

A Review of The Valorisation and Management of Industrial Spent Catalyst Waste in The Context of Sustainable Practice: The Case of The State of Kuwait in Parallel to European Industry

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Abstract

Industrial solid waste management encompasses a vital part of developed and developing countries strategies alike. It manages waste generated from vital industries and governs the hazardous waste generated as a major component of integrated waste management strategies. This communication reviews the practices that govern the management approaches utilised in the developed world for industrial spent catalysts. It critically assess the current situation of waste management within the developing world region focusing on the industrial waste component, in a novel attempt to crucially develop a way forward strategy based on best practices and future directions with major European industries. The review also draws parallels with European countries to compare their practices with those of the State of Kuwait, which rely solely on landfilling for the management of its industrial waste. Spent catalysts recovery methods are discussed in length covering conventional methods of valuable metals and chemicals recovery (e.g. hydrometallurgical, solid/liquid and liquid-liquid extraction) as well as biological recovery methods. A major gap exists within regulations that govern the practice of managing industrial waste in Kuwait, where it is essential to start regulating industries that generate spent catalysts in-view of encouraging the establishment of valorisation industries for metal and chemical recovery. This will also create a sustainable practice within state borders, and can reduce the environmental impact of landfilling such waste in Kuwait.

Keywords: Spent catalysts, Industrial Waste, Hydrometallurgical treatment, Extraction, Waste management.

1. Introduction

Solid Waste Management (SWM) has become the centre of attention within research and academic circles in recent years due to its paramount importance from environmental, social and economic points of view. SWM covers the concept of waste reduction and reuse as well as the processes and technologies of recycling, valorisation/recovery, aerobic or anaerobic treatment, thermal treatment with or without energy recovery, fuel production and landfilling. Typically, solid waste (SW) is classified as municipal solid waste (MSW), industrial solid waste (ISW), agriculture waste or commercial waste (CW). In general, MSW refers to the mixture of residential and commercial refuse such as garden and food waste, paper, textiles and plastics film/rigid products. On the other hand, ISW refers to the waste generated by the industrial, and on a lesser extent, the institutional sector (Dixon and Jones, 2005; Prabakaret al., 2018). The inclusion of various ISW components is a subjective matter, where construction and demolition solid waste (C&DSW), chemicals from the medical and pharmaceutical industry and wastewater are not always included in assessment reports. The ISW contains valuable metals that could be valorised to boost economical returns of countries and societies, as well as, reduce its associated environmental burdens that stem out of mismanaged ISW components. Typically, ISW originates from chemical plants, paint industries, cement factories, thermal power plants, metallurgical plants, pharmaceutical industry, textile industries, food processing and petroleum industry. ISW can be divided into two main categories which are hazardous and non-hazardous waste. The latter is produced from food processing plants, cotton mills, paper mills and textile industries. On the other hand, hazardous waste is the waste portion produced from industries other than the aforementioned. Common examples of hazardous waste are metals, chemical, drugs, lather, electroplating and rubbers. Table 1 shows a classification of ISW with respect to type and source (BDF, 2018).

The State of Kuwait (29°30'N *lat.* and 47°45' *E long.*) is an oil-dependent state within the Gulf Council Countries (GCC) region of West Asia. The country is inhabited by 4.1 million residents of both national and expatriates within a total area of 17,818 km². It has been reported to be the highest per capita generator of MSW with conflicted reports showing a per capita generation range between 1.55 to 5.74 kg per day according to recent estimates (World Bank, 2012, Kaza et al., 2018). Kuwait has also been reported to be the second most toxic country in the world (Whittaker-Wood, 2017). Current infrastructure doesn't support waste management (WM) activities in an integrated manner and governmental parties at the moment are defining criteria to develop sustainable and up-to-date plans to do so (Kaza, 2018). The sole method of SW disposal in the country is unsanitary landfilling in open dumps (Al-Salem, 2009). Kuwait is divided into six governorates that host major industries, mainly revolving around chemicals and petrochemicals

conversion processes. The focus of the state of Kuwait has shifted in recent years towards MSW and ISW management due to the nature of the country's industrial activities and social behaviour. The country has also embarked on various mega-scale industrial projects including the new refinery project (NRP) which is designed to process over 600 MMbpd of crude oil (Al-Salem, 2015). The project has been announced to be one of the largest in the world that will host catalytic upgrading units, including fluid catalytic cracking (FCC) and atmospheric residue desulphurisation (ARDS) units using up-flow reactor technology (Richmond, 2010). Such industrial ventures will necessarily result in the accumulation of more ISW namely industrial grade catalysts. A similar situation can be observed across Europe. Countries such as France, Germany and Sweden are leaders in their respective industries, thus generate substantial amount of waste. The majority of Europe's waste is generated from the following industrial sectors: Agriculture, mining and quarrying, plastics and rubbers, manufacturing, energy production, water distribution and treatment and construction, which all make the management of ISW more critical. Typically, MSW constitutes 15% of the total solid waste generated across European countries, whilst ISW represents some 40% of the total waste load (Jordan and Heidorn, 2003). On an average per capita assessment by recent published estimates of the World Bank (Kaza et al., 2018), ISW is generated in high income countries (e.g. Kuwait) by 42.62 kg per day. Comparatively, MSW and electronic waste are produced (on average) at a rate of 0.81 and 0.05 kg per capita per day, respectively. These estimates also represent some 950 kg of ISW for every 1000 Euros (€) of added value.

The industry in Kuwait mostly falls under oil and gas activities. Currently, Kuwait processes about 1000 M bpd of crude oil within its country limits representing a feedstock for the light derivatives and petrochemical industries. It also exports over 3.1 MM bpd of crude oil as it is one of the oldest members of the Organization of the Petroleum Exporting Countries (OPEC). Al-Muzaini (1998) stated that there were twelve industries located in Shuaiba Industrial Area (SIA), which is the largest industrial area in the Arabian Gulf hosted on the western coastal line of Kuwait. The total production of industrial wastewater alone is 23,000 m³ d⁻¹, which carry heavy metals, organic chemicals and suspended solids and mostly ends up in the Arabian Gulf. Different technologies of treating such waste is based on physical, chemical and biological aspects (Syed, 2006). Industrial activities grew considerable in Kuwait within the past decade. Alhumoud and Al-Kandari (2008) showed in their work that a drastic increase of industrial waste was noted in Kuwait between the years 2000 (12,660 tonnes) to 2005 (47,169 tonnes). Figs.1-2 show approximately the percentages of factories by type and the percentage of hazardous industrial solid waste, respectively. In waste management, one of the main classifications is identifying the waste regarding to its harshness to fall either under the hazardous or non-hazardous categories. On an annual basis, hazardous waste formulates 18.86% of the total

production of industrial waste generated in Kuwait (\approx 8,895 tonnes), including heavy oil sludge, asbestos and expired chemicals (Alhumoud and Al-Kandari, 2008, Al-Qallaf et al., 2016).

Petroleum refining is considered to be the most significant pillar of the economy, due to Kuwait's oil and gas based industry. Despite the strength of the financial return, oil and gas industries may cause various environmental problems. Petroleum waste contains high concentrations of heavy and toxic metals (Obiajunwa et al., 2002). To manage the potential side effects of petroleum waste, Mansour et al. (2016) examined petroleum-based waste such as sludge and sand. Over 17 elements including metals were recorded in their findings. The samples were derived from petroleum companies waste in Kuwait. The results reflect six samples that were dried for one day under 110°C. The amount of elements was detected through the technique of X-Ray Fluorescence (XRF). The level of iron (Fe) was very high in both sludge and sand samples in addition to manganese (Mn) and calcium (Ca). Manganese was noted to be consistent with previous studies (0.25-0.28%), whereas Ca is higher (0.9-1.02%) (Table 2). A study published in Kuwait (Alshammari et al., 2008) declared that all industrial oil and gas plants plan to dispose some 240 ktpa of industrial waste, in order to achieve an integrated waste management strategy in the refining industry. To deal with this waste, they classified hazardous waste as incinerable and non-incinerable. Catalysts are one of non-incinerable hazardous waste, which contains various metals (e.g. platinum, cobalt, copper, molybdenum, iron zinc, nickel and aluminium). Typical catalysts composition is presented below for the three main operating refineries within state borders of Kuwait, namely Mina Al-Ahmadi (MAA), Mina Abdullah (MAB) and Shuibah (SHU) refineries (Table 3).

According to the official European Statistics published by EUROSTAT, the EU generated a total of 58 million tonnes of hazardous waste back in 2002 which includes hazardous waste from all economic sectors encompassing hazardous municipal waste (European Commission, 2005). This estimate increased to 100 million tonnes in 2016 comprising 4% of the total generated waste across the EU-28 (Euro Statistics, 2019). The UK alone generates 335 million tonnes of waste per year (mtpa) of which 225 million tonnes are MSW (Lupa et al, 2011). Due to the environmental impact of waste accumulation, recycling has gained increasing interest across the EU in recent years (Beigl et al., 2004; Pires et al., 2011).

Even though the EU industry is different to Kuwait, heavy metal waste is still generated from different industries in the UK and Europe. Mercury (Hg) arising from the industrial sector; lead (Pb) mainly from road transport; cadmium (Cd) due to abatement technologies and chromium (Cr) are some of the most commonly generated heavy metals that pose numerous environmental and health risks. One of the major contributors of such toxins is the waste generated from the construction industry, as well as mining and extraction (European Commission, 2002). Due to recent awareness of the negative effects of

these metals, governments are devising models and implementing plans to lower the amount of heavy metal waste. For example, Pb associated waste has been reduced by 93% in the last 26 years across Europe. This was achieved by phasing out leaded petrol which currently accounts for one third of total waste emissions around the world (EEA, 2017). Despite the awareness and overall decrease in heavy metal emissions, in the last few decades, there is still a dire need for SWM, further reducing emissions and developing metal recovery methods. Regression models results, baseline studies and the development of integrated frameworks to reduce waste accumulation, have also been adopted recently in Kuwait in-light of EU strategies (Al-Salem et al., 2018a). In addition, strategies to mitigate plastic solid waste (PSW) and the development of standards to govern the use of polymeric products, are also considered two main highlights of Kuwait's recent waste management strategies development by governing bodies (Al-Salem et al., 2018b). In light of the aforementioned, this review showcases the major ISW management activities and potential of valorisation within the State of Kuwait with an emphasis on spent catalysts as a waste component. The work also draws parallels with the EU in reviewing ISW activities and major valorisation techniques that can relate to the case of Kuwait, especially in the petroleum industry (e.g. spent catalysts). It critically assess the current situation of waste management within the developing world region focusing on the industrial waste component, in a novel attempt to crucially develop a way forward strategy based on best practices and future directions with major European industries. The work in this review can pave the way for the governmental parties, in both Kuwait and industrial countries, in targeting the main SW components that can reduce environmental burdens in industry. An examination of the main recovery techniques utilized in spent catalysts is also reported in this work.

2. Spent Catalysts in the Context of Industrial Waste Management and Operational Challenges

Spent catalysts are non-active, used and/or regenerated catalysts (containing metals/metal oxides) that are discarded as ISW. Approximately 4% of them are petroleum refinery waste regarded largely as a hazardous

waste component. The amount of spent catalyst waste is in direct correlation with the amount of fresh catalysts used and the regeneration cycles of unit operations. The spent waste can be managed via chemical/microbial treatment, regeneration and reuse or landfilling (Akciil et al., 2015). The petroleum industry is responsible for the generation, accumulation and disposal of spent catalysts. There are three main contributing sectors to spent catalyst waste: Hydroprocessing (hydrotreating and hydrocracking), Fluid Catalytic Cracking (FCC) and reforming catalysts along with any desulphurising processes. Hydroprocessing is the name given to processes that are used to refine and treat fuels. In particular, hydrotreating is used to eliminate hetero atoms and saturated carbon-carbon bonds through removing sulphur, nitrogen, oxygen and other metals. On the other hand, hydrocracking is used to form smaller molecules by breaking carbon-carbon bonds as well as increasing the fuel yield. To carry out these processes, hydroprocessing catalysts are utilised. In recent years, there has been a substantial increase in spent catalysts, with an annual expected rise of 4.4% in hydrotreatment catalysts. The following factors are responsible for this increase: higher demands of low-sulphur fuel (via distillates hydrotreating capacity); reduction of catalyst cycles to overcome operational challenges in diesel hydrotreating units; processing of more viscous feedstock and unavailability of catalyst reactivation processes (Marafie and Stanislaus, 2008). The hydrodesulphurisation (HDS) method is used to remove sulphur from different kinds of organic materials. The catalysts utilised usually are a combination of bimetallic of Ni/Co on an aluminium oxide support. Fly ash is a residue of coal from thermal power plants, accounting up to a maximum of 20% of the original coal feed, containing catalysts as well. Approximately 750 million tonnes of fly ash are generated each year and almost all of it is disposed into landfill. HDS and fly ash disposal further contribute to the spent catalyst disposal challenge, as well as, causing further strain on the environment (Akciil et al., 2015). To overcome this, many refineries are looking into recycling fly ash into the cement industry by potentially using it as a raw feedstock material.

FCC units, used to optimise the yield of gasoline (with high octane number) from crude oil, are another major source of spent catalysts. FCC is used to convert distillates into gasoline range hydrocarbons (Gianetto et al., 1994). FCC catalyst are usually made from active silica dioxide (SiO_2) and aluminium oxide (Al_2O_3). The leading Oman refineries (e.g. Sohar and Mina Al-Fhal Refineries) which are located in the same region as Kuwait (i.e. GCC), produce approximately 20 tonnes per day of FCC catalysts' waste and an average of 250 kg of spent alumina waste. The majority of which is disposed of onsite or at various disposal sites leading to environmental issues (Taha et al., 2011). Tables 4 and 5 show the generic properties and composition of spent catalyst waste produced from Oman refineries (Al-Jabri et al., 2013). FCC spent catalyst metal composition can vary across the world. Metals such as vanadium (V) and nickel (Ni) are also commonly present amongst the ones listed in Table 4.

A typical FCC catalyst is a mixture of an inert matrix of kaolin, alumina and silica. Different kinds of zeolites are also applied such as types X, Y and ZSM-5. Approximately 750 ktpa of spent catalyst waste is generated worldwide through FCC processing (Kasliwal et al., 2015) In extension to this, FCC catalyst have recently been utilised for cement production and as a cement additive (for aluminate calcium cement). These catalysts contain additional cobalt metals. In India, FCC spent catalyst are also known for being used as a refractory for furniture manufactured from clay-based kiln. The particle size ranges from 60 to 100 μm (Ramezani et al., 2017). The generation and untreated disposal of such fine particles causes major environmental concerns due to wide and uncontrolled dispersion of harmful metals present in the catalysts. Recently, Su et al. (2019) showed that spent FCC displays advanced desulfurization properties. The seriousness of spent catalyst waste disposal has brought forth a new research potential for spent catalysts disposal along with recovery and reuse of metals. Amongst which molybdenum has gained substantial attention to be recovered from hydrogenation plant wastes. This transition metal is widely applied in the desulphurisation of petrochemicals and coal-based liquids/ fuels (Kar et al., 2004). Due to the toxicity of catalysts, the United States Environmental Protection Agency (EPA) has classified all these metals and catalysts as hazardous waste (Marafi and Rana, 2016). Metals such as V, Ni, Mo and Co get leached by water and pollute the environment as well as generating harmful toxic gases such as hydrogen cyanide (Marafi and Stanislaus, 2008). The hydrotreating of spent catalysts can have a life cycle between three to four years and FCC catalysts get lost in the atmosphere daily and are offloaded daily/ fortnightly (dependent upon the use and requirement) (Chiranjeevi et al., 2016). The increased exposure, toxicity and disposal has developed numerous spent catalysts recovery methods, which are discussed in the sections hereafter.

3. Recovery Methods Used in Industrial Waste Management

3.1. Hydrometallurgical and Liquid-Liquid Extraction Process

The hydrometallurgical process is defined as the recovery of metals post chemical leaching in aqueous solutions aimed at recovering metals from ISW (Kentish and Stevens, 2001; Al-Qassimi et al., 2018).

Hydrometallurgical pre-treatment is typically applied to recover metals such as iron, steel, copper and aluminium from electric-electronic waste (Tuncuk et al., 2012). The procedure follows three consecutive stages starting with leaching followed by purification of solution and concentrate of metals; and finally the process of recovering (electrolysis) recuperates the desired metals (Xu et al., 2007; Cerruti et al., 1998; Brandl et al., 2001). This method has low environmental impact, capital and high metal recoveries, as well as, having the ability to be applied for small scale projects which makes it versatile and efficient.

Molybdenum (Mo) and platinum (Pt) are commonly used as catalysts with other base metals, rooted (entrenched) upon catalyst pores supported on various materials such as aluminium oxide (Al_2O_3). Vanadium (V) and Mo are valuable metals that can be recovered from different process such as desulfurization catalyst, oil sands, slags, ashes and lean ores. Extensive research was conducted in recovering V and Mo from waste catalyst from heavy oil desulphurization in Japan, Germany and the USA. The common catalyst used in this process is MoO_3 catalyst promoted with CoO on $\gamma\text{-Al}_2\text{O}_3$ base. It is reported that the experimental procedure follows four main steps: Pretreatment of waste catalyst (washing with ligroin and drying), sodium chloride-water vapour roasting of the calcined catalyst, leaching of the roasted catalyst and finally, liquid-liquid extraction, stripping and precipitation (Biswas, 1985). To convert the metal values selectively (V and Mo) into the water-soluble form in the second step, NaCl- H_2O vapour is used to roast the catalyst (calcined at 630°C). Since the thermal hydrolysis of NaCl is much faster above its melting point (i.e. 800°C), experiments are conducted above this temperature. The roasting reaction is measured by the absorption of HCl gas in NaOH solution at pH 10.5 and correcting the pH by adding 1 M NaOH solution. Dried NaCl (400°C) is weighed and grinded in a mortar to $152\ \mu\text{m}$ then placed in the furnace. The temperature of the furnace is maintained within $\pm 10^\circ\text{C}$. When the desired temperature is reached ($\approx 630^\circ\text{C}$), the saturated gas with water vapour is passed through the furnace (Biswas, 1985).

3.2. Metal Recovery Using Solvent and Liquid/Soil Extraction

LIX 84-I (2-hydroxy-5-nonylacetophenone oxime) is a chelating organic extract. Solvent extraction with LIX 84-I dissolved in kerosene at an O:A phase ratio of 1 to 1, is a technique applied to catalyst leachate solutions containing up to $10\ \text{g L}^{-1}$ Mo, $27\ \text{g L}^{-1}$ Al and $2\ \text{g L}^{-1}$ Ni to extract Mo(VI) (Park et

al., 2010). The procedure is carried out to extract Mo(VI) from leached liquor with an initial pH range of 0.5-3.0. The leaching solution is typically performed after baking the spent catalyst then leaching it with sulphuric acid (H_2SO_4). By using a separating funnel for 5 minutes to equilibrate both aqueous and organic solutions in equal volume, the trace content of the organic component present in the solution is separated and pH is measured for raffinate. Afterwards, the raffinate is diluted to reach a suitable concentration with 1% HNO_3 where the organic sample is stripped with 1 M NH_4OH (Park et al., 2010). The work aforementioned covered the effect of different variables on the process such as pH, concentration of LIX 84-I, different stripping reagents, phase ratio and diluents. The extraction of Mo(VI) increased with decrease in equilibrium pH and increased with an increase in LIX 84-I concentration.

A different technique to recover V, Mo and Ni from waste catalyst produced from heavy gasoil hydrodesulfurization is by using caustic soda solution (Rojas-Rodríguez et al., 2012). Spent catalyst with a particle size between 1.5 and 7.3 mm is calcinated at temperatures up to $450^\circ C$. The reactions lead to the removal of the sulphur, carbon, and the oxidation of vanadium sulphide. V and Mo are precipitated as vanadium pentoxide and molybdenum trioxide, respectively. Nickel aluminate is obtained from the residue after the removal of vanadium and molybdenum. The recovery achieved is up to 95.1% and 95.5% for the V and Mo, respectively.

Solid/liquid extraction is also used to recover valuable metals from spent catalysts. The procedure published previously by Rojas-Rodríguez et al. (2012) shows that a temperature between 20 and $100^\circ C$ is typically employed in the hydrometallurgical extraction process, which uses citric acid for leaching purposes. Firstly, the catalyst is exposed to citric acid after washing with distilled water for 30 min at $64^\circ C$. Spent catalyst is also autoclaved and rewashed with de-ionized water. Al, Ni, and Mo recovery is achieved during this process with temperatures around $80^\circ C$. The importance of spent catalysts is notable in several ways in catalyst preparation or for use in the metal industries. Marafi and Rana (2016) showed that catalyst derived from atmospheric desulfurization (ARDS) can be treated in five stages which were de-oiling, drying, grinding, sieving, de-coking. In fact, the spent catalyst is a mixture obtained from four reactors in fixed portions suitable for metal recovery (Marafi et al., 2007; Sheeha et al., 2013). When spent catalyst reaches the de-coking process, the catalyst is combusted (with oxygen) for 8 hours under a temperature range $300-600^\circ C$. Fig.3 shows the five stages of pretreatment of spent catalyst typically used in ARDS processes.

3.3. Soda Roasting and Metal Leaching

Soda roasting is used to extract high yields of V and Mo. High pressure is applied to recover Ni(CO) as a solid using NaOH. Mo and V are recovered in high percentages reaching 95% when a roasting temperature of 550°C is applied (Marafi and Stanislaus, 2011). In this process, leaching reagents which are basic in nature, such as ammonium salts, are typically used. Ammonium per-sulphate (APS) is an example of high efficiency leaching agents, due to its ability to oxidize and increase Ni and Al extraction percentages. APS is formed of 7 wt% of active oxygen which release free radicals that promote metal recovery especially for V, Ni, and Al, however, the acidic nature minimizes the ability of extracting Mo. Valuable metals (e.g. Co, Cr, Cu, Ni, Mo, Ti, V, and W) form the majority of catalysts used in industrial sectors with an estimate of 35 wt.%. A study performed by Gaballah et al. (1994) investigated the degree of metal recovery by monitoring selective chlorination over a wide range of temperatures (300-600°C). Mixtures of chlorinated gas were able to recover 98% of Ni and Co from chlorinated deposits, 98% % of Mo, Ti, and W and 80% of vanadium compounds. Thermal cracking between 20-1000°C was applied on hydrodesulfurization spent catalysts followed by the process of chlorination (Gaballah et al., 1990). The volatiles were condensed through two condensers at different temperatures as shown in Fig.4.

3.4. A Note on the Spent Catalysts Generated Through Thermal Cracking and SW Upgrading

Both ISW and MSW have been researched extensively over the past few decades, namely in fuel and energy recovery processes. These processes will typically utilise various types of catalysts for upgrading products and distillates such as HZSM-5 and PZSM-5 (Demirbaş, 2005). These processes also revolve around the concept of oils and hydrocarbon (HC) cracking to achieve the desired products acceptable to the

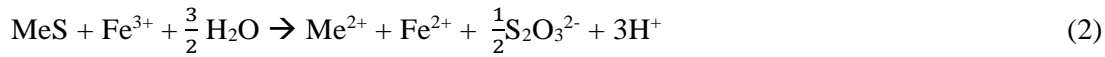
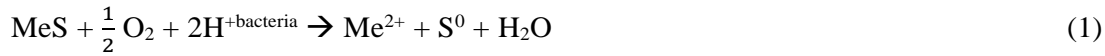
marketplace and standards (Vasile et al., 2001; Chandrasekaran and Sharma, 2019a; Al-Salem, 2019). Further upgrading for the generated products can also be achieved with catalytic reforming in the petroleum downstream industry (Sharma et al., 2014; Sharma and Bansal, 2016; Sharuddin et al., 2016; Hafeez et al., 2019; Muhammad et al., 2015). All of which combined can lead to the accumulation of spent catalysts that is not typically accounted for in ISWM surveys, strategy development and studies. It is essential to understand the possible routes of spent catalysts accumulation as an ISW component within such upgrading technologies. This will enable the determination of the best course of action for future developmental plans in industrial waste mitigation and management strategies. The types of catalysts used in such processes will be the focus of this section where the aforementioned recovery techniques in the previous two sections can be successfully applied to extract valuable metals and products.

A prominent example of ISW upgrading and management in petroleum downstream industries is the process of pyrolysis. This is directed (mainly) towards producing valuable oils and tars that are free of metals (Muhammad et al., 2015). Pyrolysis subjects a feedstock to inert gas deterioration at elevated temperatures typically between 500 to 800°C. Once catalytic pyrolysis is considered, some 300 to 400°C reduction in the operating temperature is achieved whilst obtaining cleaner distillates and products (Xue et al., 2015). Pyrolysis has also been applied in the past as a replacement to direct combustion for industrial waste oil treatment (Demirbaş, 2005).

In an effort to study the possibility of integrating cracking technologies with the petroleum downstream industry, Chandrasekaran and Sharma (2019b) have detailed a plan to consider pyrolytic units treating Plastic Solid Waste (PSW) as a feedstock for fuel production whilst integrated to existing industrial infrastructure. Butler et al. (2011) has also proposed to integrate both thermal and catalytic pyrolysis in petroleum downstream industries to upgrade and produce gasoline and diesel; while utilising a feedstock from PSW. Catalysts that are usually used in such processes are zeolite based ones. Bargi and Williams (2002) showed the effect of using Y-zeolite on the pyrolysis of polyethylene (PE) in a two stage fixed bed reactor system. The evolved gases and oil generated consisted mainly of aliphatic compounds. Lin et al. (2012) used a hybrid FCC series catalysts to pyrolyse a mixed PSW feedstock under an operating temperature between 330 to 450°C. Oil produced was estimated to be 87 wt.% of the total product yield. Table 6 also depicts major studies conducted in recent years using catalytic pyrolysis to upgrade SW. On the other hand, gasification technology where sub-oxygen content of carrier gas is applied in the degrading media, has also been used with aid of catalysts to upgrade various feedstock. Readers are referred to Arena (2012), Wu and Williams (2010) and Al-Salem et al. (2017) for additional content on both pyrolysis and gasification of various organic substances.

3.5. Biotechnological Processes

Biotechnological processes require longer leaching times to gain efficient extraction when compared to other conventional methods. They are typically directed at winning processes for copper (Cu) recovery. On the other hand, bioleaching methods are more cost effective and environmentally friendly than other conventional recovery techniques. They have been investigated on a small scale for exhaust catalysts to study their potential as a recovery process. The following reactions show a simplified mechanism for metal sulphide recovery from exhaust catalyst in a solid matrix form. Equation 1 represents direct *bio-oxidation* of metal sulphides onto the matrix. Equation 2 shows the chemical oxidation by iron which is generated by bio-oxidation in Equation 3. Equations 4 and 5 show the formation of sulphide ion through bio-oxidation of sulphur and thiosulphate, respectively, for a complete reaction case.



In the process, the hydrocarbons (HC) from the catalysts are first removed by washing with ethyl alcohol. The microorganism culture, containing Fe/S oxidizing bacteria, are cultivated under acidic conditions and the bioleaching is carried out by incubation at 30°C. Results show that Ni and V could be successfully extracted of (Beolchini et al., 2010). This process is a cost effective and environmentally method for spent metal recoveries.

3.5.1. Precious metal recovery via AquaCat

AquaCat is a method to recover metals from spent heterogeneous and homogenous catalysts using a process based on supercritical water oxidation which converts carbonaceous material to less noxious compounds, leaving the precious metals as their oxides (Grumett, 2003). The technology was commissioned at Johnson Matthey's Brimsdown (UK) facility in 2002 and operated until 2007 when the process and technology rights were purchased by Supercritical Fluids International (Smith et al.,

2013). It consists of two stages, the determination of the metal content by direct sampling and the utilisation of supercritical oxidation to convert carbon materials into less harmful compounds. This method targets organometallic-based catalysts which have historically been treated by high energy intensive methods such as combustion. In the direct sampling, the spent catalyst in the form of a wet filtered cake (between 5-500 μm particle size) is added to water and a surfactant in a vessel and agitated to form a homogenous dispersed mixture, which is analysed to determine the metal content. The water based slurry is then pumped to the feeding tank where the supercritical water oxidation takes place. Water becomes supercritical above 374°C and 221 bar, and by that stage its viscosity will be close to that of its vapour combined with a higher fluid density. At this stage, the organic substances become soluble and the water will act as a solvent for the oxidation. For homogenous catalysts, high pressure water is fed into the economiser. The catalyst is inserted directly into the reactor after oxygen injection as it does not mix with the supercritical water. The AquaCat process requires less energy and exhibits lower CO₂ emissions and doesn't give rise to SO_x and NO_x emissions as opposed to incineration. Direct sampling allows safer handling and treatment of hazardous materials as it can be collected in bulk (Grumett, 2003). The precious metals are recovered in a separator as depicted in the figure.

3.5.2. Bio- hydrometallurgical Process

In this process, microorganisms have the primary role of leaching instead of using reagents to do this activity. Microorganisms (e.g. bacteria and fungi such *Bacillus sp.*, *Aspergillus niger* and *Penicillium simplicissimum*, *Saccharomyces cerevisiae*, *Yarrowia lipolytica*) interact with metals for the purpose of solubilization. Previous studies were conducted on the biological recovery of metals from sludge, fly ashes, batteries, and electronic waste (Lombardi et al., Wu and Tin, 2009; Carranza et al., 2009; Xin et al., 2009; Bayat and Sari, 2010; Zheng et al., 2009). Gaballah et al. (1994) showed that various

hydrometallurgical processes are available for metal recovery. They recovered metals when catalyst roasting is the typical recovery route. After biological uptake, it was reported that chlorides of Mo and V were volatilised at 500°C whilst those of Co and Ni remained at solid state until 700°C was reached. During bio-uptake hazardous compounds such as HCL, H₂SO₄ and alkalis were separated from valuable metals (e.g. Mo, V and Al).

3.5.3. Pyrometallurgical process

The pyrometallurgical process is a nominal choice when physical properties are negligible. It recovers metals from industrial waste after thermal treatment (smelting, roasting, and refining). In synthesis gas production, especially in low temperature processes of carbon monoxide conversion with steam to form hydrogen for the production of ammonia or methanol, CuO-ZnO-Al₂O₃ catalyst was considered by Malecki and Gargul (2018). The spent catalyst could be a valuable source of metal using pyrometallurgical and hydrometallurgical processes to recover more than 66% of the copper in metal form and 70% of zinc as ZnO. The objective in the pyrometallurgical process is to maximize the yields of copper (Cu) and zinc (Zn) extracted from the spent catalyst in the recovery process so test melting is initially performed. Slag-forming additives are needed in the recovery process to obtain the lowest melting point of the slag which s also has a meaningful effect on the recovery of Cu to alloy and Zn to dust. In the additives CaO, SiO₂ and Na₂O were shown to give the lowest melting point when the components were in the same weight percentage. The catalyst was loaded into a graphite crucible and placed in an induction furnace at a temperature range of 1100-1300°C to obtain the maximum stripping of zinc and the formation of liquid copper. Coal is added to the process to reduce CuO and ZnO. After melting, the liquid products were cooled, separated and weighed for chemical analysis. On the other hand, the hydrometallurgical method consists of two main processes, leaching and filtration. The zinc oxide and copper oxide leaching process follows two stages: leaching in NaOH solution (temperature 75°C for 120 min, NaOH concentration = 200g dm⁻³, 1/s = 10) followed by leaching in H₂SO₄ solution (temperature 60°C, for 120 min, H₂SO₄ concentration = 180 g dm⁻³, 1/s = 10). Zinc has high resistance to both acid and alkaline so after leaching an insoluble residue is formed, which was filtered to separate the precipitate. The resulting yield of copper in the solution is about 98% with 62% zinc in the alkaline solution.

3.5.4. Recovery of Catalysts from Automotive Catalyst Deposits

The use of platinum group metals in automotive catalysts is widespread. There are numerous reports in the literature on the fate of these metals in the environment and on human health from countries around the world (Khan and Strand, 2018; Sen et al., 2013; Gao et al., 2012; Spaziani et al., 2008). Road dust

containing these metals has been assessed as an anthropogenic resource and methods have been established to recover the spent catalyst. Methods include leach solutions such as aqua regia to solubilise the metals as well as a microwave-assisted leaching method (Yong et al., 2003). The microwave approach gave 80% metals recovery, with the leach time reduced from 2 hours to 15 minutes using 50% (aq.) diluted aqua regia compared to conventional acid leaching to give potentially a more biocompatible leachate. Authors have used aqua regia leachates rich in platinum group metals as feedstock for bacteria such as *Desulfovibrio desulfuricans*, *Cupriavidus metallidurans* or *Escherichia coli* (Yong et al., 2003; Murray et al., 2017) which reduces the soluble metals to cell-bound insoluble base metals, for example Pd(II) to Pd(0)). It was reported that bacteria immobilised in a biofilm preloaded with Pd(0) loaded in a flow-through electrobioreactor performed better as chemical catalysts for the reductive recovery of precious metals when compared to free cells with a recovery of spent automotive catalysts of up to 90% efficiency at a residence time of 15 minutes. Model solutions were found to give better results than real automotive leachate and from crushed spent automotive catalyst due to interference by other contaminants. The bacterial Pd(0) functioned as a superior chemical catalyst in a test reaction which liberated hydrogen from hypophosphite (Yong et al., 2002). These catalysts have also been tested as cheap nanocatalysts for fuel cell electrodes (Yong et al., 2010).

3.5.5. Recovery of catalysts from in situ heavy oil upgrading

In situ methods to recover heavy oil fractions are gaining momentum. These are largely based on combustion methods but in situ catalytic upgrading process such as CAPRI (Catalytic Petroleum Recovery In situ) are employed to further improve the upgrading of the heavy oil. The catalyst is typically packed into an annulus around the horizontal production well, however some researchers have investigated the use of dispersed catalysts to improve the issues of deactivation associated with packed bed catalysis (Al-Marshed et al., 2016). The recovery of spent catalyst from in situ recovery processes poses challenges. The catalyst can be retained in the formation and it has been suggested that dispersed catalyst injected in the form of nanoparticles may either agglomerate into larger particles or adsorb to the rock surface especially

at the temperature and pressure conditions. To negate this ultradispersed suspensions with high stability and selectivity are needed (Guo et al., 2016). Spent dispersed catalysts can be recovered from the oil using conventional demetallisation processes that are used to remove metals from heavy oil. Demetallisation processes are valuable in their own right as metal recovery processes; a third of all vanadium produced by Russia stems from demetallisation of heavy oil and 8% of vanadium world production comes from oil feedstocks. Demetallisation takes place in the electrostatic desalter at a refinery although this processes is typically modified to deal with stable organometallics with electrolysis cells and polymeric sorbents being used to recover metals (Magomedov et al., 2015).

4. Regulations Governing Spent Catalysts Handling and Industrial Waste

4.1. European Union (EU) Regulations

The European Union (EU) has some of highest waste management standards in the world. The EU Waste Management regulations and directives EC 98/2008 and EC 1013/2006 aim to protect the environment and human health through highlighting the importance and emphasising the application of waste recovery and recycling techniques (EC, 2006; EC 2008). These regulations also govern the shipment and handling of ISW and spent catalysts trade between EU countries. To implement this, the original waste producer must pay for the costs of proper and adequate waste management as well as introduce extended producer

responsibility. This is where the manufacturer accepts and disposes of products that are returned after use. The producers of waste are required to treat the waste before disposing or have it professionally tested; this is tracked by regular inspections (EU 2008).

EU regulations for waste have been divided into various sections. The Directive of landfill waste (EC/35) aims to reduce and prevent disposal as much as possible, to have little to *no impact* on surface water, groundwater, soil or human health. To achieve this, specific guidelines have been set. EU landfill sites are usually split into three different sections: hazardous waste, non-hazardous waste and inert waste (non-incinerable/ decomposable waste). Biodegradable waste is discouraged and used tyres, liquid waste, flammable waste, explosive or corrosive waste are not allowed in landfill sites. Only treated waste can enter landfill sites. This is tracked by issuing permits and regular operator checks (EU, 2000).

Hazardous waste regulations were set by the European Economic Community and the Basel Convention. This regulates the boundaries for which the hazardous waste disposal must abide by. It consists of three main sections: minimising transported quantities, treatment and disposal of wastes as close to the place of generation and to prevent/ minimise the generation of waste from the beginning (Community 1993). Due to the recent increase in ISW generation, the waste safety and guidelines have become more severe. EU has also given formal consent for a ban prohibiting the export of waste to non-OECD countries a while ago (Parties and This, 1987).

To control industrial emission, the EU has devised a framework of interconnected permitting. This is where the emission permit must take into consideration the industrial plant's whole environmental performance (from start up to shut down) and to avoid the pollution shift between mediums (such as air, water and land). Priority is given to prevent pollution by intervening at the generation point and ensuring efficient and sustainable use/ management of natural resources. This legislation covers the following industrial sectors: energy, metal production/ processing, minerals, chemicals and waste management. This allows the public to be given an early opportunity to contribute to the permitting process and installations (EU 2004).

The European Catalysts Manufacturers Association has set guidelines for the management of spent catalysts, which was established back in 1993. The association abides by the European Chemical Industry Council. The guidelines state that whilst the catalyst is in use, the user is required to pay attention to precautions and safety measures that will be required once the catalyst has been deactivated and devise an adequate disposal plan. The hazardous properties of the catalyst should be well known to the user to help aid the disposal plan. Once the catalyst has been discharged it can either be reused (via off-site regeneration) or the material can be discarded recovering the metals. Regeneration of a catalyst usually involves international movement, which has to be carried out by adhering to the EU Waste Transportation Act (EC, 2006). According to the Organisation for Economic Co-operation and Development (OECD) decision,

transportable waste has been coded, Green and Amber. The Green coding includes wastes that have low risk for humans and the environment and thus fall under normal commercial transactions. The Amber code refers to waste that has sufficient risk to borderline under the satisfaction of the OECD control. This requires advance notice for all the concerned authorities along with a tracking document. A Green coded spent catalyst can be treated as Amber should it contain impurities or contaminants that might prevent recovery (Cefic Group, 2001). The EU also promotes the activities of its governing agency of Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) which adopts regulations to protect health and environment of EU countries. Chemical substances and metals recovered from ISWM are approved through this program for trading amongst EU countries (EU REACH, 2006).

4.2. Governing Standard Within the State of Kuwait and Lessons Learnt

The governing body within the State of Kuwait concerning the handling and disposal of waste is the Kuwait Environment Public Authority (KEPA). One of the first things that comes to mind concerning the issue of ISWM and waste standards within the state, is the fact that various components of waste fall under the jurisdictions and responsibilities of various sectors. A prime example is the fact that MSW is managed by Kuwait Municipality (KM), whereas ISW with the exception of oil and gas industries fall under the responsibilities of the Public Authority for Industry (PAI). Each petroleum refinery is contracted to manage its own waste through national landfill sites, and industrial wastewater is managed by a different sector of

the government through the Ministry of Public Works (MOPW). This trend goes on to create major controversy among various parties in Kuwait, and there exist no governing body to liaise between all responsible parties. On the other hand, the regulations that KEPA have developed are being revised and improved constantly. The current regulations within the state also present major gaps and are not descriptive enough. Major technical and scientific input is required to have a comprehensive regulation by KEPA for governing WM activities within Kuwait. Generally, the management of SW is governed and regulated by Law No. 16/1996 and by-law Directive 210/2001 (Kuwait Al Youm, 2001). These laws assign waste in Kuwait to the categories of hazardous and non-hazardous based on the Basel Convention (BC, 1989). Private and cottage industries in Kuwait have to abide by these regulations by law. In addition, KEPA Directive (law) No. 5/2016 identifies various definitions and aspects with regards to WM, and law No. 6/2017 sets regulations for managing waste generated from medical and hazardous sources. It also regulates radioactive waste within the country (Kuwait Al Youm, 2016; 2017). By comparison to the case of the EU, and examining the aforementioned generation trends of ISW in Kuwait, a number of recommendations can be withdrawn as a strategy for the country. The State of Kuwait can benefit immensely by supporting the establishment of governmental and private industries alike, in creating a market for ISW valorisation. These industries also can benefit immensely and within state borders by trading recovered metals and chemical from ISW namely spent catalysts. The regulations in Kuwait can also start to accommodate such industrial practice, and one governing body can be responsible for managing the various waste management aspects in the country, instead of the current situation that creates confusion between waste generating sectors. The sustainability of the development of such practice is also something that can't be neglected. The sole method of disposal for ISW in Kuwait is landfilling in a governmental site. This is a major cause of land loss, generation of environmental and social associated burdens and land reclamation/rehabilitation costs. These issues can be eliminated by establishing both the appropriate standards and industry to govern ISW, more including spent catalyst which Kuwait consumes by a large amount due to its industrial nature.

Conclusion

Improper management of industrial solid waste is beginning to be recognised by many business sectors. However, the action to address the problem in an efficient and sustainable manner is yet to be established. Manufacturers are gradually shifting towards the reuse of spent catalyst and have developed recovery methods such as hydrometallurgical and liquid-liquid extraction process (chemical leaching method post metal recovery, commonly used to recover Mo and V); Solvent and Liquid/soil extraction (solvent extraction with LIX-84-1 dissolved in kerosene, commonly used to recover V, Mo and Ni); soda roasting and metal leaching (used to extract V and Mo at high percentages but at the expense of a temperature range of 500°C – 700°C). Biotechnological processes are also commonly used to extract V, Mo and Ni, at the

expense of longer leaching time however, these methods prove to be more cost effective than conventional ones (including thermal cracking, gasification and pyrolysis). All of these proposed and applied processes mostly aim at a small number of precious metals, making them limited to the recovery of catalysts that may contain V, Mo and Ni. Other valuable metals such as Pt, Al, Zi, may not be compatible. Legal guidelines across Europe and Kuwait has set strict guidelines in regard to ISW and its management, based on the hazardous properties of catalysts. Regeneration of spent catalyst/ metal recovery require international transport and numerous post and pre-treatment steps. The transport across different borders is one the biggest drawbacks as different countries have different rules, regulations and standards thus making the management plan harder to execute and successfully implement.

Abbreviations

| | |
|----------------------------------|-----------------------------|
| Al ₂ O ₃ ; | Aluminium Oxide |
| ARDS; | Atmospheric Desulfurization |
| Cd; | Cadmium |
| Cr; | Chromium |
| EC; | European Commission |
| EU; | European Union |
| EU; | European Union |
| FCC; | Fluid Catalytic Cracking |

| | |
|--------------------|--|
| GCC; | Gulf Council Countries |
| HDS; | Hydrodesulphurisation |
| ISW; | Industrial Solid Waste |
| KEPA; | Kuwait Environment Public Authority |
| KM; | Kuwait Municipality |
| Mo; | Molybdenum |
| MOPW; | Ministry of Public Works |
| MSW; | Municipal Solid Waste |
| Ni; | Nickel |
| OECD; | Organisation for Economic Co-operation and Development |
| OPEC; | Organization of the Petroleum Exporting Countries |
| PAI; | Public Authority for Industry |
| Pb; | Lead |
| PE; | Polyethylene |
| PSW; | Plastic Solid Waste |
| Pt; | Platinum |
| SiO ₂ ; | Silica Dioxide |
| SWM; | Solid Waste Management |
| V; | Vanadium |

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Table 6: A Review of Main Thermo-Chemical Conversion Conducted In Recent Years Using Catalytic Processes.

Table 1: Industrial Waste Classification. Source: BDF (2018); Hahladakis and Iacovidou (2018).

| Products | Hazardous wastes |
|------------|--|
| Medicine | Organic solvents and residues, heavy metals (mercury and zinc). |
| Metals | Heavy metals, fluorides, cyanides, acids, alkaline clearness and pigments. |
| Paints | Heavy metals, pigments, solvents and organic residue. |
| Leather | Heavy metals and organic solvents. |
| Oil/gas | Oil, phenols, organic compounds and heavy metals. |
| Pesticides | Organic chlorine compounds and organic phosphate compounds. |
| Plastics | Organic chlorine compounds, fire retardants, bromine compounds and fluorine. |
| Textiles | Heavy metals, dyes, organic chlorine compounds and solvents. |

Table 2: Percentile (wt.%) of Elements Found in Kuwait Petroleum Waste. Source: Mansour et al. (2016).

| Element | Kuwait | |
|---------|--------|-------|
| | Sludge | Sand |
| Si | 1.07 | 45.7 |
| P | 6.7 | nd |
| S | 10.58 | 13.12 |
| K | 26.15 | 6.4 |
| Ca | 15.83 | 20.36 |
| Mn | 0.28 | 0.12 |
| Fe | 38.07 | 7.53 |
| Zn | nd | nd |
| As | nd | nd |
| Br | 0.57 | nd |
| Sr | 0.61 | 0.24 |
| Rh | nd | 0.04 |
| Ba | nd | nd |
| Ho | nd | nd |

Table 3: Characteristics of Industrial Spent Catalysts Exposed to Thermal, Chemical, and Physical Treatment. Source: Alshammari et al. (2008).

| Source | Chemical Constituents | Maximum Quantity (tpa) |
|---|--|------------------------|
| SHU Refinery | Co, Ni, Mo, Fe, Cr, Zn, Al | 1,900 |
| Petrochemical Industries Co. Fertilizer Plant | Co, Mo, ZnO, NiO, Fe ₂ O ₃ , CuO, FeO | 205 |
| MAB Refinery | Co, Mo, NiO, Al ₂ O ₃ , ZnO, CoO, MoO, Fe ₂ O ₃ , Cr ₂ O ₃ , CuO, SiO, CaO, FeO, Ni, W | 2,500 |
| MAA Refinery | Co, CoO, Mo, MoO, Ni, NiO, FeO, Fe, ZnO, Zn, Al ₂ O ₃ , Fe ₂ O ₃ , Cr ₂ O ₃ , CuO, SiO, CaO, V | 6,185 |
| Total | | 10,790 |

Table 4: Properties of petroleum spent catalyst waste. Source: Taha et al. (2011)

| Main Reported Property | MAF refinery | SR refinery |
|---|--|--------------------------------------|
| Physical state | Solid | Solid |
| Colour | White to off-white | Gray |
| Shape | Spheres or granules | Crystalline powder |
| Odour | Acidic smell and reacts very vigorously in water | Odourless |
| Solubility | Insoluble in water, oil and solvents | Insoluble in water, oil and solvents |
| Liquid limit (%) | 51.9 | 72.8 |
| Bulk specific gravity | 2.79 | 2.60 |
| Sand equivalent (%) | 92.6 | NA |
| L.A. abrasion (%) | 72.4 | NA |
| Absorption (%) | 31.2 | NA |
| Surface area (cm ² g ⁻¹) | 3235 | 900 |

Table 5: Composition of petroleum spent catalyst waste. Source: Taha et al. (2011)

| Chemical Compound | Composition (%) | |
|--------------------------------|-----------------|-------------|
| | MAF refinery | SR refinery |
| SiO ₂ | 1.71 | 39.21 |
| Al ₂ O ₃ | 66.66 | 37.68 |
| Fe ₂ O ₃ | 0.07 | 0.66 |
| CaO | 0.08 | 0.05 |
| MgO | 0.02 | 0.26 |
| Na ₂ O | 8.29 | 0.43 |
| K ₂ O | 0.26 | 0.06 |
| Loss on ignition value (LOI) | 26.13 | 2.43 |

Table 6: A Review of Main Thermo-Chemical Conversion Conducted In Recent Years Using Catalytic Processes.

| Operation in Pyrolysis Mode | | | |
|-----------------------------|---|---|---|
| Reference | Feedstock/Catalyst Used | Operating Conditions | Notes |
| Cardona and Corma (2000) | Catalytic cracking of polypropylene (PP) using zeolites, amorphous/silica–aluminas and a spent equilibrium FCC commercial catalyst | 250 to 400°C in a stirred bed reactor | Spent catalysts were used |
| Zhang et al. (2009) | Biomass conversion was achieved using recovered FCC spent catalyst | Operating temperature at around 400°C | Fluidization media used was sand with different catalyst percentages. |
| Seo et al. (2003) | High density polyethylene (HDPE) using powder and pellets catalysts of Mordenite, Zeolite-Y and ZSM-5. | Catalytic degradation yielded more light hydrocarbons (C6-C12) than thermal degradation | |
| Sarker et al. (2011) | Waste polyethylene terephthalate (PET) using Ca(OH) ₂ catalyst | 405°C in a distillation unit | |
| Ali et al. (2002) | HDPE pyrolysis using HZSM-5, USY and an equilibrated FCC catalysts | Fluidized bed reactor used at 450°C | Gasoline was main product obtained |
| Mertinkat et al. (1999) | PE on an FCC catalyst at 515°C in a fluidized bed reactor | | Yield of waxes was below 1% |
| Donaj et al. (2012) | Ziegler-Natta catalyst (TiCl ₄ / MgCl ₂) in the pyrolysis of a mixture of polyolefins at 650°C | | Increase in gas produced with catalyst employed |
| Gasification Process | | | |
| He et al. (2009) | Catalytic steam gasification of MSW with calcined dolomite catalyst | Bench-scale fixed bed reactor temperature range of 750–950°C with a steam to MSW ratio of 0.77. | |
| Ro et al. (2007) | Review of wet waste including manure as a feedstock to gasification technologies recommending the use of spent catalysts to reduce cost | | |
| Nada et al. (2019) | Waste cooking oil was gasified in supercritical water over Ru/Al ₂ O ₃ | | Glycerol and propionic acid were obtained |

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Fig.3. Pretreatment Stages Applied For Spent Catalyst. Adapted from Marafi and Rana (2016).

Fig.4. Selective Chlorination For The Recovery of Metals. Adapted from Gaballah et al. (1994).

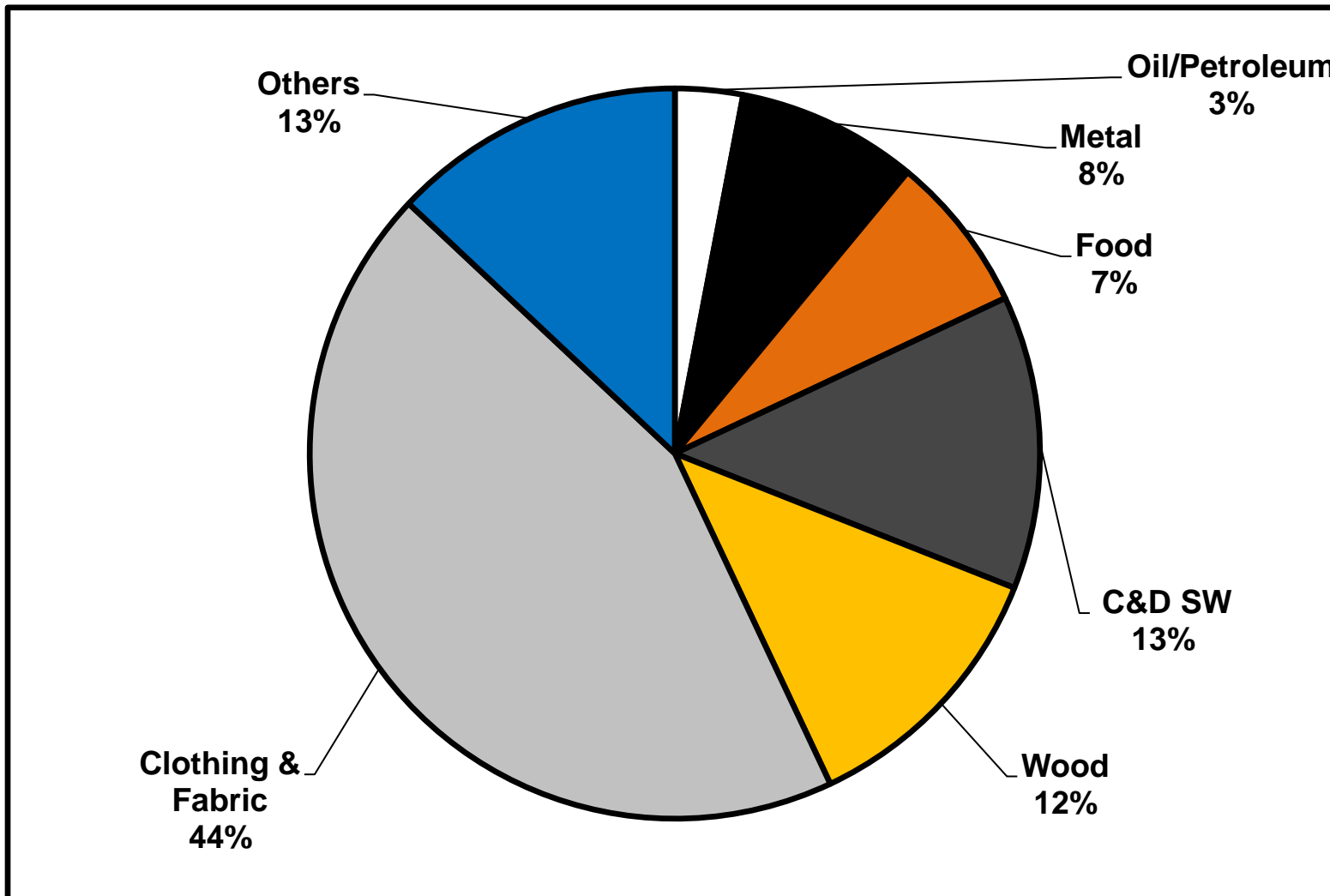


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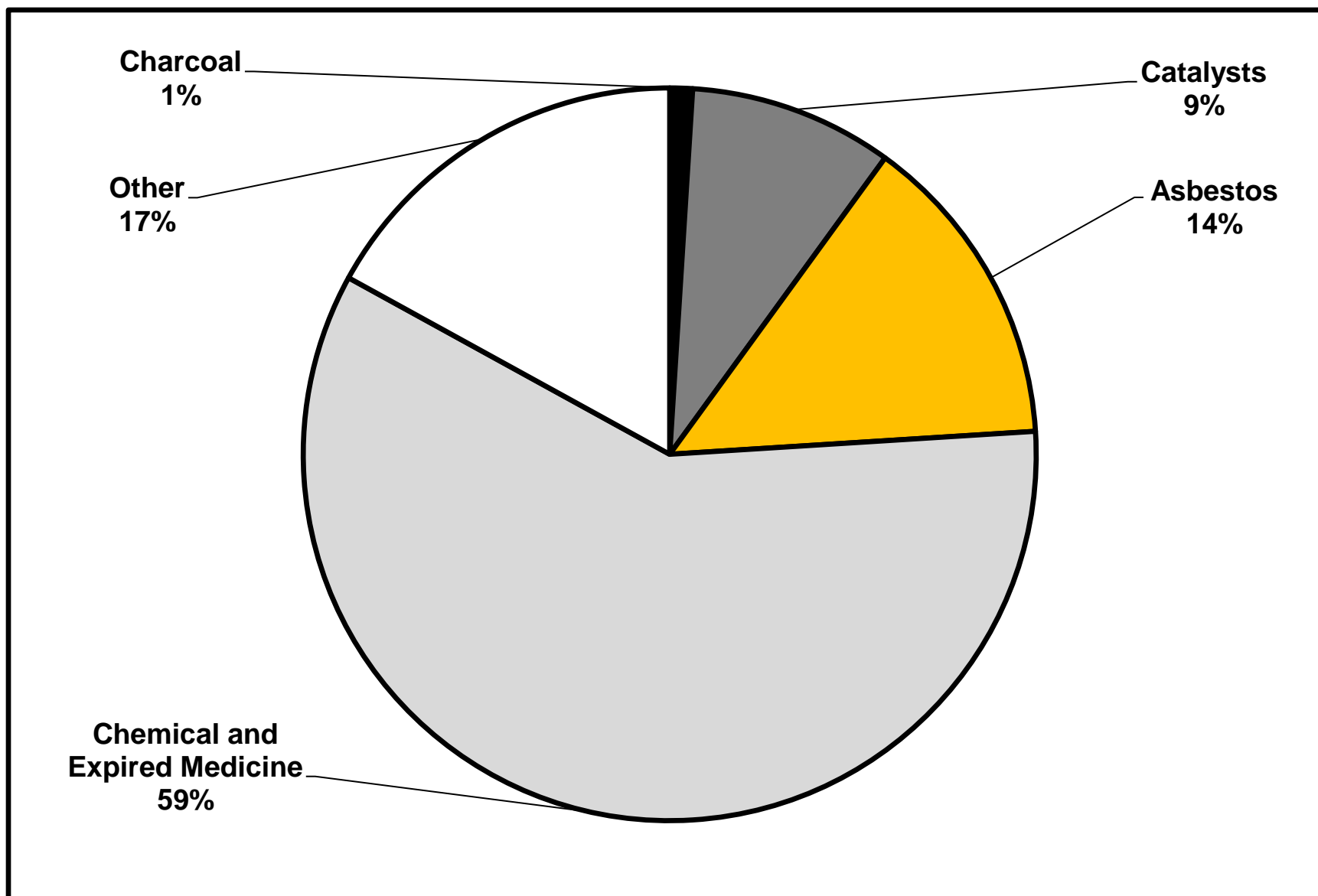


Fig.2. Approximate Percentages Of Industrial Solid Waste In The State of Kuwait. Adapted from Alhummod and Al-Kandari (2008).

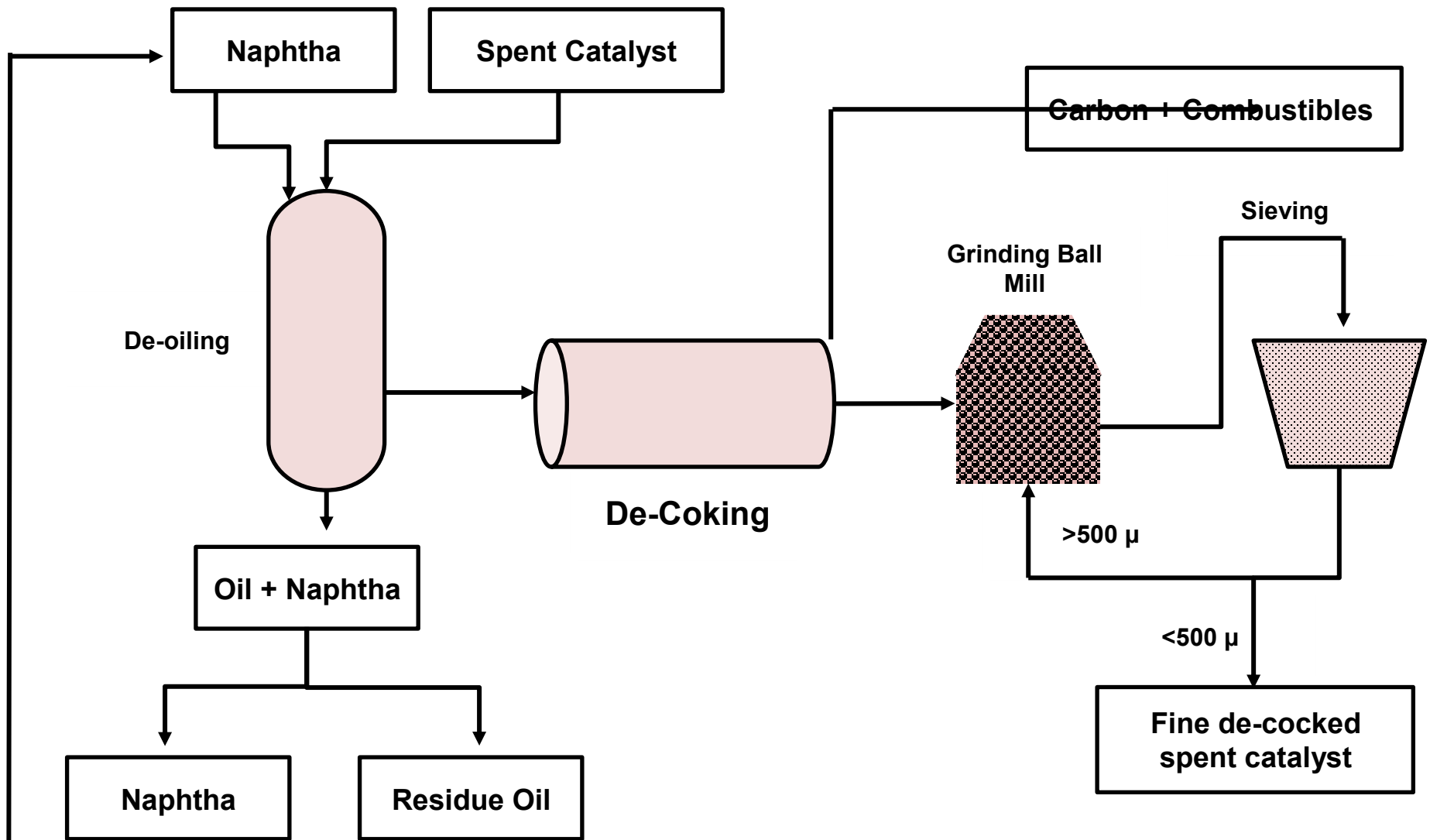


Fig-3. Pretreatment Stages Applied For Spent Catalyst. Adapted from Marafi and Rana (2016)

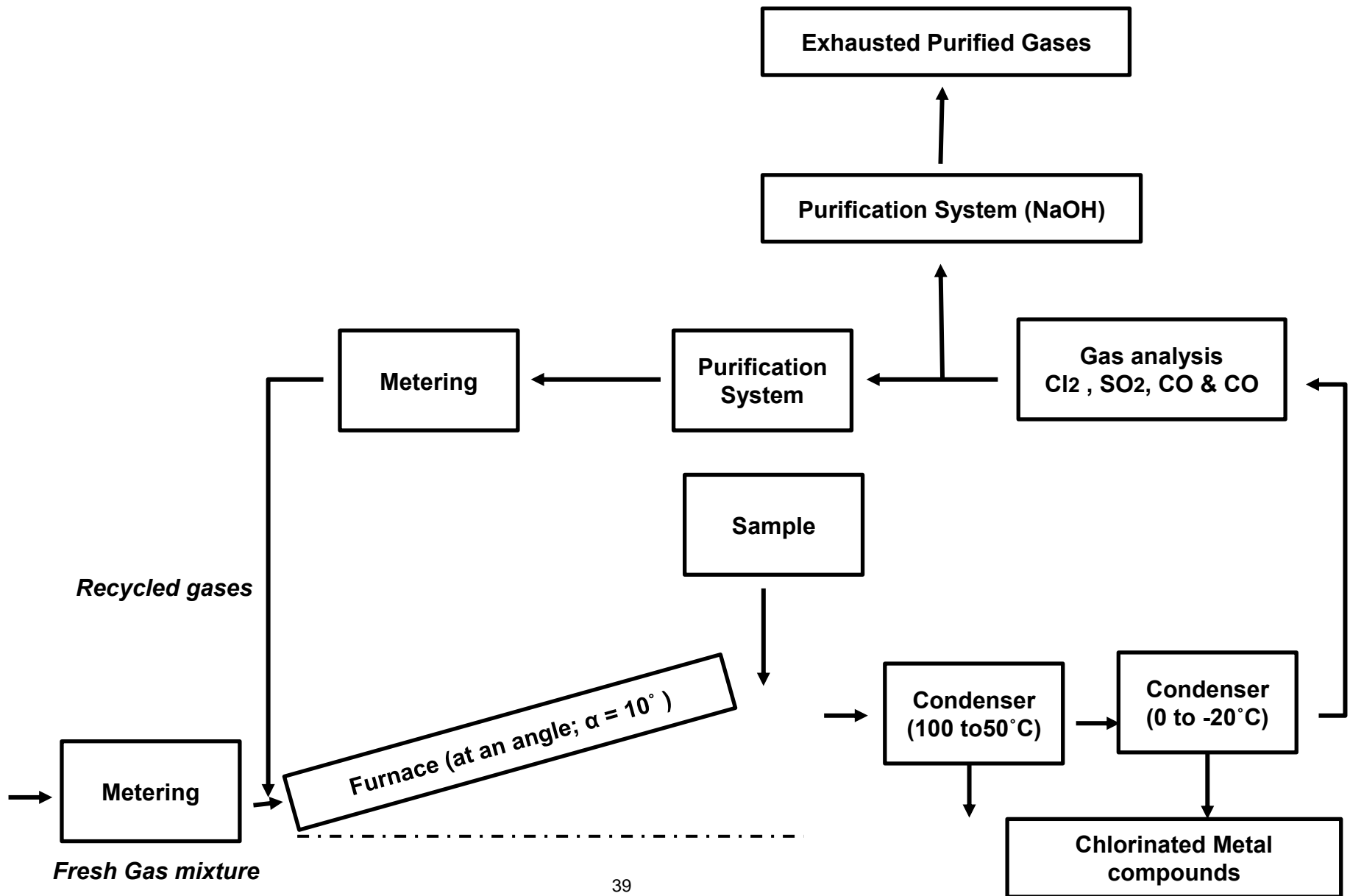


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