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ORIGINAL PAPER

Environmental impacts arising from the production of two surface coating formulations

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Abstract

The objective of this study is to comparatively appraise the environmental impacts of formulating two metal surface coating chemicals (Product A and B) that can substitute each other via life cycle assessment methodology. The effect of using various energy sources during manufacturing is investigated. The functional unit is defined as 1000 kg product. A cradle-to-gate approach is adopted as system boundaries. The explored environmental impact categories are as follows: global warming (GWP), abiotic depletion (ADP fossils and elements), acidification (AP), eutrophication (EP), freshwater aquatic ecotoxicity (FAETP), human toxicity (HTP), ozone depletion (ODP), photochemical ozone creation (POCP) and terrestrial ecotoxicity (TETP) potentials. GWP of Product A is 7% higher than that of Product B. For all the other impact categories apart from GWP, Product A yields lower results. FAETP, ADP elements, ODP, EP, HTP, POCP, AP, ADP fossil and TETP of Product B are 116%, 72%, 55%, 49%, 38%, 33%, 26%, 26% and 18% higher than Product A, respectively. Noteworthy reductions on environmental impacts generated by energy consumption are obtained for almost all of the impact categories apart from ADP elements, when photovoltaic cells are used instead of grid electricity. Similarly, reductions in all environmental impact categories except for ADP elements are found in the case of using wind turbines instead of the grid. More than 95% decreases are observed for ADP fossil, AP, EP, GWP, ODP and POCP by getting energy from wind instead of grid. The most environmentally friendly energy alternative is addressed as wind energy except for ADP elements. It is recommended to perform LCA studies related to zinc phosphating chemicals, as very limited studies can be found. These results can be used to guide the environmental policies related to the chemical, metal and coating sectors.

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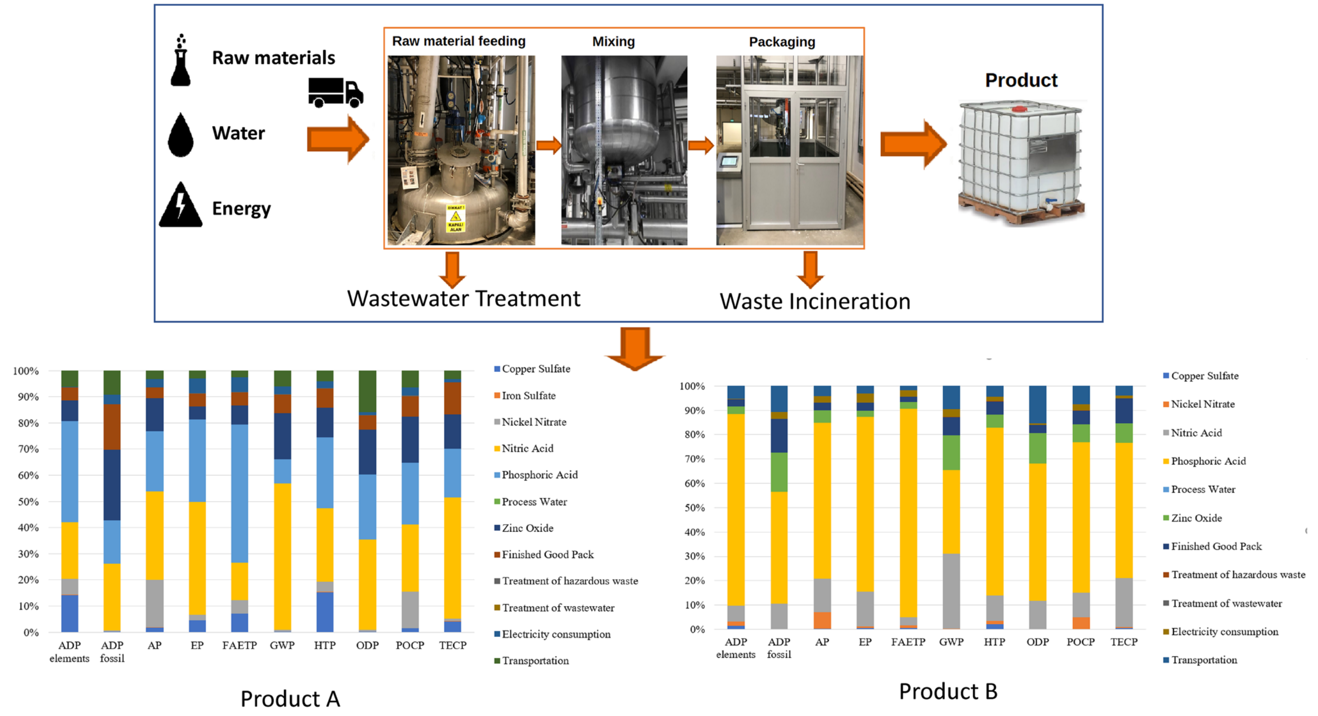
Graphical abstract



Keywords Metal coating · Chemicals · Formulation · Environmental impacts · Life cycle assessment

Introduction

Sustainable production of goods is the mainstay of current industrial development (Durana et al. 2021; Novak et al. 2021). Sustainability applicable to industrial sectors is not limited with the operations that take place in the manufacturing premises such as renewable energy usage in production. Besides, it covers a wide range of activities ranging from checking the supply chain for auxiliary chemicals, finding a vehicle and route to lower the transportation costs and impacts, using the proper type of chemicals in products that will yield less unwanted environmental impacts. Future research should look into ways to improve the environmental sustainability of coating chemicals, taking into account modern manufacturing methods and alternative raw materials. Furthermore, for a more sustainable metal sector, environmental sustainability should be integrated with economic costs.

Metals are the backbone of civilization and industrialization. They are commonly used in lots of industrial activities in different ways for complying with various functions (Cyril et al. 2017). Today, metals are used as indispensable inputs for many industries. Over time due to environmental conditions unwanted outcomes such as corrosion, rust, etc. can be obtained on metal surfaces. In order to prevent the mentioned problems and prolong the material life, various chemicals must be used to cure the metal surfaces. These chemicals are called metal pre-treatment chemicals, and various types of surface treatment methods are applied on the metal with the aid of them.

Surface coating operations are an important part of the metal industry as they protect the metal from environmental conditions as well as give a required appearance to a metal surface. The surface treatment of metals serves many industrial sectors such as the automotive and aerospace industry, food and beverage, printing, telecommunication, and information technology systems, domestic appliances and furniture, medicals, constructions, general supplies, etc. (European Commission 2006). The projections show that the global metal coatings market will be valued as USD 14.34 Billion by 2026 (MarketsandMarket 2021).

Manufacturers apply surface treatment chemicals to improve paint adhesion and corrosion protection on metal surfaces. These chemicals are also used to lower the consumption of other inputs in the subsequent steps of production. They reduce process steps, improve efficiency and facilitate process cost savings. Research and development activities intensify on corrosion-resisting technologies (Hadzima et al. 2007). Environmentally friendly, efficient surface coating operations are suggested in the literature (Alkaya and Demirer 2014; Balgude and Sabnis 2012). Besides, adding these chemicals during manufacturing processes provides elevated mechanical, electrochemical and thermal performance of a metal that in turn prolongs its lifetime (Marder 1997; Mozetič 2019).

Thin crystalline layers of phosphate compounds adhere to the surface of the metal substrate to form phosphate coatings. Zinc, manganese, or iron phosphate solutions can be used to make porous phosphate crystals. Each form of phosphate coating has somewhat varied features, such as crystal size and coating thickness. Carbon steel, low-alloy steel, and cast iron are the most often coated metals. The coating is applied to the substrate by spraying or immersing it (Ferreira et al. 2012).

In the surface coatings sector, the formulation is very essential since it influences not only the ultimate properties and features of the coating, but also the method and ease with which it may be created, applied, and transformed into its final form (Harris and Phillip 2016). The mechanism that causes a coating to form determines its structure. Metallic powders are formed through three major steps: partially or completely melting and heating, contacting the surface of the base metal or a contiguous layer, interacting with the oxygen in the air in a surface (Tushinsky et al. 2002).

A variety of chemicals are applied during metal surface coating operations. Some of these chemicals are used as substitutes for each other. The general attitude of the industries that will use the chemicals is to choose the cheapest ones that yield the same quality. On the other hand, the manufacturers of the chemicals try to lower the financial burdens they are facing without giving any importance to environmental impacts. To get an integrated outcome, a deeper evaluation combining the complexity of chemistry, environmental science and economics is required. There are literature studies on certain metal surface coating chemicals indicating that they are environmentally friendly (Ali et al. 2020; Nazeer and Madkour 2018), without presenting adequate information of their environmental impacts.

Life cycle assessment (LCA) methodology can be adopted as a useful tool to point out the environmental impacts of products, processes and services by covering various life cycle stages ranging from cradle to grave. Some studies focus on the whole life cycle (Atılgan Türkmen 2021; Atılgan Türkmen et al. 2021) while others only concentrate on a specific stage (Elginoz et al. 2019; Kim and Overcash 2003; Ozkan et al. 2020; Yalamacilar et al. 2021) or a specific process (Cuéllar-Franca et al. 2019; Karacal et al. 2019).

Studies on the whole life cycle yield the complete picture related to environmental impacts, drawing attention to the life stages that generate most of the negative impacts. Whereas pondering on the manufacturing stage can generate clues on how to reduce negative environmental impacts during the production of goods. Therefore, valuable information can be derived from these studies even when a restricted scope is defined. Stieberova et al. (2017) performed a LCA study on the environmental burdens of self-cleaning coating with nanoparticles on aluminum sheets. The scope of this literature study covers the whole life cycle of coating.

This study aims to comparatively evaluate the environmental impacts arising from the formulation of two metal surface coating chemicals (Product A and B) that can substitute each other. It should be noted that the same amount of chemicals is used during coating operations, and a coating quality that is equal to each other is obtained with these chemicals. Moreover, the effect of using various energy sources on environmental impacts is investigated. The significance of this study lies in the fact that represents a pioneering effort performed for the formulation of metal coating chemicals.

Product A and B are those that form a layer of zinc phosphate on the surface of iron and steel wires during cold drawing operations. Product A is used in the phosphating of metals. Phosphate coating of metals is a preliminary process that occurs before subsequent processes such as painting, etc. It improves the material's corrosion resistance and performance in processes where phosphate will be present after coating.

The aim and scope of this study are described in the next section, which is followed by a detailed inventory of data and assumptions. Section 3 explains the results. Finally, in Sect. 4, the conclusions are drawn.

Materials and methods

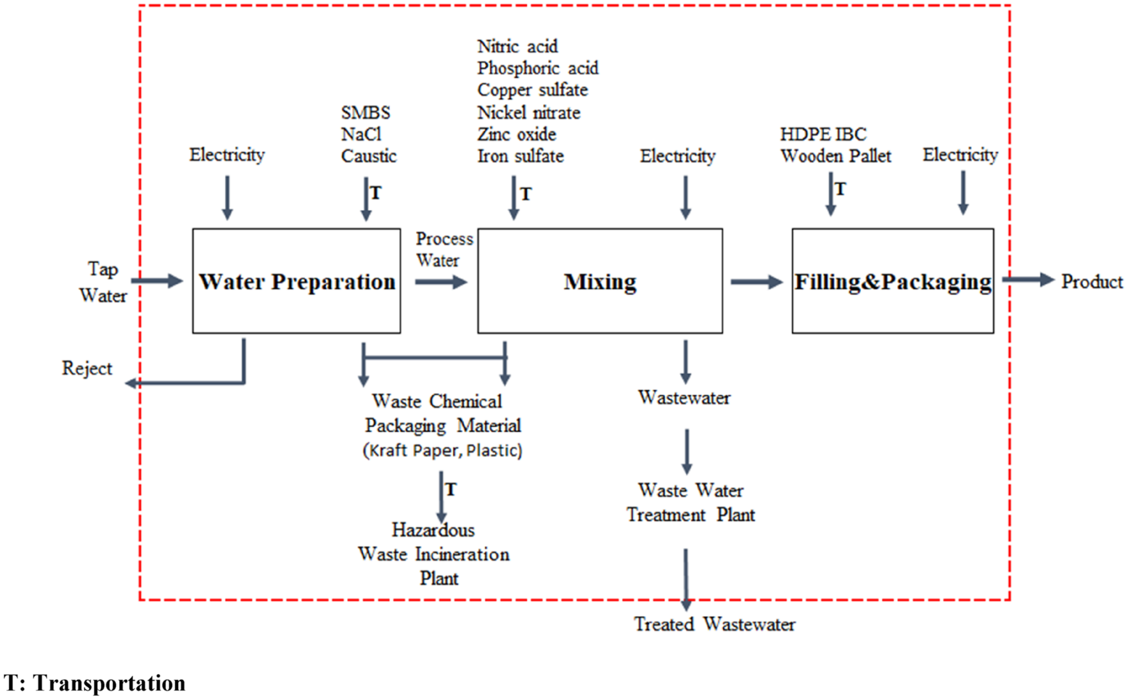
The LCA methodology used in this paper is formulated according to the ISO 14040/14044 guidelines (ISO 2006a; b). Therefore, the iterative steps of (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation are followed.

The GaBi software version 7.3 (Sphera 2017) is used to perform LCA.

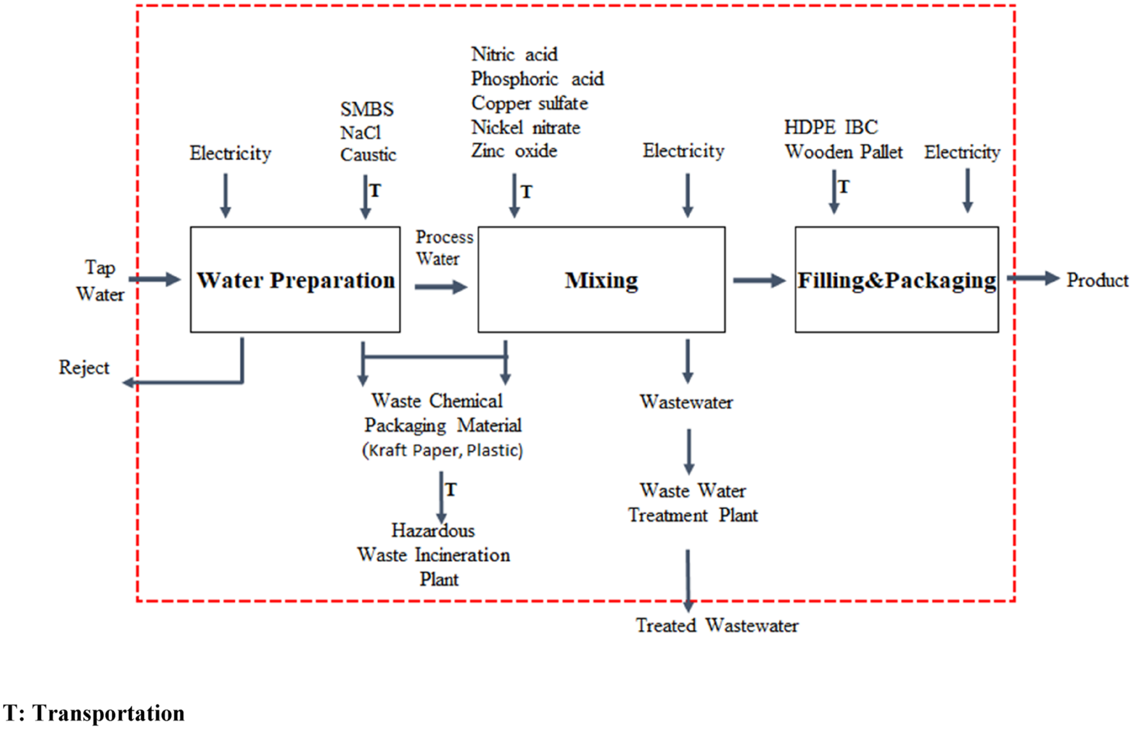
The data used in this study are obtained from a chemical formulation industry. Intensive data collection is conducted for 6 months in 2019. The background data are mostly sourced from the Ecoinvent database (Ecoinvent 2013). The following parts detail the system, assumptions, and data used within the LCA model.

The functional unit is defined as a 1000 kg product as both of the produced chemicals have the same function in the surface coating industry. Furthermore, the same amount of these substitute chemicals is required during surface coating operations. It must also be mentioned that the cost of these chemicals is very close to each other. Product B is 8% expensive than Product A.

System boundaries defined for the production of the two formulations are illustrated in Fig. 1. The same figure also shows the production flowcharts of the formulations under investigation. As can be seen from the figure, a cradle-to-gate approach is adopted. Tap water production, reject water



a **Product A**



b **Product B**

Fig. 1 System boundaries for the modelling

generated from the water preparation system and treated wastewater discharge steps are beyond the scope of the study.

Three consecutive steps of operations are performed to produce both of the formulations: raw material feeding, mixing and packaging. In the first stage, raw materials are fed manually or automatically. Liquid chemicals such as phosphoric acid, nitric acid, etc. are fed to the mixer automatically. Zinc oxide, iron sulfate, nickel nitrate, and copper sulfate are in powder form. These powder chemicals, on the other hand, are fed manually. The same mixer and the automatic filling system are used for the production of both chemicals. Although it seems that the only difference of Product A and Product B is the iron sulfate input in Fig. 1, according to the inventory data tabulated in Table 1, the amount of inputs and outputs to formulate these products differ considerably from each other. During packaging operations, intermediate bulk containers (IBC) made up of high-density polyethylene (HDPE) and wooden pallets are used for both of the products. There are no direct emissions generated by the production processes.

Deionized water with a conductivity level less than 10 µS/cm and a pH lower than 7 is required as an input for both of the products. In the facility, there is a water preparation system that converts tap water with an average pH of 8.77 and an average conductivity of 234 µS/cm, into deionized water. A simple flowchart of the mentioned water preparation system is given in Fig. 2. The water preparation system has two subsequent stages of pre-treatment and reverse osmosis. Multimedia filters and activated carbon filters are the units of pre-treatment. Chlorine is used for the disinfection of the tap water entering the system. However, chlorine can cause damages to reverse osmosis membranes. In order to get rid of this, sodium metabisulfite (SMBS) is added before the reverse osmosis unit in the water preparation system. At the end of the treatment, caustic is fed to the system to neutralize the water with acidic nature.

Hazardous wastes composed of the packaging of spent chemicals, either plastic or paper, are collected and sent to a licensed hazardous waste incineration facility. It should be noted that nitric and phosphoric acid are transported to the production facility with a tanker and fed to the system

Table 1 Aggregated inventory for formulations (per 1000 kg product)

Inputs	Unit	Product A	Product B
Nitric acid	kg	464	238
Phosphoric acid	kg	144	506
Zinc oxide	kg	190	135
Nickel nitrate	kg	4	1.90
Iron sulfate	kg	4	–
Copper sulfate	kg	2	0.38
Tap water	kg	320	198
Table salt	kg	0.05	0.03
SMBS[a] (liquid)	kg	1.72E−04	1.06E−04
Caustic (liquid)	kg	7.63E−04	4.72E−05
Electricity	kWh	115	111
HDPE[b] IBC[c]	kg	60	60
Wooden pallet	kg	30	30
Outputs	**Unit**	**Product A**	**Product B**
Hazardous waste (waste paper)	kg	1.98	1.36
Hazardous waste (waste plastic)	kg	9.91E−08	2.31E−5
Wastewater	kg	2.50	2.50
Reject water	kg	128	79

[a] *SMBS*: sodium metabisulfite

[b] *HDPE*: high-density polyethylene

[c] *IBC*: intermediate bulk container)

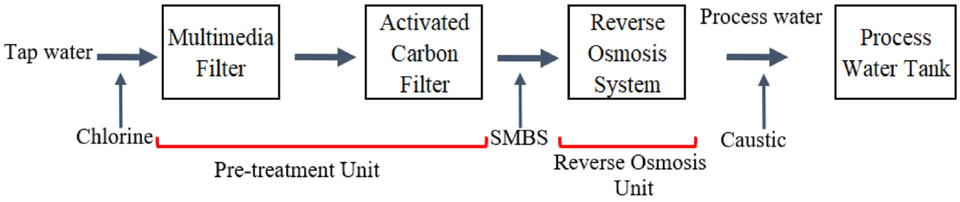


Fig. 2 Details of water preparation system

directly from the tanker. Therefore, no packaging wastes are involved for these chemicals.

Wastewater is generated from cleaning operations. The industry that formulates the products produces several other chemicals both organic and inorganic. Besides, this industry is located in an organized industrial district. The industry discharges its wastewaters to the wastewater treatment plant of this organized industrial district. In this respect, the wastewater treatment process is selected from the Ecoinvent database that is specific to the coating industry. The wastewater treatment plant has mechanical, biological, and chemical treatment stages and sludge digestion. The capacity of the treatment plant is 1.1E10 l/year. The efficiency of the treatment plant is more than 85%.

Transportation information is given in Table 2. All the transportation is conducted in trucks using diesel. One should note that both of the formulations are produced in the same factory; therefore, the transportation distances are the same for the formulations.

The background life cycle inventory data are mainly sourced from the Ecoinvent database (Ecoinvent 2013). SMBS which is one of the inputs for the process water production process is not available in the database so data obtained from the literature (ChinaChemNet 2019) are added manually. The details of the materials and the background inventory data information are summarized in Table 3.

The total impact of each environmental effect is defined for each formulation process of these zinc phosphating chemicals by LCA modelling with GaBi software.

The CML 2 Baseline 2001 January 2016 update (Guinee et al. 2001) methodology has been used to estimate the life cycle environmental impacts. The investigated environmental impact categories are as follows: global warming potential (GWP), abiotic depletion potential (ADP fossils and elements), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity (FAETP), human toxicity potential (HTP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) and terrestrial ecotoxicity potential (TETP).

Table 2 Information on transportation

Materials	Formulation	Distance (km)
Nitric acid	Product A, B	267
Phosphoric acid	Product A, B	614
Zinc oxide	Product A, B	380
Nickel nitrate	Product A, B	628
Iron sulfate	Product A	140
Copper sulfate	Product A, B	26
Tablet Salt	Product A, B	53
SMBS	Product A, B	53
Caustic (liquid)	Product A, B	53
HDPE IBC	Product A, B	32
Wooden pallet	Product A, B	35
Hazardous waste to the incineration plant	Product A, B	19

Table 3 Data sources

Input/output	Process	Source
Nitric acid	Nitric acid, without water, in 50% solution	Ecoinvent 3.1
Phosphoric acid	Phosphoric acid, without water, in 85% solution	Ecoinvent 3.1
Nickel	Nickel, 99.5%	Ecoinvent 3.1
Nitric acid	Nitric acid, product in 50% solution	Ecoinvent 3.1
Zinc oxide	Zinc oxide	Ecoinvent 3.1
Iron sulfate	Iron sulfate	Ecoinvent 3.1
Copper sulfate	Copper sulfate	Ecoinvent 3.1
Tap water	Tap water	Ecoinvent 3.1
Tablet salt	Sodium chloride, powder	Ecoinvent 3.1
Caustic, liquid	Sodium hydroxide, without water, in 50% solution	Ecoinvent 3.1
Sodium meta bisulfite	Sodium meta bisulfite	ChinaChem[a]
Soda ash	Soda ash, dense	Ecoinvent 3.1
Hydrogen sulfide	Hydrogen sulfide	Ecoinvent 3.1
Electricity	Turkey electricity mix, medium voltage	Ecoinvent 3.1
Plastic package and bulk container	Polyethylene bottle (PE-HD)	Ecoinvent 3.1
Wooden pallet	EUR-flat pallet	Ecoinvent 3.1
Wastewater treatment	Treatment of wastewater from coating	Ecoinvent 3.1
Waste chemical packaging material (Waste paper and plastics)	Hazardous waste, for incineration	Ecoinvent 3.1

[a] ChinaChemNet (2019)

Results and discussion

Results of the study cover detailed process information, chemical usage, energy and materials consumption for environmental LCA of different two zinc phosphating chemicals, namely product A and product B.

Table 4 shows the environmental impact categories and assessment results of both products. The formulation of two surface coating chemicals is comparatively evaluated in terms of the aforesaid environmental impact categories as shown in Fig. 3. It must be noted that a normalization is performed in this figure, where for all the impact categories apart from GWP, Product A yields lower results. On the other hand, GWP of Product A is approximately 7% higher than that of Product B.

Table 4 The environmental impact categories and assessment results of product A and B

Environmental impact category	Unit	Impact value Product A	Impact value Product B
ADP elements	[kg Sb-Eq.]	1.44E−02	2.48E−02
ADP fossil	[MJ]	2.42E+04	3.06E+04
AP	[kg SO_2-Eq.]	1.61E+01	2.02E+01
EP	[kg Phosphate-Eq.]	5.07E+00	7.58E+00
FAETP	[kg DCB-Eq.]	8.82E+02	1.91E+03
GWP	[kg CO_2-Eq.]	2.51E+03	2.35E+03
HTP	[kg DCB-Eq.]	1.45E+03	1.99E+03
ODP	[kg R11-Eq.]	1.64E−04	2.54E−04
POCP	[kg Ethene-Eq.]	8.65E−01	1.15E+00
TETP	[kg DCB-Eq.]	1.75E+01	2.07E+01

FAETP, ADP elements, ODP, EP, HTP, POCP, AP, ADP fossil and TETP of Product B are 116%, 72%, 55%, 49%, 38%, 33%, 26%, 26% and 18% higher than for Product A, respectively. Therefore, from these findings, the usage of Product A instead of B is recommended as lower environmental impacts are associated with Product A. As mentioned earlier Product B is 8% expensive than Product A. Thus, the environmental impacts together with the rough cost comparison favor usage of Product A.

The contribution of various factors to environmental impact categories for Product A and B is illustrated in Fig. 4. As given in Fig. 4, around 39%, 22% and 14% of ADP elements are due to phosphoric acid, nitric acid and copper sulfate inputs, respectively, for Product A. On the other hand, 79% of ADP elements is generated as a result of phosphoric acid input for Product B. For both of the products, the non-renewable elements such as cadmium, lead, gold and copper cause the impact on ADP elements.

The major factors constituting ADP fossil for Product A can be given as, zinc oxide (with 27% contribution to total ADP fossil), nitric acid (25%), phosphoric acid (17%) and finished good packaging material (17%). ADP fossil arising from Product B is mainly because of phosphoric acid (with 46% contribution to total ADP fossil), zinc oxide (16%), finished good packaging (14%), transportation (11%) and nitric acid (10%). When considering Product A, the use of non-renewable energy sources such as crude oil and natural gas generates ADP fossil. In contrast, crude oil consumption is the primary source of ADP fossil for Product B.

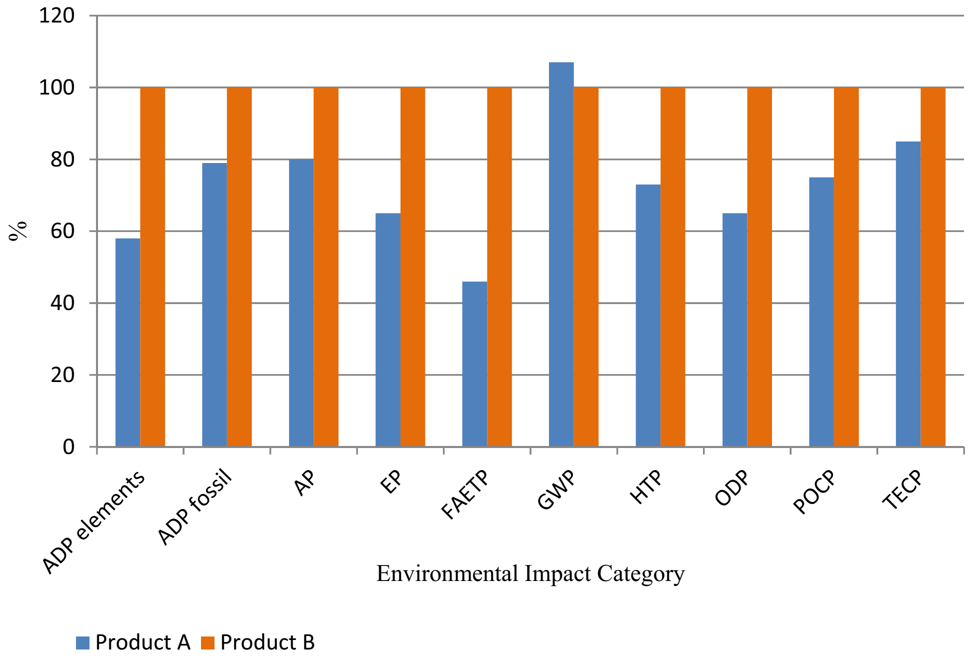
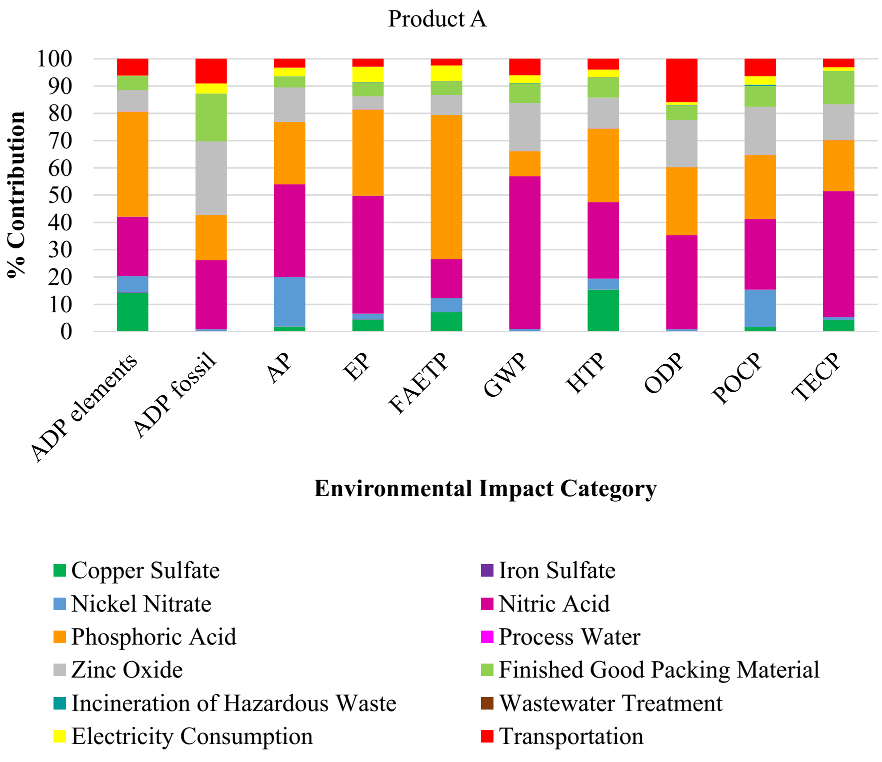
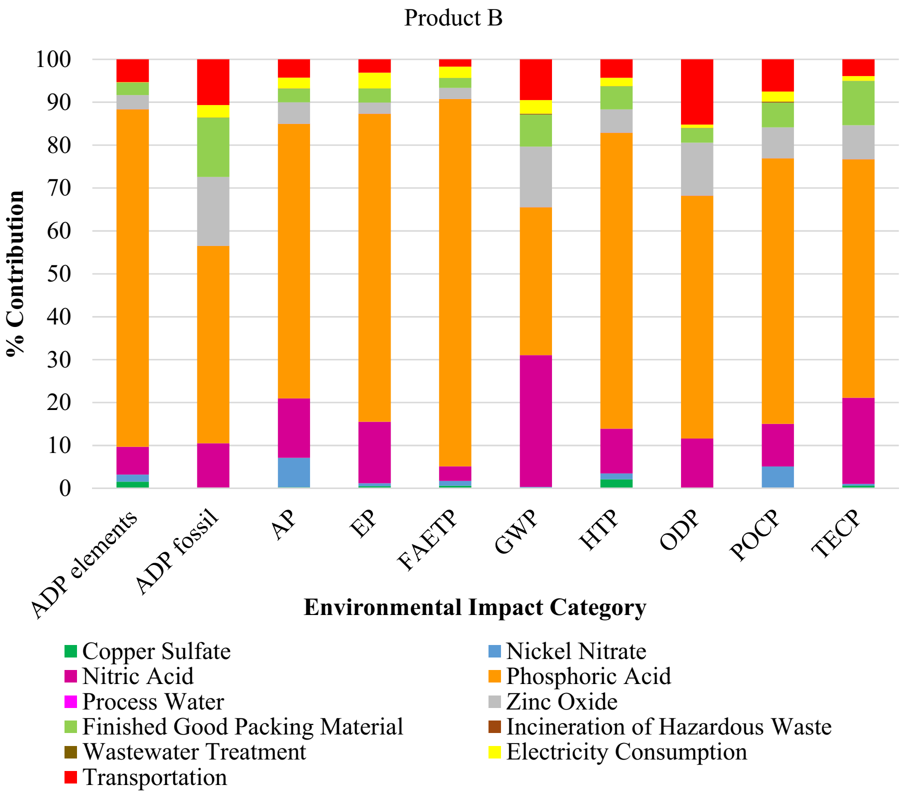


Fig. 3 Comparison of environmental impacts for Product A and B



a **Product A**



b **Product B**

Fig. 4 Contribution of various factors to environmental impacts for Product A and B

In Product A, nitric acid production is the biggest contributor to the AP impact category with 34%. The total effect of nitric acid production is coming from releasing emissions into the air. This emission consists of 35% ammonia, 26% nitrogen oxide, and 38% sulfur dioxide. Approximately, 64% and 14% of total AP are generated as a result of phosphoric acid and nitric acid inputs for Product B, respectively. The total impact of phosphoric acid production is originated from releasing inorganic emissions to the air; sulfur dioxide has the biggest impact with an 89% share in the total impact of phosphoric acid production.

For Product A, around 34%, 23%, 18% and 13% of the total AP is of nitric acid, phosphoric acid, nickel nitrate and zinc oxide origin, respectively. Approximately, 64% and 14% of total AP are generated as a result of phosphoric acid and nitric acid inputs for Product B, respectively. The release of ammonia, nitrogen oxide and sulfur dioxide emissions to air cause AP for Product A. Sulfur dioxide emissions to air produce AP for Product B. In product B, phosphoric acid production has the most contribution with a 64% share to the AP impact category. The total impact of phosphoric acid production is caused by the release of inorganic emissions into the atmosphere. Sulfur dioxide has the biggest impact with an 89% share in the total impact of phosphoric acid production.

Nitric acid and phosphoric acid contribute 43% and 32% to total EP, respectively, for Product A. The total EP percentage of nitric acid production is mainly divided into two categories. These are inorganic emissions discharging to air with 81% participation and emission releasing to the freshwater with 16%. In product B, the main contribution of EP is coming from phosphoric acid with 72%. And nitric acid is following with 14% participation in total. Phosphoric acid is primarily caused by emissions into freshwater. Phosphate emissions account for the majority of freshwater emissions.

Nitric acid and zinc oxide, respectively, have 56% and 18% shares in total GWP for Product A. GWP for Product A is generated because of releasing inorganic emissions, especially nitrous oxide into the air. The factors producing total GWP for Product B are phosphoric acid (34% of the total), nitric acid (31%) and zinc oxide (14%). The release of inorganic emissions into the atmosphere, such as carbon dioxide and nitrous oxides, causes GWP for Product B.

Nitric acid, phosphorus acid, zinc oxide and nickel nitrate have 26%, 24%, 18% and 14% shares in total POCP, namely for product A. In the case of Product B, phosphoric acid and nitric acid contribute to total POCP by 62% and 10%, respectively. POCP of Product A is caused by sulfur dioxide and nitrogen oxide emissions into the atmosphere. Instead, sulfur dioxide emissions combined with organic emissions to air of primarily non-methane volatile organic compounds (NMVOC) produce POCP for Product B.

The main factors constituting ODP for Product A can be listed as nitric acid (34% of the total), phosphoric acid (2%), and zinc oxide (17%) emissions to air. For Product B, total ODP is generated mainly due to phosphoric acid (57% of the total), zinc oxide (12%), and nitric acid (11%). The main cause of ODP for both products is the release of halogenated organic emissions, specifically halon to the air.

Finally, when a brief evaluation is performed in terms of impact categories related to toxicity, the following findings are revealed. Phosphoric acid together with nitric acid contributes 53% and 14% of the total FAETP for Product A, respectively. On the other hand, Product B phosphoric acid has an 86% share in FAETP. For both of the products, vanadium emissions to freshwater are the main source of FAETP.

For Product A, total TETP is produced mainly as a result of nitric acid (46% of the total), phosphoric acid (19%), zinc oxide (12%) and finished good packing material (12%). Phosphoric acid with 56%, nitric acid with 20% and finished good packing material with 10% contributions are the main reasons for TETP for Product B. Vanadium and chromium emissions to air cause TETP of Product A. For Product B, the main origin of TETP is chromium emissions to air. TETP for Product B is generated to a lesser extent in order to reduce pesticide emissions to the soil.

Major factors contributing to HTP can be tabulated as nitric acid (28% of the total), phosphoric acid (27%), copper sulfate (15%) and zinc oxide (11%) for Product A. Phosphoric acid and nitric acid have 69% and 10% contributions to HTP, respectively, for product B. HTP for Product A is primarily caused by the release of chromium, nickel, arsenic, and vanadium into the air, as well as selenium and vanadium into freshwater. HTP for Product B is primarily caused by chromium and arsenic emissions into the air, as well as vanadium and selenium discharge into freshwater.

Products A and B yield different values for the investigated environmental impact categories. The main reason is the different structure of both chemicals. There are two main differences between the products. The first is the amount of inputs. As can be seen from the results, the proportion of chemicals used in the products plays a key role in the obtained impact values. The second difference is that while product A contains iron sulfate, product B does not. Since only 2 kg of iron sulfate is used in formulating 1000 kg of product A, impacts are not significantly altered with the existence of iron sulfate. This fact can easily be seen from Fig. 4a that illustrates the contribution of various factors to environmental impacts. Furthermore, phosphoric acid input plays an important role in most of the environmental impacts for Product B. The input of phosphoric acid in Product B is 3.5 times that is for Product A.

Although electricity consumption does not have a significant share in environmental impacts (with less than 6% contribution for both of the formulations), a sensitivity analysis on energy sources is performed for the sake of minimizing the environmental impacts arising from the industry. The factory which formulates both of the products has future investment plans about obtaining energy from renewable sources to mitigate greenhouse gas emissions. Moreover, the energy policy of Turkey emphasizes the importance of using renewable energy sources such as photovoltaic and wind energy in the next ten years (EUAS 2018). Due to this fact, certain subsidizes will be offered to the industries. For all these purposes, the current source of energy, that is Turkish grid electricity, is compared with renewable sources of solar and wind energy, in terms of environmental impacts. The facility supplies energy from the grid that is composed of 37.4% coal, 29.9% from natural gas, 19.8% from hydroelectric power plants, 6.6% from wind, 2.5% from geothermal, 0.3% from liquid fuels, 3.3% from biofuels and solar energy and 0.2% from waste heat (TEIAS 2019). The comparative evaluation of energy sources is illustrated in Fig. 5.

Significant reductions are observed for almost all of the investigated impact categories apart from ADP elements where a huge jump is obtained when photovoltaic cells are used in place of energy from the grid. Consumption of elements during the manufacturing of solar panels can be a source of the mentioned elevation in ADP elements. Most of the impact is due to the use of rare materials such as cadmium, tellurium, silver and gold. Such results are also obtained in the literature (Saad et al. 2019; Stamford and Azapagic 2012).

Improvements on all environmental impact categories except for ADP elements can be obtained when wind turbines are used as a source of energy instead of a grid mix. An increase of 55% on ADP elements is attained for both of the products in the case of adopting wind energy. The finding is in accordance with the literature (Lieberei and Gheewala 2017) that states element consumption during the construction of renewable energy power plants is high. Furthermore, the study of Atılgan and Azapagic (2016) denotes almost all of the depletion of wind power elements incurred in the construction stage due to the use of metals such as chromium, copper, molybdenum and nickel. Recycling the construction materials after the decommissioning stage could reduce the environmental impacts.

Reductions of more than 95% are observed for impact categories of ADP fossil, AP, EP, GWP, ODP and POCP by using wind energy instead of grid. FAETP and HTP categories show over 82% reductions; TETP is 57% lowered when the wind is adopted. The reduction in TETP in the case of wind energy is slightly smaller than the one obtained with photovoltaic energy. Therefore, the most environmentally friendly alternative is quoted as wind energy when ADP elements impact category is not considered.

Conclusions

In various environmental impact categories, products A and B perform differently. The main reason for this is the distinct chemical structures involved in both products. The investigated products are distinct in two ways. The first is the amount of raw material consumption in the formulations. The second one is, while product A contains iron sulfate, product B does not. The percentage of chemicals used in the products has a significant impact on the impact categories, as shown by the results. It is determined that using 2 kg of iron sulfate per 1000 kg of product A has no direct effect on the environmental impacts under question.

When the environmental impact categories of the two products are compared, it is found that in GWP category Product A has 7% higher impacts than that of Product B. In all other impact categories except the GWP, Product B has a

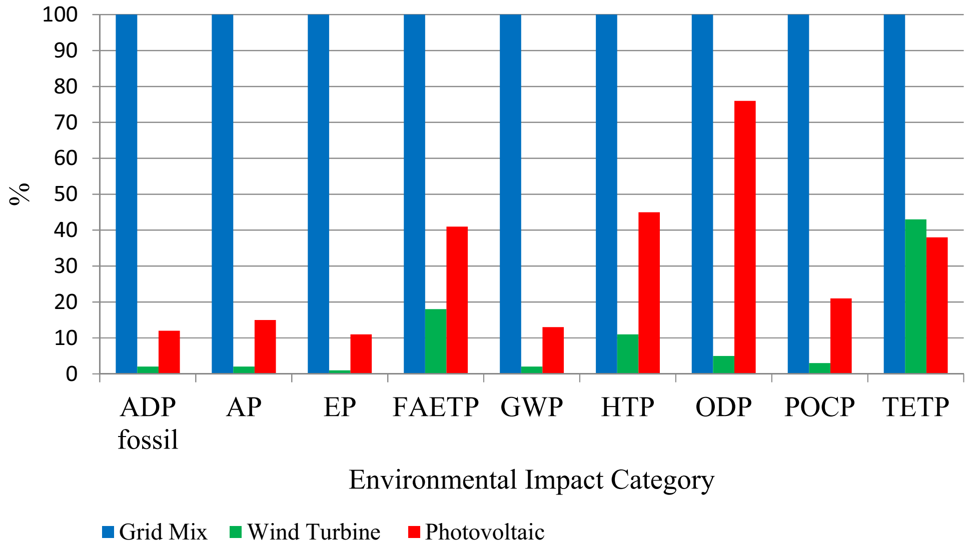


Fig. 5 The sensitivity of environmental impact categories to various energy sources

greater negative impact on the environment than Product A. The main cause of the difference between the GWP values of Product A and Product B is because of the nitric acid input. Product A contains nearly twice the amount of nitric acid used in Product B.

Product B has 72% more ADP elements than product A. The use of phosphoric acid is the most significant contributor to ADP elements arising from Product B where half of the 1000 kg mixture is composed of phosphoric acid.

Product B has a 26% greater impact than product A in the ADP fossil category. The use of phosphoric acid again is the primary cause of this difference.

In the AP impact category, Product B contributes 26% more environmental burdens than Product A. The most important factor is phosphoric acid input, which accounts for 64% of the total for Product B.

In the EP impact category, there is a 50% difference between Product B and Product A. The amount of phosphoric acid used in Product B caused this difference with a 72% contribution to the total.

Product B has 117% more impact on the environment than Product A in the FAETP impact category. The main source of this huge difference between products is quoted as the input of phosphoric acid in formulation. Phosphoric acid has an 86% contribution to the total result for Product B.

Product B exerts 34% higher environmental impact than Product A in the POCP category. In Product B, phosphoric acid accounts for 62% of total impacts. In the TETP impact category, there is an 18% difference between products A and B. Product B has a greater impact in this category than product A due to the high amount of phosphoric acid used. Product B has a 38% greater HTP than Product A. The dominant reason for this difference between the two products is again the phosphoric acid usage.

The energy requirement is obtained from the Turkish grid during the formulation of the products. Instead of considering the grid mix, renewable energy sources are taken into account when determining environmental effects. The energy required to formulate the products A and B is nearly identical. Only the water preparation system accounts for the difference in energy consumption between the two products. Product A requires 4 kWh more energy per 1000 kg because it requires more deionized water input. As a result, both products have the same impacts when renewable energy sources are adopted. As grid mix alternatives, wind turbines and photovoltaics have been chosen. Except for the ATP elements category, all other impact categories show positive results with lower environmental impacts when wind turbines are used. Getting energy from wind turbines has a 55% more negative impact than a grid on ATP elements. The main cause of this result is the consumption of elements during the manufacturing of wind turbines. Except for the ADP element category, all environmental impact categories are reduced when photovoltaic is used as an energy source. The element consumption during the production of photovoltaic cells causes the mentioned negative effect in the ADP element category.

When the environmental effects of Product B and Product A are compared, it is clear that one should choose Product A as it exerts a lower impact on the environment. Furthermore, due to the scarcity of studies on zinc phosphating chemicals, it is recommended to conduct research activities on the cleaner production of these chemicals. Besides, widespread research activities similar to this one will promote life cycle thinking in Turkish industry yielding sustainable manufacturing practices.

The analysis of the environmental sustainability of the selected metal surface coating chemicals is based on real and detailed data from a company in Turkey. The background life cycle inventory data are obtained from the Ecoinvent database, but it is adapted to Turkey's conditions as much as possible. The use of more complete and country-specific background data could improve the overall data quality.

In order to have sound decision-making in industrial production, financial analysis along with an environmental perspective are required. In this respect, it is suggested to run further studies on life cycle cost analysis for these chemicals.

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Declarations

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References

Ali M, Hoque M, Matsushita T, MdMayez M, Seno Y, Shibuya Y, Yamada S, Hyuga T, Nemoto H (2020) An environmentally friendly lipophilic coating of metal surface. Tetrahedron Lett. https://doi.org/10.1016/j.tetlet.2020.152242

Alkaya E, Demirer GN (2014) Improving resource efficiency in surface coating/painting industry: practical experiences from a small-sized enterprise. Clean Technol Environ Policy 16(8):1565–1575. https://doi.org/10.1007/s10098-014-0732-9

Atılgan B, Azapagic A (2016) Renewable electricity in Turkey: life cycle environmental impacts. Renew Energy 89:649–657. https://doi.org/10.1016/j.renene.2015.11.082

AtılganTürkmen B (2021) Environmental performance of high-efficiency natural gas combined cycle plant. Energy Sources Part A Recov Utilization Environ Effects. https://doi.org/10.1080/15567036.2020.1856974

AtılganTürkmen B, BudakDuhbacı T, KarahanÖzbilen Ş (2021) Environmental impact assessment of ceramic tile manufacturing: a case study in Turkey. Clean Technol Environ Policy 23(4):1295–1310. https://doi.org/10.1007/s10098-021-02035-w

Balgude D, Sabnis A (2012) Sol–gel derived hybrid coatings as an environment friendly surface treatment for corrosion protection of metals and their alloys. J Sol-Gel Sci Technol 64(1):124–134. https://doi.org/10.1007/s10971-012-2838-z

ChinaChemNet (2019) *Sodium metabisulfite* http://www.chinachemnet.com/Products/sodiummetabisulfite/Suppliers-1.html

Cuéllar-Franca R, García-Gutiérrez P, Dimitriou I, Elder RH, Allen RWK, Azapagic A (2019) Utilising carbon dioxide for transport fuels: the economic and environmental sustainability of different Fischer-Tropsch process designs. Appli Energy 253:113560. https://doi.org/10.1016/j.apenergy.2019.113560

Cyril O, Oyelaran OAD, Agbo N (2017) The steel industry: a stimulus to national development. J Powder Metall Min. https://doi.org/10.4172/2168-9806.1000156

Durana P, Perkins N, Valaskova K (2021) Artificial intelligence data-driven internet of things systems, real-time advanced analytics, and cyber-physical production networks in sustainable smart manufacturing. Econ Manag Financ Mark 16(1):20–30. https://doi.org/10.22381/emfm16120212

Ecoinvent (2013) Ecoinvent Database v3.1

Elginoz N, Alzaboot M, GermirliBabuna F, Iskender G (2019) Construction of a large water treatment plant: appraisal of environmental hotspots. Desalin Water Treat 172:309–315. https://doi.org/10.5004/dwt.2019.25107

EUAS (2018) Electricity generation and trade sector report. https://www.euas.gov.tr/tr-TR/sektor-raporu

European Commission (2006) Integrated pollution prevention and control reference document on best available techniques for the surface treatment of metals and plastics, August, Sevilla Spain, p 546

Ferreira MGS, Zheludkevich ML, Tedim J, Yasakau KA (2012) 9-Self-healing nanocoatings for corrosion control. In: Saji VS, Cook R (eds) Corrosion protection and control using nanomaterials. Woodhead Publishing, New York, pp 213–263. https://doi.org/10.1533/9780857095800.2.213

Guinee JB, Gorrèe M, Heijungs R, Huppes G, Kleijn GR, van Oers RL, Wegener L, Sleeswijk A, Suh S, de Hhaes HA, Udo de Bruijn H, van Duin HR, Huijbregts MAJ (2001) Life cycle assessment, an operational guide to the ISO standards. Part 2a: guide. Kluwer Academic Publishers, Dordrecht

Hadzima B, Janeček M, Estrin Y, Kim H (2007) Microstructure and corrosion properties of ultrafine-grained interstitial free steel. Mater Sci Eng A 462:243–247. https://doi.org/10.1016/j.msea.2005.11.081

Harris DR, Philip C (2016) Formulating surface coatings. In: Hughes MJA, Zheludkevich M, Buchheit R (eds) Active protective coatings, vol 233. Springer, Berlin, pp 85–104

ISO (2006a) ISO 14040-Environmental management—life cycle assessment—principles and framework. Journal of Powder Metallurgy & Mining, Issue

ISO (2006b) ISO 14040-Environmental management–life cycle assessment—requirements and guidelines. Journal of Powder Metallurgy & Mining, Issue

Karacal P, Elginoz N, GermirliBabuna F (2019) Environmental burdens of cataphoresis process. Desalin Water Treat 172:301–308. https://doi.org/10.5004/dwt.2019.24800

Kim S, Overcash M (2003) Energy in chemical manufacturing processes: gate-to-gate information for life cycle assessment. Chem Technol Biotechnol 78(9):995–1005. https://doi.org/10.1002/jctb.821

Lieberei J, Gheewala S (2017) Resource depletion assessment of renewable electricity generation technologies—comparison of life cycle impact assessment methods with focus on mineral resources. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-016-1152-3

Marder AR (1997) Effects of surface treatments on materials performance. In: Dieter GE (ed) Materials selection and design, vol 20. ASM International, New York

MarketsandMarket (2021) Metal coatings market by type (polyester, plastisol, siliconized polyster, fluropolymer, polyurethane), process (coil, extrusion, hot dip galvanizing), technology (liquid, powder), end use industry, and Region-Global Forecast to 2026. Retrieved 02.12.2021 from https://www.marketsandmarkets.com/Market-Reports/metal-coating-market-96303322.html

Mozetič M (2019) Surface modification to improve properties of materials. Materials 12(3):441

Nazeer AA, Madkour M (2018) Potential use of smart coatings for corrosion protection of metals and alloys: a review. J Mol Liq 253:11–22. https://doi.org/10.1016/j.molliq.2018.01.027

Novak A, Bennett D, Kliestik T (2021) Product decision-making information systems, real-time sensor networks, and artificial intelligence-driven big data analytics in sustainable industry 4.0. Econ Manag Financ Mark 16(2):62–72. https://doi.org/10.22381/emfm16220213

Ozkan E, Bas B, Elginoz N, GermirliBabuna F (2020) Environmental sensitivity of printed circuit board manufacturing to Cu recycling rate, transportation and various energy sources. Int J Global Warm 20:237. https://doi.org/10.1504/IJGW.2020.10028206

Saad A, Elginoz N, GermirliBabuna F, Iskender G (2019) Life cycle assessment of a large water treatment plant in Turkey. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-018-3826-9

Sphera (2017) GaBi V7.3 software and database

Stamford L, Azapagic A (2012) Life cycle sustainability assessment of electricity options for the UK. Int J Energy Res. https://doi.org/10.1002/er.2962

Stieberova B, Zilka M, Ticha M, Freiberg F, Caramazana-González P, McKechnie J, Lester E (2017) Application of ZnO nanoparticles in a self-cleaning coating on a metal panel: an assessment of environmental benefits. ACS Sustain Chem Eng 5(3):2493–2500. https://doi.org/10.1021/acssuschemeng.6b02848

TEIAS (2019) Electricity Generation and Transmission Statistics of Turkey. Turkish Electricity Transmission Corporation. http://www.teias.gov.tr/TurkiyeElektrikIstatistikleri.aspx

Tushinsky LI, Kovensky I, Plokhov A, Sindeyev V, Reshedko P (2002) Structure. In: Tushinsky LI, Kovensky I, Plokhov A, Sindeyev V, Reshedko P (eds) Coated metal: structure and properties of metal-coating compositions. Springer, Berlin, Heidelberg, pp 1–84

Yalamacilar B, Elginoz N, GermirliBabuna F (2021) Benchmarking industrial water purification systems with the aid of life cycle assessment. Desalin Water Treat 211:422–431