the calculations because of the lower impacts compared to the materials and energy consumption. The PEI contribution of the input streams for energy generation was assumed to be zero because the electrical power plants consisted of the utilization of coal, air, and water. Accordingly, the PEI calculations were carried out more accurately using the reduced expression in the steady state shown in eq 2. The total PEI output rate, total mass output, total generation rate, and total mass generation are calculated using the eqs 3–6, respectively, where \( M_{\text{in}}^{(a)} \) and \( M_{\text{out}}^{(a)} \) are the input and output mass flow of stream \( j \), respectively, \( X_{\text{k}} \) is the mass fraction of component \( k \) in the stream \( j \), \( \Psi_{\text{k}} \) is the global PEI of the chemical compound \( k \), and \( P_{\text{p}} \) is the mass flow rate of product \( P \).

Four environmental scenarios were studied: scenario 1 considers calculation without the contribution of energy usage and product streams; scenario 2 considers only the contribution of product streams; scenario 3 includes calculation with the contribution of energy usage; scenario 4 includes both contributions. Additionally, natural gas, oil, and coal were evaluated, aiming to determine the PEI contribution using different energy sources only for scenario 3 (only energy usage contribution). The WAR analysis considered eight environmental categories including toxicological and atmospheric, HTPI, HTPE, TTP, ATP, GWP, ODP, PCOP, and AP.

Exergy Analysis. The exergy analysis considered indicators such as irreversibilities, exergy loss, and exergy efficiency. The calculations were performed for each process stage and for the entire system, in which the indicators included the following variables: exergy of work, the exergy of heat transfer, or exergy of the process stream. Assumptions were established and included steady state for the entire process, neglectation of kinetics and potential exergy, and 298 K as the reference temperature. Moreover, the composition and properties of the streams were identified. Equation 7 allowed to calculate the physical exergy using the enthalpy (\( H \)), entropy (\( S \)), and the reference temperature (\( T_0 \)).

\[
Ex_p = H - H_0 - T_0(S - S_0)
\]

The chemical exergy was calculated for each compound according to eq 8, which involves the work achieved through chemical reactions, allowing to achieve a thermodynamic equilibrium. This work was calculated using the standard free energy of formation (\( \Delta G^0 \)), the chemical exergy (\( Ex_{\text{ch,j}} \)), and number of atoms (\( V_j \)) for the element \( j \). According to the chemical exergy for each compound, the exergy of the streams was calculated using eq 9, considering the universal gas constant (\( R \)), and the mole fraction (\( y_i \)) of compound \( i \).
The exergy of mass flow was calculated with the sum of chemical, physical, potential (Ex\textsubscript{pot}), and kinetic (Ex\textsubscript{kin}) exergies. However, the low values for potential and kinetic exergies allowed their neglection in eq 10 and the simplification as shown in eq 11.

\[ \frac{\partial i(t)}{\partial t} = i\text{\textsubscript{in}}(cp) + i\text{\textsubscript{in}}(ep) - i\text{\textsubscript{out}} - i\text{\textsubscript{out}}(ep) - i\text{\textsubscript{we}} - i\text{\textsubscript{we}}(ep) + i\text{\textsubscript{gen}} \]  

\[ 0 = i\text{\textsubscript{in}}(cp) - i\text{\textsubscript{out}}(cp) - i\text{\textsubscript{out}}(ep) + i\text{\textsubscript{gen}} \]  

\[ i\text{\textsubscript{out}}(t) = i\text{\textsubscript{out}}(cp) + i\text{\textsubscript{out}}(ep) + i\text{\textsubscript{we}} + i\text{\textsubscript{we}}(cp) + i\text{\textsubscript{we}}(ep) \]  

\[ i\text{\textsubscript{out}}(t) = \sum_{j}^{cp} M_{j}^{(out)} \sum_{k}^{cp} X_{kj} \Psi_k + \sum_{j}^{ep-g} M_{j}^{(out)} \sum_{k}^{ep-g} X_{kj} \Psi_k \]  

\[ i\text{\textsubscript{out}}(t) = \frac{i\text{\textsubscript{out}}(cp) + i\text{\textsubscript{out}}(ep) + i\text{\textsubscript{we}}(cp) + i\text{\textsubscript{we}}(ep)}{\sum_{p} P_{p}} \]  

\[ i\text{\textsubscript{gen}}(t) = i\text{\textsubscript{out}}(cp) - i\text{\textsubscript{out}}(ep) + i\text{\textsubscript{we}}(cp) + i\text{\textsubscript{we}}(ep) \]  

\[ i\text{\textsubscript{gen}}(t) = \sum_{j}^{cp} M_{j}^{(out)} \sum_{k}^{cp} X_{kj} \Psi_k - \sum_{j}^{cp} M_{j}^{(in)} \sum_{k}^{cp} X_{kj} \Psi_k + \sum_{j}^{ep-g} M_{j}^{(out)} \sum_{k}^{ep-g} X_{kj} \Psi_k \]  

\[ i\text{\textsubscript{gen}}(t) = \frac{i\text{\textsubscript{out}}(cp) - i\text{\textsubscript{out}}(ep) + i\text{\textsubscript{we}}(cp) + i\text{\textsubscript{we}}(ep)}{\sum_{p} P_{p}} \]  

\[ i\text{\textsubscript{gen}}(t) = \sum_{j}^{cp} M_{j}^{(out)} \sum_{k}^{cp} X_{kj} \Psi_k - \sum_{j}^{cp} M_{j}^{(in)} \sum_{k}^{cp} X_{kj} \Psi_k + \sum_{j}^{ep-g} M_{j}^{(out)} \sum_{k}^{ep-g} X_{kj} \Psi_k \]  

\[ \sum_{p} P_{p} \]  

\[ \text{Ex\textsubscript{chem}} = \sum_{j} y \text{Ex}_{j\text{\textsubscript{ch,-i}}} + RT_{0} \sum_{j} y \ln y \]  

\[ \text{Ex\textsubscript{mass}} = \text{Ex\textsubscript{chem}} + \text{Ex\textsubscript{p}} + \text{Ex\textsubscript{pot}} + \text{Ex\textsubscript{kin}} \]  

\[ \text{Ex\textsubscript{mass}} = \text{Ex\textsubscript{chem}} + \text{Ex\textsubscript{p}} \]  

\[ \text{Ex\textsubscript{mass}} = \text{Ex\textsubscript{chem}} + \text{Ex\textsubscript{p}} \]  

\[ \text{On the other hand, the exergy of utilities was calculated using the exergy of work (Ex\textsubscript{w}) and exergy of heat transfer (Ex\textsubscript{Q}). Because no changes are produced in the system volume, the work (W) is equal to the exergy of work, as shown in eq 12.} \]
In the case of eq 13, the exergy of heat transfer is related to the temperature of the stream, which depends on the heat transfer rate \( Q \) and the temperature \( T \) of the entire system. 

\[
Ex_W = W 
\]

(12)

\[
Ex_Q = \dot{Q} \left( 1 - \frac{T_0}{T} \right) 
\]

(13)

The total exergy of all streams \( (Ex_{\text{mass-in}}) \) along with the total industrial utilities \( (Ex_{\text{utilities-in}}) \) were used for the calculation of the total exergy entering \( (Ex_{\text{Total-in}}) \) the system. This calculation was performed in eq 14.

\[
Ex_{\text{Total-in}} = \sum Ex_{\text{mass-in}} + \sum Ex_{\text{utilities-in}} 
\]

(14)

The total exergy leaving \( (Ex_{\text{Total-out}}) \) the system was calculated from eq 15, which consisted of the exergy output streams containing the total products \( (Ex_{\text{Products-out}}) \) and waste \( (Ex_{\text{Waste-out}}) \).

\[
Ex_{\text{Total-out}} = \sum Ex_{\text{Products-out}} + \sum Ex_{\text{Waste-out}} 
\]

(15)

The irreversibilities \( (Ex_{\text{loss}}) \) are the exergy loss, consisting of the amount of work that was not used in the system, and can be calculated using eq 16. Additionally, eq 17 aims to identify the stage \( k \) of the system that contributes to an exergy loss percentage \( (\% Ex_{\text{loss}}) \). Finally, the global efficiency \( (\eta_{\text{exergy}}) \) provides the energetic performance of the large-scale production and is expressed in eq 18.

\[
Ex_{\text{loss}} = \sum Ex_{\text{Total-in}} + \sum Ex_{\text{Products-out}} 
\]

(16)

\[
\% Ex_{\text{loss}} = \left( \frac{Ex_{\text{loss,k}}}{Ex_{\text{loss}}} \right) \times 100 
\]

(17)

\[
\eta_{\text{exergy}} = \left( 1 - \frac{Ex_{\text{loss}}}{Ex_{\text{Total-in}}} \right) \times 100 
\]

(18)

According to the exergy results, a sensitivity analysis was performed for the stage with the most critical results in the exergy efficiency. The sensitivity analysis evaluates the changes in the global exergy efficiency concerning the variation of the exergy efficiency of a specific stage or operating unit. Therefore, this analysis allows establishing potential improvements to increase the energetic performance of the entire production process.

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#### Notes

The authors declare no competing financial interest.

#### ACKNOWLEDGMENTS

The authors would like to thank Universidad de Cartagena for the financial support through the project entitled “Plan de Fortalecimiento de Grupos de Investigación 2019”, and for the equipment and software to perform this study. The financial support of the Canadian Queen Elizabeth II Diamond Jubilee Scholarship Program (QES), Western University, Ryerson University, and Universidad de Cartagena is greatly appreciated.

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