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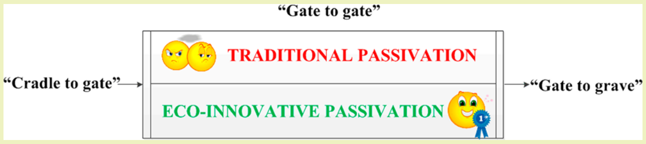
Environmental Sustainability Assessment of an Innovative Cr (III) Passivation Process

Verónica García,* María Margallo, Rubén Aldaco, Ane Urtiaga, and Angel Irabien

Departamento de Ingeniería Química y Química Inorgánica, Universidad de Cantabria, Av de los Castros, s/n., 39005, Santander, Cantabria, Spain

Supporting Information



ABSTRACT: A life cycle assessment was conducted for the Zn-electroplating products passivated by different processes in a small and medium enterprise. The goal was to evaluate and to compare the environmental impact associated to the conventional and alternative passivation process from a "cradle to grave" analysis. The assessment was divided into "cradle to gate", "gate to gate", and "gate to grave" steps for natural resources usage and environmental burdens. The innovative process was based on the integration of emulsion pertraction technology to the passivation bath in order to extend its lifetime. Results showed that the transferred hazardous waste from the process to the landfill was the major contributor to the environmental impact of the conventional and innovative passivation. The manufacture of the sodium hydroxide needed in the wastewater treatment process had a main role in the impacts of the "cradle to gate" cycle. This work concluded that the innovative passivation decreased most of the generated waste (92%) during the manufacture cycle of the passivated product as a consequence of the extension of the lifetime of the passivation bath. A reduction of the total environmental burdens to air and to water and the resource usage during the whole manufacture cycle of the product was stated. The environmental burdens to air and to water were mainly connected to the environmental impacts: human health effects and ecotoxicity to aquatic life, respectively.

KEYWORDS: *Life cycle assessment, Chromium (III) passivation, Emulsion pertraction technology, Hazardous waste minimization, Material recovery*

INTRODUCTION

Trivalent chromium(III) baths are commonly used in the passivation or conversion of zinc-electroplated surfaces. The main aim of these formulations is to provide the surface with an extra protective film against corrosion and/or a decorative finishing. The immersion of electroplated pieces during the passivation step causes the release of Zn (II) and iron (III) to the bath, while a layer of chromium salts covers the metallic piece. The Zn (II) and Fe (III) contamination negatively affects the effectiveness of the Cr (III) formulation reducing its lifetime. The bath is replaced when it does not fulfill its purpose, and it is managed as a hazardous waste due to its high content of heavy metals and nitrates.

The effluent is commonly treated by means of physical–chemical processes that consume high amounts of chemicals and generate considerable quantities of metallic sludge.[1] Diban et al. estimated that the amount of sludge generated in the treatment of a passivation bath was 1240 kg per m^3 of spent formulation.[2] Consequently, the traditional passivation implies an inefficient use of resources and materials and exhibits an important environmental impact.

The in situ removal of Zn (II) and Fe (III) impurities from the Cr (III) bath during the passivation is essential in order to avoid the loss of efficiency, reduce waste, and promote the resource efficiency of the process. Emulsion pertraction technology (EPT) enables the separation of Zn (II) and Fe (III) in acidic media while maintaining the concentration of Cr (III) constant.[3−5] EPT is a liquid−liquid extraction technology in which the extraction and back-extraction are conducted in a single membrane contactor. The membrane contactor consists of hollow fiber membranes that are microporous and hydrophobic, allowing the nondispersive contact between the passivation fluid and extractant phase. In EPT (Figure 1), the solution containing the targeted heavy metals is circulated through the shell side of the membrane module while an emulsion is circulated through the inside of the hollow fibers. The emulsion is formed by the dispersion of a stripping acid into an organic extractant phase. The pores of the fiber are filled with the extractant because of the hydrophobic character of the membrane material.[7] The fact that the target components are extracted while others remain in the solution is based on the selection of the operational variables (pH) and the extractant.[4] Added advantages are its flexible and compact design.

The main benefit of passivating the Zn-electroplated piece by the integrated EPT passivation process is that the lifetime of the chemical formulation is extended. The need for bath replacement diminishes; hence, the environmental impact of

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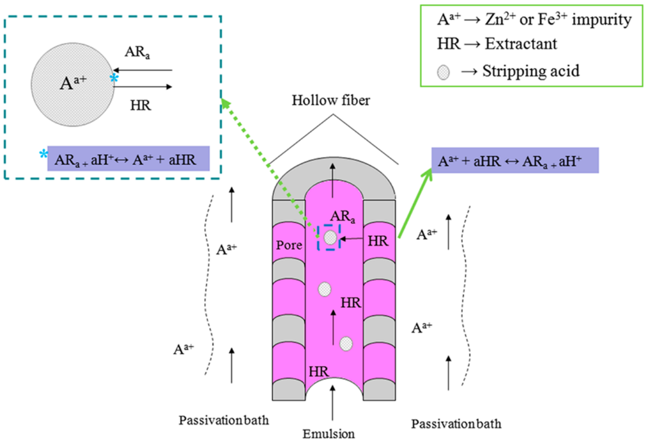

Figure 1. EPT process (adapted from Klassen et al.[6]).

the passivation is reduced. However, the EPT step may also increase the total environmental impact of the conversion practice as the purification technology consumes energy and hazardous chemicals and generates an acidic effluent that needs to be managed. Further, the wastewater is enriched in Zn and Fe and may be treated by conventional physical−chemical processes or may be valorized by means of material recovery. The former entails the use of chemicals, while the latter may be environmentally advantageous. In order to state the environmental benefits of obtaining the passivated product by the innovative process, the evaluation of the environmental impacts of the products passivated by the reference and by the alternative process is essential. Life cycle assessment (LCA) is a powerful tool used for assessing the environmental performance of a product, process, or activity that helps in identifying clean and sustainable alternatives in the process design activity.[8−10] LCA also allows analysis at the different stages of the product life cycle: "cradle to gate", "gate to gate", and "gate to grave".

LCA was previously used for evaluating the improvement of different manufacture processes or for comparison among different technologies.[11−16] However, to the best of our knowledge, no LCA studies are reported on products involving Cr (III) passivation processes. The present study focuses on the application of LCA for the evaluation of the products passivated by the traditional conversion process and by the integrated EPT passivation. The "cradle to gate", "gate to gate", and "gate to grave" steps were individually studied. Additionally, the environmental impact of different options for the management of the effluent generated in the EPT step was considered.

METHODOLOGY

Goal and Scope. The reported LCA followed the recommendations and met the requirements of the ISO 14040:2006 and ISO 14044:2006 international standards.[8,9] The study referred to Zn-electroplated pieces passivated using a particular Cr (III) formulation utilized in small and medium enterprises (SMEs). The main objective was to quantify the environmental impacts of the conventional Cr (III) passivation process and to evaluate the environmental benefits and drawbacks of the integration of EPT to the passivation. An additional goal was to assess the effect of recovering material from the effluent generated in the EPT process. Recovering material resulted in the production of co-products. These multi-output processes are handled in different manners: (1) The processes are disaggregated into subprocesses or the system boundaries are expanded to include the additional functions, (2) The environmental impacts are allocated among the products.[17,18] In this work, the co-product allocation was handled by non-causality mass allocation. This was done due to the difficulties of performing an allocation based on a physical−causal relationship.

The scope of the assessment was based on the "cradle to grave" life cycle of a product and entailed resources usage and environmental impacts (Figure 2). The LCA started with the "cradle to gate" step where the natural resources—water, energy, and materials—needed for the manufacture of the resources used in the process were considered. The "gate to gate" step included traditional or the eco-innovative passivation and management of the waste produced in the passivation. The treatment of waste and the recovery of valuable compounds were considered as management options. The LCA ended with the "gate to grave" step that consisted of the transfer of the stabilized waste to a landfill. Different disposal options were not considered in the assessment.

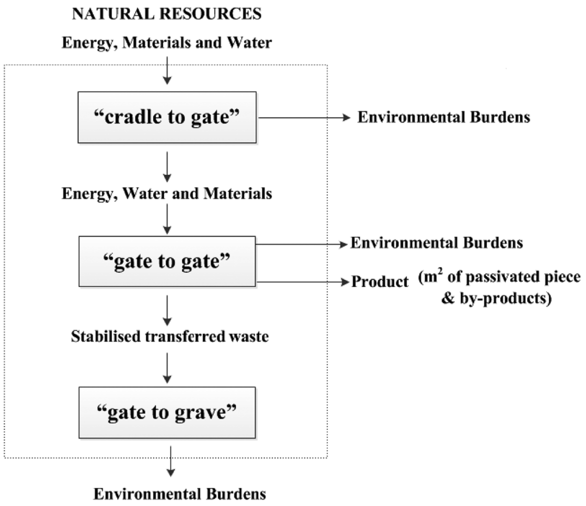

Figure 2. LCA for the environmental performance of passivated pieces using the reference and the alternative processes.

Functional Unit. In this work, the functional unit (FU) was related to the product, the passivated metallic pieces, which is the objective of the process under evaluation, the passivation. In order to compare the environmental performance of the traditional and eco-innovative process, the "cradle to grave" LCA of the different manufacture processes must be referred to the same quantity of the final product. The eco-innovative passivation enhances the lifetime of the bath from 6 to 104 weeks (see Supporting Information for further information). The square meter of passivated product was established as the most appropiate unit to describe the FU considering the available data. All the emission, consumption of materials, water, and energy during the scenarios are referred to this FU.

Description of Systems under Study. A Spanish SME was selected as representative of the Zn-electroplating sector. In this work, the following systems were studied: passivated products using the traditional passivation that acted as the reference scenario (Scenario 1), passivated products utilizing the novel conversion process in which the Cr (III) formulation was continuously purified by EPT using the commercial chelating extractant Cyanex 272 (Scenario 2), and passivated

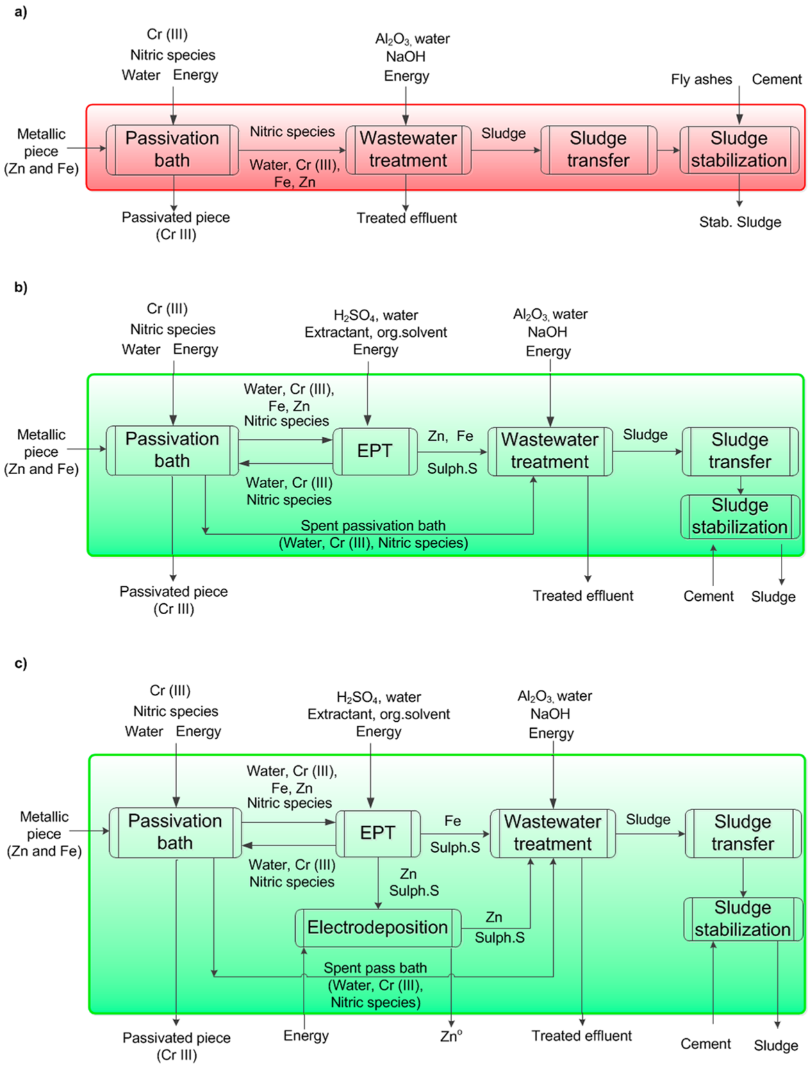

Figure 3. Flow diagrams of the gate-to-gate step of the LCA: a) reference passivation process (Scenario 1), and the innovative process integration b) Scenario 2 and c) Scenario 3. Abrev: Sulph.S: Sulphuric Species; EPT: Emulsion Pertraction Technology.

products using the novel process and considering the valorisation of the effluent generated in the EPT step (Scenario 3). The waste valorisation consisted of selecting the EPT operational conditions in order to obtain an effluent enriched in Zn and getting metallic Zn by means of electrodeposition.

Figure 3 illustrates the boundaries of the three scenarios under study. The considerations taken are provided in the Supporting Information for a better understanding of the scenarios and of their system boundaries.

Life Cycle Inventory. The life cycle inventory (LCI) regarding the "gate to gate" step was developed using the data given by the SME, EPT unit supplier, literature, regulation, ELCD-PE database,[19] or chemical analysis, or was estimated by the authors using stoichiometric calculations. Data source, time frame, and geography are included in the Supporting Information. Further, Ecoinvent[20] and ELCD-PE database[19] were mainly used for building the "cradle to gate" inventory. Data regarding the production of Cr (III) was obtained from the literature[21] and estimated by the authors using stoichiometric calculations. The inventories were compiled taking into account that the conventional passivation step performed in the SME needed 17 times more passivation baths (104/6 weeks) to produce the same amount of product than when the bath was purified during the passivation. Table 1 encompasses the energy, water, and materials required in the scenarios, and Table 2 lists the generated outcome in the LCA steps.

As illustrated in Figure 2, the LCA considered the use of primary resources energy, water, and materials for obtaining the raw materials needed in the process or "gate to gate" cycle. This step generated some environmental burdens (EBs) caused by the substance upon the receiving environment. Further, the use of the resources needed in the process produced new EBs. The "gate to grave" step refers to the waste transfer to landfill and also produced EBs, which refers to the stabilized waste. In this step, no natural resources were used. EB for emissions to air and to water were estimated using GaBi 4.4.[19]

Life Cycle Impact Assessment. The life cycle impact assessment (LCIA) quantifies the contribution of the inventory data to a full spectrum of environmental impacts described by certain environmental indicators. This work considered the environmental sustainability metrics developed by the Institution of Chemical Engineers (IChemE) that give a balanced view of the environmental impact of inputs—resource usage and outputs—emissions, effluents, and waste.[22] In relation to the outputs, a set of environmental impacts to the atmosphere, aquatic media, and land was chosen. The EB

Table 1. Natural Resources Usage in Scenario 1, Scenario 2, and Scenario 3

		“cradle to gate”		
	units	Scenario 1	Scenario 2	Scenario 3
energy	MJ/m^2	0.969	0.265	0.249
water	L/m^2	0.153	0.085	0.084
materials	g/m^2	572	276	272
bauxite		12.94	1.32	1.32
gypsum (natural gypsum)		1.25	0.10	0.087
inert rock		222	98.7	96.1
lead−zinc ore (4.6%−0.6%)		5.23	2.35	5.23
limestone		22.26	0.18	2.099
soil		1.79	5.42	0.159
sodium chloride (rock salt)		25.38	5.42	4.89
chromium ore (Cr_2O_3 30%)		0.22	0.05	0.052
clay		0.59	0.05	0.043
iron ore (56%, 86%)		0.11	0.09	0.089
iron ore (65%)		0.14	0.01	0.009
lead−zinc−silver ore		0.21	5.23	0.208
natural aggregate		0.75	0.21	0.204
zinc−copper ore (4.07%−2.59%)		0.86	0.86	0.86
zinc−lead−copper ore (12%−3%−2%)		0.36	0.36	0.36
air		277	161	159
		“gate to gate”		
	units	Scenario 1	Scenario 2	Scenario 3
energy	MJ/m^2	0.043	0.388	0.401
water	L/m^2	0.177	0.017	0.017
materials	g/m^2	123	22.2	20.5
Cr (III)		0.406	0.094	0.094
Fe (III)		0.048	0.048	0.048
Zn (II)		0.666	0.666	0.666
nitric species		7.01	1.23	1.23
cyanex 272		−	0.007	0.007
org. solvent		−	0.028	0.028
sulfuric species		−	3.23	3.23
NaOH 50% w/w		57.6	12.2	11.0
Al_2O_3		7.66	0.781	0.781
cement		33.1	2.63	2.28
		“gate to grave”		
	Units	Scenario 1	Scenario 2	Scenario 3
energy	MJ/m^2	0.016	1.70×10^{-4}	1.54×10^{-4}

approach was used to estimate and quantify the potential environmental impacts. The EB caused by the emission of a range of substance was calculated by adding the weighted emission of each substance. The weighting factor of the impact is known as the potency factor. In particular, the environmental impacts were classified into atmospheric, aquatic, and land impacts. The EBs for emission to air were divided into atmospheric acidification (AA), global warming (GW), human health (carcinogenic) effects (HHE), stratospheric ozone depletion (SOD), and photochemical ozone (smog) formation (POF). The EBs for emission to water were defined by the aquatic acidification (Aq. Ac.), aquatic oxygen demand (AOD), ecotoxicity to aquatic life (metals to seawater) (MEco), ecotoxicity to aquatic life (other substances) (NMEco), and eutrophication (Eutroph). The EB to land was given by the amount of generated hazardous and non-hazardous waste and its management.

The environmental sustainability indicators used in this study had different units depending on the environmental impact. In order to compare the EBs to air, water, and land, the threshold values stated in the European regulation EC No. 166/2006[23] for the main contributors to the environmental impacts were considered as weighting factors to obtain dimensionless impacts indicators (Table 3).

■ RESULTS AND DISCUSSION

The majority of the materials and energy used in Scenario 1 were needed in the “cradle to gate” step: 82.3% of the materials and 95.7% of the energy (Table 1). The resources of air, inert rock, sodium chloride (rock salt), and non-renewable energy were mostly utilized in the production of the sodium hydroxide used in the treatment of the effluent generated in the passivation step. The energy used in the “gate to grave” step was neglected. Further, 46.4% of the water demand occurred during the “cradle to gate” step, 80.0% of which occurred during sodium hydroxide production. The “gate to gate” contributed to 53.6% of the water usage, mainly for preparing the Cr (III) formulation. It is important to note that the water footprint was out of the scope of this work, and only the use of natural resources was considered when comparing the passivation processes.

The “gate to gate” step (process) produced a stabilized industrial waste, and its environmental impact was assigned to the “gate to grave” step (landfill) in order to avoid the double counting of the waste (Figure 2). The impact of the transferred waste was due to its disposal inside the landfill, and it was considered to be proportional to the amount of transferred waste. The dimensionless EBs/Impacts referred to the E-PRTR threshold[23] are shown in Table 4 and point out that the transferred industrial waste was the major environmental burden of Scenario 1 followed by the aquatic and atmospheric emissions of the “cradle to gate” step. The EB to water and to air were mainly based on the contribution of the release of chemicals during the manufacture of sodium hydroxide to NMEco and HHE, respectively. The emissions of chloride resulted in the NMEco impact and the release of nickel and its inorganic compounds in the HHE impact category.

LCIA results indicated that the continuous purification of the passivation bath enhanced the environmental profile of the production of the passivated metallic pieces. Figures 4 and 5 illustrate the benefits of the eco-innovative process compared to the traditional process in terms of resource usage and EB, respectively. The environmental impact improvements were based mainly on the reduction of the waste generated in the passivation step. Lowering the effluent implied lowering the amount of chemicals involved in the wastewater treatment, the amount of produced sludge, the mass of chemicals involved in the stabilization process, and the quantity transferred to the landfill.

The obtained results showed that the use of energy, materials, and water in Scenario 2 decreased 35.4%, 57.0%, and 69%, respectively (Figure 4). The energy utilized in the EPT unit made the “gate to gate” step the major contributor to energy consumption, 59.4%. The materials were mainly required for the production of the energy needed in the EPT step (47.7%, inert rock and air) and for the manufacture of sodium hydroxide in the wastewater treatment (31.6%, inert rock, sodium chloride (rock salt), and air). The eco-innovative

Table 2. Environmental Burdens of Scenario 1, Scenario 2 and Scenario 3

		“cradle to gate”			
		units	Scenario 1	Scenario 2	Scenario 3
EB to air	AA	10^3ge SO_2/m^2	85.6	147.5	149.9
	GW	10^3 ge CO_2/m^2	74739	38016	37593
	HHE	10^3 ge benz./m^2	18.5	2.41	2.43
	POF	10^3 ge ethylene/m^2	11.1	10.8	10.8
	SOF	10^3 ge CFC-11/m^2	0.008	0.006	0.006
EB to water	Aq. Ac.	10^3ge H^+/m^2	8.72×10^{-4}	8.10×10^{-5}	7.50×10^{-5}
	AOD	10^3ge O_2/m^2	2.85	0.525	0.524
	MEco	10^3ge Cu/m^2	0.005	0.004	0.004
	NMEco	10^3ge formaldehyde/m^2	945	258.0	243.2
	Eutroph	10^3ge phosphate/m^2	0.588	0.248	0.242
		“gate to gate”			
		units	Scenario 1	Scenario 2	Scenario 3
EB to air	AA	10^3ge SO_2/m^2	0.038	4.20×10^{-4}	3.60×10^{-4}
	GW	10^3ge CO_2/m^2	1141	12.7	11.0
	HHE	10^3ge benz./m^2	0.007	7.95×10^{-5}	6.89×10^{-5}
	POF	10^3ge ethylene/m^2	0.036	3.95×10^{-4}	3.42×10^{-5}
	SOF	10^3ge CFC-11/m^2	–	–	–
EB to water		–	–	–	–
		“gate to grave”			
		units	Scenario 1	Scenario 2	Scenario 3
EB to land	hazardous waste	10^3 g/m^2	215000	17073	14795
	non-hazardous waste	10^3 g/m^2	–	–	–

Table 3. Threshold Values from E-PRTR (18) for Normalization and Impact Weighting purposes[a]

EB		threshold value (kg/year) (18)	no. of substances (17)
EB to air	AA (kge SO_2)	150000	6
	GW (kge CO_2)	100 million	23
	HHE (kge benzene)	1000	52
	POF (kge ethylene)	1000	100
	SOF (kge CFC-11)	1	60
EB to water	AOD (kge H^+)	50000	14
	MEco (kge Cu)	50	11
	NMEco (kge formaldehyde)	50	18
	Eutroph (kge phosphate)	5000	8
EB to land	WG (Haz)	2000	

[a]Abbrev: AA, atmospheric acidification; AOD, aquatic oxygen demand; EB, environmental burden; Eutroph, eutrophication; GW, global warming; HHE, human health effects; MEco, ecotoxicity to aquatic life (metals to seawater); NMEco, ecotoxicity to aquatic life (other substances); POF, photochemical ozone (smog) formation; WG (Haz), hazardous waste generated.

process implied a lower use of water in the passivation compared to the reference scenario. This was due to the fact that fresh water was utilized for preparing the Cr (III) formulation and that Scenario 2 used less passivation liquid to obtain the same quantity of final product. This caused the role of the “gate to gate” step in the impact related to the water usage to decrease to 16.7% and the contribution of the “cradle to gate” step to increase to 83.3% (Table 1).

Further, Figure 5 shows that the highest improvement in the EB/Impacts was related to the generated waste. The waste transfer decreased 92.0%. The EB emission to water of Scenario 2 decreased 73.1% compared to the reference scenario. This was due to the diminution of the value of NMEco impacts (Table 4). The total EB to air decreased 58.6%. This was the result of the betterment of the HHE indicator, which was reduced 87.1% (Table 4). In Scenario 2, the release of arsenic, beryllium, cadmium, formaldehyde, and nickel during the production of the energy needed in the EPT subsystem contributed the most to this impact.

The valorisation of the effluent generated in the EPT system (Scenario 3) most affected the waste generated indicator (Figure 5). In this scenario, the waste was transformed into a product. Consequently, the value of this indicator decreased 13.5% compared to its value in Scenario 2. The effluent valorisation affected moderately the use of resources. The electrodeposition of Zn from the EPT effluent implied an input of energy and a reduction in the resources needed for the management of the effluent because the concentration of Zn in the effluent was lowered (Figure 4). Hence, the contribution of the “gate to gate” step of the resource use to the environmental profile increased and the one related to the “cradle to gate” step decreased. The LCIA of Scenario 3 pointed out an improvement of the resource efficiently of the passivation practice as the generation of waste was reduced compared to Scenario 2 in spite of the resource input being similar. According to Figure 5, the EB to air and water were not altered significantly. The recovery of Zn contributed to these environmental indicators; however, it was compensated with the reduction of the subsystems wastewater treatment, transfer of the sludge, and stabilization of the sludge.

The LCA assessment of the passivation practices demonstrated that the environmental profile of the “cradle to gate”, “gate to gate”, and “gate to grave” steps are directly related and that the “cradle to gate” and “gate to grave” steps of the scenarios contributed significantly more to the environmental impacts than the “gate to gate” step. In this work, the reduction of the environmental impact of “cradle to gate” and “gate to

Table 4. Weighted Environmental Burdens of Scenario 1, Scenario 2, and Scenario 3[a]

environmental indicator		"cradle to grave"			"cradle to gate"			"gate to gate"			"gate to grave"		
		S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
EB to air	total	2.00×10^{-2}	8.29×10^{-3}	8.32×10^{-3}	1.99×10^{-2}	8.29×10^{-3}	8.32×10^{-3}	1.94×10^{-5}	2.16×10^{-7}	1.87×10^{-7}	–	–	–
	AA	3.61×10^{-4}	6.22×10^{-4}	6.32×10^{-4}	3.61×10^{-4}	6.22×10^{-4}	6.32×10^{-4}	1.60×10^{-7}	1.77×10^{-9}	1.54×10^{-9}	–	–	–
	GW	4.80×10^{-4}	2.41×10^{-4}	2.38×10^{-4}	4.73×10^{-4}	2.41×10^{-4}	2.38×10^{-4}	7.22×10^{-6}	8.03×10^{-8}	6.96×10^{-8}	–	–	–
	HHE	1.18×10^{-2}	1.52×10^{-3}	1.54×10^{-3}	1.18×10^{-2}	1.52×10^{-3}	1.54×10^{-3}	4.52×10^{-6}	5.03×10^{-8}	4.36×10^{-8}	–	–	–
	SOD	4.95×10^{-3}	3.62×10^{-3}	3.60×10^{-3}	4.95×10^{-3}	3.62×10^{-3}	3.60×10^{-3}	–	–	–	–	–	–
	POF	2.33×10^{-3}	2.29×10^{-3}	2.31×10^{-3}	2.33×10^{-3}	2.29×10^{-3}	2.31×10^{-3}	7.51×10^{-6}	8.35×10^{-8}	7.23×10^{-8}	–	–	–
EB to water	total	12.1	3.26	3.08	12.1	3.26	3.08	–	–	–	–	–	–
	AOD	1.20×10^{-5}	2.22×10^{-6}	2.21×10^{-6}	1.20×10^{-5}	2.22×10^{-6}	2.21×10^{-6}	–	–	–	–	–	–
	MEco	4.37×10^{-5}	5.08×10^{-5}	5.13×10^{-5}	4.37×10^{-5}	5.08×10^{-5}	5.13×10^{-5}	–	–	–	–	–	–
	NMEco	12.1	3.26	3.08	12.1	3.26	3.08	–	–	–	–	–	–
	Eutroph	7.44×10^{-5}	3.14×10^{-5}	3.06×10^{-5}	7.44×10^{-5}	3.14×10^{-5}	3.06×10^{-5}	–	–	–	–	–	–
EB to land[b]	total	68.0	5.41	4.68	–	–	–	–	–	–	68.0	5.41	4.68

[a] Abbrev: AA, atmospheric acidification; AOD, aquatic oxygen demand; EB, environmental burden; Eutroph, eutrophication; GW, global warming; HHE, human health effects; MEco, ecotoxicity to aquatic life (metals to seawater); NMEco, ecotoxicity to aquatic life (other substances); POF, photochemical ozone (smog) formation; S1, Scenario 1; S2, Scenario 2, S3, Scenario 3; SOF, stratospheric ozone depletion. [b] Hazardous waste.

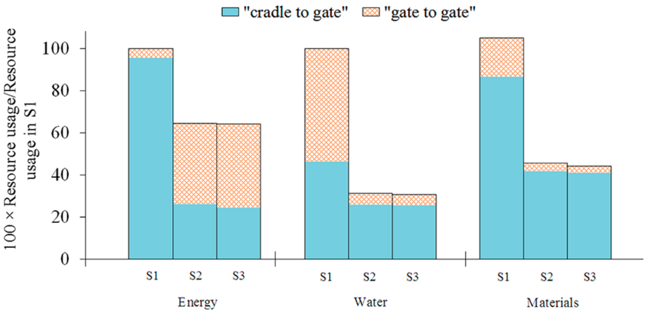

Figure 4. Normalized resource usage during the "cradle to grave" life cycle of Scenario 1 (S1), Scenario 2 (S2), and Scenario 3 (S3).

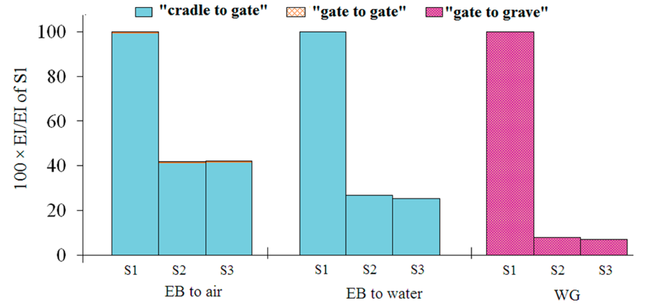

Figure 5. Weighted and normalized environmental impacts (EI) of Scenario 1 (S1), Scenario 2 (S2), and Scenario 3 (S3): environmental burden (EB) to air and water and the waste generated (WG).

grave" steps was obtained by reducing the materials consumption of the "gate to gate" step. However, other measures may be implemented to the "cradle to gate" and "gate to grave" in order to further reduce the environmental impact of the overall LCA. These measures may consist of using greener extraction methods, utilizing previously reused water, or renewable energy. This work concludes that the eco-innovative passivation is positive in terms of resource usage and EB. Finally, this work remarks that future research should focus on evaluating and implementing measures to reduce the economic costs related to the eco-innovative passivation process.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Data source, time frame, and geography of the "gate to gate" life cycle inventory of the scenarios and the considerations taken when conducting the LCA. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: garciapv@unican.es. Tel: +34 942 206778. Fax: +34 942 201591.

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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■ ABBREVIATIONS

AA, atmospheric acidification; AOD, aquatic oxygen demand; EBs, environmental burdens; EI, environmental impacts; EPT, emulsion pertraction technology; Eutroph, eutrophication; FU, functional unit; GW, global warming; HHE, human health effects; LCA, life cycle assessment; LCIA, life cycle impact assessment; MEco, ecotoxicity to aquatic life (metals to seawater); NMEco, ecotoxicity to aquatic life (other substances); POF, photochemical ozone (smog) formation; SME, small and medium enterprise; SOF, stratospheric ozone depletion; WG, waste generated; WG (Haz.), hazardous waste generated

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