

**ISTANBUL TECHNICAL UNIVERSITY★GRADUATE SCHOOL OF SCIENCE**  
**ENGINEERING AND TECHNOLOGY**

**ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF ZINC PHOSPHATING  
CHEMICALS**



**M.Sc. THESIS**

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**Department of Environmental Engineering**  
**Environmental Science and Engineering Programme**

**MAY 2020**



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**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ**

**ÇİNKO FOSFATLAMA KİMYASALLARININ ÇEVRESEL YAŞAM  
ANALİZ DEĞERLENDİRMESİ**

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## TABLE OF CONTENTS

	<u>Page</u>
<b>FOREWORD</b> .....	vii
<b>TABLE OF CONTENTS</b> .....	ix
<b>ABBREVIATIONS</b> .....	xi
<b>LIST OF TABLES</b> .....	xiii
<b>LIST OF FIGURES</b> .....	xiv
<b>SUMMARY</b> .....	xvii
<b>ÖZET</b> .....	xxi
<b>1. INTRODUCTION</b> .....	<b>1</b>
1.1.Importance of the Study .....	1
1.2.Aim and Scope of the Study .....	3
<b>2. LITERATURE REVIEW</b> .....	<b>5</b>
2.1. Metal Surface Treatment Technologies .....	5
2.3. Phosphate Coating Process.....	8
2.4. Life Cycle Assessment .....	12
2.5. Applied Life Cycle Assessment Studies .....	15
<b>3. MATERIALS AND METHODS</b> .....	<b>21</b>
3.1.Aim and Scope of the Study .....	21
3.2.Functional Unit.....	23
3.3.System Boundary .....	23
<b>4. ZINC PHOSPHATING CHEMICALS PRODUCTION PROCESS</b> .....	<b>27</b>
4.1. Zinc Phosphating Chemicals Production.....	27
4.2. Inventory of the Formulations .....	29
<b>5. RESULTS AND DISCUSSION</b> .....	<b>35</b>
5.1. Environmental Impacts of Zinc Phosphating Chemicals .....	35
5.1.1. LCIA results .....	35
5.2. Environmental Impacts Comparison in Products A and B.....	42
5.2.1. Global warming potential (GWP).....	42
5.2.2. Abiotic depletion (ADP elements) .....	44
5.2.3. Abiotic depletion (ADP fossil) .....	46
5.2.4. Acidification potential (AP) .....	47
5.2.5. Ozone depletion potential (ODP) .....	49
5.2.6. Eutrophication potential (EP) .....	51
5.2.7. Freshwater aquatic ecotoxicity potential (FAETP) .....	52
5.2.9. Terrestrial ecotoxicity potential (TETP).....	56
5.2.10. Human toxicity potential (HTP) .....	58
5.3. Environmental Impact Comparison between Products and Literature....	60
5.4. Energy Supply Scenarios for Zinc Phosphate Production.....	62
5.4.1. Wind turbin usage.....	63
5.4.2. Photovoltaic system usage.....	65

**6. CONCLUSIONS AND RECOMMENDATIONS ..... 69**  
**REFERENCES ..... 73**  
**CURRICULUM VITAE ..... 77**



## **ABBREVIATIONS**

<b>AP</b>	: Acidification Potential
<b>BAT</b>	: Best Available Technic
<b>EP</b>	: Eutrophication potential
<b>EPD</b>	: Environmental Product Declaration
<b>FAETP</b>	: Freshwater Aquatic Ecotoxicity Potential
<b>GaBi</b>	: Ganzheitliche Bilanz (Holistic Balance)
<b>GLO</b>	: Global and represents activities
<b>GWP</b>	: Global Warming Potential
<b>HDPE</b>	: High-density polyethylene
<b>HTP</b>	: Human Toxicity Potential
<b>IBC</b>	: Intermediate Bulk Container
<b>IBU</b>	: Institute Construction and Environment e.V.
<b>ITU</b>	: Istanbul Technical University
<b>LCA</b>	: Life Cycle Assessment
<b>LCI</b>	: Life Cycle Inventory
<b>LCIA</b>	: Life Cycle Impact Assessment
<b>NMVOC</b>	: Non-methane volatile organic compound
<b>ODP</b>	: Ozone Layer Depletion Potential
<b>PM</b>	: Particulate Matter
<b>POCP</b>	: Photochemical Ozone Creation Potential
<b>RER</b>	: Europe
<b>RO</b>	: Reverse Osmosis
<b>RoW</b>	: Rest-of-the-World.
<b>TETP</b>	: Terrestrial Ecotoxicity Potential



## LIST OF TABLES

	<u>Page</u>
<b>Table 2.1 :</b> The environmental impact results of methacrylate resin products, highly - filled, flow coatings EPD(Url-4). ....	16
<b>Table 2.2 :</b> The environmental impact results of epoxy powder coating EPD(Url-5). ....	17
<b>Table 2.3 :</b> The environmental impact results of polyester-based powder coating EPD(Url-6).....	18
<b>Table 3.1 :</b> GaBi and Ecoinvent database selection list of zinc phosphating chemical production. ....	26
<b>Table 4.1 :</b> Process inputs of zinc phosphating chemical formulation.....	30
<b>Table 4.2 :</b> Quality of tap water and process water. ....	31
<b>Table 4.3 :</b> Information on transportation of the materials for both products.....	33
<b>Table 5.1 :</b> The Environmental Impact Categories and Assessment Results of product A and B. ....	35
<b>Table 5.2 :</b> Percentage contribution of impact sources to impact categories for both products A and B (%).....	38
<b>Table 5.3 :</b> GWP impact sources and its contribution to each process in products A and B .....	42
<b>Table 5.4 :</b> ADP elements sources and its contribution for each process in products A and B. ....	44
<b>Table 5.5 :</b> ADP fossil sources and its contribution for each process in products A and B.....	46
<b>Table 5.6 :</b> AP sources and its contribution for each process in products A and B. ....	48
<b>Table 5.7 :</b> ODP sources and its contribution for each process in products A and B.....	49
<b>Table 5.8 :</b> EP sources and its contribution for each process in products A and B.....	51
<b>Table 5.9 :</b> FAETP sources and its contribution for each process in products A and B.....	53
<b>Table 5.10 :</b> POCP potential sources and its contribution for each process in products A and B. ....	54
<b>Table 5.11 :</b> TETP potential sources and its contribution for each process in products A and B. ....	56
<b>Table 5.12 :</b> HTP potential sources and its contribution for each process in products A and B. ....	58
<b>Table 5.13 :</b> EPD1, EPD2, EPD3 and products A and B environmental impact results comparison (Url-4,Url-5,Url-6).....	60
<b>Table 5.14 :</b> Database selection for renewable energy scenarios and grid mix .....	62
<b>Table 5.15 :</b> Environmental impact of Zinc phosphating chemicals based on grid mix of Turkey and wind turbine. ....	63

**Table 5.16** : Percentage change of impact categories by using wind turbines instead of grid mix..... 64

**Table 5.17** : Environmental impact of Zinc phosphating chemicals based on grid mix of Turkey and photovoltaic..... 65

**Table 5.18** : Percentage change of impact categories by using photovoltaic ..... 66



## LIST OF FIGURES

	<u>Page</u>
<b>Figure 2.1</b> : Upstream and downstream of surface treatment chemicals .....	7
<b>Figure 2.2</b> : Applications of phosphating chemicals.....	9
<b>Figure 2.3</b> : Phosphate Coating Process Flowchart.....	10
<b>Figure 2.4</b> : System boundary stages (EPA,1993) .....	13
<b>Figure 2.5</b> : Basic options to select system boundaries.....	14
<b>Figure 2.6</b> : Life cycle assessment framework (ISO 14044) .....	14
<b>Figure 3.1</b> : System boundary of ZN phosphate chemical production with life cycle assessment perspective. ....	24
<b>Figure 3.2</b> : Stoichiometry of 1 kg nickel nitrate production in GaBi (Url-6).....	25
<b>Figure 3.3</b> : 1000 Kg SMBS production in GaBi (ChinaChemNet, 2019). ....	25
<b>Figure 4.1</b> : Water preparation system flowchart.....	28
<b>Figure 4.2</b> : Production flowchart of product A.....	29
<b>Figure 4.3</b> : Production flowchart of product B.....	29
<b>Figure 5.1</b> : LCIA percentage distributions. ....	36
<b>Figure 5.2</b> : Product-A percentage contribution to LCIA results.....	39
<b>Figure 5.3</b> : Product-B percentage contribution to LCIA results.....	47
<b>Figure 5.4</b> : Percentage contribution of units to GWP for products A and B. ....	48
<b>Figure 5.5</b> : Percentage contribution of units to ADP (elements) for products A and B.....	44
<b>Figure 5.6</b> : Percentage contribution of units to ADP (fossil) for products A and B. ....	47
<b>Figure 5.7</b> : Percentage contribution of units to AP for products A and B.....	48
<b>Figure 5.8</b> : Percentage contribution of units to ODP for products A and B.....	55
<b>Figure 5.9</b> : Percentage contribution of units to EP for products A and B. ....	57
<b>Figure 5.10</b> : Percentage contribution of units to FAETP for products A and B.....	59
<b>Figure 5.11</b> : Percentage contribution of units to POCP for products A and B.....	55
<b>Figure 5.12</b> : Percentage contribution of units to TETP for products A and B .....	57
<b>Figure 5.13</b> : Percentage contribution of units to HTP for products A and B .....	59
<b>Figure 5.14</b> : Environmental impact comparison of grid mix, wind turbine, and photovoltaic sage.....	68



# **ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF ZINC PHOSPHATING CHEMICALS**

## **SUMMARY**

The industrialization has gained importance with the rapidly increasing world population. Over time, productions have evolved from physical strength to machine power, and have diversified in terms of quality and quantity. With the need for more production, industrialization has started to be mentioned with the environmental problems that it causes. In the period from the industrial revolution to the present day, sustainability has become a subject that is closely followed by everyone, especially in the last period. Increasing social sensitivity has started to reveal the necessity of making necessary improvements in new projects or existing production systems with product life cycle analyses. The product lifecycle is a common method that provides to evaluate product or service the environmental impacts that each of the stages of raw material extraction, production, use, disposal, and all other stages have over the duration. The rapid disappearance of natural resources and the increase of environmental impacts arising from industry in nature caused the developed countries to increase their product life analysis studies and take necessary measures.

Metal has been widely used in many industries since ancient times. Metal is damaged depending on environmental conditions and over time. In order to prevent damage and prolong material life, various additional chemicals must be used. These chemicals are called metal pretreatment chemicals and, it is a type of surface treatment. The surface treatment is a process applied to the surface of a material to make it better in some way. It can be used in different applications and purposes. These chemicals are used in wide areas and different applications. Automotive, electronics, construction, and packaging are common application areas in the industry. The metal pretreatment chemical usage is directly affected and increases with the ever-growing of metal usage. The metal pretreatment chemicals are generally classified into three categories, zinc phosphating chemicals, mangan phosphating chemicals, and iron phosphating chemicals. In this study, zinc phosphating chemical production is examined in the scope of environmental impacts. This chemical is used for corrosion protection, lubrication, decoration, and insulation purposes in industries.

The main purpose of this study is to evaluate the results of the environmental effects that occur during the production of metal surface treatment chemicals that commonly used in the metal industry by using the product life cycle assessment approach. For this purpose, two zinc phosphating chemicals are used with different formulations in the study. These chemicals can be used substitutes for each other. There are two differences between the products. These are the type of raw material, and raw material amount in products. In this study, these products are called as product A and product B.

In this study, there is an evaluation in terms of raw material, water, material, and energy consumption used in the production of surface treatment chemicals, which is

an indispensable part of the metal industry. The current state of the production process in terms of sustainability is analyzed with an environmental life analysis approach. In the study, all production stages of two different zinc surface coating chemicals of a factory producing metal surface treatment chemicals are examined. The system limits cover the duration of the processes from the supply of raw materials to the moment the product leaves the factory. Also, the effects of transportation are investigated in the study. Chemicals and materials transportation, and waste transportation to the hazardous waste incineration plant data are included. Distances between supplier and production plant, transportation type, vehicle, and fuel type are included in transportation analyses. In addition to that, energy optimization scenarios applied for the production plant. Electricity consumption is not a major source of environmental impact categories for two products. But the required electricity is only provided from the grid mix for all products in the factory. Wind turbine and photovoltaic systems are used for environmental impact comparison with grid mix. Energy supply scenarios show their contribution to the environment while producing 1 kW/h.

Chemicals and deionised water are widely used during the production of surface treatment chemicals. Deionized water is one of the common raw material in both products. There is a water preparation system in the factory. The system provides to convert tap water to deionized water. Production includes the mixing of the raw materials specified in the instructions with the rates for a specific time in the mixer and filling in the packaging in an automatic filling machine.

All data used in the research were taken from the real production facility for the first six months of 2019. Ganzheitliche Bilanz (GaBi) 7.3 software and Ecoinvent database were used to analyze inventory data. The data were collected based on inputs and outputs for each process within the production flow chart. Production input data includes supply and shipment of materials and chemicals, water, etc. and consumption of energy.

The results obtained of the study are determined by dividing into various CML impact categories that are located in the GaBi software program. These impact categories include global warming potential (GWP), abiotic depletion potential (ADP fossils and elements), acidification potential (AP), eutrophication potential (EP), freshwater aquatic toxicity (FAETP), human toxicity potential (HTP), ozone layer depletion potential (ODP), photochemical ozone depletion potential (POD), terrestrial ecotoxicity potential (TETP) were selected and necessary evaluations were completed.

According to the results of the comparison, it is determined that product B had more negative effects on the environmental impact categories than product A. Only in the GWP impact category, product A has a more impact on the environment than product B. The results show that almost all environmental impact categories of zinc phosphating chemical production both products A and B are affected due to raw material consumptions. Nitric acid production and phosphoric acid production are the major contributors to both products about all impact categories. Not only the environmental impact comparison of the two chemicals with each other but also the results of similar chemicals life cycle assessment studies are compared in the literature with product A and B. Three environmental product declarations (EPD) are used for comparison. These products are used as coating chemicals for different purposes in different industries. Results of EPD's and two products are different from each other in impact categories. It is seen that, the results are directly affected by type and amount of raw materials. In addition to that, to show the environmental impact of producing 1

kW/h electricity from grid mix and renewable sources, wind turbine, photovoltaic, and grid mix results were compared to each other. Producing electricity from the wind turbine is a more environmentally friendly option when it's compared with photovoltaic and grid mix.





# ÇİNKO FOSFATLAMA KİMYASALLARININ ÇEVRESEL YAŞAM ANALİZ DEĞERLENDİRMESİ

## ÖZET

Hızla artan dünya nüfusu ile birlikte sanayileşme önem kazanmıştır. Zaman içerisinde üretimler beden gücünden makina gücüne evrilmekle birlikte nitelik ve nicelik açısından çeşitlilik kazanmıştır. Daha çok üretim ihtiyacının duyulması ile birlikte sanayileşme artık doğurduğu çevresel problemlerle de anılmaya başlanmıştır. Sanayi devriminden günümüze kadar geçen süre içerisinde özellikle son dönemlerde sürdürülebilirlik herkes tarafından yakından takip edilen bir konu haline gelmiştir. Toplumsal duyarlılığın artması, yeni başlanacak projelerde ya da mevcutda bulunan üretim sistemlerinde gerekli iyileştirmeler yapılması gerekliliğini yapılan ürün yaşam döngüsü analizleri ile ortaya çıkartmaya başlamıştır. Ürün yaşam döngüsü, bir ürünün veya hizmetin hammadde elde edilmesi, üretim, kullanım, bertaraf ve bu aşamalar arasındaki tüm aşamalarının her birinin süre boyunca yol açtığı çevresel etkileri değerlendirmek için kullanılan yaygın bir yöntemdir (Journal of Environmental Management,2010). Doğal kaynakların hızlıca yok olması ve doğadaki sanayi kaynaklı çevresel etkilerin artması gelişmiş ülkeleri ürün yaşam analizi çalışmalarını arttırılmalarını ve gerekli önlemlerin alınmasına neden olmuştur. Metal yüzey işlem kaplama kimyasalları metal kullanımının süregelen artımı ile doğru orantılı olarak arttığı görülmektedir. Bu çalışmanın ana amacı, metal endüstrisinde yaygın olarak kullanılan metal yüzey işlem kimyasallarının üretimi esnasında oluşan çevresel etkilerinin ürün yaşam döngüsü değerlendirmesi yaklaşımı kullanılarak sonuçların değerlendirilmesidir.

Metal, eski zamanlardan beri birçok endüstride yaygın olarak kullanılmaktadır. Metal, çevresel koşullardan etkilenir ve zamanla hasar görür. Hasarı önlemek ve malzeme ömrünü uzatmak için çeşitli ek kimyasallar kullanılmalıdır. Bu kimyasallara metal ön işlem kimyasalları denir ve bu bir tür yüzey işlemdir. Yüzey işlemi, malzemenin yüzeyine uygulanarak değişik amaçlarla daha iyi hale getirmek için uygulanan bir işlemdir. Bu kimyasallar, farklı uygulamalarda ve çeşitli amaçlarla kullanılabilir. Bu kimyasallar geniş alanlarda ve farklı uygulamalarda kullanılmaktadır. Otomotiv, elektronik, inşaat ve ambalajlama metal ön işlem kimyasallarının yaygın olarak kullanıldığı sektörlerdir. Metal ön işlem kimyasal kullanımı doğrudan metal kullanımından etkilenir ve artar. Metal ön işlem kimyasalları genellikle üç kategoride sınıflandırılır: çinko fosfatlama kimyasalları, mangan fosfatlama kimyasalları ve demir fosfatlama kimyasalları. Bu çalışmada çinko fosfatlama kimyasal üretimi çevresel etkileri kapsamında incelenmiştir. Bu kimyasal, endüstrilerde korozyon koruması, yağlama, dekorasyon ve yalıtım amaçları için kullanılır.

Bu çalışma içerisinde, metal endüstrisinin vazgeçilmez bir parçası olan yüzey işlem kimyasallarının üretimi aşamasında kullanılan hammadde, su, malzeme ve enerji tüketimi açısından değerlendirmesi bulunmaktadır. Bu amaçla, çalışmada farklı formülasyonlara sahip iki çinko fosfatlama kimyasalı kullanılmıştır. Bu kimyasallar

birbirlerinin yerine kullanılabilenmektedir. Ürünler arasında iki fark vardır, bunlar ürünlerdeki hammadde türü ve hammadde miktarıdır. Bu çalışmada, bu ürünler A ürünü ve B ürünü olarak adlandırılmaktadır.

Üretim sürecinin sürdürülebilirlik açısından mevcut durumu çevresel yaşam analizi yaklaşımı ile analiz edilmektedir. Çalışma içerisinde, metal yüzey işlem kimyasalı üretimi yapan bir fabrikanın farklı iki çinko yüzey kaplama kimyasallarının tüm üretim aşamaları incelenmektedir. Sistem sınırları hammadde temininden başlayarak, ürünün fabrikadan çıktığı ana kadar geçirdiği işlemleri süreyi kapsamaktadır. Ayrıca çalışmada ulaşımın etkileri araştırılmıştır. Kimyasalların ve malzemelerin taşınması ve atıkların tehlikeli atık yakma tesisine taşınma ait bilgiler dahil edilmiştir. Tedarikçi ve üretim tesisi arasındaki mesafe, nakliye tipi, araç ve yakıt tipine ait bilgiler analiz içerisinde yer almaktadır. Ek olarak, üretim tesisi için enerji optimizasyon senaryosu bulunmaktadır. Elektrik tüketimi her iki ürün için de çevresel etki kategorileri içerisinde baskın kaynak değildir. Ancak, fabrikada üretilen tüm ürünler için gerekli olan enerji şebekeden sağlanmaktadır. Şebekeden elde edilen elektriğin çevresel etki sonuçları ile karşılaştırmak üzere üzgar tribünü ve güneş paneli kullanılmıştır. Enerji temin senaryoları 1 kW/h elektrik tüketimi sırasında oluşan çevresel etkileri göstermektedir.

Yüzey işlem kimyasallarının üretimi esnasında kimyasallar ve deiyonize suyu ağırlıklı olarak kullanılmaktadır. Deiyonize su her iki üründe de ortak olarak kullanılan hammaddelerden biridir. Fabrikada su hazırlama sistemi bulunmaktadır. Sistem musluk suyunun deiyonize suya dönüştürülmesini sağlar. Üretim genel anlamda, reçete içerisinde oranlar ile belirtilen hammaddelerin mikser içerisinde belirli bir süre karışması ve otomatik dolum makinasında ambalaja doldurulmasını kapsamaktadır.

Araştırmada kullanılan tüm veriler gerçek üretim tesisinden 2019 yılı ilk altı ayı için alınmıştır. Envanter verilerini analiz edebilmek için Ganzheitliche Bilanz (GaBi) 7.3 yazılımı kullanılmıştır. Veriler, üretim akış şeması içerisinde her bir işlem için girdilere ve çıktılara bağlı olarak toplanmıştır. Üretim girdi verileri enerji ve kimyasal, su vb malzemelerin teminini ve sevkiyatını içermektedir. Çalışma sonucunda elde edilen sonuçlar, GaBi yazılımı içerisinde etki kategorisi başlığı altında çeşitli etki kategorilerine bölünerek belirtilmiştir. Bu etki kategoriler, küresel ısınma potansiyeli (GWP), abiyotik tükenme (ADP fosilleri ve elementleri), asitleşme potansiyeli (AP), ötrofikasyon potansiyeli (EP), tatlı su sucul toksisitesi (FAETP), insan toksisite potansiyeli (HTP), ozon tabakası incelme potansiyeli (ODP), fotokimyasal ozon tüketme potansiyeli (ODP), arazi ekotoksisite potansiyeli (TETP) seçilmiş ve gerekli değerlendirmeler yapılmıştır.

Karşılaştırma sonuçlarına göre, B ürününün çevresel etki kategorileri üzerinde A ürününden daha olumsuz etkileri olduğu belirlenmiştir. Yalnızca GWP etki kategorisinde A ürününün çevre üzerinde B ürününden daha fazla etkisi vardır. Sonuçlar, çinko fosfatlama kimyasal üretiminden kaynaklanan hemen hemen tüm çevresel etki kategorilerinin hem A hem de B üründe hammadde tüketimi nedeniyle olduğunu göstermektedir. Nitrik asit üretimi ve fosforik asit üretimi, her iki ürüne de tüm etki kategorileriyle ilgili önemli katkılarda bulunmaktadır. Sadece iki kimyasalın birbiriyle çevresel etkileri açısından karşılaştırması değil, literatürde yer alan benzer kimyasallar ait yaşam döngüsü değerlendirme çalışmalarının sonuçları da ürün A ve B'nin sonuçları ile karşılaştırılmıştır. Karşılaştırma için üç çevresel ürün bildirim (EPD) kullanılmıştır. Bu ürünler farklı endüstrilerde farklı amaçlar için kullanılan kaplama kimyasallarıdır. Çevresel ürün beyanları ve iki ürünün sonuçları etki

kategorileri aısından birbirinden farklıdır. Sonuların hammadde tr ve miktarından doėrudan etkilendiėi grlmektedir.

Buna ek olarak, Őebekeden ve yenilenebilir kaynaklardan 1 kW/s elektrik retmenin evresel etkisini gstermek iin rzgar trbini, gneŐ enerjisi ve Őebekenin sonuları birbirleriyle karŐılaŐtırıldı. GneŐ enerjisi ve Őebeke ile karŐılaŐtırıldıėında rzgar trbiniinden elektrik retmek daha evre dostu bir Őeenektir.





## **1. INTRODUCTION**

### **1.1. Importance of the Study**

Nowadays, the population of the world grows day by day, and the consumption of natural resources is rapidly increasing to meet people's needs. Every new day is a risk for today's populations and the next generations in the view of environmental conditions. Many types of natural sources are depleted due to industrial demands and unfortunately, there is no option to create a new natural source. The important point is that it is possible to minimize damage to natural sources with engineering solutions.

The depletion of natural sources and environmental pollution because of the industry can be addressed as one of the most important environmental problems (Gutti B. and oth., 2012). Because of the increasing consumption of sources with industrialization, natural resources are decrease and its more and more polluted day by day.

Metals are the backbone of civilization and industrialization. It is commonly used in lots of industries and different ways and functions (Cyril O. and oth., 2017). Today, metals are used as indispensable input in many industries. Metal manufacturers have some issues with metal life. Corrosion, rust and some problems seen in metals have suggested that metal coating chemicals are a need (Fine Homebuilding,1997). The metal coating chemicals are commonly used in industries in different processes. The treatment of metals is an essential significance in many different industries. It is possible to say it is not a new process in today's condition because the similar process of coating has been used for gold decoration in 4000 BC (Practical Building Conservation: Metals, 2012).

There are lots of companies that produce metal surface and pre-treatment chemicals which depends on the demand of customers' requirement in all around the world.

The coating of metal materials has evolved into a big business, covering a huge amount of commercial applications. Metal is very prone to corrosion because of its structure. Corrosion is a chemical reaction that in metal reactions with atmospheric moisture and oxygen gas convert to metallic oxides within the environment. According to The World Corrosion Organization, the global cost of corrosion to be approximately US\$

2.5 trillion yearly based, and that a huge part of this cost - as much as 30%-35% - could be resolved by applying basic precautions (Url-1).

The tendency of metals to corrosion caused the formation of protective chemicals it is called pre-pretreatment chemicals. The consumption of pretreatment chemicals directly affected by the usage of metals. The pre-treatment chemicals offer an option to make metals more resistant to corrosion and have a long life.

One of business company it is called a Markets& Markets has researched about metals consumption in all around the world with a global company. Related research shows that coating pretreatment market size was estimated to grow from USD 2.89 Billion in 2016 to USD 3.83 Billion by 2021. Increasing demand from its end-use industries is the main reason for the rapid growth of the coating pretreatment market is the increment (Coating Pretreatment Market Report,2016). According to the Paint and Coating Industry Report that was released by Republic of Turkey Ministry of Economy, Turkish paint and coatings industry has a big place in paint and coating markets in Europe. Turkey reached a 2% market size in total market size of 850.000 tons with 2 billion USD in global paint and coating industry according to the 2018 data. Environmental problems will be inevitable that occurred with increasing production amount of metal pretreatment chemicals shortly soon.

In addition to that, there is a piece of limited information in the literature on the sustainability and life cycle assessment of zinc phosphating chemical production and usage in industry. It is an area that requires scientific attention for the next years.

A life cycle assessment is a method of monitoring the different phases of the life of a product or a process. It provides to determine the main environmental impact categories (Li Y. and oth. (ed),2016). By this mean, the manufacturer may work on their process that reduces the impact on the environment and make the product more sustainable. Life cycle assessment is a method of monitoring the different phases of the life of a product or a process. It provides to determine the environmental impact of the life cycle, by this mean manufacturer may work on their process that reduces the impact on the environment and make the process more sustainably. Previous research shows that the results of the study and new approaches contribute to protecting the environment.

## **1.2. Aim and Scope of the Study**

The main objective of this study is to evaluate the environmental burdens of widely used two different zinc phosphating chemical formulations by the life cycle approach. By doing so the more environmentally friendly alternative will be addressed, zinc phosphating chemicals are among the type of metal coating chemicals. It can be a type of manual for producers, and also it can be used in selecting of chemicals stage before the production. Finding more environmental-friendly production applications are always the most effective way of reducing environmental impacts. Therefore, it can be a good opportunity to decrease to environmental impacts of chemicals with replacement methodology.

In this context, an inventory of inputs and outputs of the production stage was collected from the formulation plant that is located in Kocaeli/Turkey. This study covers information and assessment from raw material production to production in the plant. All results are given according to the functional unit of 1000 kg chemical.

In this study, two different zinc phosphate chemicals that can be used as substitutes, are compared in the scope of environmental impacts. There are two differences between two chemicals. The first one is, one of the comparable chemicals it is called A has an additional input of iron sulfates, the other chemical that is called B, does not include iron sulfate input. The second difference is, besides the iron sulfate the rest of the chemicals input the same but the amount of them is different. Both chemicals are produced in the same production mixer and all inputs like raw materials, electricity, process water, and packages are provided from the same supplier.

The study divided into 6 chapters. General information and literature review about metal surface treatment, life cycle assessment and applied life cycle assessment related to zinc phosphating chemical's inputs are presented in Chapter 2. The materials and methods of this study in the view of goal and scope, functional unit and system boundary are considered in Chapter 3. Chapter 4 describes the process of zinc phosphating chemicals production in the scope of input and output data of the system is mentioned. Information about results and discussion of the study is described in Chapter 5. In Chapter 6 concluding remarks and recommendations are given.



## **2. LITERATURE REVIEW**

### **2.1. Metal Surface Treatment Technologies**

Most materials need an additional coating to improve the appearance of the material and to protect it from the environment. Surface finish chemicals can be applied by different practices like brushing, spraying, and dipping (European Commission, 2006). The practice of surface chemicals depends on the surface and the material's qualifications.

The metal pre-treatment industry has a key role in extending the life of metals. Generally, surface treatment products are preferred for many types of processes such as cleaning, coating, and sealing of metal surfaces. It provides to improve paint adhesion and corrosion protection on metal surfaces. It is also used for increasing the safety of materials and decreasing consumption of other materials and raw materials. The surface treatment products do not create products or new materials, they only change the surface specifications of beforehand formed products or materials for ensuing use. It is a process that provides to increase the mechanical, electrochemical, and thermal performance of a material. Using surface treatment chemicals it is possible to reduce process steps, improve efficiency and facilitate process cost savings. The surface treatment of metals service to largely in many industries such as 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). In addition to that, surface treatment chemicals also provide to reduce the consumption of raw materials that will be used in other steps of production.

The metals have been common use in the industry since old times. The selection of proper surface treatments is based on getting a complete set of requirements on the surface parts with a suit to intended both operating and process conditions. There are two essential points for selecting correct surface treatment; the first one is, part specifications should be converted into specifications of materials and layers, the second one is chosen surface technologies must be suitable in corresponding process

steps (Tillmann W., Vogli E., 2006). In addition to that, another important point is production costs and environmental expectations. Some specialized products may need specific functions and it creates cost. For selecting any type of surface treatment, it needs to understand and assess the requirement of operation, a very large variety of possible materials and technological processes. The correct time to decide which type of surface treatment is used is an early stage of product or process development.

Surface treatment technologies provide some advantages:

- To decrease requirement energy and water
- To decrease the consumption of a product
- To decrease the generate of wastes
- Reduction of process steps
- Reduction of cycle periods
- To provide environmental benefits

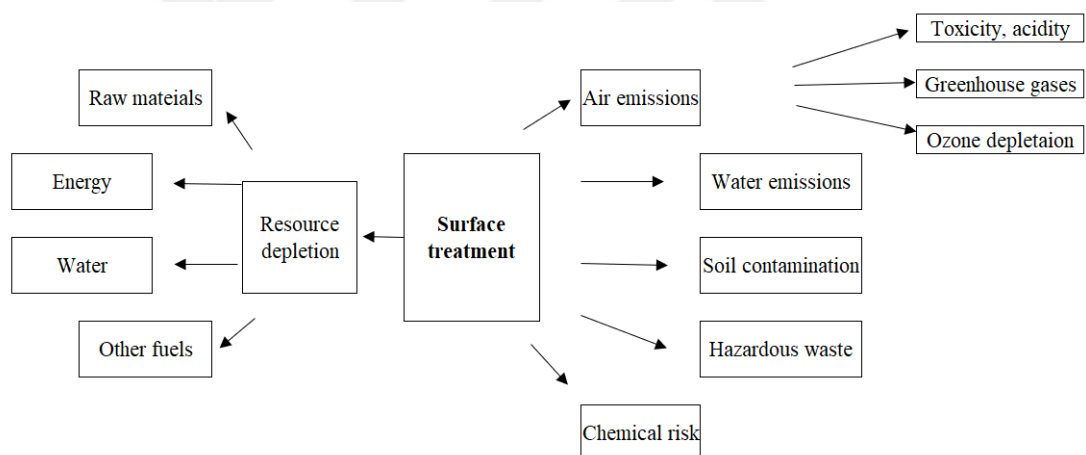
## **2.2. Environmental Impact of Metal Surface Treatment Chemicals**

The surface treatment industry has a key role in the life of metals. The metal industry is important in the country's economics due to manufacturing, employment, and export. By the year 2029, the stainless steel market is estimated to growth 150% in terms of market volume (Cottage V. 2019). The increase in the production of surface chemicals is directly proportional to the increase in metal production. The surface treatment chemicals have a lot of environmental impacts. The main environmental problems from the surface treatment of metals relate to energy and water consumption, the consumption of raw materials, emissions to surface and groundwater, hazardous and nonhazardous wastes, the production plant condition on the shutdown of activities (European Commission, 2006). The chemicals used in the process have the potential to affect environmental harm especially to surface waters, groundwaters, and soil. It can be classified as a chemical risk. With the environmental perspective, the things that we do not want to emit are substances that are stable, toxic and/or bio-accumulable effects on the environment.

- Decreasing the effect on the external environment,
- Integrating processes that are not harming the environment,

- Finding a new solution for pollutant chemicals like using substitutes,
- Decreasing the amount of waste (Url-2)

In addition to that, source consumption is another important environmental burden of surface treatment chemical. These are energy, water, raw materials (SPIN Sustainable Production through Innovation in SMEs,2012). The water is required for cleaning, activation, and phosphating stage. The sources of chemicals are working as an additive in stages of phosphating. The solid waste occurs from packaging activities, and wastewater occurs from the cleaning steps of the process. Electricity consumption of process and emission from transportation materials are also caused more carbon footprint. Conventional coating processes produce VOC emissions because these are a solvent-based type of coatings. It needs to be required under control with several devices as carbon adsorption units, condensers or thermal catalytic oxidizers (Tamilselvi M. And oth. 2015). Figure 2.1 describes upstream and downstream of the surface treatment chemicals chart.



**Figure 2.1 :** Upstream and downstream of surface treatment chemicals.

Producers and users of surface treatment chemicals should consider environmental conditions to achieve better environmental performance. The surface treatment production plants that exist in the industrialized part of the world should use chemical precipitation to minimize environmental burdens. The metal coating chemicals are necessary for metals in the scope of a lifetime. On the other hand, it has some important environmental impacts both on the production step and usage step (European Commission, 2006).

- Reduction of the consumption of raw materials, energy and water sources

- Reduction of emissions using pollution control parameters
- Reduction of waste generation and its appropriate management
- Progress of chemical safety and decrease of environmental accidents.

### **2.3. Phosphate Coating Process**

Phosphate coating is one of the most appropriate methods for surface treatment of metal in the industrial area. The phosphating chemicals have been used most widely in several industries to provide corrosion protection since the last century. Generally, they are used to treat steel, aluminium, and zinc: (European Commission, 2006).

- Cold forming: this includes very high surface forces and, phosphating can be used in all types of cold forming processes.
- Coil coating: this includes steel strip electroplated by zinc phosphate in the process to improve formability in consequent drawing processes
- Rustproofing: heavy zinc and manganese phosphate coatings maintain a protective oil film and, it presents important corrosion prevention.
- Bearing surface lubrication: manganese phosphate increases the retention of lubricant and reduces running-in times.
- Painting: phosphating improves the adhesion and corrosion stability of paints

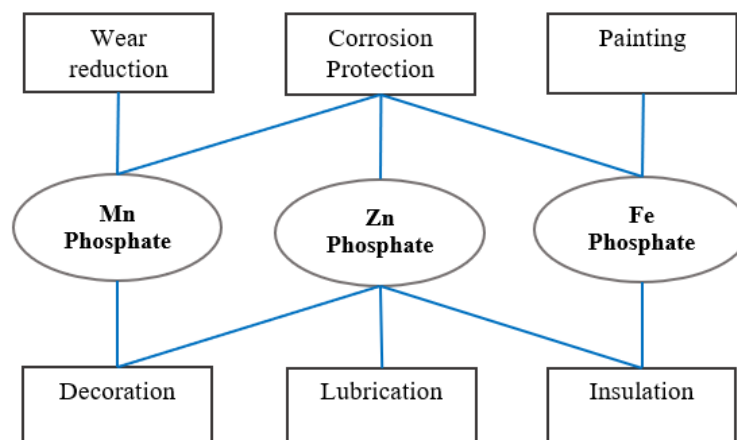
The coating process generally applies in industries that have a metal surface in their production stage. Phosphating chemicals are the most common process that preferred for metals in surface treatments. It is a typical pretreatment process to save surfaces from environmental conditions in time. Thus, it is possible to create a new layer of material using phosphating chemicals and it provides new specifications for materials. It has a key role in many production areas because of the price, operation speed, resistance of corrosion and wear, adhesion and lubricative properties.

The phosphating process can be defined as the treatment of a metal surface. End of the treatment it gives a hard, electrically non-conducting surface coating with insoluble phosphate. And, it is a type of topochemical reaction (Narayanan,2005). The topochemical reaction is a chemical reaction that happens at the top of solid phases. The coating is a result of a topochemical reaction, that causes the surface of the base metal to render itself as a piece of the corrosion-resistant film.

The structure of a coating is determined by the mechanism of its formation. There are three major steps contribute to metallic powders;

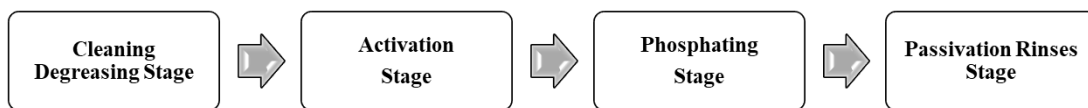
- Heating and melting in partial or total,
- Interacting with the oxygen of the air in a surface,
- Contacting with the surface of the base metal or contiguous layer (Tushinsky L. and oth., 2002)

A wide variety of coating processes have been developed in the past years to achieve coatings with desired specifications to meet surface requirements. The phosphate coating chemicals involve the chemical conversion of metal surfaces between chemicals. Phosphate crystals are formed on surfaces including zinc, manganese or iron phosphates. The iron phosphate coating is a simple process, but it has lower corrosion resistance (Wang C. and oth. 2006). Iron phosphate coating is commonly used for temporary corrosion resistance applications rather than permanent works (Wang C. and oth. 2006). Iron phosphate can provide paint adherence with more flexibility. Another advantage of iron phosphate is it can be used in cleaning and etching steps of aluminium or galvanized metals (Url-3). Zinc phosphate coating has a good impact on corrosion resistance. Generally, it is used for the surface finishing process and also as a bond coat for the painting process. This coating chemical is commonly used in industries like automotive, metals and aluminium due to high performance on corrosion. Manganese phosphate coating has the highest hardness of the three types of phosphate coating chemicals and, it has the best corrosion and wear resistance performance on products (Wang C. and oth. 2006). Figure 2.2 shows that general application of three phosphate coating chemicals.



**Figure 2.2 :** Applications of phosphating chemicals.

The phosphating process is not a single chemical process, it is a tiered process. It takes place at the solid-liquid phases and continues until the balance is completed (Duszczuk J. and oth., 2018). In general, the phosphating process includes four main stages and figure 2.3 shows the phosphate chemical process flowchart. Also, that depending on the surface conditions of the metal, some of these stages may be taken out or additional stages may be integrated into the operation. The phosphating process includes the cleaning degreasing stage, activation stage, phosphating stage, and final passivation stage. In practice, the process can be extended using additional baths and chemicals to get high quality of product and reduce costs of operations (Ozcanak,2008).



**Figure 2.3 :** Phosphate coating process flowchart.

There are lots of phosphating chemicals for use in different types of materials and surfaces. The main differences are their ingredients between each other.

A few simple activities require to reach for final treatments. The stage of the process is changeable due to the requirements of materials coated with phosphating chemicals.

The phosphating process forms a layer of the desired property that comprises multiple steps. In every stage, surfaces are prepared for the next one with some operations. By this means, the time needs of the next stages may be shorter and it may provide to be faster for processes (Narayanan,2005).

- Benefits of stage application include:
- Decreasing time of the process,
- Decreasing rejects,
- Making a product with high quality,
- Decreasing costs of the process,
- Decreasing the environmental impact of products

**Cleaning Stage:** Chemical cleaning is the first part of a process to prepare products for the next steps or final treatment. It is possible to dispose of unwanted taints, contamination, dust or accumulation from the surface.

There are many options for chemical decreasing stages. It depends on the type, size, and properties of products. Dipping and spraying are most preferable in industries. A very simple cleaning system may include only force, such as an air blower or a dry grit blast. For example, if the equipment size is so huge as an automobile, the process should be dipping. The dipping process occurs in a huge tank, the equipment immerses in the chemical tank or pool to clean the entire surface. Chemical spraying applies with nozzles and sprays tubes, it is related to equipment.

The main purpose of the cleaning stage is;

- Total elimination of surface soils, oils, dirt's
- Prevention of contamination of soil on the surfaces
- Removing of all residues of the cleaner solution and soils
- Prevention of cleaner drag out from entering the surface conditioning stage

For the cleaning degreasing process generally, surfactants and alkaline components such as carbonate, caustic, alkaline phosphate and silicates are preferred. To select degreasing chemicals, there are some important points: (Yoshihara, 1983). Chemicals should be capable of degreasing even component subjected to dipping.

- Even the surface is rust-preventive oil, chemicals should be having degreasing capability
- Chemical should be hard to generate foam in spray operations
- Chemical should be having satisfactory qualification for oil separating

The rinsing step should be followed when chemical degreasing operation is completed. Rinsing prevents the hold of chemicals used in the earlier stages. And, it prevents contamination to the next stages.

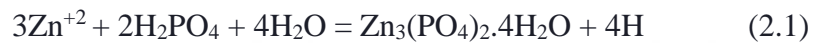
**Activation stage:** The activation step is applied for an increasing amount of phosphate crystals per unit area. This process is used to coat the surface with a uniform film layer in the next process naming the phosphating process.

**Phosphating stage:** Properly cleaned and activated surfaces are next subjected to the phosphating stage. The correct choice of the components and the operating conditions and requirements of the phosphating bath are made based on the properties of the material to be processed and its final use. The phosphating process takes in steps at the

solid-liquid interface and continues until the balance is completed. It should be carried out at temperatures from 30 C to 99 C (Narayanan,2005). The main components of phosphating reactions:

- Phosphoric acid (H<sub>3</sub>PO<sub>4</sub>)
- Ions, cations of bivalent metals: Zn<sup>2+</sup>, Fe<sup>2+</sup>, Mn<sup>2+</sup>
- Accelerator – an oxidizing reagent (nitrate, nitrite, peroxide) (Saji, 2007)

The main principle of phosphating is that it converts to a coated phosphate layer of the metal surface after immersion in phosphoric solutions. The normal reaction for zinc phosphate coated can be defined as follows: (Weng and oth.,1998)



Or



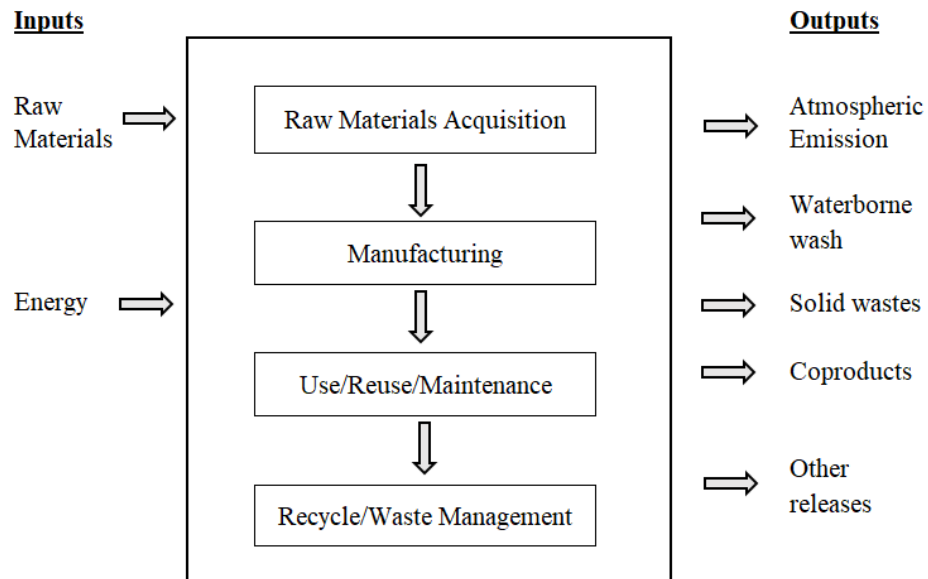
**Passivation rinses:** After phosphating, it is necessary to remove water from soluble salts, acid residue, and nonadherent particles. The important thing is, ensure that the water supply is sufficiently free. The passivation process prevents surface contamination with a type of chemical dissolution. Generally, nitric acid is used widely in the passivation rinses stage (Parsons S. and oth., 2019).

The main purpose of passivation rinses stage is:

- Prevention of surface drying and flash rusting
- Prevention of drag outs
- Prevention of blister formation

#### 2.4. Life Cycle Assessment

Life Cycle Assessment is a tool that provides to assess the environmental impacts throughout a product, materials, and processes. It is possible to evaluate for all supply chain of materials from raw material extraction to final products and it includes the assessment of environmental impacts of products or services. Life cycle assessment (LCA) is an ISO 14040 type of methodology for the environmental assessment of industrial systems (ISO 14040). Figure 2.4 illustrates the system boundary stages according to EPA,1993.



**Figure 2.4 :** System boundary stages (EPA,1993).

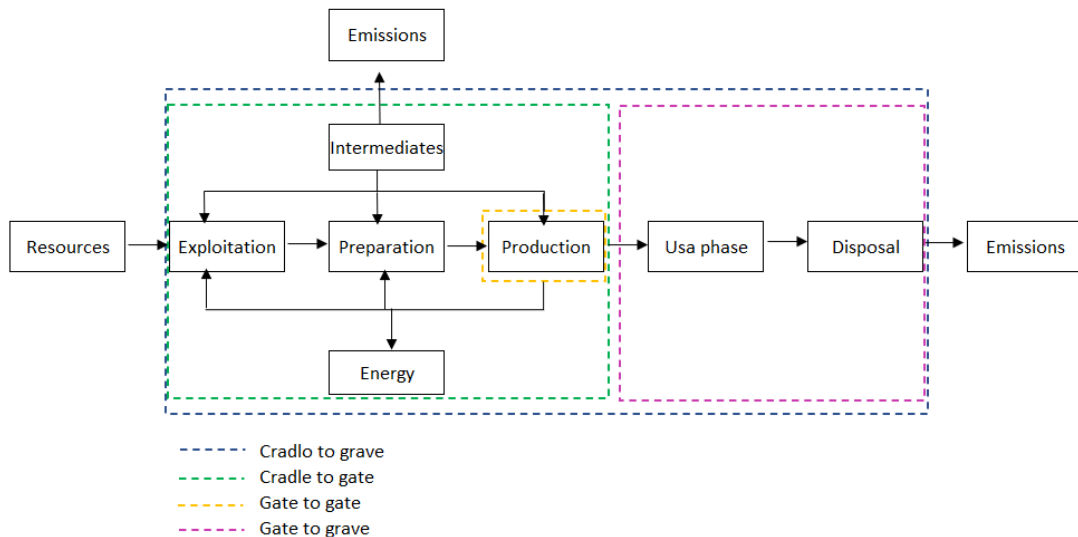
There are many approaches to assess or calculate to environmental impacts of a product or process based on a step by step. Selecting the approach method is can be variable in production processes or services and also the aim of the study.

Cradle to grave is commonly used in studies and it means that, all life cycles of a product from raw material extraction stage to disposal stage (Curran,2006). This approach includes the staging of raw material extractions, transportation of the product, the process of products and its end of life with disposal method.

Cradle to the gate is another approach, that includes the raw material extraction stage to the production stage. It is not assessed product life after leaves the production area.

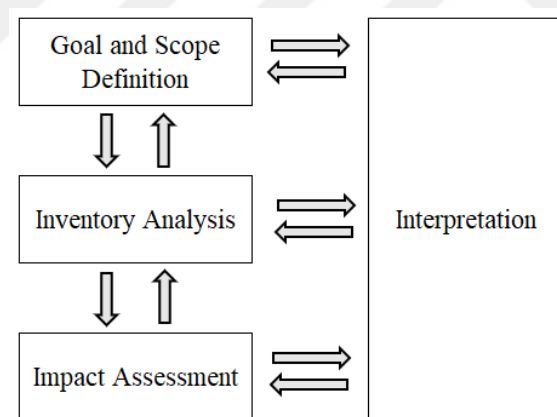
Cradle to cradle approach is a technique that provides to assess all environmental burdens associated with all stages of a product; from extraction raw materials to reuse stage that means it is possible to use it as a raw material in different or same processes (Muralikrishna I. and Manickam V., 2017).

Gate to gate approach is another option for assessing the environmental impact of products, it is only related in production stage; in this approach no need assess to background information or end of life information of a products. Figure 2.5 shows the basic system boundary types within a life cycle assessment.



**Figure 2.5 :** Basic options to select system boundaries.

It is possible to assess of environmental impacts of a product from one stage to many stages. With this approach, only one stage can be assessed or emphasize one stage's environmental burdens. According to the ISO 14044, life cycle assessment framework is available in figure 2.6.



**Figure 2.4 :** Life cycle assessment framework (ISO 14044).

### 2.4.1. Goal and scope definition

The process is determined to the goal and scope of the process that includes the boundary of the system and details. The important point for determining goals and scope is closely related to the subject and intent of the study. The detail and level of study can be different according to the goal that is set (ISO 14044:2006). It is possible to give useful inputs to drive correct specific behaviour with well determining to goal

and scope. The functional unit is defined to compare the performance of a product system or services as a reference unit.

#### **2.4.2. Inventory analyses**

The inventory analyses are collecting all of the input and output data regarding products or services. It's the second phase of LCA, and it provides to create an inventory with all raw materials, natural sources, wastes, products, co-products, etc. (ISO 14044:2006). Inventory analyses is one of the most important and time-consuming phases for all study to get an outcome of a life cycle impact.

#### **2.4.3. Life cycle impact assessment**

The main purpose of the Life Cycle Impact Assessment (LCIA) is to evaluate the results from inventory analysis of a product's environmental impacts in a comparable way. It provides to consider the potential environmental impacts of the products. LCIA includes three stages to get a result from the study; selection of impact assessment methods, selection impact categories and characterization (Capaz, Seabra, 2016). In the first stage, impact assessment methods aim to reach a life cycle inventory result in its potential environmental burdens. Life cycle inventory results are classified with impact categories according to the ISO 14042 Environmental management-Life cycle assessment-Life cycle impact assessment.

In the characterization stage, each selected category in the last stage is quantified the potential impacts due to the flows defined in the product system. These potential impacts are evaluated according to the characterization factors.

#### **2.4.4. Interpretation**

In the interpretation stage, the results are obtained from the life cycle inventory assessments and discussed to the goal and scope of the study. The not only result of the study, but also potential environmental impacts are also considered.

### **2.5. Applied Life Cycle Assessment Studies**

Various LCA databases can be used to identify and compare the environmental effects and loads of phosphating chemicals. The metal surface treatment chemicals are commonly used in different industries as a part of their processes. It is produced by many companies globally and locally. Unfortunately, there is no directly LCA study related to this subject and different options with the green industry. There are some

environmental product declarations (EPD) for various coating chemicals. The environmental product declarations do not consist of detailed information about the process or service like literature studies, it just gives results of the assessment. Three different coating chemicals EPD are used for comparison in this study. (Url-4), (Url-5), (Url-6).

Deutsche Bauchemie e.V. prepared an EPD related to methacrylate resin products, highly-filled, flow coatings preliminary products in 2013. (Url-4) It's a two-component reactive resin. The chemical is widely used in different areas such as construction, furnishing, repairing, and waterproofing of buildings Methacrylate formulations and hardening agents are used in the production step. In this EPD, the environmental impacts of the product were declared according to 1 kg functional unit and the GaBi 6 software program was used for calculations with background data. The system boundary includes the manufacturing of raw material extraction and production and packages, transportation to plant, energy usage, waste treatment and installation of the plant. The functional unit was declared as a 1 kg product.

This EPD will be referred to as EPD1. Table 2.1 illustrates the results of the study based on environmental impact categories.

**Table 2.1** : The environmental impact results of methacrylate resin products, highly-filled, flow coatings EPD (Url-4).

Impact Categories	Unit/fu	Results
GWP	[kg CO <sup>2</sup> eq.]	1.92E+00
ODP	[kg CFC11 eq.]	3.03E-10
AP	[kg SO <sup>2</sup> eq.]	6.84E-03
EP	[kg (PO <sub>4</sub> ) <sup>3</sup> eq.]	4.68E-04
POCP	[kg ethene eq.]	1.38E-03
ADP Elements	[kg Sb eq.]	1.95E-05
ADP Fossil	[MJ]	4.30E+01

According to the results, in ODP, material extraction and production phases (> 80%) and production (<10%) are largely contributed (Url-4). Approximately 60% of the AP is coming from to sulphur dioxide which is emitted during the production of the resins.

Preliminary products have approximately 75% and production have approx. 10% of the AP. Approximately 65% of the EP is caused by the manufacture of preliminary products, and the resins have the highest influence on the EP. On the contrary of the other impact categories results, in POCP category is not dominated by the production of preliminary products. The largest share (50%) is coming from the installation of the methyl methacrylate product (Url-4).

Verband der deutschen Lack- und Druckfarbenindustrie e.V. prepared an EPD about epoxy powder coating chemicals 2017 (Url-5). The coating chemical is an organic, thermally-hardening, duroplastic material. The coating chemical generally used in used on steel and aluminum substrates in internal applications and provides some specifications for materials like protection and resistance to chemicals. In addition to that, it's used in the construction sector, heating and sanitary ware, pipes, doors, and railings. Declared functional unit is 1 kg epoxy powder chemical and the EPD was prepared following with cradle to gate approach. The system boundary includes supplying raw materials and energy input, manufacturing, and transportation of materials and the treatment of all waste. In this study, this EPD will be referred to as EPD2 (Url-5). Table 2.2 shows the detailed results of the epoxy powder coating's EPD.

**Table 2.2 :** The environmental impact results of epoxy powder coating EPD (Url-5).

Impact Categories	Unit/fu	Results
GWP	[kg CO <sup>2</sup> eq.]	6,47E+00
ODP	[kg CFC11 eq.]	3,43E-10
AP	[kg SO <sup>2</sup> eq.]	1,32E-02
EP	[kg (PO <sub>4</sub> ) <sup>3</sup> eq]	1,60E-03
POCP	[kg ethene eq.]	1,94E-03
ADP Elements	[kg Sb eq.]	2,80E-05
ADP Fossil	[MJ]	1,12E+02

The largest contribution is coming from the production phase and the upstream chain related to the raw material supply. The main cause of the raw material production step's impact is coming from binding agents and titanium dioxide (Url-5). The titanium dioxide also the main cause of AP of Soil and Water and ADP of non-fossil resources

(Url-5). The binding agent plays a big role in all other environmental impacts within raw material supply impact categories (Url-5). An exemption is expressed by the are fundamentally dominated by the binding agent and ODP section in which the titanium dioxide in the numerous environmental impacts is the principal reason for pollution (Url-5).

Polyester-based powder coating EPD study was prepared by Verband der deutschen Lack- und Druckfarbenindustrie e.V. in 2017 (Url-6). The coating chemical refers to a weatherproof polyester powder. The chemical includes polyester resin with a similar curing agent, additives, proper filler, and weather-resistant dyes. This coating chemical is widely used in the construction industry for aluminum and steel materials. 1 kg polyester-based powder coating was declared as a functional unit and cradle to plant gate approach was defined as a system boundary (Url-6). Supplying raw material and system energy, material transportation to plant, production and waste treatment stages were discussed in the EPD (Url-6). In this study, this EPD will be referred to as EPD3. Environmental impact category results according to study are given in table 2.3.

**Table 2.3 :** The environmental impact results of polyester-based powder coating EPD (Url-6).

Impact Categories	Unit/fu	Results
GWP	[kg CO <sup>2</sup> eq.]	4,67E+00
ODP	[kg CFC11 eq.]	3,45E-10
AP	[kg SO <sup>2</sup> eq.]	2,87E-02
EP	[kg (PO <sub>4</sub> ) <sup>3</sup> eq]	9,54E-04
POCP	[kg ethene eq.]	1,93E-03
ADP Elements	[kg Sb eq.]	5,23E-06
ADP Fossil	[MJ]	9,24E+01

Similarly, with epoxy powder coating EPD study results the main environmental loads are coming from the raw material supply and using of binding agent and titanium dioxide. The main impact of AP of soil and water, POCP and ADP elements is coming from the using titanium dioxide. Pigments are directly affected by the ODP category (Url-6). These EPD's have not been directly related to phosphating chemicals. In all

three studies, LCA studies were conducted for different coating chemicals. Since the product's raw materials and usage areas are different, the results are different.





### **3. MATERIALS AND METHODS**

#### **3.1. Aim and Scope of the Study**

The objective of this study is to evaluate the life cycle environmental impacts of two different zinc phosphating chemical formulations that can substitute each other. The study can provide to new environmentally sound solutions in the pre-treatment industry. In addition to that, it can make a key role in finding green substituors besides using chemicals that have a huge environmental impact.

In this study, all inputs and output data that used inventory analysis stage were obtained from the production plant and its standardized according to the ISO 14040:2006 and 14044:2016 (ISO 2006, ISO 2016). The production of zinc phosphating chemicals is considered as a main environmental impact. The production plant located in Kocaeli/Turkey. The study was conducted according to the first 6-months data in 2019. The GaBi software was used to perform LCA with the EcoInvent database. The results that are obtained from the study were compared with surface treatment literature. This study can be used as a guideline for analyzing the environmental impacts of phosphating chemicals production process.

Ten different impact categories are chosen for LCA studies according to the products and processes. These impact categories are global warming potential (GWP), abiotic depletion potential (ADP fossils and elements), acidification potential (AP), eutrophication potential (EP), freshwater aquatic toxicity (FAETP), human toxicity potential (HTP), ozone layer depletion potential (ODP), photochemical ozone depletion potential (ODP), terrestic ecotoxicity potential (TETP) were selected and necessary evaluations were completed.

GWP refers to a long-term change in the planet's weather conditions and average temperatures. It is the main aspect of climate change and has been explained by direct temperature measurements and by measurements of different outcomes of warming. The global warming potential values are calculated in units of kg CO<sub>2</sub> Eq. Transportation is an important contributor to global warming. Because in the transportation process, vehicles consume a large amount of petroleum and energy. In

addition to that, it produces air pollution with particulates and oxides. Trucks and tankers emit carbon dioxide, carbon monoxide, methane, nitrogen oxides, nitrous oxide, particulates during transport. GWP is directly affected by to distance between supplier and production plant, also the amount of the chemicals. The depletion of resources category is an important point of the LCA approach because depletion of one particular natural resource is directly affected to another.

The ADP of a resource was determined as the rate of the yearly total production and the square of the last reserve for the resource distributed by the same ratio for a reference resource(Oers L. and oth. ,2019). ADP (elements) presents an assessment of the availability of natural elements, while ADP (fossil), considered in MJ, involves the fossil energy carriers, such as thick oil, natural gas, and coal(Christoforoua E and oth.,2015). Kg Sb.-Eq. values are considered as the units of ADP elements effect.

AP is an outcome of acids being released to the atmosphere and consequently accumulated in surface soils and waters (Pacheco-Torgal F. and oth., 2016). Kg SO<sub>2</sub>-Eq. values are considered as the units of acidification potential effect.

ODP regards for results correlated to the reduction of the protecting ozone layer within the stratosphere affected by emissions of ozone-depleting materials (Url-7). The kg R11 equivalent values are considered as the units of ozone depletion potential effect.

EP is related to the pollution land of marine ecosystems in which the extreme-fertilization of water and soil has turned into an extended mass of biomass. Kg Phosphate-Eq. values are considered as the units of EP effect.

FAETP defines to impact on freshwater ecosystems caused by emissions of toxic materials to air, water and soil (Url-8). The kg DCB-Eq. values are regarded as the units of FAETP effect.

POCP is related to particular volatile organic compounds and it does not include information about concentrations history and meteorological conditions (Finkbeiner M.,2020). It is declared and assessed in kg Ethene-Eq.

Impacts of chemical material on terrestrial plants are examined in the scope of the TETP category. Studies with TETP are important for protecting our ecosystem. Kg DCB-Eq. values are considered as the unit of TETP in this study.

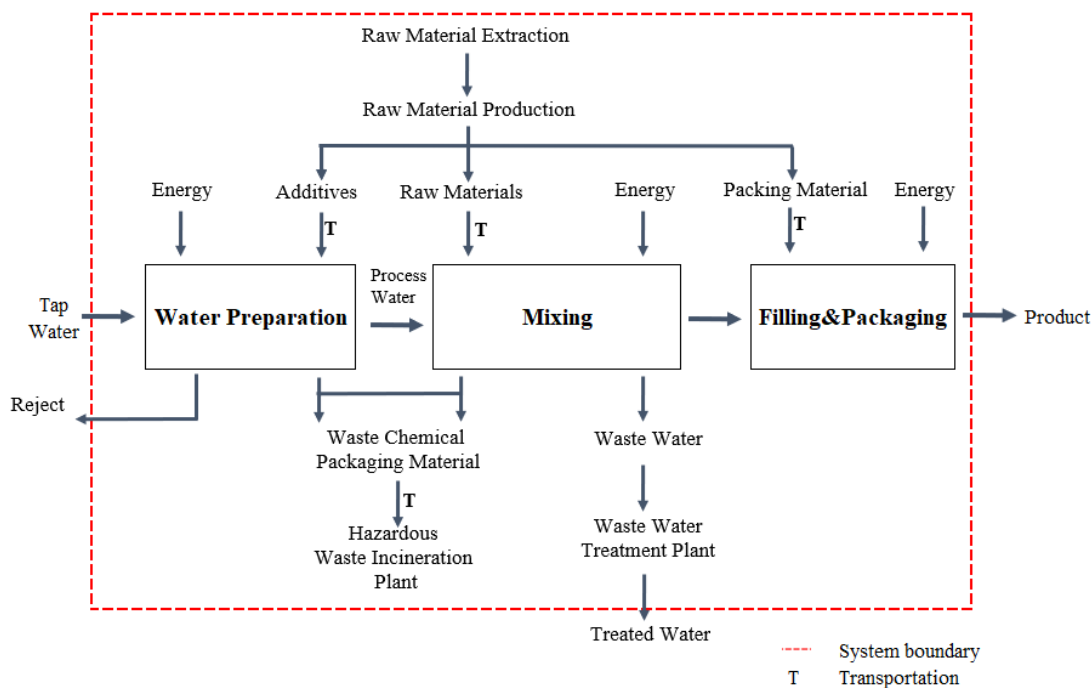
The HTP category concerns the impacts of toxic materials on the human habitat. Kg DCB-Eq. values are considered as the unit of HTP in this study.

### **3.2. Functional Unit**

Scope of the study is defined as the zinc phosphating chemicals production in a factory. The production includes information on raw materials extraction, production and transportation, transportation of materials, production and waste management. Waste packages occur from powder raw material packages and liquid materials packages. Wastes are collected in a temporary waste area and send to a licensed hazardous waste incineration plant facility. Wastewater occurs from a mixer cleaning operation. There is no wastewater treatment system in the factory, wastewater directly sends to organized industrial zone wastewater treatment plant. The function of the production system should be determined clearly in the first step to analyze the results of the study in the correct way. The functional unit can be variable because it is directly related to the process or production system. In this study, the functional unit (fu) is defined as 1000 kg zinc phosphating chemical, because similar studies in literature use the same fu (Genderen E., and oth.,2016). All input and output data of raw materials, process water, packages, and energy were calculated for per 1000 kg product in the framework.

### **3.3. System Boundary**

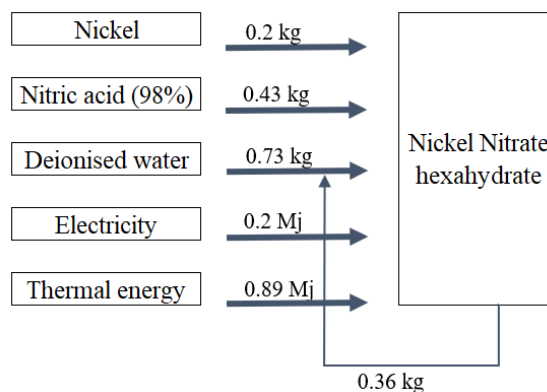
The system boundary shows the scope of the study by pointing out the inputs and outputs. Figure 3.1 shows the system boundary of zinc phosphate chemical production. In this study, an environmental impact assessment performed on the chemical production stage in a factory. The cradle to gate approach was followed in this study while producing zinc phosphating chemicals. Tap water production, reject water from the water preparation system, treated water from the wastewater treatment system and zinc phosphating chemical product are not included in system boundary. The inputs were defined according to the required product quality. Chemical amounts were calculated for the 1000 kg zinc phosphating product.



**Figure 3.1 :** System boundary of zinc phosphate chemical production with life cycle assessment perspective.

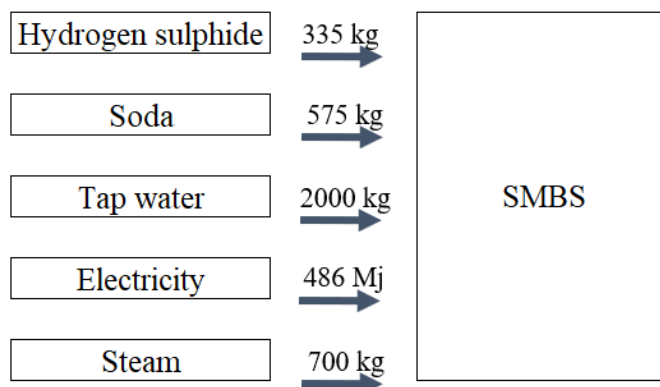
Table 3.1 shows all inputs and outputs of the formulation process that were selected from the GaBi database. Chemicals, materials, and energy types were selected most suitable items from the GaBi and EcoInvent databases.

Nickel nitrate production process is not available in the GaBi database. It was added manually to the database according to the GaBi datasets in the GaBi's website (Url-9). The data set includes all relevant process steps/technologies covering the supply chain of the described cradle to gate inventory with good overall data quality. Nickel, nitric acid (98%), water (desalinated, deionized), electricity grid mix and thermal energy were added, to process with mixing according to the input data of datasheet. Nickel nitrate hexahydrate is produced by dissolving nickel metal in diluted nitric acid. (Url-9). In the model, the stoichiometric amounts are used to produce 1 kg nickel nitrate hexahydrate. 0.2 kg nickel, 0.43 kg nitric acid, and 0.74 kg deionized water are used for producing 1 kg nickel nitrate hexahydrate. In addition to chemical inputs, 0.2 Mj electricity and 0.89 Mj thermal electricity are used during production. 0.36 kg of excess water occurs during production. It is distilled from the mixture and reintroduced into the process with deionized water input (Url-9). Figure 3.2 illustrates the production of 1 kg nickel nitrate in GaBi according to the dataset data (Url-9).



**Figure 3.2 :** Stoichiometry of 1 Kg nickel nitrate production in GaBi (Url-9).

Sodium metabisulfite (SMBS) which is one of the inputs for the process water production process is not available in the database so it was added manually from literature data (ChinaChemNet, 2019). 335 kg hydrogen sulphide, 575 kg soda, 2000 kg tap water are used for producing 1000 kg SMBS. The required energy for production is provided by electricity with 486 Mj and steam with 700 kg (ChinaChemNet, 2019). Figure 3.3 shows the production of SMBS in GaBi according to the literature data.



**Figure 3.3 :** 1000 kg SMBS production in GaBi (ChinaChemNet, 2019).

In addition to that, there is no appropriate process for water input because of quality concern. According to the design parameters received from the plant, the water preparation facility was created within the GaBi database. The water preparation system consists of pretreatment and reverse osmosis units. The system was added to the GaBi database manually with electricity consumption data for all systems and required chemical data for dosage units. Tablet salt, chlorine and sodium metabisulfite are used in dosage units.

**Table 3.1** : GaBi and Ecoinvent database selection list of zinc phosphating chemical production.

<b>Database Selection in GaBi 7.3 and Ecoinvent</b>	
Nitric Acid	GLO: nitric acid, without water, in 50% solution state [allocatable product] <sup>1</sup>
Phosphoric Acid	GLO: phosphoric acid, industrial grade, without water, in 85% solution state [allocatable product]
Nickel	GLO:market for nickel, 99.5% ecoinvent
Nitric acid	RoW: nitric acid production, product in 50% solution state ecoinvent
Zinc Oxide	RoW: zinc oxide [allocatable product] <sup>2</sup>
Iron Sulfate	RER: iron sulfate [allocatable product] <sup>3</sup>
Copper Sulfate	GLO: copper sulfate [allocatable product]
Tap Water	CH: tap water [allocatable product]
Tablet Salt	GLO: sodium chloride, powder [allocatable product]
Caustic, liquid	GLO: sodium hydroxide, without water, in 50% solution state [allocatable product]
Sodium Meta Bisulfite	It's not available in GaBi, it was created according to the literature data.
Soda ash	GLO: market for soda ash, dense ecoinvent
Steam	GLO: market for steam, in chemical industry ecoinvent
Hydrogen sulfide	RoW: hydrogen sulfide production ecoinvent
Total Electricity (Water preparation, Mixing, Filling and Packaging)	TR: electricity, medium voltage [allocatable product]
High-density polyethylene Plastic package (for chemicals) and Intermediate bulk container (for packaging the product)	RER: Polyethylene Bottle (PE-HD)
Wooden Pallet(for packaging the product)	GLO:EUR-flat pallet ecoinvent
Wastewater treatment	RoW: treatment of wastewater from coating, capacity 1.1E10l/year ecoinvent

<sup>1</sup> global and represents activities that are thought to be a common valid for all countries in the world.

<sup>2</sup> describes the Rest of the World apart from Europe

<sup>3</sup> describes Europe.

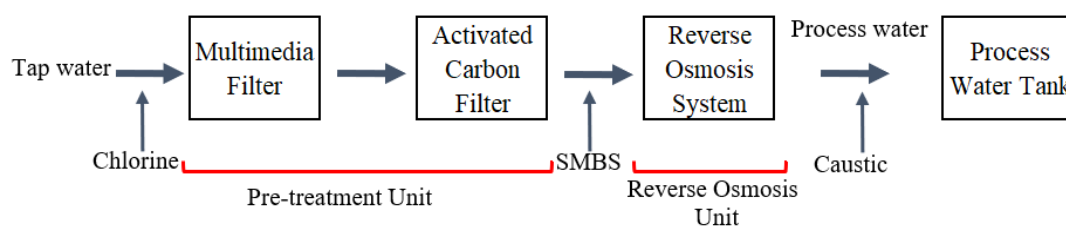
## **4. ZINC PHOSPHATING CHEMICALS PRODUCTION PROCESS**

### **4.1. Zinc Phosphating Chemicals Production**

The formulation of zinc phosphating chemicals occurs three steps; raw material feeding, mixing and packaging. In the first stage, raw materials are fed manually or automatically. There are two options for feeding operations because of the chemical properties and usage rate in products. There is a tank area in the production plant, and liquid chemicals like phosphoric acid and nitric acid are fed in mixer automatically. Zinc oxide, iron sulfate, nickel nitrate, and copper sulfate are in powder form. The powder chemicals and small quantities of liquid chemicals are fed manually by using the feeding point of the mixer. The manufacturing of both zinc phosphating chemicals has the same type of production processes. The same mixer is used in the production of both chemicals. Both zinc phosphating chemicals include the same raw materials almost. The mixer works with electrical energy and it is provided from the electricity grid. After the mixing operation is completed, the packing operation is started in the automatic filling system. And the automatic filling system works with electrical energy like the mixer. In packaging operation, high-density polyethylene intermediate bulk container and wooden pallet are used for both products. The input materials used in the production of both products are obtained from the same suppliers.

Deionized water is used as a raw material in both products. Tap water can not directly be used in the product because of the water quality criteria. There is a water preparation system in the production plant to convert tap water to deionized water that has required qualification. After tap water converting operation is completed, deionized water is called process water in the process. The water preparation system includes pretreatment and reverse osmosis units. Multimedia filters and activated carbon filter are used in the pretreatment unit. Three additional chemicals are used in dosage units for different purposes. Chlorine is used for disinfection purposes in the tap water tank. The chlorine in the tap water damages the membranes in the reverse osmosis system. To prevent this situation, SMBS is dosed to the system before the reverse osmosis system. The caustic dosage unit is located before the process of water tank. It is used

for the neutralization of acidic specification in tap water. The deionized water tank has 10 m<sup>3</sup> capacity and, the required deionized water is fed from the tank to mixer. Figure 4.1 shows a flowchart of the water preparation system.

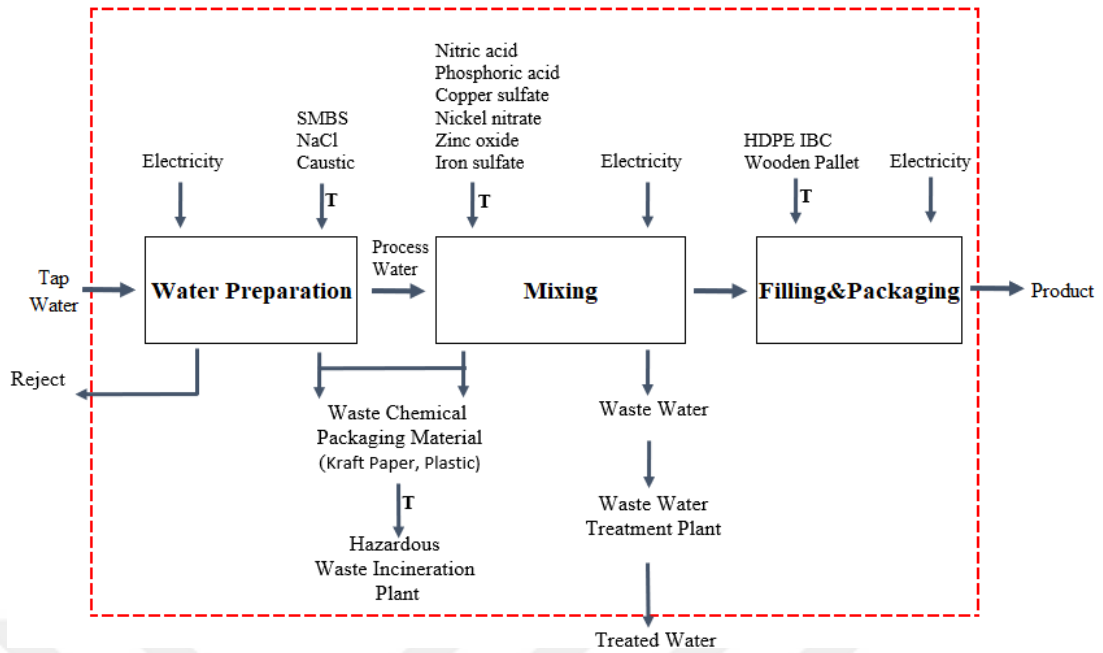


**Figure 4.1 :** Water preparation system flowchart.

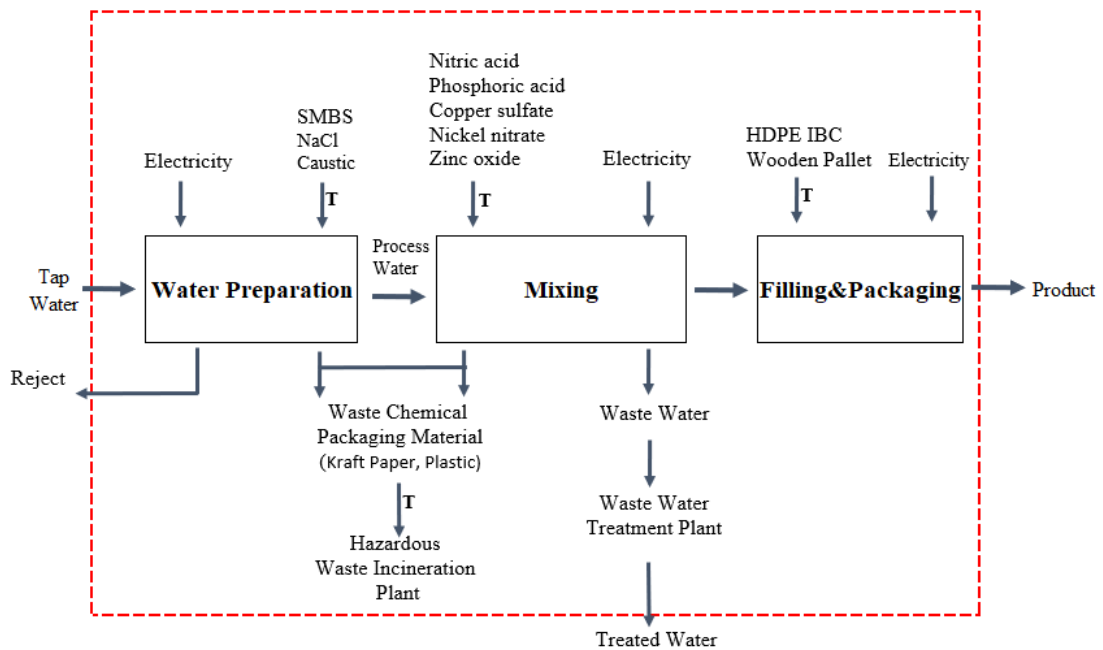
After the raw material and deionized water feeding processes are completed, the second step is started in the mixer. Raw materials and process water are mixed for approximately five hours in mixer. The mixer is worked with electricity. In the last step, zinc phosphate chemical product is filled in high-density polyethylene (HDPE) intermediate bulk container (IBC) automatically. There is an automatic filling system in the production area. HDPE IBC is used for finished goods filling, and the required time of filling operation for one IBC is 25 minutes. The IBC is used together with a wooden pallet for transportation.

Hazardous wastes occur from used raw material packs. Raw materials are in paper packs, and additional chemicals that are used in the water preparation system are in paper and plastic packs. The hazardous wastes are transferred to the hazardous waste incineration plant and processed in there.

The only wastewater source is mixer washings. Approximately 95% of total washing water is collected in a tank and used for the next production process. There is no wastewater treatment system in the plant and, the wastewater is directly sent to the industrial zone area wastewater treatment plant. The environmental impacts of the wastewater treatment system are also included in the system boundary. Wastewater treatment plant data was used from the coating chemicals wastewater treatment system in the GaBi. All impacts categories results were obtained according to the coating chemicals wastewater treatment system data. Figure 4.2 and Figure 4.3 illustrates the production flowcharts of the zinc phosphating chemicals that are called A and B.



**Figure 4.2 :** Production flowchart of product A.



**Figure 4.3 :** Production flowchart of product B.

#### 4.2. Inventory of the Formulations

Inventory analysis of the process was prepared according to the defined functional unit is 1000 kg zinc phosphating chemical. Detailed information about process inputs is outlined for both A and B products in table 4.1 It is possible to reach data about all inputs of raw materials, energy consumption, packaging and outputs of the finished

good, waste and wastewater with this table. All data were obtained from the production plant in the first six months of 2019.

**Table 4.1:** Inputs and outputs of zinc phosphating chemical formulation

Inputs	Units	Product A	Product B
Nitric acid	kg	464	238
Phosphoric acid	kg	144	506
Zinc oxide	kg	190	135
Nickel nitrate	kg	4	1.9
Iron sulphate	kg	4	-
Copper sulphate	kg	2	0.38
Tap water	kg	320	198
Tablet Salt	kg	5.09E-02	3.15E-02
Sodium Meta Bisulfit 35% (Liquid) (SMBS)	kg	1.72E-04	1.06E-04
Caustic,liquid	kg	7.63E-04	4.72E-05
Total electricity (water preparation, mixing, filling and packaging)	kW/h	115	111.3
IBC	kg	60	60
Wooden pallet	kg	30	30
Outputs			
Paper packages for chemicals	kg	1.98	1.36
Plastic packages for chemicals	kg	9.91E-08	2.31E-5
Waste water	kg	2.5	2.5
Reject from water preparation system	kg	128	79

The main water consumption comes from water usage as a raw material in production. There is a water preparation system in the plant and, process water is obtained from tap water with a reverse osmosis unit. The reverse osmosis is a type of membrane technology. It provides water demineralization from high mineral to low mineral via

osmotic pressure. Before the reverse osmosis unit, there is a pretreatment unit to eliminate undesirable particles in water. Multimedia filters and activated filters are used in the pretreatment unit. Tap water does not meet the quality requirement of process water in the product. Table 4.2 illustrates the tap water quality and required process water quality.

**Table 4.2 : Quality of tap water and process water.**

Parameter	Units	Process Water	Tap Water
pH	-	< 7.0	7.88
Conductivity	μS/cm	< 10 μS/cm	234
Silicate	ppm	free	-
Solid matter	ppm	none	0
CO <sub>2</sub>	ppm	< 20 ppm (if Pb-containing paint)	-
Bacteria	ppm	< 10 <sup>3</sup>	0
Temperature	-	10 - 35 °C	20

In the water preparation system, three additional chemicals are used for reaching defined water quality. Tablet salt, SMBS and caustic are used for reaching the required water quality. Table 4.1 includes the amount of additional chemicals used in water preparation system. The process water inputs are different in both products, therefore the amount of chemicals used is also different. In order to produce 1000 kg zinc phosphating chemicals, product A contains 192 kg deionized water and, product B contains 119 kg deionized water. But, the water preparation system does not work with a 100% yield. The system works with a 60% yield according to the design data. In product changeover, the mixer is washed with process water. The amount of wastewater generated per 1000 kg product is 2.5 kg according to weekly production and machine wash information. The main and only energy source is electricity in the plant. The required electricity for the mixer and the automatic filling system is provided from the same system. Both chemicals are produced in the same mixer. The mixer operates with electricity and it consumes 22 kW/h according to the datasheet. The mixing step of A and B products takes approximately 5 hours. After production is

completed, the product goes to the automatic filling system via pipeline and the system consumes 0.1 kW/h. There is an air pump for transferring chemicals to automatic filling equipment. The air pump operates with air that generates by the compressor. In this study, the effects of air pumps were not evaluated because air pumps consume very low electricity. The energy consumption is approximately the same for producing both of A and B products. Because these two chemicals are produced in the same production mixer and finished good is filled in the same automatic filling system. In addition to the production and filling process, the water preparation system is the other electricity consumption source in the plant. Table 4.2.1 includes the total electricity consumption both products for all steps in production, filling processes and water preparation system.

HDPE IBC is used with a wooden pallet for finished good packing. Both A and B products are filled in the same type of package after the production process is completed. HDPE gives the tank bladder of the IBC that level of protection, for instance, to qualify it for the transport of dangerous goods. It provides high stability for the product. The most significant thing is that it persists stable and does not leak. The intermediate bulk container is a reusable type of package for using as mass handling, transporting and storing liquid or semi-liquid. The IBC is suitable for transport and storage of liquids. Phosphating chemicals contain a high ratio of acidic raw materials, so stability and tightness are a key factor for selecting finished good packing material. IBC is used with wood pallet for transporting activities. The wooden pallet is supplied with a different company from the IBC supplier. HDPE IBC has 1000 kg capacity and the empty container is 60 kg weight.

Waste chemical packaging material and wastewater occur in the zinc phosphating chemical production process as a waste. Two raw materials nitric acid and phosphoric acid are fed to mixer from a tank through the pipeline. Both of these chemicals are transported to the factory by using a chemical tanker. Other raw materials copper sulfate, zinc oxide, iron sulfate, and nickel nitrate are fed manually through a manual feeding point. The powder chemicals are in 25 kg paper packages and the chemicals come at the factory by truck. The wastes are transferred to the licensed hazardous waste incineration plant. The main cause of the small number of waste packages per tonne of chemical is the other liquid raw materials are coming to plant via tanker truck. Wastewater occurs from the mixer washing. According to the production data for six

months, the mixer is cleaned once a week approximately. In every cleaning operation, 50 kg process water is used. A huge portion of process water in cleaning operation is transferring to the water holding tank and it is used for as process water in the next product. And 2.5 kg process water is sending to the chemical wastewater treatment plant.

In this study, also the effects of transportation are investigated for chemical and material transportation to the factory and waste chemical packaging material transportation to the hazardous waste incineration plant. All chemicals and materials are supplied by manufacturers that are located in different cities in Turkey. Tankers and trucks are used for transportation from suppliers. Distance between supplier and production plant, the technology of vehicles, road type, fuel type, and other conditions are the main transportation factors affecting directly to the emission. Table 4.3 shows the distance between the chemical suppliers and production plant. The distance between the supplier and the factory was calculated through Google maps.

**Table 4.22:** Information on transportation of the materials for both products.

Materials	Distance (km)	Location	Transportation Type
Nitric acid	267	Tekirdag/Turkey	Road transport
Phosphoric acid	614	Antalya/Turkey	Road transport
Zinc oxide	380	Ankara/Turkey	Road transport
Nickel nitrate	628	Aydin/Turkey	Road transport
Iron sulphate	140	Istanbul/Turkey	Road transport
Copper sulphate	26	Istanbul/Turkey	Road transport
Tablet Salt	53	Kocaeli/Turkey	Road transport
SMBS	53	Kocaeli/Turkey	Road transport
Caustic,liquid	53	Kocaeli/Turkey	Road transport
HDPE IBC	32	Kocaeli/Turkey	Road transport
Wooden pallet	35	Istanbul/Turkey	Road transport
Hazardous waste to incineration plant	19	Kocaeli/Turkey	Road transport



## 5. RESULTS AND DISCUSSION

The study contains the required information on the production steps for comprehensive research according to the functional unit of 1000 kg products. The study covers detailed process information, chemical usage, energy and materials consumption for life cycle assessment for different two zinc phosphating chemicals.

### 5.1. Environmental Impacts of Zinc Phosphating Chemicals

The inputs and outputs of chemicals, materials, electricity, water that result in environmental impacts have been covered in this study. Data were collected for the life cycle inventory of zinc phosphating chemical production processes in surface treatment production plant to define main causes that have a great effect on environmental impacts, also find environmental-friendly solutions to exist causes. LCA modelling with GaBi Software

#### 5.1.1. LCIA results

In this study, the total impact of each environmental effect was defined. Also, the environmental impacts for each process of two different zinc phosphating chemicals are given. The results were assessed according to the functional unit of 1000 kg of zinc phosphate chemical. Ten different environmental impact categories are examined in this study. The categories are related to specific environmental problems. The table 5.1 shows the environmental impact categories and assessment results of both products A and B.

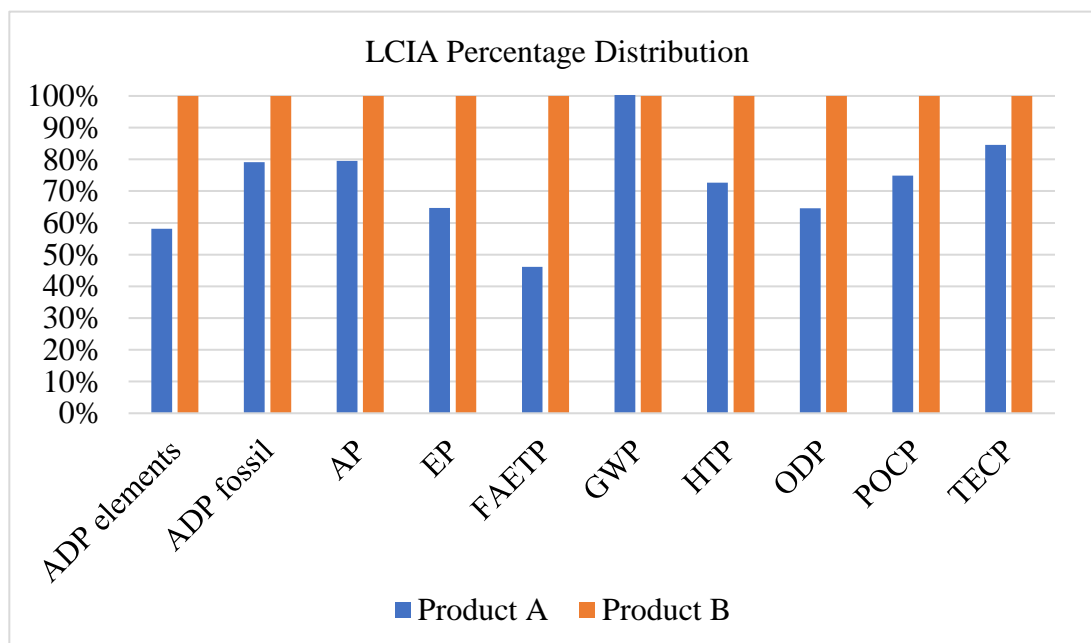
**Table 5.1 :** The environmental impact categories and assessment results of product A and B.

Environmental Impact Category	Unit Equivalent	Impact value Product A	Impact value Product B	Percent difference
ADP elements	[kg Sb-Eq.]	1.44E-02	2.48E-02	Product B is 72% greater than product A
ADP fossil	[MJ]	2.42E+04	3.06E+04	Product B is 26% greater than product A

**Table 5.1 (continued) :** The environmental impact categories and assessment results of product A and B.

Environmental Impact Category	Unit Equivalent	Impact value Product A	Impact value Product B	Percent difference
AP	[kg SO <sup>2</sup> -Eq.]	1.61E+01	2.02E+01	Product B is 26% greater than product A
EP	[kg Phosphate-Eq.]	5.07E+00	7.58E+00	Product B is 49% greater than product A
FAETP	[kg DCB-Eq.]	8.82E+02	1.91E+03	Product B is 116% greater than product A
GWP	[kg CO <sup>2</sup> -Eq.]	2.51E+03	2.35E+03	Product A is 7% greater than product B
HTP	[kg DCB-Eq.]	1.45E+03	1.99E+03	Product B is 38% greater than product A
ODP	[kg R11-Eq.]	1.64E-04	2.54E-04	Product B is 55% greater than product A
POCP	[kg Ethene-Eq.]	8.65E-01	1.15E+00	Product B is 33% greater than product A
TETP	[kg DCB-Eq.]	1.75E+01	2.07E+01	Product B is 18% greater than product A

In order to compare products A and B, all environmental impact categories results in product B production were accepted as 100%, and the percentage distribution of product A was determined according to this acceptance. Figure 5.1 shows the percentage distribution of product B and A.



**Figure 5.1:** LCIA percentage distributions.

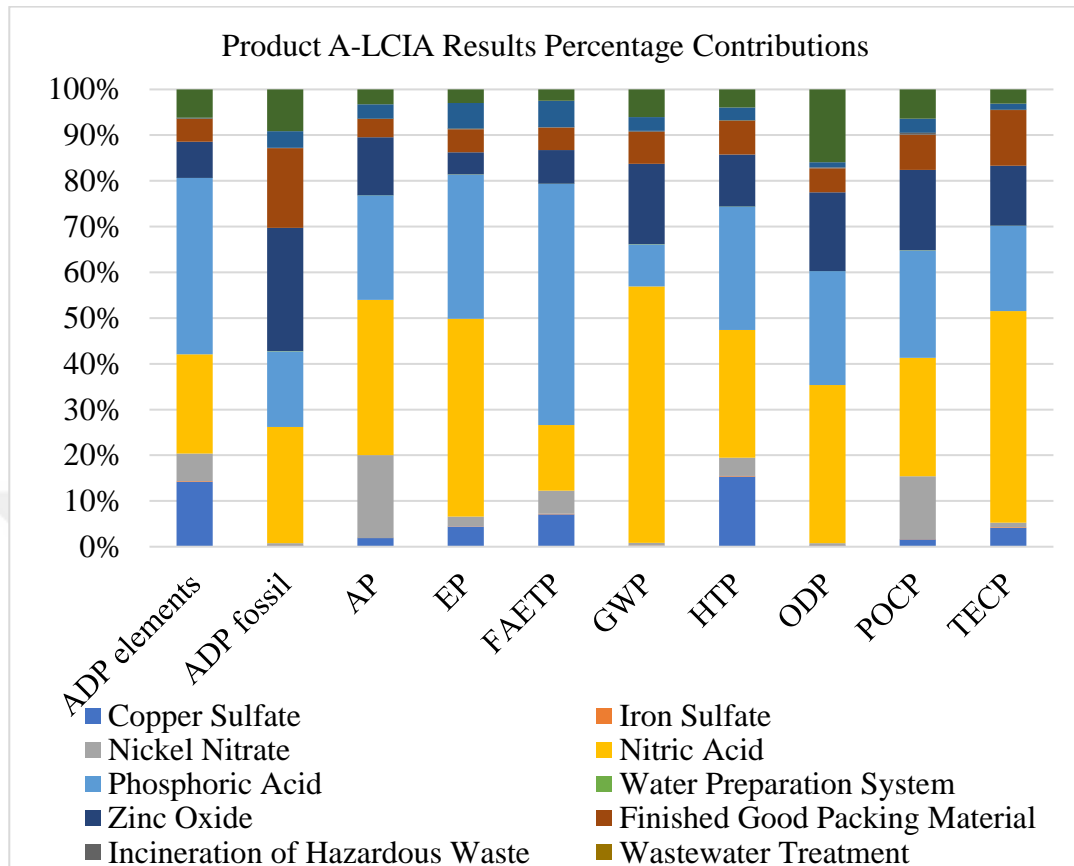
Except for the results of the GWP impact category, it is seen that in all other categories, Product A is more environmental friendly than Product B. While the GWP impact category results difference between product B and A was 7%, it was observed that difference of results were higher in other impact categories. The main difference between the two products is the raw material usage amount in the mixture. LCIA results are directly affected by the rate of chemicals using. Product B has 72% more impact on ADP elements category, 26% more impact on ADP fossil category, 26% more impact on AP category, 49% more impact on EP category, 116% more impact on FAETP category, 38% more impact on HTP category, 55% more impact on ODP category, 33% more impact on POCP category and 18% more impact on TETP category than product A.

The results of the impact categories were analyzed in separate sections to determine where the greatest impact came from. These impact categories are raw materials used in products, energy consumption, production of finished good packing, incineration of hazardous wastes, water preparation system, wastewater treatment and transportation. Transportation values are given in total for all materials. Details of all impact sources information are given in table 5.2 with their percentage contribution to impact categories for product A and B.

**Table 5.2 : Percentage contribution of impact sources to impact categories for both products A and B (%).**

Impact Categories/ Impact Sources	ADP elements		ADP fossil		AP		EP		FAETP		GWP		HTP		ODP		POCP		TETP	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Copper Sulfate	14	2	0	0	2	0	4	1	7	1	0	0	15	2	0	0	2	0	4	1
Iron Sulfate	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-
Nickel Nitrate	6	2	0	0	18	7	2	1	5	1	1	0	4	1	0	0	14	5	1	0
Nitric Acid	22	6	25	10	34	14	43	14	14	3	56	31	28	10	35	11	26	10	46	20
Phosphoric Acid	39	79	17	46	23	64	32	72	53	86	9	34	27	69	25	57	24	62	19	56
Process Water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zinc Oxide	8	3	27	16	13	5	5	3	7	3	18	14	11	5	17	12	18	7	13	8
Finished Good Packing Material	5	3	17	14	4	3	5	3	5	2	7	7	7	5	5	3	8	6	12	10
Incineration of Hazardous Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wastewater Treatment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electricity Consumption	0	0	4	3	3	3	6	4	6	3	3	3	3	2	1	1	3	2	1	1
Transportation	6	5	9	11	3	4	3	3	2	2	6	9	4	4	16	15	6	8	3	4
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Figure 5.2 illustrates the percentage contribution of different impact sources to impact categories results for product A.



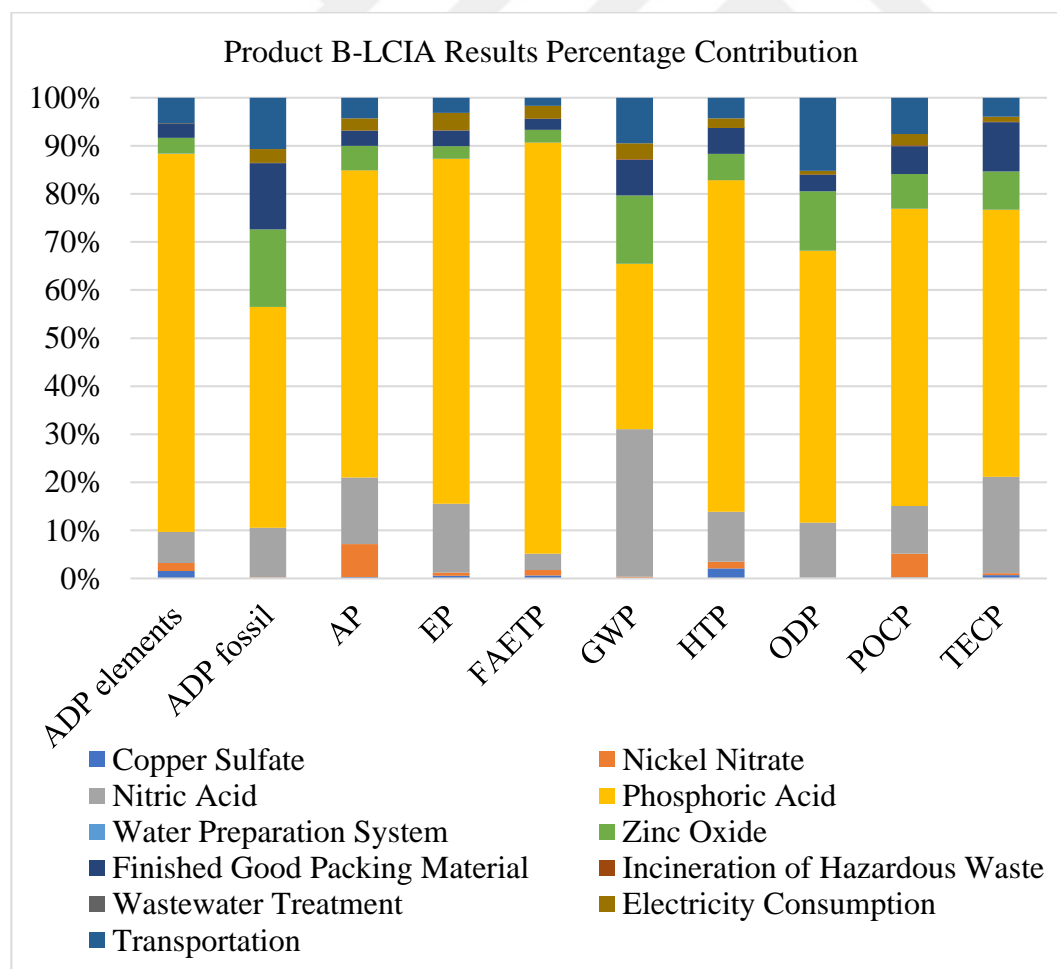
**Figure 5.2 :** Product A-percentage contribution to LCIA results.

It is seen that the results of Product A are mostly caused by the use of nitric acid and phosphoric acid. Nitric acid and phosphoric acid have the largest contribution to all impact categories in product A. 1000 kg product A includes 464 kg nitric acid and 144 kg phosphoric acid. These two chemicals have a 61% place in the product in total. Chemical amounts in the mixture and environmental specifications of the chemical are directly effecting the impact category results.

In ADP elements impact category, copper sulfate production has 14%, nitric acid production has 22% and phosphoric acid production has 39% contribution in total impact. In the ADP fossil impact category, nitric acid production has 25%, phosphoric acid production has 17%, zinc oxide production has 27% and finished good packing material has a %17 share in total impact. In the AP impact category, nickel nitrate production has 18%, nitric acid production has 34%, phosphoric acid has 23% and zinc oxide has a 13% contribution in total impact. In the EP impact category, most of the total impact is caused by nitric acid production with 43% and the rest is due to

phosphoric acid production with 32% contributions. In FAETP impact category, nitric acid production has 14% and phosphoric acid production has a 53% share in total impact. In the GWP impact category, nitric acid production has 56% and zinc oxide production has a 18% contribution in total impact. In the HTP impact category, copper sulfate has 15%, nickel nitrate has 28%, phosphoric acid has 27% and zinc oxide has an 11% share in total impact. In the ODP category, nitric acid production has 35%, phosphoric acid production has 25%, zinc oxide production has 17% and transportation of all materials has a 16% contributions in total impact. In the POCP impact category, nickel nitrate production has 14%, nitric acid production has 26%, phosphoric acid production has 24% and zinc oxide production has a 18% share in total impact. In the TETP impact category, nitric acid production has 46%, phosphoric acid production has 19%, zinc oxide production has 13% and finished good packaging material production has a 12% share in total impact.

Figure 5.3 illustrates the percentage contribution of different impact sources to impact categories results for product B.



**Figure 5.3 :** Product B-percentage contribution to LCIA results.

The chemical production step has the highest impact on all environmental impact categories in product B similarly with product A. The phosphoric acid has almost half of the share in 1000 kg products. The impact category results are directly affected by the inputs of the products. For this reason, the most contribution in all of the effects almost categories is due to the use of this chemical.

In the ADP elements impact category, phosphoric acid production has a 79% contribution in total impact. The rest is caused by other impact sources but they have lower than 10% contributions. In the ADP fossil impact category, nitric acid production has 10%, phosphoric acid production has 46%, zinc oxide production has 16%, finished good packing material has 14% and transportation of all material has 11% share in total impact. In the AP impact category, phosphoric acid production has the most contribution with %64. Then, nitric acid production has a 14% contribution in total impact. In the EP impact category, the biggest contribution is due to the production of phosphoric acid with %72 share in total. After that, nitric acid production has a 14% impact on the total. In the FAETP impact category, the most dominant source is phosphoric acid production with 86% contribution in total. The rest impacts are due to other impact sources but the sources have not higher than 10% impacts on the total. In The GWP impact category, nitric acid production has 31%, phosphoric acid production has 34%, and zinc oxide production has a 14% share in total impact. In the HTP impact category, phosphoric acid production has 69%, and nitric acid production has a 10% share on total impact. In the ODP impact category, nitric acid production has 10%, phosphoric acid production has 57%, zinc oxide production has 12%, and transportation of all materials has a 15% contribution in total impact. In the POCP impact category, phosphoric acid production has 62% and nitric acid production has 10% share in total impact. In the TETP impact category, nitric acid production has 20%, phosphoric acid production has 56%, and finished good packing material has a 10% share on total impact.

The product B and product A can be used as substitutes in many applications. The results between the two products were compared in the next step according to their contribution to the impact categories.

## 5.2. Environmental Impacts Comparison in Products A and B

The results obtained from the two different chemical products in this study are compared with each other, and the literature of coating chemicals LCA studies. The main difference between the two zinc chemical product is the consumption of raw materials. Raw material consumption is directly effected to impact categories result. Transportation impact categories results were calculated as a total for all materials supplied from different suppliers. While calculating the environmental impact arising from the transportation, the distance between the suppliers and the factory, the type of vehicle used in transportation and the type of fuel was taken as a basis and how the transportation was made.

All comparisons were performed according to the common fu, as 1000 kg zinc phosphating chemical for both products.

### 5.2.1. Global warming potential (GWP)

According to the results of the study, a total of 2510 kg CO<sub>2</sub> Eq./1000 Kg product A, and 2350 kg CO<sub>2</sub> Eq./1000 Kg product B are obtained. The main contributors of GWP are nitrous oxide with 44% in product A, carbon dioxide with 70% in product B. GWP impact sources and its contribution to each process in products A and B are shown in table 5.3.

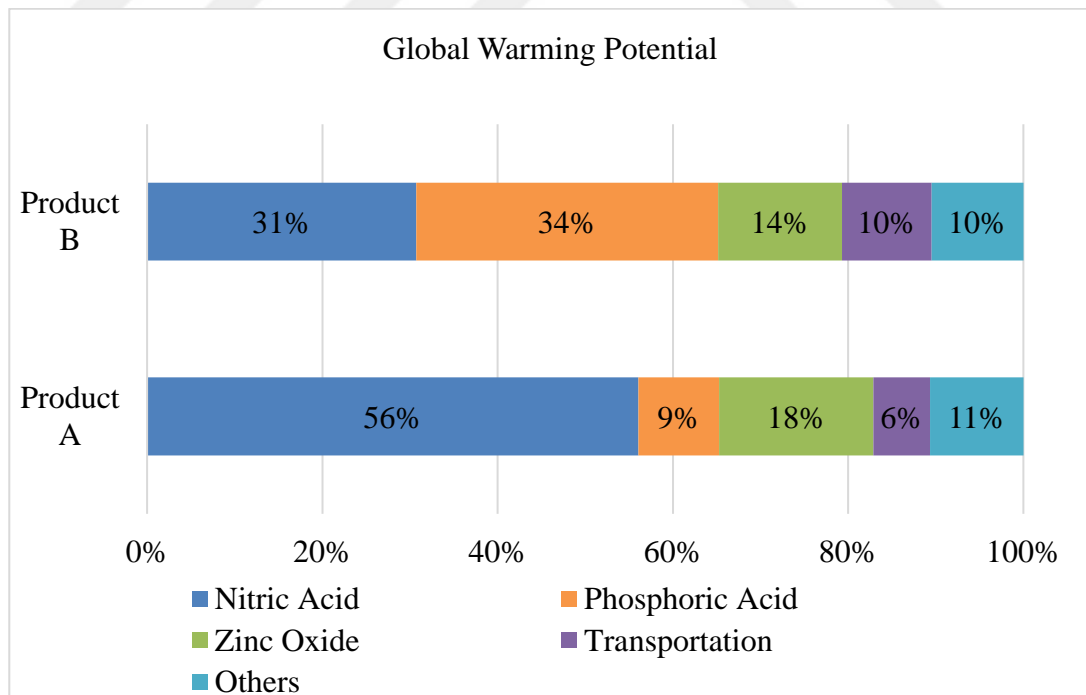
**Table 5.3 :** GWP impact sources and its contribution to each process in products A and B.

GWP Source	Product A		Product B	
	[kg CO <sub>2</sub> -Eq.]/fu	Impact Percentage	[kg CO <sub>2</sub> -Eq.]/fu	Impact Percentage
Copper Sulfate	5.30E+00	0.21%	1.01E+00	0.04%
Iron Sulfate	1.01E+00	0.04%	-	0.00%
Nickel Nitrate	1.51E+01	0.60%	7.16E+00	0.30%
Nitric Acid	1.41E+03	56.08%	7.23E+02	30.71%
Phosphoric Acid	2.31E+02	9.19%	8.11E+02	34.46%
Process Water	2.28E-01	0.01%	8.66E-02	0.00%
Zinc Oxide	4.43E+02	17.63%	3.33E+02	14.15%

**Table 5.3 (continued) : GWP impact sources and its contribution to each process in products A and B.**

GWP Source	Product A		Product B	
	[kg CO <sup>2</sup> -Eq.]/fu	Impact Percentage	[kg CO <sup>2</sup> -Eq.]/fu	Impact Percentage
Finished Good Packing Material	1.76E+02	7.00%	1.76E+02	7.47%
Incineration of Hazardous Waste	5.11E+00	0.20%	3.68E+00	0.16%
Wastewater Treatment	7.40E-04	0.00%	7.40E-04	0.00%
Electricity Consumption	7.79E+01	3.00%	7.55E+01	3.21%
Transportation	1.52E+02	6.04%	2.24E+02	9.50%
Total	2.51E+03	100%	2.35E+03	100%

It is seen that product A has %7 more effect on GWP than product B. Figure 5.4 illustrates the large percentage distribution [kg CO<sub>2</sub>-Eq.] values for both A and B products.



**Figure 5.4 : Percentage contribution of units to GWP for A and B products**

The big portion of GWP amount is coming from the nitric acid. Nitric acid has 56% share in GWP for Product A. The whole effect of nitric acid production is due to the

releasing of inorganic emissions. Nitrous oxide is the main source with 75% contributions to nitric acid production.

Unlike product A, the highest GWP is caused by using phosphoric acid in product B. The biggest source of GWP in phosphoric acid production by 92% is carbon dioxide as an inorganic emission release into the air. After that, nitric acid production comes with a 31% share in total GWP. The effect in nitric acid production results from the release of inorganic emissions into the air. In this effect, nitrous oxide has 70% shares.

### 5.2.2. Abiotic depletion (ADP elements)

According to the results of the study, product A has 1.44E-02 Kg Sb.-Eq. and product B has 2.48E-02 Kg Sb.-Eq for ADP elements. The main contributors ADP elements are copper with 28%, gold with 20%, and cadmium with 17% in product A. In product B, major contributors are cadmium with 27%, lead with 19%, gold and lead with 16% individually. Table 5.4 gives the ADP elements category results of the study for products A and B.

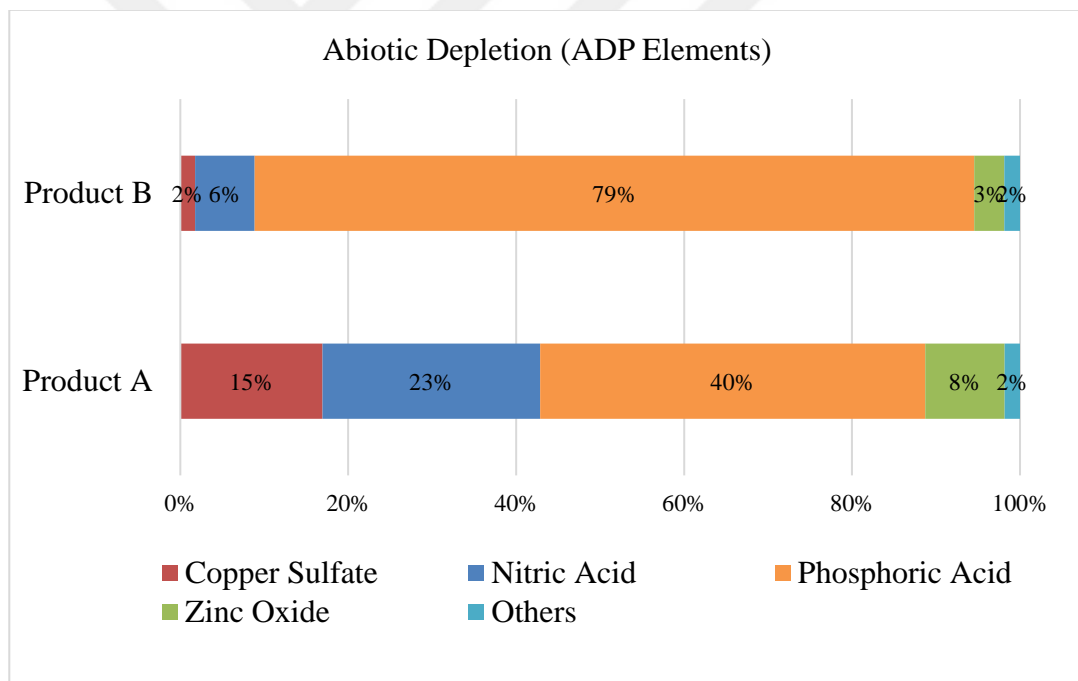
**Table 5.4 :** ADP elements sources and its contribution for each process in products A and B.

ADP Elements Source	Product A/fu		Product B/fu	
	[kg Sb-Eq.]/fu	Impact Percentage	[kg Sb-Eq.]/fu	Impact Percentage
Copper Sulfate	2.05E-03	14.95%	3.90E-04	1.57%
Iron Sulfate	2.03E-05	0.15%	-	0.00%
Nickel Nitrate	8.62E-04	6.28%	4.09E-04	1.65%
Nitric Acid	3.14E-03	22.86%	1.61E-03	6.49%
Phosphoric Acid	5.55E-03	40.45%	1.95E-02	78.65%
Process Water	2.21E-06	0.02%	8.39E-07	0.00%
Zinc Oxide	1.14E-03	8.34%	8.13E-04	3.28%
Finished Good Packing Material	7.26E-04	5.29%	7.26E-04	2.93%
Incineration of Hazardous Waste	8.27E-06	0.06%	5.96E-06	0.02%

**Table 5.4 (continued) :** ADP elements sources and its contribution for each process in products A and B.

ADP Elements Source	Product A/fu		Product B/fu	
	[kg Sb-Eq.]/fu	Impact Percentage	[kg Sb-Eq.]/fu	Impact Percentage
Wastewater Treatment	4.81E-09	0.00%	4.81E-09	0.00%
Electricity Consumption	2.19E-05	0.15%	2.12E-05	0.09%
Transportation	8.92E-04	6.50%	1.32E-03	5.32%
Total	1.44E-02	100%	2.48E-02	100%

There is a 42% difference between the results of the ADP element for both products. The detailed ADP elements contribution percentages for both products are given in figure 5.5.



**Figure 5.5 :** Percentage contribution of units to ADP (elements) potential for products A and B.

Considering the results of the study, the greatest contribution to abiotic depletion in both products comes from the production of phosphoric acid. In product A, the phosphoric acid contribution is due to the consumption of non-renewable elements during production. The consumed elements are cadmium with 40%, copper with 13%, gold with 15%, and lead with an 20% share in total.

In product B, phosphoric acid has 79% contribution to ADP elements. The total phosphoric acid production contribution is originated from the consumption of non-renewable elements. Cadmium has 30%, lead has 21%, gold has 15%, copper has 13% shares in non-renewable elements.

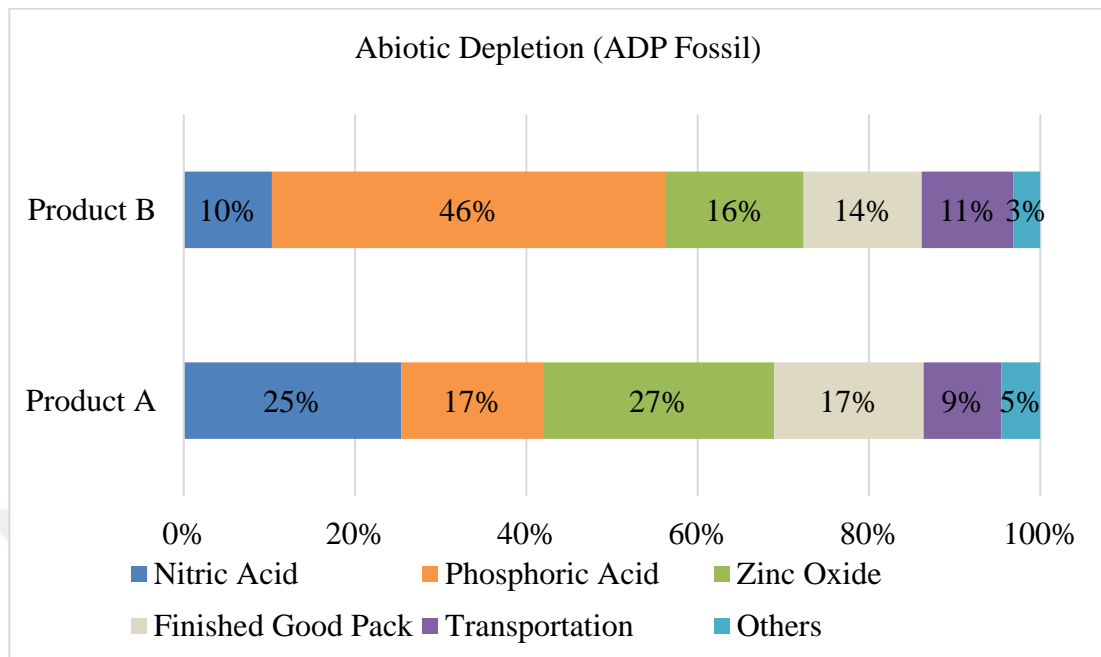
### 5.2.3. Abiotic depletion (ADP fossil)

Product A has 2.42E+04 Mj Eq. and product B has 3.06E+04 Mj Eq. In product A, major contributors are natural gas with 48% and crude oil with 40%, The main contributors in product B, are crude oil 48%, and natural gas with 38%. Table 5.5 illustrates the ADP fossil results for both products in the unit of MJ Eq.

**Table 5.5 :** ADP fossil sources and its contribution for each process in products A and B.

ADP Fossil Source	Product A		Product B	
	[MJ Eq.]/fu	Impact Percentage	[MJ Eq.]/fu	Impact Percentage
Copper Sulfate	6.30E+01	0.26%	1.20E+01	0.04%
Iron Sulfate	7.93E+00	0.03%	-	0.00%
Nickel Nitrate	1.20E+02	0.50%	5.72E+01	0.19%
Nitric Acid	6.15E+03	25.40%	3.15E+03	10.30%
Phosphoric Acid	4.00E+03	16.54%	1.41E+04	45.97%
Process Water	2.68E+00	0.01%	1.02E+00	0.00%
Zinc Oxide	6.53E+03	26.97%	4.92E+03	16.08%
Finished Good Packing Material	4.22E+03	17.46%	4.22E+03	13.81%
Incineration of Hazardous Waste	1.95E+01	0.08%	1.40E+01	0.05%
Wastewater Treatment	6.87E-03	0.00%	6.87E-03	0.00%
Electricity Consumption	9.13E+02	3.65%	8.82E+02	2.88%
Transportation	2.20E+03	9.11%	3.27E+03	10.67%
Total	2.42E+04	100%	3.06E+04	100%

The detailed dominant impact sources of ADP fossil contribution percentages for both products are given in figure 5.6.



**Figure 5.6 :** Percentage contribution of units to ADP (fossil) for products A and B.

Nitric acid and zinc oxide productions are dominant sources of ADP fossil with 27% and 25% shares respectively for product A. Total zinc oxide production impact is obtained from the consumption of non-renewable energy sources. The main contributor to the non-renewable resource is natural gas with a 93% share. In nitric acid production, the total contribution is coming from the energy resources by non-renewable energy. 52% is crude oil, and 36% is natural gas contributed to total nitric acid impact.

In product B, phosphoric acid production has a great effect on the impact category, and it is due to non-renewable energy sources consumption, crude oil has 56% as the main contributor.

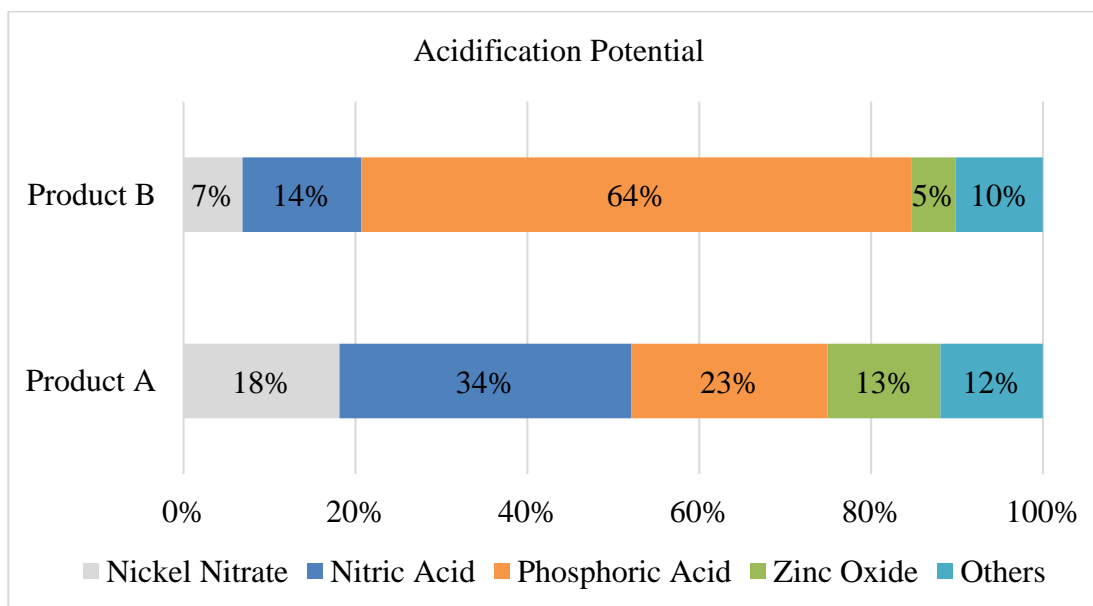
#### 5.2.4. Acidification potential (AP)

Product A has 1.61E+01 kg SO<sub>2</sub>-Eq. and product B has 2.02E+01 kg SO<sub>2</sub>-Eq. The main contributors of AP is sulphur dioxide in both products. In product A, sulphur dioxide has 78%, and in product B, it has 70% contributions. Table 5.6 shows the SO<sub>2</sub>-Eq for both products A and B.

**Table 5.6** : AP sources and its contribution for each process in products A and B.

Acidification Potential Source	Product A		Product B	
	[kg SO <sup>2</sup> -Eq.]/fu	Impact Percentage	[kg SO <sup>2</sup> -Eq.]/fu	Impact Percentage
Copper Sulfate	3.00E-01	1.87%	5.71E-02	0.28%
Iron Sulfate	4.64E-03	0.03%	-	0.00%
Nickel Nitrate	2.92E+00	18.13%	1.39E+00	6.85%
Nitric Acid	5.46E+00	33.95%	2.80E+00	13.85%
Phosphoric Acid	3.68E+00	22.89%	1.29E+01	63.96%
Process Water	1.50E-03	0.01%	5.68E-04	0.00%
Zinc Oxide	2.04E+00	12.65%	1.02E+00	5.04%
Finished Good Packing Material	6.42E-01	3.99%	6.42E-01	3.17%
Incineration of Hazardous Waste	1.25E-02	0.08%	9.00E-03	0.04%
Wastewater Treatment	3.27E-06	0.00%	3.27E-06	0.00%
Electricity Consumption	5.30E-01	3.18%	5.12E-01	2.53%
Transportation	5.21E-01	3.23%	8.65E-01	4.27%

There is a %26 difference between the results of the AP impact category for both products The detailed impact source of the AP is illustrated in figure 5.7.



**Figure 5.7** : Percentage contribution of units to AP for products 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 release emissions to air. This emission consists of 35% ammonia, 26% nitrogen oxide, and 38% sulphur dioxide.

While phosphoric acid production is not a dominant impact source in product A, it is dominant in product B. The consumption of non-renewable energy sources constitutes the total effect of phosphoric acid production. These resources and their contributions are crude oil with 56%, and natural gas with 26%.

### 5.2.5. Ozone depletion potential (ODP)

According to results of study, 1.64E-04 R11 Eq./1000 Kg product A and 2.54E-03 R11 Eq./1000 Kg product B are obtained. The main contributors of ODP is halogenated organics with 100% in both products. Table 5.7 shows the kg R11 Eq. ODP for both products A and B.

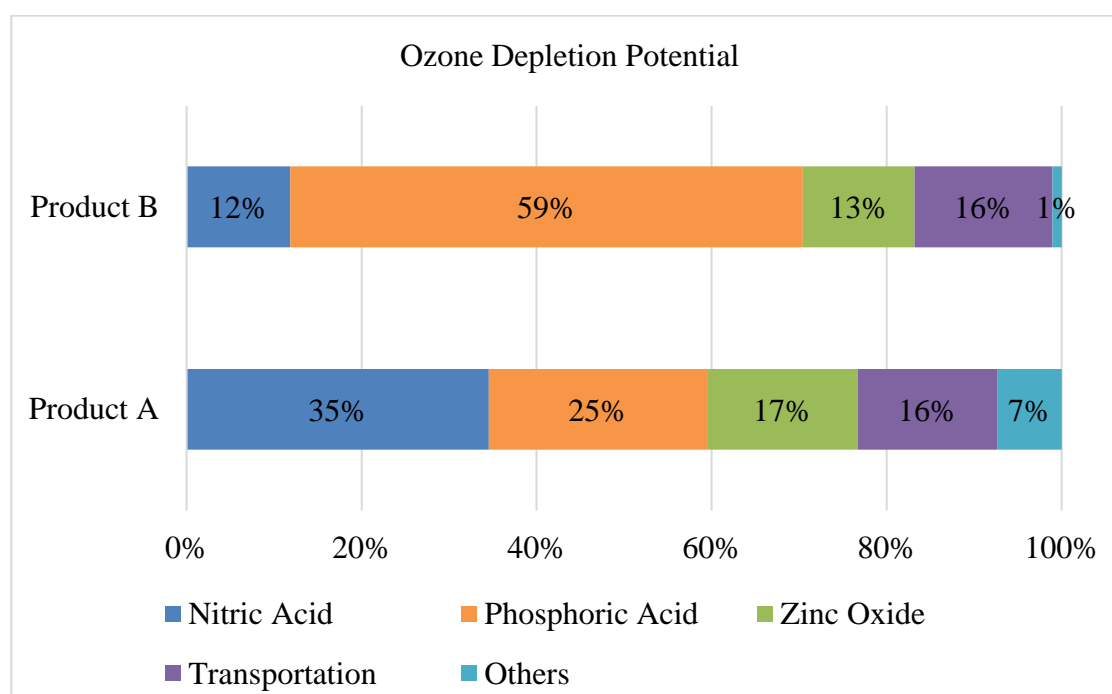
**Table 5.7 :** ODP sources and its contribution for each process in products A and B.

Ozone Depletion Potential Source	Product A		Product B	
	[kg R11-Eq.]/fu	Impact Percentage	[kg R11-Eq.]/fu	Impact Percentage
Copper Sulfate	4.48E-07	0.27%	8.51E-08	0.03%
Iron Sulfate	6.61E-08	0.04%	-	0.00%
Nickel Nitrate	7.95E-07	0.49%	3.78E-07	0.15%
Nitric Acid	5.66E-05	34.54%	2.90E-05	11.45%
Phosphoric Acid	4.08E-05	24.93%	1.44E-04	56.59%
Process Water	2.71E-08	0.02%	1.03E-08	0.00%
Zinc Oxide	2.82E-05	17.24%	3.13E-05	12.34%
Finished Good Packing Material	8.58E-06	5.24%	8.58E-06	3.38%
Incineration of Hazardous Waste	3.46E-07	0.21%	2.49E-07	0.10%
Wastewater Treatment	4.23E-11	0.00%	4.23E-11	0.00%
Electricity Consumption	1.91E-06	1.12%	1.84E-06	0.73%

**Table 5.7 (continued) :** ODP sources and its contribution for each process in products A and B.

Ozone Depletion Potential Source	Product A		Product B	
	[kg R11-Eq.]/fu	Impact Percentage	[kg R11-Eq.]/fu	Impact Percentage
Transportation	2.61E-05	15.90%	3.86E-05	15.23%
Total	1.64E-04	100%	2.54E-04	100%

Product B has a 55% more impact on the ODP impact category than product A. All contribution percentages to ODP impacts for products A and B are illustrated in figure 5.8.



**Figure 5.8 :** Percentage contribution of units to ODP for products A and B.

In product A, dominant impact source is nitric acid production. Releasing halogenated organic emissions to air is the main cause of nitric acid production impact on the ODP category. %97 of halogenated organic emissions impact is caused by halon(1301).

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 originated from releasing inorganic emissions to air. Sulphur dioxide has the biggest impact with 89% share in the total impact of phosphoric acid production.

### 5.2.6. Eutrophication potential (EP)

Product A has 5.06E+00 kg Phosphate-Eq. and product B has 7.58E+00 Phosphate-Eq. as a total. The main contributors of EP are nitrous oxide with 20% for air emission, and phosphate with 28% for freshwater emission in product A. In product B, phosphate is dominant for freshwater and seawater emissions with 41% and 21% respectively. Table 5.8 illustrates the kg Phosphate-Eq. for both products A and B.

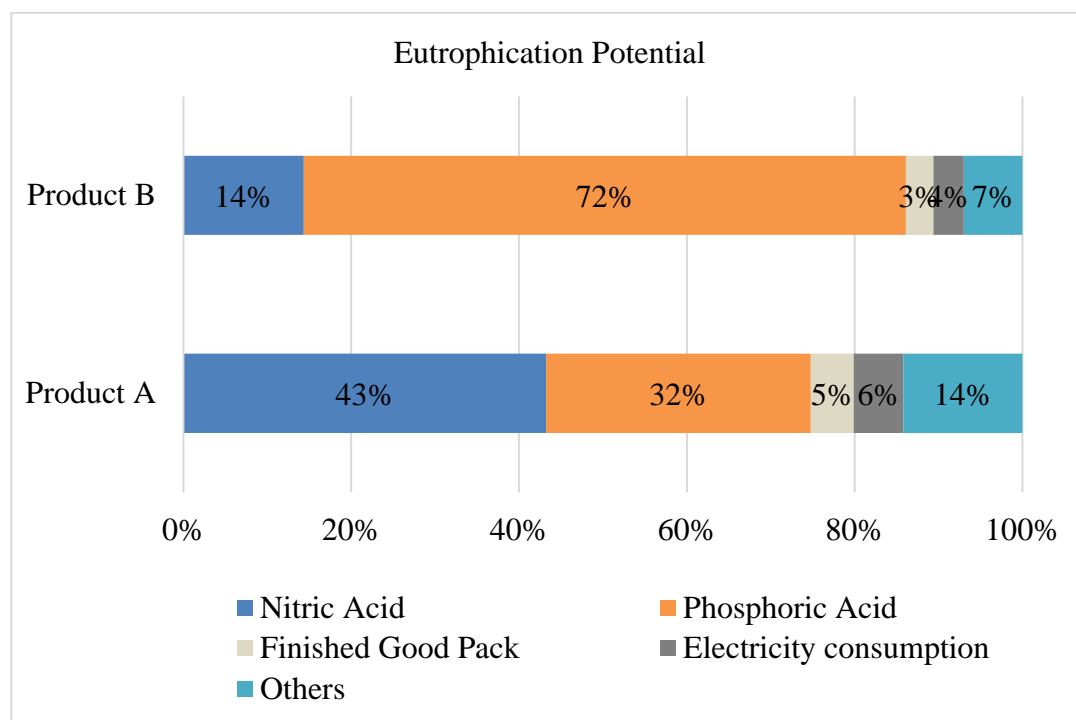
**Table 5.8:** EP sources and its contribution for each process in products A and B.

Eutrophication Potential	Product A		Product B	
	[kg Phosphate-Eq.]/fu	Impact Percentage	[kg Phosphate-Eq.]/fu	Impact Percentage
Copper Sulfate	2.25E-01	4.45%	4.28E-02	0.55%
Iron Sulfate	2.65E-03	0.05%	-	0.00%
Nickel Nitrate	1.06E-01	2.10%	5.06E-02	0.65%
Nitric Acid	2.19E+00	43.23%	1.12E+00	14.36%
Phosphoric Acid	1.60E+00	31.55%	5.61E+00	71.77%
Process Water	7.12E-04	0.01%	2.70E-04	0.00%
Zinc Oxide	2.46E-01	4.87%	2.03E-01	2.60%
Finished Good Packing Material	2.55E-01	5.04%	2.55E-01	3.26%
Incineration of Hazardous Waste	7.09E-03	0.14%	5.11E-03	0.07%
Wastewater Treatment	1.97E-06	0.00%	1.97E-06	0.00%
Electricity Consumption	2.94E-01	5.61%	2.84E-01	3.63%
Transportation	1.49E-01	2.95%	2.44E-01	3.13%
Total	5.07E+00	100%	7.58E+00	100%

There is a %49 difference between the results of the EP impact category for both products. In figure 5.9 is illustrated the percentage contribution of the unit to EP for products A and B.

In product A, the main reason for EP is nitric acid production with 43% contribution. The total EP percentage of nitric acid production is divided into two categories. 81%

part of the EP is from discharges inorganic emissions to air, and 16% is from releases emissions to freshwater. Inorganic emissions released into the air is mainly due to nitrous oxide with 46%.



**Figure 5.9:** Percentage contribution of units to EP for products A and B.

In product B, the total share of phosphoric acid production is originated from releasing halogenated organic emissions into the air. The total impact of phosphoric acid production ODP impact is obtained from halon(1301) with 78% share.

### 5.2.7. Freshwater aquatic ecotoxicity potential (FAETP)

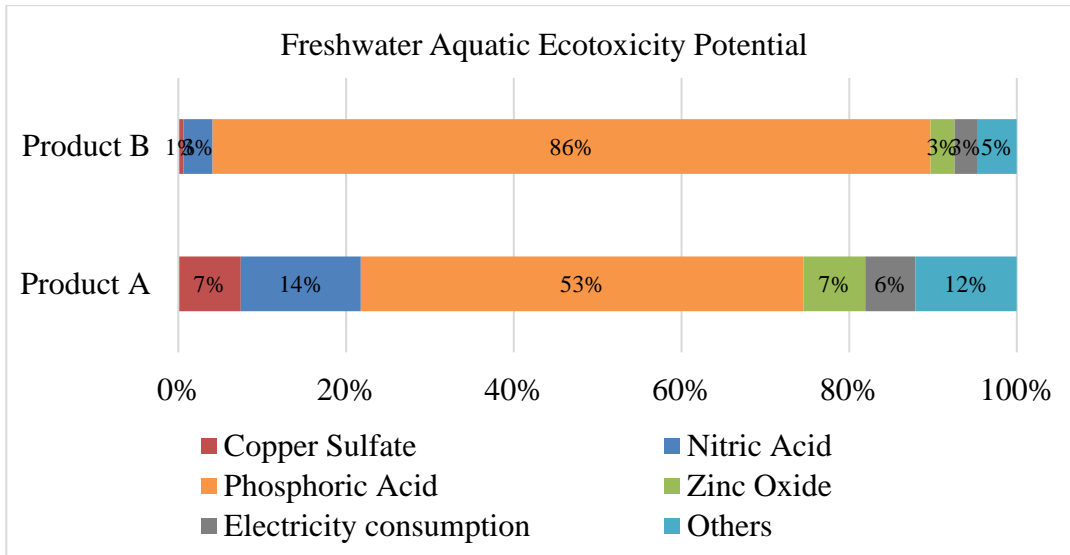
Table 5.9 presents the Kg DCB-Eq. for both products A and B according to assessment results, 8.80E+02 Kg DCB-Eq./1000 Kg product A and 1.91E+03 DCB-Eq. /1000 Kg product B DCB-Eq. are calculated for FAETP. The main contributors of FAETP are vanadium ion in both products. In product A, sulphur oxide has 43%, and in product B, it has 63% contributions.

**Table 5.9 : FAETP sources and its contribution for each process in products A and B.**

Freshwater Aquatic Ecotoxicity Potential	Product A		Product B	
	[kg DCB-Eq.]/fu	Impact Percentage	[kg DCB-Eq.]/fu	Impact Percentage
Copper Sulfate	6.24E+01	7.08%	1.18E+01	0.62%
Iron Sulfate	8.56E-01	0.10%	-	0.00%
Nickel Nitrate	4.47E+01	5.07%	2.13E+01	1.12%
Nitric Acid	1.26E+02	14.34%	6.47E+01	3.39%
Phosphoric Acid	4.65E+02	52.79%	1.63E+03	85.61%
Process Water	1.64E-01	0.02%	6.25E-02	0.00%
Zinc Oxide	6.47E+01	7.34%	4.98E+01	2.61%
Finished Good Packing Material	4.30E+01	4.88%	4.30E+01	2.25%
Incineration of Hazardous Waste	1.57E+00	0.18%	1.08E+00	0.06%
Wastewater Treatment	4.20E-03	0.00%	4.20E-03	0.00%
Electricity Consumption	5.22E+01	5.71%	5.03E+01	2.64%
Transportation	2.19E+01	2.48%	3.24E+01	1.70%
Total	8.82E+02	100%	1.91E+03	100%

Product B has a 116% more impact on the ODP impact category than product A. Percentage contribution to FAETP impact category for products A and B are shown in figure 5.10

In product A, phosphoric acid production is the main impact source with a 53% contribution to the FAETP impact category. Releasing emission to freshwater is the dominant resource of phosphoric acid production. And, the major contributor vanadium ion has a %75 share.



**Figure 5.10 :** Percentage contribution of units to FAETP for products A and B.

In product B, phosphoric acid production has the biggest contribution to the total FAETP impact category. The main contributor to phosphoric acid production is represented as releasing emissions to freshwater and it is accounted for 85%. The major contributor is vanadium ion with 72%.

### 5.2.8. Photochemical ozone creation potential (POCP)

Table 5.10 shows the results of the study in the scope of POCP with kg Ethene-Eq. for both products A and B. 8.64E-01 kg Ethene-Eq. for product A and 1.15E+00 Ethene-Eq. for product B were obtained according to the results. The main contributors of POCP is sulphur dioxide in both products. In product A, sulphur dioxide has 55%, and in product B, it has 56% contributions.

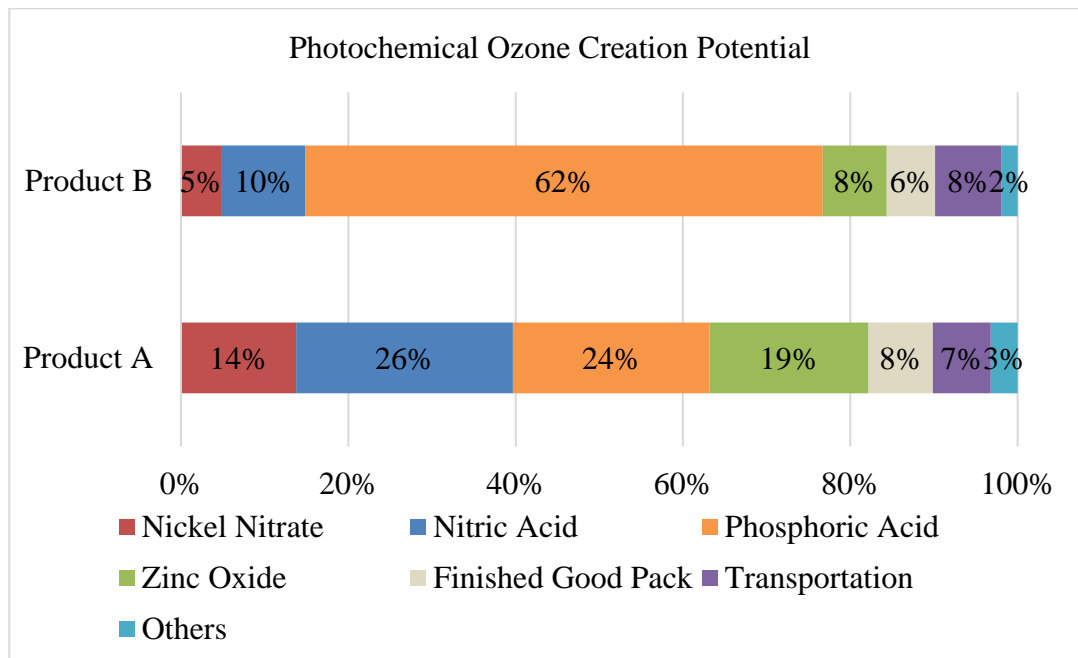
**Table 5.10 :** POCP potential sources and its contribution for each process in products A and B.

Photochemical Ozone Creation Potential	Product A		Product B	
	[kg Ethene-Eq]/fu	Impact Percentage	[kg Ethene-Eq]/fu	Impact Percentage
Copper Sulfate	1.37E-02	1.58%	2.60E-03	0.23%
Iron Sulfate	2.83E-04	0.03%	-	0.00%
Nickel Nitrate	1.19E-01	13.77%	5.65E-02	4.90%
Nitric Acid	2.24E-01	25.89%	1.15E-01	9.94%
Phosphoric Acid	2.03E-01	23.51%	7.14E-01	61.86%

**Table 5.10 (continued) : POCP potential sources and its contribution for each process in products A and B.**

Photochemical Ozone Creation Potential	Product A		Product B	
	[kg Ethene-Eq]/fu	Impact Percentage	[kg Ethene-Eq]/fu	Impact Percentage
Process Water	9.10E-05	0.01%	3.45E-05	0.00%
Zinc Oxide	1.52E-01	17.57%	8.33E-02	7.22%
Finished Good Packing Material	6.66E-02	7.71%	6.66E-02	5.77%
Incineration of Hazardous Waste	3.57E-03	0.41%	2.46E-03	0.21%
Wastewater Treatment	3.43E-07	0.00%	3.43E-07	0.00%
Electricity Consumption	2.79E-02	3.13%	2.70E-02	2.34%
Transportation	5.51E-02	6.38%	8.68E-02	7.53%
Total	8.65E-01	100%	1.15E+00	100%

There is a 34% difference between the results of the POCP impact category for both products. Figure 5.11 illustrates detail percentage contribution to POCP for all steps in both products A and B.



**Figure 5.11 : Percentage contribution of units to POCP for products A and B.**

The contributions of nitric acid production and phosphoric acid production are quite similar in the POCP impact category for product A. The biggest contributions of nitric

acid production are collected from releasing inorganic emissions with 74% and organic emissions with 22% into the air. In nitric acid production, inorganic emissions released into the air are nitrogen oxides with 38% and sulfur dioxide with 42% shares. Similarly with nitric acid production, releasing inorganic emissions with 83% and organic emissions with 16% are major contributors to phosphoric acid production. Sulphur dioxide has 66% contribution to inorganic emission releasing.

In product B, the total phosphoric acid production impact is obtained in releasing inorganic and organic emissions into the air. Releasing inorganic emissions have 82% contribution, and the major contributor is sulphur dioxide with 63%. . Releasing organic emissions have 19% contribution, and Non-methane volatile organic compound (NMVOC) is a contributor to organic emission releasing with a 10% share.

### 5.2.9. Terrestrial ecotoxicity potential (TETP)

1.75E+01 kg DCB-Eq. for product A and 2.07E+01 for product B were calculated. The main contributors of TETP are chromium and vanadium in both products. In product A, chromium has 36%, and vanadium has 31% shares. In product B, chromium has 44%, and vanadium has 16% shares. Table 5.11 illustrates the TETP category results with using kg DCB-Eq. unit for both products A and B.

**Table 5.11 :** TETP potential sources and its contribution for each process in products A and B.

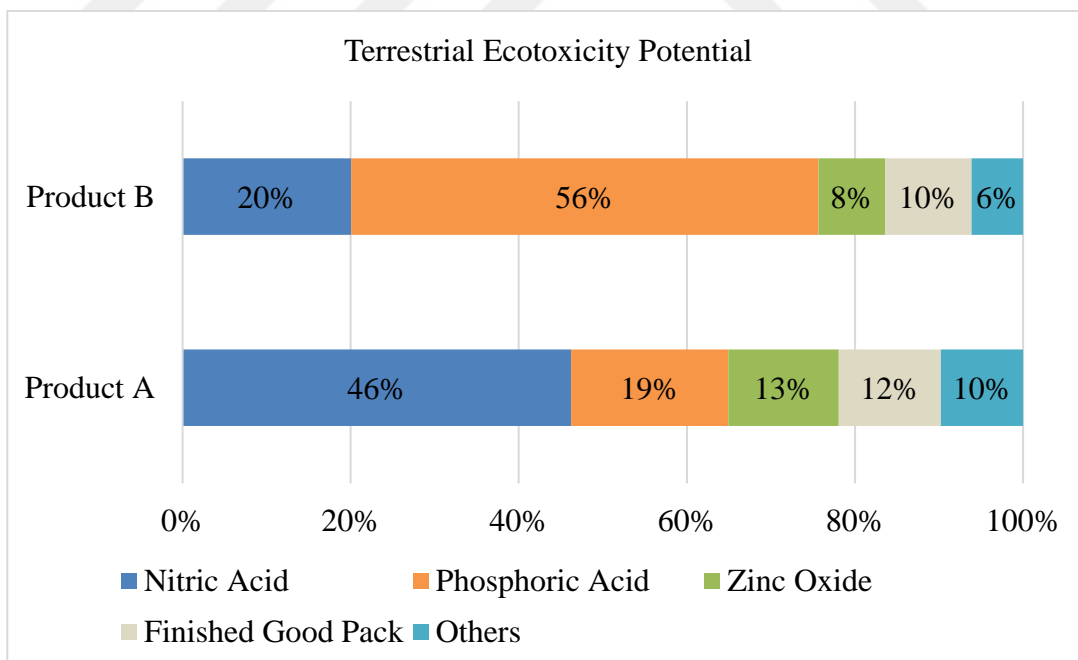
Terrestrial Ecotoxicity Potential	Product A		Product B	
	[kg DCB-Eq.]/fu	Impact Percentage	[kg DCB-Eq.]/fu	Impact Percentage
Copper Sulfate	7.30E-01	4.17%	1.39E-01	0.67%
Iron Sulfate	2.08E-02	0.12%	-	0.00%
Nickel Nitrate	1.70E-01	0.97%	8.06E-02	0.39%
Nitric Acid	8.10E+00	46.24%	4.15E+00	20.07%
Phosphoric Acid	3.27E+00	18.70%	1.15E+01	55.59%
Process Water	1.81E-03	0.01%	6.86E-04	0.00%
Zinc Oxide	2.30E+00	13.12%	1.64E+00	7.92%
Finished Good Packing Material	2.13E+00	12.16%	2.13E+00	10.29%
Incineration of Hazardous Waste	1.11E-02	0.06%	7.50E-03	0.04%

**Table 5.11 (continued) : TETP potential sources and its contribution for each process in products A and B.**

Terrestrial Ecotoxicity Potential	Product A		Product B	
	[kg DCB-Eq.]/fu	Impact Percentage	[kg DCB-Eq.]/fu	Impact Percentage
Wastewater Treatment	1.12E-03	0.01%	1.12E-03	0.01%
Electricity Consumption	2.39E-01	1.32%	2.31E-01	1.11%
Transportation	5.47E-01	3.12%	8.10E-01	3.91%
Total	1.75E+01	100%	2.07E+01	100%

Product B has a 18% more impact on the ODP impact category than product A. Detailed percentage contribution for all steps in both products A and B to TETP are illustrated in figure 5.12.

In product A, nitric acid production has a 46% contribution to the TETP impact category. Releasing heavy metals to air was accounted for 90% of the total nitric acid production. The main contributors are chromium with 30% and vanadium with a 60% share.



**Figure 5.12 : Percentage contribution of units to TETP for products A and B.**

In product B, phosphoric acid production has a 56% contribution to the TETP impact category. Phosphoric acid production's total impact is caused by releasing emissions to air and agricultural soil. The air emissions have 81% contribution and it is originated

from heavy metals, and the dominant element is chromium with 57%. The agricultural soil emissions are originated from pesticides with a 14% share in total phosphoric acid production impact. The major pesticide is cypermethrin, and it is caused the total effect on the emission of agricultural soil.

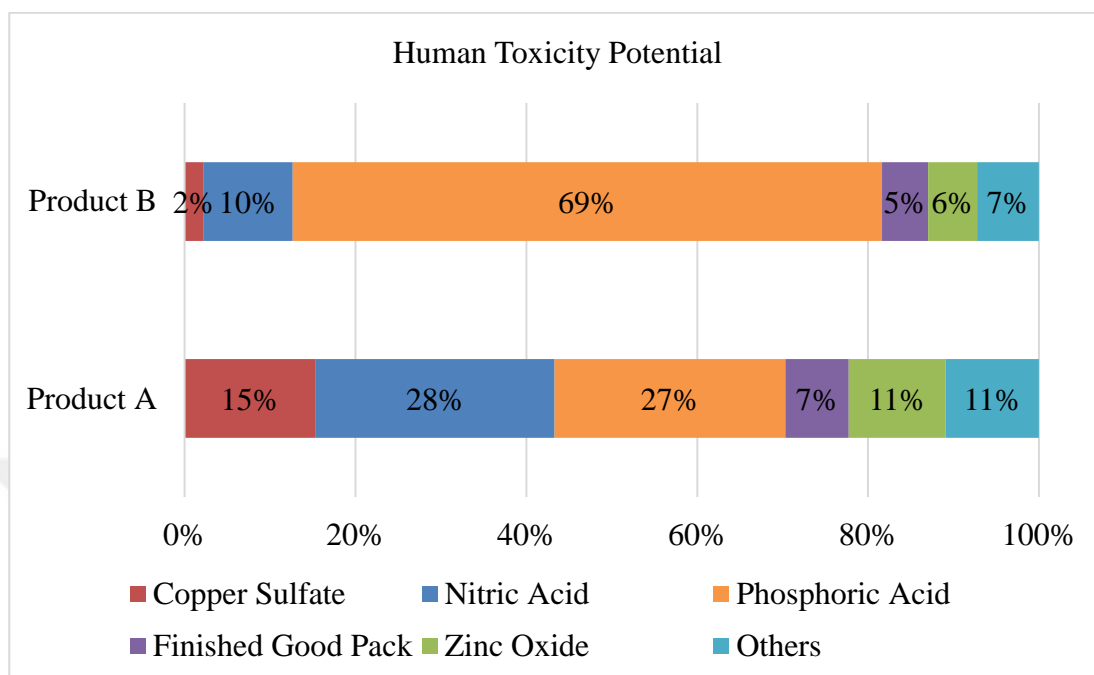
#### 5.2.10. Human toxicity potential (HTP)

Product A has 1.45E+03 Kg DCB-Eq. and, product B has 1.99E+03 Kg DCB-Eq. The main contributors of HTP are chromium with 19% and arsenic 12% in product A. In product B, chromium has 36%, and vanadium has 31% shares for air emissions. In addition to that, vanadium has 22% share for freshwater emissions. Table 5.12 shows the HTP impact category results with Kg DCB-Eq. for both products A and B.

**Table 5.12 :** HTP potential sources and its contribution for each process in products A and B.

Human Toxicity Potential	Product A		Product B	
	[kg DCB-Eq.] /fu	Impact Percentage	[kg DCB-Eq.] /fu	Impact Percentage
Copper Sulfate	2.22E+02	15.36%	4.22E+01	2.12%
Iron Sulfate	1.65E+00	0.11%	-	0.00%
Nickel Nitrate	5.73E+01	3.97%	2.72E+01	1.37%
Nitric Acid	4.04E+02	27.95%	2.07E+02	10.42%
Phosphoric Acid	3.90E+02	27.01%	1.37E+03	68.96%
Process Water	1.73E-01	0.01%	6.58E-02	0.00%
Zinc Oxide	1.64E+02	11.36%	1.08E+02	5.43%
Finished Good Packing Material	1.07E+02	7.43%	1.07E+02	5.40%
Incineration of Hazardous Waste	1.06E+00	0.07%	7.15E-01	0.04%
Wastewater Treatment	3.04E-03	0.00%	3.04E-03	0.00%
Electricity Consumption	3.98E+01	2.76%	3.94E+01	1.98%
Transportation	5.74E+01	3.97%	8.53E+01	4.29%
Total	1.45E+03	100%	1.99E+03	100%

There is a 37% difference between the results of the HTP impact category for both products. All contribution percentages to the HTP category are shown in Figure 5.13 for both products A and B.



**Figure 5.13 :** Percentage contribution of units to HTP for products A and B

In product A, the total share of nitric acid production is divided into two categories; release emissions to air with 82% and freshwater with 18% shares. Releasing emissions to air category is consisted of releasing heavy metals to air with 75%. Arsenic, nickel, chromium have 18% shares individually, and vanadium has a 11% share. In phosphoric acid production impact consist of two categories, releasing emissions into the air with 45%, and releasing emissions to freshwater with 60% contributions. The major freshwater emission contributors are selenium with 15%, and vanadium ion with 33%. Arsenic has 11%, and chromium has a %15 share in inorganic emission discharging to air in phosphoric acid production impact.

In product B, the impacts of phosphoric acid production were categorized into releasing emissions into the air with 43% and releasing emissions to freshwater with 56% shares. The air emissions are mainly originated from heavy metals. The major heavy metals are chromium with 13%, and arsenic with 10%. Principally sources of freshwater emissions are vanadium ion with %32, and selenium with 13% respectively.

### 5.3. Environmental Impact Comparison between Products and Literature

Three different EPD (Url-4,Url-5,Url-6) were used for comparing the results obtained for product A and product B. All of these chemicals are used for surface coating purposes. Generally, EPD's do not include all environmental impact categories because they are prepared as voluntarily by companies and verified independently. Only the some impact categories could be compared with results of products A and B. All three studies that discussed were carried out on different coating chemicals that are used in many applications in industry. Therefore, the inputs of the chemicals mentioned in the EPD studies and the inputs of the products B and A are different.

The EPD1(Url-4) is related to methacrylate resin products and flow coatings. Cradle to gate approach is used in study. The system boundary was defined as a cradle to gate and it includes raw material supply, transport to site and manufacturing steps. GaBi 6 data base was used as background data. GWP, AP, EP, POCP, and ADP fossil resources impact categories were used for comparison.

The EPD2(Url-5) is related to epoxy powder coating chemicals. Cradle to gate approach was followed in this EPD and, the study covered raw material supply, transport to site and manufacturing steps. GaBi 7.3 was used for modelling the life cycle of the declared product. GWP, AP, EP, POCP, and ADP fossil resources impact categories were used for comparison with product A and B LCA study results.

The EPD3(Url-6) is about weatherproof polyester powder coating. The system boundary was defined cradle to plant gate in the study. Raw material supply, transportation, and manufacturing stages were evaluated in the EPD. GaBi ts 7.3 software system was used for modeling the life cycle of the declared product. The EPD includes assessment and results of GWP, AP, EP, POCP, and ADP fossil resources impact categories. The comparable results for EPD1, EPD2 ,EPD3 and products B and A are illustrated according to the 1000 kg chemical of fu in table 5.13.

**Table 5.13 :** EPD1, EPD2, EPD3 and products A and B environmental impact results comparison (Url-4,Url-5,Url-6).

Impact Categories	Unit	EPD1	EPD2	EPD3	Product A	Product B
GWP	[kg CO <sup>2</sup> Eq.]	1.92E+03	6.47E+03	4.67E+03	2.34E+03	2.19E+03
AP	[kg SO <sup>2</sup> Eq.]	6.84E+00	1.32E+01	2.87E+01	1.55E+01	1.97E+01

**Table 5.13 (continued) : EPD1, EPD2, EPD3 and products A and B environmental impact results comparison (Url-4,Url-5,Url-6).**

Impact Categories	Unit	EPD1	EPD2	EPD3	Product A	Product B
EP	[kg (PO <sub>4</sub> ) <sup>3</sup> Eq.]	4.68E-01	1.60E+00	9.54E-01	5.14E+00	7.91E+00
POCP	[kg ethene Eq.]	1.38E+00	1.94E+00	1.93E+00	8.01E-01	1.10E+00
ADP Fossil	[MJ]	4.30E+04	1.12E+05	9.24E+04	2.01E+04	2.65E+04

The results in the GWP category were at the same level for products A and B with three EPD studies. EPD2 has the highest GWP impact among all studies. In the GWP category, the big contributions are coming from the nitric acid and zinc oxide production step for both products A and B. In EPD1, resin components production plays a great role in the study. There is no information about GWP impact category contributors in EPD2 and EPD3.

In the AP impact category, a large contribution comes from nitric acid and phosphoric acid usage in products B and A. In EPD1, sulphur dioxide was used and it has a big contribution to AP. EPD3's AP impact category result is higher than other studies' results. According to the study, titanium dioxide is the main cause of the AP results.

In the EP impact category, product B has the highest impact on the environment in all studies. The product A has the second-highest EP effect among studies. The main cause of EP is phosphoric acid production step in product B, and nitric acid production step in product A.

EPD2 and EP3 have the highest impact on the POCP category. There is a 1% difference between the two EPD results. The binding agent was used as a raw material in EPD2 and EPD3, and it dominates all impact categories. In product B, phosphoric acid production step dominates to POCP category, nitric acid, and phosphoric acid production steps dominate to POCP category in product A.

In ADP fossil impact category, EPD2 result is higher than the other EPD's and product B and A results. The environmental loads within raw material supply are fundamentally dominated by the binding agent and titanium dioxide in the several environmental impacts categories in EPD2. In LCA study of product B, phosphoric acid has a large contribution with 69% percentage in total share.

#### 5.4. Energy Supply Scenarios for Zinc Phosphate Production

The energy required for the operation of the equipment used in the production plant is electrical energy. Production consists of three stages, raw material feeding, mixing and packaging. Energy is required for the operation of the mixer and packaging equipment. Additionally, it works with energy in the instruments in the water preparation facility that prepares the quality water required for production.

In GaBi software, it is possible to reach different electricity databases according to the country-specific usages with different production methods. All the results delivered are collected by using grid mix electricity for Turkey in the database. According to the EUAS report, in terms of resources as of 2018, 37.4% of the total electricity production is from coal, 29.9% from natural gas, 19.8% from hydraulic sources, 6.6% from wind, 2.5% is supplied from geothermal, 0.3% from liquid fuels, 3.3% from biofuels and solar energy and 0.2% from waste heat (EUAS,2018). According to the energy policy of Turkey, it is aimed that increase to capacity an additional 10 000 MW of both photovoltaic and wind energy in the next ten years (EUAS,2018). For this purpose, wind and photovoltaic renewable resources were investigated separately in the study in the scope of their environmental impacts. Two different scenarios are applied in this study, wind turbines and photovoltaic energy sources were used as renewable sources instead of the grid mix of Turkey electricity. The LCA model was set up in the Gabi database for both scenarios. TR nation processes were selected for electricity production from grid mix and wind turbines. Unfortunately, there is no TR nation process for electricity production from photovoltaic. Table 5.14 illustrates the selected process for scenarios in ecoinvent database.

**Table 5.14 :** Database selection for renewable energy scenarios and grid mix.

Electricity Sources	Process
Grid Mix	TR: market for electricity, medium voltage ecoinvent
Wind Turbine	TR: electricity production, wind, 1-3MW turbine, onshore ecoinvent
Photovoltaic	RoW: electricity production, Photovoltaic, 3kWp flat-roof installation, single-Si ecoinvent

### 5.4.1. Wind turbin usage

The wind turbines model includes both an average onshore and offshore wind model. The data set includes all related process stages and technologies within the supply chain. Following the life cycle stages are considered production, transportation, installation, operation, dismantling and removal of the wind turbines includes electrical gear in both models. The onshore model is based on a 300 MW wind park, and working 182 wind turbines with 1.65 MW each. Differently from the onshore model, the offshore model is based on a 300 MW wind park and operating 100 wind turbines with 3.00 MW each. The operational lifetime of both wind turbines and cables is 20 years (Url-10). Table 5.15 illustrates the environmental impacts categories of Zinc phosphating chemicals production which works by conventional grid mix electricity of Turkey compared with the wind turbine. The functional unit was defined according to the required energy for producing 1000 kg zinc phosphating chemical.

**Table 5.15 :** Environmental impact of zinc phosphating chemicals based on grid mix of Turkey and wind turbine.

Impact Categories	Unit	Grid Mix Product A	Wind Turbine Product A	Grid Mix Product B	Wind Turbine Product B
ADP elements	kg Sb-Eq.	2.19E-05	3.38E-05	2.12E-05	3.38E-05
ADP fossil	MJ	9.13E+02	1.70E+01	8.84E+02	1.70E+01
AP	kg SO <sup>2</sup> -Eq.	5.30E-01	8.89E-03	5.13E-01	8.89E-03
EP	kg Phosphate-Eq.	2.94E-01	4.24E-03	2.85E-01	4.24E-03
FAETP	kg DCB-Eq.	5.22E+01	9.30E+00	5.05E+01	9.30E+00
GWP	kg CO <sup>2</sup> -Eq.	7.79E+01	1.42E+00	7.54E+01	1.42E+00
HTP	kg DCB-Eq.	4.12E+01	4.68E+00	3.98E+01	4.53E+00
ODP	kg R11-Eq.	1.91E-06	1.03E-07	1.85E-06	1.03E-07
POCP	kg Ethene-Eq.	2.79E-02	9.66E-04	2.70E-02	9.66E-04
TETP	kg DCB-Eq.	2.39E-01	1.04E-01	2.31E-01	1.04E-01

In case the energy is supplied from the wind turbines instead of the grid mix, the environmental impact of the impact sources decreases. The table 5.16 illustrates reduction percentages of impact categories for both products A and B.

**Table 5.16 :** Percentage change of impact categories by using wind turbines instead of grid mix.

Impact Categories	Unit/fu	Product A	Product B
ADP elements	kg Sb-Eq.	+55%	+55%
ADP fossil	MJ	-98%	-98%
AP	kg SO <sup>2</sup> -Eq.	-98%	-98%
EP	kg Phosphate-Eq.	-99%	-99%
FAETP	kg DCB-Eq.	-82%	-82%
GWP	kg CO <sup>2</sup> -Eq.	-98%	-98%
HTP	kg DCB-Eq.	-89%	-89%
ODP	kg R11-Eq.	-95%	-95%
POCP	kg Ethene-Eq.	-97%	-97%
TETP	kg DCB-Eq.	-57%	-57%

The amount of energy required for the production of both products is very close to each other. In terms of the grid mix, the difference is 3.7 kW/h. Therefore, if the required energy is provided from wind turbines, the impact categories of both products are affected in the same amount.

In the ADP element impact category, environmental impacts 55% increase was observed caused by using wind turbines instead of the grid mix. Renewable electricity production plants have higher impacts on the environment due to consuming lots of elements (Gheewala S. And oth., 2016). Wind turbine constructions most entirely (99.7%) source for the consumption of the elements because of the use of metals (Atilgan B., Azagapic A., 2015). Therefore, facilities producing renewable energy sources have negative contributions to mineral resources and abiotic conditions. In ADP fossil category, usage of wind turbines has contributed positively by reducing the ADP fossil impact on the environment by 98%. In AP impact category, there was a 98% decrease in the results of the impact category while providing energy from the

wind turbine. Together with the electricity provided by wind turbines, a 99% contribution was decreased to the EP impact category. In the FAETP impact category, a 82% reduction was observed by using wind turbines. The GWP impact category impacts have resulted in a 98% reduction with supplying energy from wind turbines. In the HTP impact category, using wind turbines contributed to a 89% reduction. 95% reduction was observed in the ODP impact category thanks to the usage of wind turbines instead of the grid mix. In the POCP impact category, using wind turbines provided a 97% impact reduction on the environment. The least positive effect in all impact categories was achieved in the TETP category with a reduction of 57%.

#### 5.4.2. Photovoltaic system usage

The photovoltaic model is based on the global average market mix of photovoltaic technologies. It includes Mono-Silicon 42 %. Multi-Silicon 47 %. Cadmium-Telluride (CdTe) 7 % and Copper-Indium-Gallium-Diselenide 4 %. The data set covers all related process stages and technologies within the supply chain. The production and operation of the system are considered. The End-of-life of the panels is not included in the data set because there are no current technologies to reuse/ recycle them. Operational lifetimes of the panels are modelled with 20 years (Url-11). Table 5.17 illustrates the environmental impacts categories of zinc phosphating chemicals production which works by conventional grid mix electricity of Turkey compared with the photovoltaic system. The functional unit was defined according to the required energy for producing 1000 kg zinc phosphating chemical.

**Table 5.17 :** Environmental impact of zinc phosphating chemicals based on grid mix of Turkey and photovoltaic.

Impact Categories	Unit/fu	Grid Mix Product A	Photovoltaic Product A	Grid Mix Product B	Photovoltaic Product B
ADP elements	kg Sb-Eq.	2.19E-05	3.43E-04	2.12E-05	3.3E-04
ADP fossil	MJ	9.13E+02	1.11E+02	8.84E+02	1.1E+02
AP	kg SO <sup>2</sup> -Eq.	5.30E-01	8.03E-02	5.13E-01	7.8E-02
EP	kg Phosphate-Eq.	2.94E-01	3.21E-02	2.85E-01	3.1E-02
FAETP	kg DCB-Eq.	5.22E+01	2.15E+01	5.05E+01	2.1E+01
GWP	kg CO <sup>2</sup> -Eq.	7.79E+01	9.91E+00	7.54E+01	9.6E+00

**Table 5.17 (continued) :** Environmental impact of zinc phosphating chemicals based on grid mix of Turkey and photovoltaic.

Impact Categories	Unit/fu	Grid Mix Product A	Photovoltaic Product A	Grid Mix Product B	Photovoltaic Product B
HTP	kg DCB-Eq.	4.12E+01	1.86E+01	3.98E+01	1.80E+01
ODP	kg R11-Eq.	1.91E-06	1.44E-06	1.85E-06	1.4E-06
POCP	kg Ethene-Eq.	2.79E-02	5.99E-03	2.70E-02	5.8E-03
TETP	kg DCB-Eq.	2.39E-01	9.05E-02	2.31E-01	8.8E-02

With supplying the required energy from the photovoltaic instead of the grid mix, it is possible to decrease the environmental impact of the impact sources. Table 5.18 shows reduction percentages of impact categories for both products A and B.

**Table 5.18 :** Percentage change of impact categories by using photovoltaic.

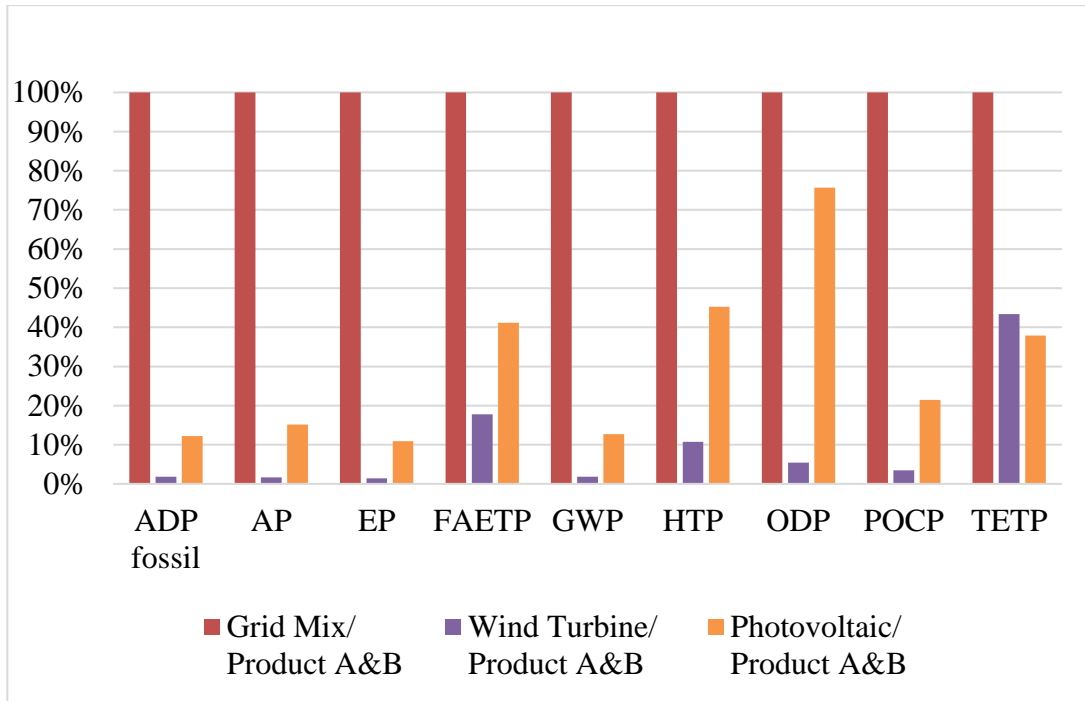
Impact Categories	Unit/fu	Product A	Product B
ADP elements	kg Sb-Eq.	+1464%	+1464%
ADP fossil	MJ	-88%	-88%
AP	kg SO <sup>2</sup> -Eq.	-85%	-85%
EP	kg Phosphate-Eq.	-89%	-89%
FAETP	kg DCB-Eq.	-59%	-59%
GWP	kg CO <sup>2</sup> -Eq.	-87%	-87%
HTP	kg DCB-Eq.	-55%	-55%
ODP	kg R11-Eq.	-24%	-24%
POCP	kg Ethene-Eq.	-79%	-79%
TETP	kg DCB-Eq.	-62%	-62%

Since the amount of energy required for both product's production process is nearly the same, in case the required energy is supplied from photovoltaic the impact categories of both products are affected in the same amount.

In the ADP element impact category, if the energy is supplied from the photovoltaic instead of the grid mix, there was a big increase in the environmental impact with 1464%. Since natural resources are consumed during photovoltaic production as well as wind turbine construction it has a great negative effect on the abiotic exhaustion category. In addition to that, it is observed that when renewable energy production compared to fossil electricity production from coal, mineral resource depletion is increased (Gheewala S. And oth.,2016). In the ADP fossil impact category, there was a 88% decrease in the results of the impact category while providing energy from the photovoltaic. The AP impact category impacts have resulted in a 85% reduction with supplying energy from photovoltaic. The use of photovoltaic has contributed positively by reducing the EP impact on the environment by 89%. Together with the electricity provided by photovoltaic, a 59% contribution was decreased to the FAETP impact category. In the GWP impact category, a 87% reduction was observed through using photovoltaic. In the HTP impact category, using photovoltaic contributed to a 55% reduction. The least positive effect in all impact categories was achieved in the ODP category with a reduction of 24%. 79% reduction was observed in the POCP impact category thanks to the usage of photovoltaic instead of the grid mix. In the TETP impact category, using photovoltaic provided a 62% impact reduction on the environment.

#### **5.4.3. Comparison of renewable energy sources with grid mix**

It is observed that, positive contributions to the use of renewable energy sources in all other impact categories except for the ADP elements category for both wind turbine and photovoltaic. According to the results of the study, the use of wind turbines has more positive effects on environmental impact categories. Figure 5.14 shows the percentage difference between grid mix, wind turbine, and photovoltaic system usage. The ADP elements impact category result was not included in the comparative graphic because the results show an increase by more than 1000% when compared with grid mix.



**Figure 5.14 :** Environmental impact comparison of grid mix, wind turbine, and photovoltaic usage.

## 6. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are gathered from this study that evaluates the two different zinc phosphating chemicals that are different in structurally from each other but functionally the same.

Products A and B had different results in different environmental impact categories. The main reason is the different structure of both chemicals. There are two differences between the products. The first is the rate of use of raw materials in the products. As can be seen from the results, the proportion of chemicals used in the products play a key role in the impact categories. The second difference is that while product A contains iron sulfate, product B does not. Since iron sulfate is used 2 kg in 1000 kg product A, it was observed that it does not directly affect the results.

When looking at the results of the two products in the environmental impact categories, it is observed that product A had more effects than product B in the GWP impact category only. It is seen that in all impact categories except the GWP impact category, product B has a more negative impact on the environment than product A.

There is a 7% difference between the results of products A and B in the GWP impact category. Nitric acid usage is the main reason why product A has more impact than product B. The amount of nitric acid used in product A is almost twice the amount used in product B.

In the ADP element impact category, product B has 72% more impact than product A on the environment. The major contributor to product B comes from the use of phosphoric acid. Phosphoric acid corresponds to half of the 1000 kg mixture.

In the environmental impact results of the ADP fossil impact category, product B has 26% more impact than product A. The main factor of this difference is due to the use of phosphoric acid.

Product B has 26% more contribution than product A in the view of environmental impact in the AP impact category. Phosphoric acid usage is the dominant factor with a 64% share in total.

In the EP impact category, the difference between product B and product A is accounted for 50%. The use of phosphoric acid in product B caused this difference with a 72% contribution to the total.

The greatest difference between in all effect categories results in products A and B are calculated in the FAETP impact category. Product B has 117% more impact on the environment than product A. The main source of this great difference in product B is due to the use of phosphoric acid, and it has an 86% contribution in the total result.

In the POCP impact category, product B has 34% more environmental impact than product A. This effect of Product B is due to a 62% share of phosphoric acid in total impact.

There is an 18% difference between the contribution of products A and B in the TETP impact category. Product B has a greater effect than product A, due to the use of a high amount phosphoric acid contained in product B. Phosphoric acid is the dominant factor in with 56% share in the total result of product B.

In the HTP effect category results, it is determined that product B had 38% more impact than product A. Phosphoric acid is the dominant factor and the reason for the difference between the two products, with a 69% contribution in product B.

There is no LCA study on zinc phosphate chemicals in literature. For this reason, the results of products A and B were compared with the EPD studies results conducted on coating chemicals. This coating chemicals are different from product A and B in the scope of their raw materials and finished good usage areas. In EPD studies, the most impact is obtained from the production stage, and it is stated that this is due to raw material extraction and production steps. Similarly with this result, products A and B's LCA studies represent that the most contribution occurred during the production of raw materials. Phosphoric acid production and nitric acid production are the main sources of all impact categories.

In both LCA studies, Turkey grid mix data is used as an energy source during the production of products A and B. To determine the environmental effects of using renewable energy sources instead of grid mix, two scenarios are created in the model.

While the energy produced by wind turbines is used in the first scenario, photovoltaic is preferred for the second scenario. There is no big difference between the required energy of producing products A and B. The only difference in energy consumption in both products is coming from the water preparation system. Product A includes more deionized water, therefore it needs additionally 4 kW/h energy. Therefore, the impact of renewable energy sources is the same for both products.

Wind turbine usage gives a positive result in all other impact categories except the ATP elements category. In the ATP elements category, using a wind turbine has a 55% negative effect when compared to using a grid mix. The main reason for this negative result is, manufacturing of wind turbines causes element consumption. %98 environmental impact reduction is obtained in the ADP fossil impact category. In the AP impact category, the %98 of environmental impact is decreased. The environmental impact reduction is calculated as %99 in the EP impact category. A decrease is obtained in impact by 82% in the FAETP impact category. In the GWP impact category, 98% of environmental impact reduction is observed. 89% of the environmental impact is decreased in the HTP impact category. In the ODP impact category, environmental impact reduction is accounted for 95%. 97% of environmental impact reduction is obtained in the POCP impact category. In the TETP impact category, 57% of environmental impact is decreased by using wind turbines.

When photovoltaic is used as an electrical source, a reduction in all environmental impact categories is achieved, except for the ADP element category. The negative effect of the use of Photovoltaic in the ADP element category is the element consumption during photovoltaic production. Supplying electricity from photovoltaic has 1464% more impact on the environment than from the grid mix. In the ADP fossil impact category, an 88% decrease is obtained. %85 reduction is received in the AP impact category. A decrease is obtained in impact by 89% in the EP impact category. The environmental impact reduction is calculated as %59 in the FAETP impact category. In the GWP impact category, 87% of environmental impact reduction is observed. A decrease is obtained in impact by 55% in the HTP impact category. %24 environmental impact is decreased in the ODP impact category. In the POCP impact category, environmental impact reduction is accounted for 79%. And, 62% environmental impact reduction is obtained in the TETP impact category.

When compared with the environmental effects of product B and product A, it is seen that product B has more negative effects on the environment. The production of these two chemicals is recommended with clean technology in order to reduce the effect of nitric acid and phosphoric acid production on the environment. In addition to that, it is recommended to perform LCA studies related with zinc phosphating chemicals, as very limited studies can be found.



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