

**University of Nevada, Reno**

**Environmental impact assessment of gold production from different types of  
ore in Nevada**

A thesis submitted in partial fulfillment of the requirements for  
the degree of Master of Science in  
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by

Saeede Kadivar

Dr. Ehsan Vahidi/Thesis Advisor

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We recommend that the thesis  
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**Saeede Kadivar**

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Ehsan Vahidi, Ph.D.  
*Advisor*

Hamid Akbari, Ph.D.  
*Committee Member*

Pengbo Chu, Ph.D.  
*Committee Member*

Victor Vasquez, Ph.D.  
*Graduate School Representative*

Markus Kemmelmeier, Ph.D., Dean  
*Graduate School*

August 2023

## Abstract

The available supply of high-grade gold ore has significantly decreased, and there is growing concern about sustainable gold mining. Despite the strict environmental management regulations, various methods of gold mining can affect the ecosystem and human health since gold mining is an energy-intensive process and discharge substantial quantities of chemicals combined into the environment and gaseous emissions into the atmosphere. Therefore, there is an urgent need to assess the environmental sustainability of producing gold from different types of ore, including refractory, double refractory, or low-grade oxidic ore. This study used a life cycle assessment (LCA) approach to evaluate the environmental burdens associated with gold production from various types of ore that used appropriate processes, including roasting, autoclave or pressure oxidation followed by flotation, and heap leaching.

Considering various stages and treatment routes utilized by the gold producers in Nevada, categories of ozone depletion, global warming, smog, carcinogenics, non-carcinogenics, respiratory effects, and fossil fuel depletion were evaluated Using the TRACI method. LCA results of this study showed more significant environmental impacts for processing refractory ores in almost all the impact categories except acidification. The potential climate change for processing refractory ore using autoclave and flotation was  $1.75\text{E}+04$  CO<sub>2</sub>-equiv, while it was  $1.17\text{E}+04$  CO<sub>2</sub>-equiv and  $6.75\text{E}+02$  CO<sub>2</sub>-equiv for roasting and heap leaching process, respectively. The higher environmental footprint related to SO<sub>2</sub> emissions (acidification) in roasting was mainly due to the direct emissions containing sulfur compounds.

The high value of electricity consumption and substantial gaseous emissions made the grinding stage the dominant contributor in almost all the impact categories for refractory and double refractory ores. No grinding was required for processing low-grade oxidic ore, and the contribution of crushing to overall global warming was insignificant. However, the contribution of grinding to the overall global warming in roasting and autoclave processes was significant and reported at 34.8% and 39.4%, respectively. This indicates that these stages need more attention and actions toward environmental regulations by using green electricity sources and additional treatment processes to achieve the goal of GHG emissions reduction. This study's results can be used as a comprehensive resource by stakeholders to compare the effects of gold mining activities and make better environmental decisions.

**To the most powerful woman in my life from whom I learned resilience, To my mother.**

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## 1. Introduction

Gold has consistently been recognized as a valuable commodity having a global attraction to humankind, and has been the preferred metal for many applications, including jewelry, electronics, and medical diagnostic devices. Due to its exceptional effectiveness as an electric conductor, gold is also a critical choice that is frequently utilized in circuit boards and many other electronic applications (Chen et al., 2018; Farjana & Li, 2021; Norgate & Haque, 2012; Ulrich et al., 2020; H. Wang et al., 2019). Gold mines are being operated by some of the world's largest mining companies, including Newmont Corporation and Barrick Gold Corporation (Ulrich et al., 2022). According to the U.S. Geological Survey, with nearly 4.5 million ounces of gold produced in 2021, Nevada, the United States' first recognized gold producer, accounted for approximately 75% of annual U.S. gold production (Visher and Patterson, 2022).

Due to the depletion of high-grade gold ores, an urgent need for processing and treating more complex ore bodies, such as refractory and double refractory ore, has been highlighted (Aylmore & Jaffer, 2012). Generally, gold ores are classified into three categories: (1) non-refractory, (2) refractory, and (3) double-refractory (Konadu et al., 2020; Lee et al., 2021; Natarajan, 2018; Qin et al., 2021; Vaughan, 2004; Xiao et al., 2022).

Several extraction techniques and processing routes for gold recovery are available, depending on the types of gold ore and its mineralogical characteristics (Marsden & House, 2006a; Natarajan, 2018). Non-refractory ore is regarded as one that is easy to treat with conventional cyanide leaching. However, refractory and double refractory ores are not easily treated by cyanidation because gold is locked within the sulfide minerals in

refractory ores (Natarajan, 2018; Norgate & Haque, 2012; Vaughan, 2004). Furthermore, double refractory ore indicates preg-robbing properties caused by carbonaceous matter in the ore. Gold ore from Barrick's Goldstrike mine is a typical type of double refractory ore containing both sulfide and carbonaceous matter (Lee et al., 2021). The presence of carbonaceous matter and encapsulation of gold in sulfide minerals in double refractory ore results in poor efficiency of the gold recovery.

According to the estimates, double refractory ore accounts for nearly a third of the global gold production that is now accessible, which indicates a developing market for the extraction of gold from such ore (Konadu et al., 2020; Xiao et al., 2022). Therefore, appropriate pretreatment methods are required before leaching to remove these impurities. These pretreatment methods include autoclave or pressure oxidation, bio-oxidation, ultrafine grinding, and roasting (Asamoah et al., 2021; Konadu et al., 2020; la Brooy et al., 1994; Lee et al., 2021; Qin et al., 2021; Thomas and Cole, 2016; Warnica et al., 2002). A general flow diagram of all different processing routes for gold recovery is shown in Figure 1.

Globally, numerous environmental and public health risks are associated with gold mining due to ecosystem degradation, vegetation loss, and soil exploitation. Furthermore, the health of individuals and species can be threatened by toxic materials released during the gold mining process, such as cyanide and arsenic compounds (Norgate & Haque, 2012; Ulrich et al., 2020). Australia, for example, reported 533.7 million tonnes of carbon dioxide equivalent in yearly GHG emissions in 2018, and contamination from the nation's gold

mining industry, which produces 5.9 million tonnes of CO<sub>2</sub>-eq, has become a severe threat to the environment and human health (Ulrich et al., 2020).

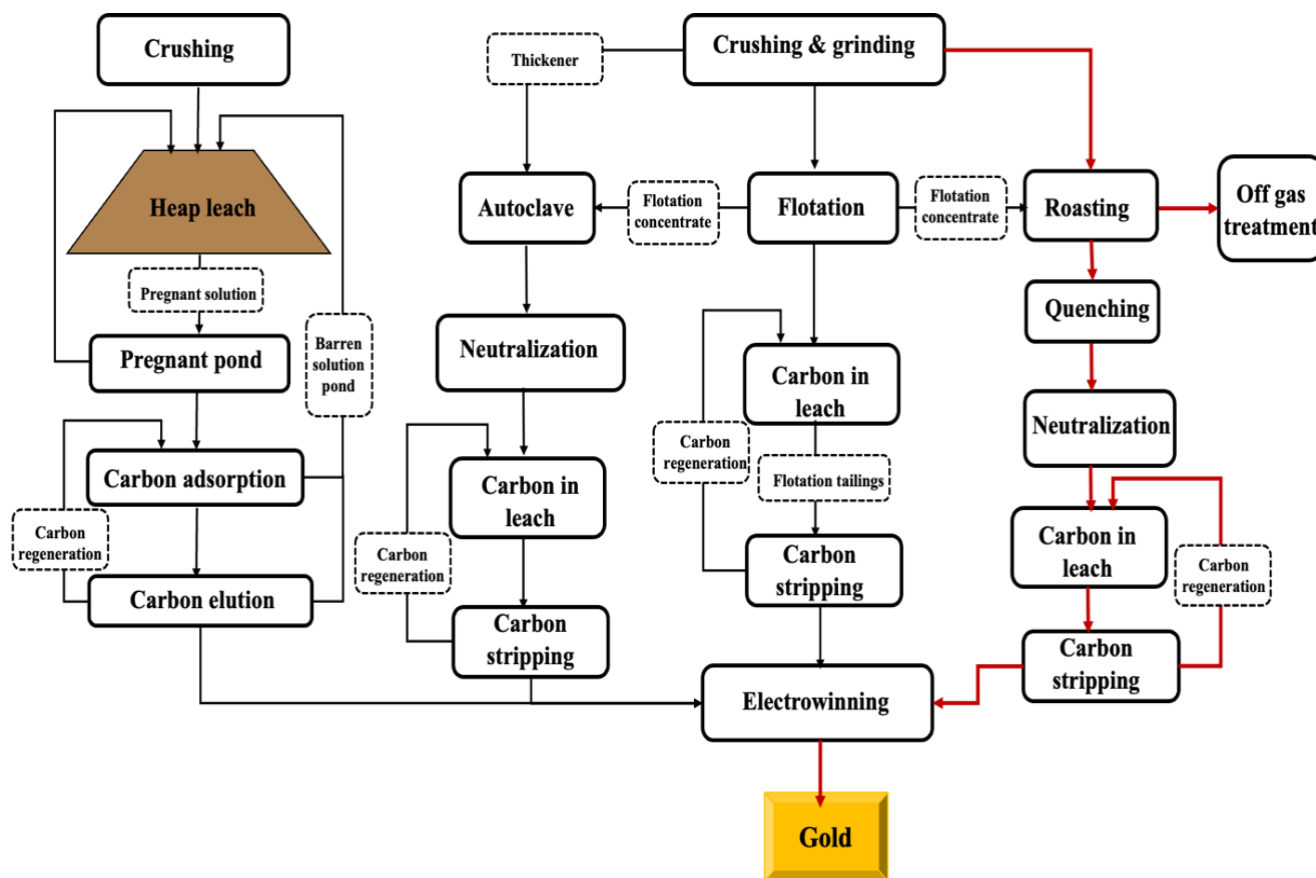


Figure 1. General flow diagram of gold recovery for different processing routes.

Furthermore, Canada accounted for 10.3% of the global gold production and 3.7% of the total emissions in 2018 (Ulrich et al., 2022). Keeping the negative impacts of gold mining in mind, focusing only on gold production value means ignoring significant sources of adverse environmental impacts including GHG emissions generated by electricity consumption and hazardous chemicals, whose use in gold production necessitates

expensive and complicated pollution treatment steps (Norgate & Haque, 2012). Several studies have investigated the environmental burdens associated with the industrial methods for metals production including aluminum, steel, zinc, nickel, copper, and lead, as well as the life cycle assessment of electronic waste management (Chen et al., 2018; Deng & Gong, 2018; Eckelman, 2010; Hong et al., 2015; Norgate & Haque, 2012; Qi et al., 2017; Strezov et al., 2021; Tao et al., 2022; van Genderen et al., 2016); however, there are only a few studies on the environmental footprints of gold production.

Thus, the goal of this thesis is to evaluate the environmental footprint of gold production through various types of ore that require different processing routes for gold production. Gold mining, which is regarded as a crucial part of the economy should undergo intense pressure to reduce its environmental footprint throughout all the processing methods. This issue can be addressed by conducting a systematic life cycle impact evaluation of the environmental footprints generated by gold production (Awuah-Offei & Adekpedjou, 2011; Chen et al., 2018; Norgate & Haque, 2012; Ulrich et al., 2022).

This evaluation is based on the life cycle assessment (LCA) approach quantifying various impact categories in gold extraction processes, including roasting, autoclave and flotation, and heap leaching.

## 2. Roasting

### 2.1 Roasting process associated with double refractory ore

Oxidative roasting is usually used as a pretreatment method for double-refractory ore. Several Carlin ores and other deposits in Nevada are associated with sulfide and carbonaceous material and gold is locked up within these minerals. The presence of sulfide and carbonaceous material can adsorb gold during conventional cyanidation. Therefore, not only does the sulfide material need to be oxidized but also the carbonaceous matter has to be destroyed which makes the oxygenated roaster the best option. Two fluid-bed roasters were constructed in 1999 to pretreat double refractory ores at Barrick Goldstrike Mines using pure oxygen to remove organic carbon and sulfidic material before cyanidation. Other pretreatment methods such as pressure oxidation were not able to overcome the preg-robbing characteristics of carbonaceous materials.

### 2.2 Chemistry of the process

The gold is mainly present as colloidal gold encapsulated in the pyrite, arsenopyrite. Sulfide sulfur and organic carbon concentrations may vary from 0.5% to 3.5% and 0.5% to 4%, respectively. Various chemical reactions occur in the roaster which will be explained more in the following sections.

1. Combustion of organic carbon
2. Combustion of carbon monoxide
3. Combustion of sulfide sulfur
4. Dehydration of the ore

5. Vaporization of mercury
6. Oxidation of nitrogen

### 2.2.1 Combustion

Carbon from all sources (ore, coal, and oil) oxidizes within the roaster-fluid beds to carbon monoxide and carbon dioxide with a resulting split between CO and CO<sub>2</sub> estimated at 4% and 96% (percent carbon by weight). Carbon monoxide may oxidize further in the roaster freeboard to reduce CO levels in the off-gas. The carbon reactions occur as follows:



#### 2.2.1.1 Combustion of sulfide sulfur

Oxidation of orpiment [As<sub>2</sub>S<sub>3</sub>], realgar [AsS], and arsenopyrite [FeAsS] proceed simultaneously until they are fully reacted. Due to the highly oxidizing environment, essentially all of the arsenic is converted into solid ferric arsenate (FeAsO<sub>4</sub>) or arsenic pentoxide (As<sub>2</sub>O<sub>5</sub>). The following reaction shows the oxidation reaction for arsenopyrite and pyrite:



The overall extent of sulfide combustion is estimated at 99%, with 97.5% reacting in the first-stage bed and 1.5% in the second-stage bed.

### 2.2.1.2 Dehydration of ore

The dehydration of clays or other hydrated minerals occurs predominantly in the first-stage bed as evaporation of water to superheated vapor. Moisture in the roaster feed ore and water vapor in air additions is also superheated.

### 2.2.1.3 Vaporization of mercury

All mercury in the feed ore vaporizes to elemental mercury in the roaster off-gas and is removed by the gas-cleaning system.

### 2.2.1.4 Oxidation of nitrogen

Nitrogen is also oxidized into  $\text{NO}_2$  in the roaster with a 9:1 volumetric ratio of  $\text{NO}$  to  $\text{NO}_2$ .

The following reaction shows the oxidation reaction of nitrogen:



## 2.3 Off-gas treatment

Various chemical reactions that occur in roasting generate hazardous gaseous emissions. As mentioned, these chemical reactions include the combustion of organic carbon, combustion of carbon monoxide, combustion of sulfide sulfur, vaporization of mercury, and oxidation of nitrogen (Thomas and Cole, 2016; Warnica et al., 2002). The gas cleaning system is one of the essential parts of the roasting plant, and operation cannot be started before meeting the criteria of the environmental regulations for the roaster overflow gas stream. Table 1 presents the components of the exhaust gas at the exit of the roaster

containing extremely high loads of dust, high concentrations of SO<sub>2</sub>, high levels of CO, and a significant amount of NO<sub>x</sub>. The overall flow diagram for the gas handling system is shown in Figure 2. Gases are initially cleaned in an open quench tower after being cooled to saturation. In the quencher, about 90% of the incoming particle is eliminated (Thomas & Cole, 2016). Removing the particulate in the quenching stage is important to minimize problems that may occur within the following scrubbing stages. Water reduces the temperature of the roaster off-gas stream to 80 °C and saturates the gas with water. The gas then enters a dust scrubber, where the remaining particulate solids are removed. Despite the scrubber's high water addition rate, 70% of the water is recycled, which lowers the need for freshwater (Thomas & Cole, 2016). A gas cooling step is required to ensure the gas temperature entering the mercury scrubbing system is about 100°F. In addition, significant amounts of water are condensed while the gas cools. In addition, significant amounts of water were condensed due to chilling the gas. The initial stage of the gas cleaning system at this point is a wet electrostatic precipitator (WESP), where gas is saturated by water sprays. In all metallurgical acid plants, wet ESP is a critical part of the gas handling system for managing fine particulate and mist. Complete collection of particulate and acid mist (SO<sub>3</sub> and H<sub>2</sub>SO<sub>4</sub>) removal is obtained in the first step of the gas cleaning system (Thomas & Cole, 2016).

The second step in the gas cleaning system is the mercury scrubber, which removes vapor phase mercury using mercuric chloride solution in the Boliden-Norzinc process (Miller, 2005; Wang et al., 2010). A mercuric chloride solution recirculating around a packed tower reacts with the vapor phase mercury to produce mercurous chloride precipitate or calomel (Thomas and Cole, 2016; Warnica et al., 2002). A portion of calomel is regenerated with

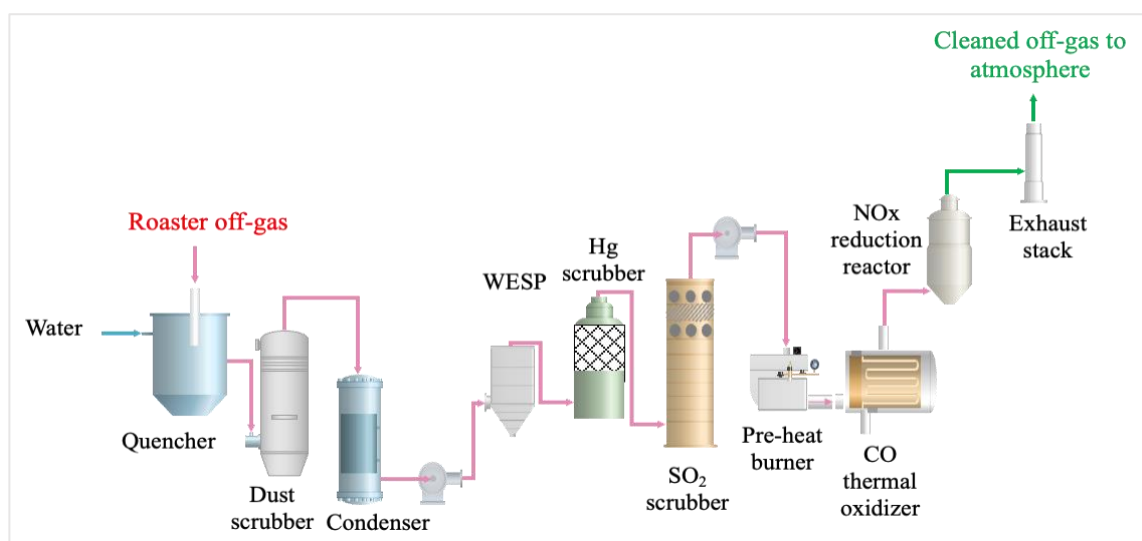
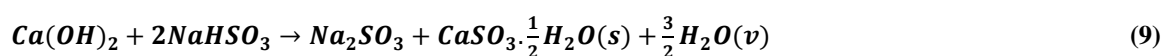
gaseous chlorine to produce the mercuric chloride solution used for reagent addition. The remaining calomel is shipped and sold to mercury producers as a product (Thomas & Cole, 2016). The by-product mercury from gold mining operations in Calin Complex is often stored for sale to mercury production companies, which collect the mercury and purify it. These companies include Bethlehem Apparatus Company Incorporation, D.F. Goldsmith Chemical and Metal Corp in Evanston, and Mercury Waste Solutions in Minnesota. According to the Nevada Division of Mineral report, calomel production in the roasting plant was 60250.22 kg in 2002. The Gold Quarry mine uses calomel scrubbers to pre-treat the feed to a sulfuric acid plant while the Goldstrike mine uses calomel only for mercury control. Mercury controlling emissions at the Goldstrike mine using the Boliden Norzink process has a mercury removal efficiency of 99.5% (Miller, 2005; Thomas and Cole, 2016).

**Table 1. Performance of roaster gas cleaning system (Thomas & Cole, 2016).**

Contaminant	Design (kg/h)		Actual (kg/h)	Removal efficiency
	Inlet	Outlet	2001	
Particulate	22680	2.7	0.9	99.99
Mercury	18	0.09	0.03	99.5
SO <sub>2</sub>	9072	20.4	6.4	99.78
CO	544	21.4	12	96.1
NO <sub>x</sub>	54	16.7	6.5	70

The next unit operation is sulfur dioxide (SO<sub>2</sub>) scrubbing. Sulfur dioxide is removed from the gas stream using a dual alkali process in which SO<sub>2</sub> absorption occurs in the scrubber tower and solid precipitates. According to equation 1 and 2, a concentrated solution using soda ash and lime is added to the scrubber and SO<sub>2</sub> is scrubbed from the off-gas stream in the absorption tower based on the following reactions (Munyongani et al., 2017; Thomas & Cole, 2016; van Beek et al., 2012)The roaster also produces sulfuric acid at the SO<sub>2</sub>

scrubber stage which is utilized for internal usage or is sold for commercial purposes (Fiddes et al., 2020). The acid is produced as a by-product of removing SO<sub>2</sub> from the off-gas roaster. According to the Carlin complex technical report, typical acid generation is about 34 kg H<sub>2</sub>SO<sub>4</sub> per ton of ore entering the roaster (Fiddes et al., 2020). The following reactions show the chemistry overview of the SO<sub>2</sub> removal unit (van Beek et al., 2012).



**Figure 2. General flow diagram of gas handling system.**

According to Figure 2, the final unit operations after the SO<sub>2</sub> scrubber unit are CO and NO<sub>x</sub> removal consisting of carbon monoxide oxidation and nitrogen oxide compounds reduction (Warnica' et al., 2002). Carbon monoxide or any other hydrocarbon is removed using a thermal oxidizer unit that consists of a heat exchanger and combustion chamber (burner). First, the incoming gas enters through the shell side of the heat exchanger to preheat before entering the burner, where the temperature increases to about 815 °C. The clean gas then

exits the combustion chamber through the tube of the heat exchanger and enters the next cleaning unit after cooling (Tomatis et al., 2019).

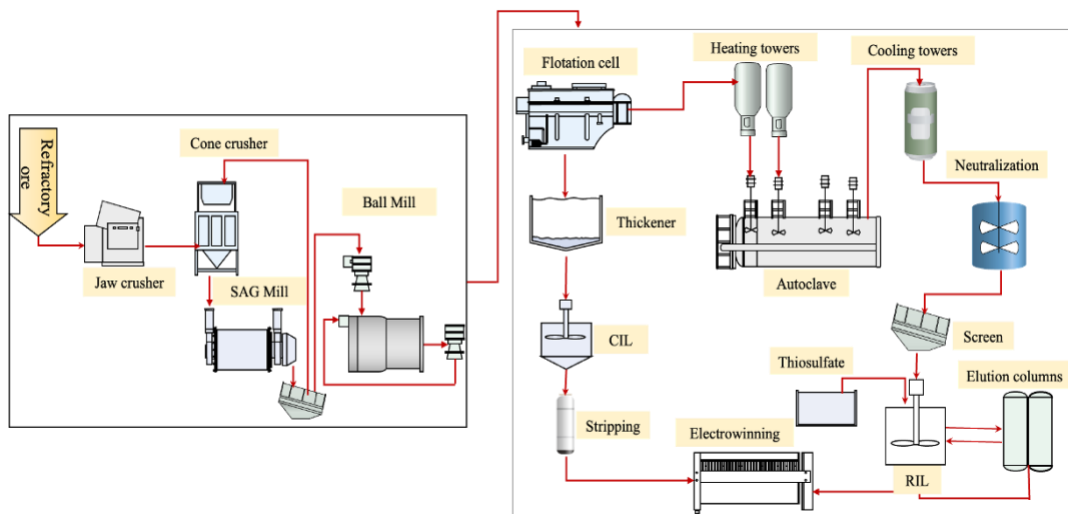
Finally, the off-gas enters the last cleaning unit, which is an ammonia-based selective catalytic reduction unit for the reduction of  $\text{NO}_x$  compounds. Aqueous ammonia is injected over a zeolite catalyst reacting with  $\text{NO}_x$  to produce nitrogen and water vapor (Thomas and Cole, 2016; van Caneghem et al., 2016). After the final gas cleaning unit, the off-gas roaster is released into the atmosphere containing the listed concentrations of emission in Table 1. Removal efficiency for each gas cleaning stage is also presented in Table 1.

### 3. Pressure oxidation

#### 3.1 Pressure oxidation for processing refractory ores

Pressure oxidation of sulfide concentrates is an essential step in the gold industry as it enhances gold recovery and has been widely utilized in mining industries as a pre-treatment procedure for refractory gold ores. Pressure oxidation refers to the oxidation of sulfides, such as pyrite [FeS<sub>2</sub>] at elevated temperature and pressure. Oxidation releases encapsulated gold grains from the sulfides and make the oxidation residue of the ore or concentrate more amenable for gold recovery by cyanidation in a subsequent leaching step. The first refractory gold pressure oxidation plant was commissioned in California in 1985 for the McLaughlin operation. Barrick Goldstrike Mine, located in Elko on the Carlin complex was also commissioned in 2000 (Thomas & Pearson, 2016). Pressure oxidation is conducted at relatively high temperatures of 180 to 225 degree Celsius, in either an acidic or alkaline medium, and achieves essentially complete oxidation of the sulfides and liberation of gold. Within the gold industry, two important steps have taken place in pressure oxidation. These steps include pressure oxidation of whole ore using both alkaline and acidic processes, and acidic pressure oxidation of sulfide concentrates. A general flow diagram for concentrating a portion of ore using flotation followed by pre-treatment methods such as autoclave is depicted in Figure 3 (Thomas & Pearson, 2016). As shown in Figure 3, sulfides are floated into a concentrate before autoclave and resin in leach (RIL) circuits. After the slurry is cooled through the flash cooling vessels, it is pumped to the neutralization tanks where the pH is elevated. Neutralized slurry from the POX circuit is then pumped to the RIL circuit where thiosulfate leaching is used for gold extraction

(Fiddes et al., 2020; Thomas & Pearson, 2016). As the initial step in processing the refractory gold ores, froth flotation has been regarded as one of the most promising concentrating procedures in which the pyrite, arsenopyrite, and sulfide minerals are floated into a concentrate (Dementyev & Voiloshnikov, 2008; Eltohamy et al., 2022; Marmiroli et al., 2022). Flotation utilizes surface characteristics variation mechanism for different minerals which causes the concentration of target metals through their attachment to bubbles. The surface characteristics of the metals, as well as the separation of valuable metals from gangue minerals, are modified during flotation using a variety of chemical reagents (Wills & Finch, 2015) The concentrate is thickened and filtered after concentration to prepare it for additional processing in a different oxidizing facility, such as an autoclave or a pressure oxidation (POX) unit (Fiddes et al., 2020).

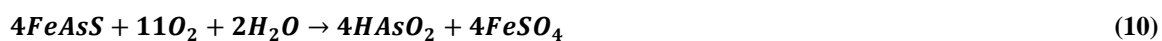


**Figure 3. A general flow diagram for processing refractory ore.**

### 3.2 Process chemistry

Pressure oxidation is conducted at relatively high temperatures of 180 to 225 degree Celsius, in either an acidic or alkaline medium, and achieves essentially complete oxidation

of the sulfides and liberation of gold. The process chemistry of the dominant reactions for pressure oxidation of pyrite and arsenopyrite in an aqueous medium are summarized in the following reactions at a temperature of 190-195 degrees Celsius.



The pressure oxidation process's primary goal is to destroy the sulfide minerals, thereby liberating the encapsulated gold (Aylmore & Jaffer, 2012; Gudkov et al., 2010; Norgate & Haque, 2012; Thomas & Williams, 2000). Organic carbon is generally not oxidized to any significant extent by POX. Thus, in contrast to roasting, there is no heat input from this source (Mason, 1990).

### 3.3 Thiosulfate leaching

There are several leaching technologies for extracting gold from refractory ores. Thiosulfate, thiocyanate, and chlorine solutions can be employed as alternatives to cyanide-leaching, which is more commonly utilized, to extract gold (Xu et al., 2017). Concerns about cyanide's toxicity (Chen et al., 2018; Norgate & Haque, 2012; J. Wang et al., 2019) and limitations in the treatment of carbonaceous materials have led to a growing interest in developing non-cyanide gold recovery techniques (Kasymova, 2019; Oraby, 2009). Thiosulfate is a less toxic alternative to cyanide and is commonly used as a fertilizer and an indirect and direct human food ingredient (Wan & LeVier, 2003). In the thiosulfate leaching system for gold, thiosulfate is used as the primary reagent but, both ammonia and cupric ions are required to stabilize copper tetraamine and adjust pH. Although thiosulfate

leaching has received substantial attention due to its non-toxicity and faster leaching compared to cyanide leaching, it has some significant drawbacks, such as high reagent consumption (Xu et al., 2017). The thiosulfate leaching process uses thiosulfate in the presence of ammonia and copper with air supply based on the following reaction (Fleming et al., 2003; Neuvonen, 2013; Oraby, 2009; Xu et al., 2017):



The specific mechanism of gold dissolution and the catalytic activity of cupric ion species are still not entirely understood due to the complexity of the ammoniacal copper-thiosulfate system's chemistry, which has been the subject of extensive study and analysis (Marsden & House, 2006b). The electrochemical catalytic mechanism of gold leaching using copper and ammonia for the thiosulfate system can be seen in Figure 4. In an aqueous solution, gold and thiosulfate form a stable combination. Ammonia stabilizes copper ions by creating the  $\text{Cu}(\text{NH}_3)_4^{2+}$  complex, with copper ions acting as oxidizing agents (Neuvonen, 2013; XIE et al., 2021). A process based on thiosulfate leaching, followed by RIL, has been developed to treat refractory ores of Barrick's Goldstrike in the Carlin Complex in Nevada, USA (Fiddes et al., 2020; Fleming et al., 2003; Sitando et al., 2020; J. Wang et al., 2019). Cyanide has been replaced with on-site production of calcium thiosulfate (CaTS) for gold dissolution (Fiddes et al., 2020). Various studies have used the thiosulfate leaching process for gold extraction, reporting that thiosulfate consumption in the gold extraction process highly depends on the ore mineralogy (Oraby, 2009).

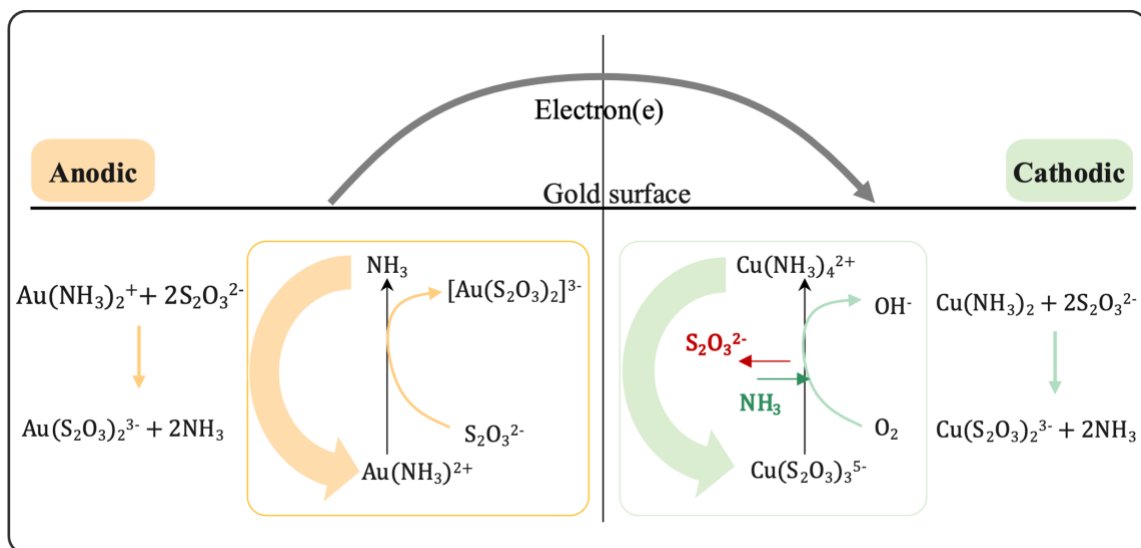


Figure 4. General reactions in gold thiosulfate dissolution mechanism.

## 4. Heap leaching

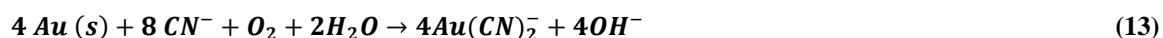
### 4.1 Heap leaching for processing low-grade oxidic ore

One alternative process method for treating precious metal ores containing low gold grades is heap leaching. Typically, gold grades are in the range of 0.25 g to 1 g per tonne of ore. The primary reason for selecting heap leaching is its low capital cost compared to other methods (Oraby et al., 2019). Nevada was the birthplace of modern gold heap leaching in the late 1960s. In the heap leaching process, the ore is placed into a heap on an impermeable pad, and then it is irrigated with a chemical solution for a specific period to dissolve precious metals into the solution. The pregnant solution containing dissolved metals then is collected given that it percolates from the base of the heap (Fiddes et al., 2020; Manning & Kappes, 2016). Percolation leaching is a different term for the method in which precious metals are recovered from ore by allowing a chemical solvent or agent to penetrate a mass or pile of materials or ore (Ghorbani et al., 2016). The basic steps in heap leaching are:

- Run of mine or crushed ore are placed onto a prepared surface.
- Gold dissolution is promoted by applying a sodium cyanide solution as the lixiviant to the surface of the heap.
- The solution is collected in the leach pad drain system and then pumped to activated carbon columns (CIC) where gold loads onto activated carbon.
- Gold loaded on carbon is reclaimed from the CIC circuit, transported to a carbon stripping system, stripped from the carbon, and recovered by electrowinning.
- Stripped carbon is recycled and reused (Fiddes et al., 2020)

## 4.2 Chemistry of precious metals heap leaching

Precious metals are dissolved in a dilute and alkaline sodium cyanide solution. The pH of the solution is important and usually is maintained between 9.5 and 11 for gold recovery. Below a pH value of 9.5, cyanide consumption is generally high; above a pH value of 11, metal recovery decreases. The average gold recovery efficiency in heap leaching is 70%, although it can be as high as 90%. The typical use of cyanide per ton of ore is between 0.1 and 1 kg/t of ore. Cement or lime consumption ranges from 0.5 to 70 kg/t of ore (Manning & Kappes, 2016). Cyanide was recognized as the most efficient reagent among several others, including sodium bisulphide, thiosulphate, thiourea, and iodide solutions (Ghorbani et al., 2016; Manning & Kappes, 2016). Cyanide reacts with solid gold in the following reaction at the surfaces of the gold grains (Yessengarayev et al., 2020):



## 4.3 Heap leach pad

A vital part of the heap leaching procedure, the heap leach pad is a substantial, engineering structure that needs to be precisely designed to ensure efficiency. An impermeable liner consisting of high-density polyethylene (HDPE) or clay is typically used as the foundation for a heap leach pad (Thiel et al., n.d.). The construction of a heap leach pad typically involves using heavy equipment such as trucks, loaders, and dozers to move and place materials and build the pad structure. To create a strong base and foundation for the heap leach pad, the site must first be prepared by removing the area of vegetation and topsoil and compacting the underlying soil. The construction of the pad can start once the site preparation is completed. The heap is then irrigated with the leach solution after the ore

has been placed onto the gravel layer. The impermeable layer protects against chemical and PLS leaks that may contaminate groundwater (Piésold, 2012). The pad is made of a geomembrane liner, clay, and over the liner, a drainage system with a drainage pipe system (Guyonnet & Touze-Foltz, 2014). Typically, three types of heap leach pads are used in mining operations, and the selection of the pad type is based on a variety of factors, including the ore characteristics, production rate, and other process requirements (Lupo, 2010). In general, liner systems for leach pads may consist of a single composite or double composite liner with a leakage collection layer. For lower hydraulic heights in heaps, when the height of the leachate solution in a heap is less than one meter, a single composite liner system is commonly employed. In contrast, the double composite liner system is utilized for heaps with high hydraulic heights, where the leachate solution's height can reach several meters. This system consists of two liner layers: an upper and a lower layer. The upper layer is a synthetic liner, while the lower layer is a compacted clay liner. This type of liner system (Ghorbani et al., 2016). In order to keep chemicals and PLS from leaking into the environment, the liner material selection is an essential part of heap leach pad design. High-density polyethylene (HDPE), linear low-density polyethylene (LLDPE), and polyvinyl chloride (PVC) are examples of synthetic materials that are frequently utilized to make geomembrane liners for heap leach pads (Fourie et al., n.d.).

The liner system used to build heap leach pads typically consists of a number of components. For protection over the geomembrane, drainage with pipes, and solution sprays over the drainage, a geotextile and geonet are used, either with or without a leak detection system, between the foundation, soil, or clay (Lupo & Morrison, 2007). The leak detection layer is mainly used in the double-construction liner, which controls the hydraulic

head on the geomembrane. The material of this layer must be chosen to meet certain performance requirements, including preventing permeation of both upper and lower geomembranes, having sufficient penetration to allow the PLS to pass through quickly, and being substantial enough for both the internal and interface to withstand the weight of the heap (Lupo, n.d.). The liner system consists of a 1-meter thick overliner (38 mm minus with less than 10% fines content), 2 mm linear low-density polyethylene (LLDPE) geomembrane, and 0.3-meter thick compacted low permeability soil liner.

## 5. Methodology

LCA methodology is recognized as a standard technique for evaluating the environmental burdens associated with a process or a product. Goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of the LCA results are the four pillars of conducting a systematic LCA (Cairncross & Tadie, 2022; Vahidi & Zhao, 2017; Yang et al., 2022; Zhou et al., 2023). In this study, the LCA technique has been employed to assess the carbon footprint and environmental performance of gold production from various types of ore, such as sulfidic ore and oxidic ore. Sulfidic ore is categorized into two types of ore: refractory and double refractory ore. Therefore, gold processing routes vary based on the types of ore. Various extraction methods have been discussed in the previous chapters. Since gold is a strategic asset for many investors worldwide, there is a clear need to understand the potential environmental impacts of the gold mining industry such as climate change (Chen et al., 2019; Farjana et al., 2019). The following sections will discuss four main stages of conducting a systematic environmental impact assessment.

### 5.1 Goal, scope, and system boundary

The main objective of this study is to draw the environmental performance of gold production from different types of ore that have been treated by roasting, pressure oxidation, and heap leaching. One critical goal and scope definition pillar is defining the system boundary and the functional unit (Rachid et al., 2023). In this study, one kg of gold production is selected as the functional unit for all different types of ore. System boundaries for various processes are shown in Figure 5, Figure 6, and Figure 7. A simplified system

boundary of the roasting process in Figure 5 shows multiple stages from comminution to electrowinning for producing 1 kg gold in a roasting process plant. The roasting facility at Carlin Complex was developed to process 12000 tonnes of double refractory ore per day (Thomas and Buckingham, 1997; Thomas and Cole, 2016). As shown in Figure 5, the process consists of crushing, dry grinding, roasting, and gaseous treatment circuit from roasting, quenching, neutralization, and carbon in leach (CIL) followed by carbon stripping and electrowinning (Thomas and Buckingham, 1997). System boundary in an autoclave plant shows all the stages such as comminution including crushing and grinding, a concentration circuit of flotation cell followed by a pre-treatment method using POX. The following process includes neutralization, CaTS leaching, RIL, elution column, and electrowinning. As seen in Figure 6, there are two main pathways after the flotation cell. The overflow which is the concentrate is further processed through a separate POX facility while the underflow from the flotation cell which is the flotation tailings or residual gangue goes through carbon in leach (CIL) circuit since it may contain sufficient residual gold that needs processing. CIL processing involves leaching the slurry with cyanide to dissolve the gold (Fiddes et al., 2020). Moreover, the system boundary for the heap leaching process includes crushing, agglomeration, heap pad construction, carbon in column (CIC), stripping, and electrowinning. Using the US EPA's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI), the categories of acidification (AC), ecotoxicity (EC), eutrophication (EU), global warming (GW), respiratory effects (RE), carcinogenics (CN), non-carcinogenics (NCN), ozone depletion (OD), resources fossil fuel depletion (RF) and smog air (SA) evaluated for the processes that occurred for gold extraction (Vahidi et al., 2016).

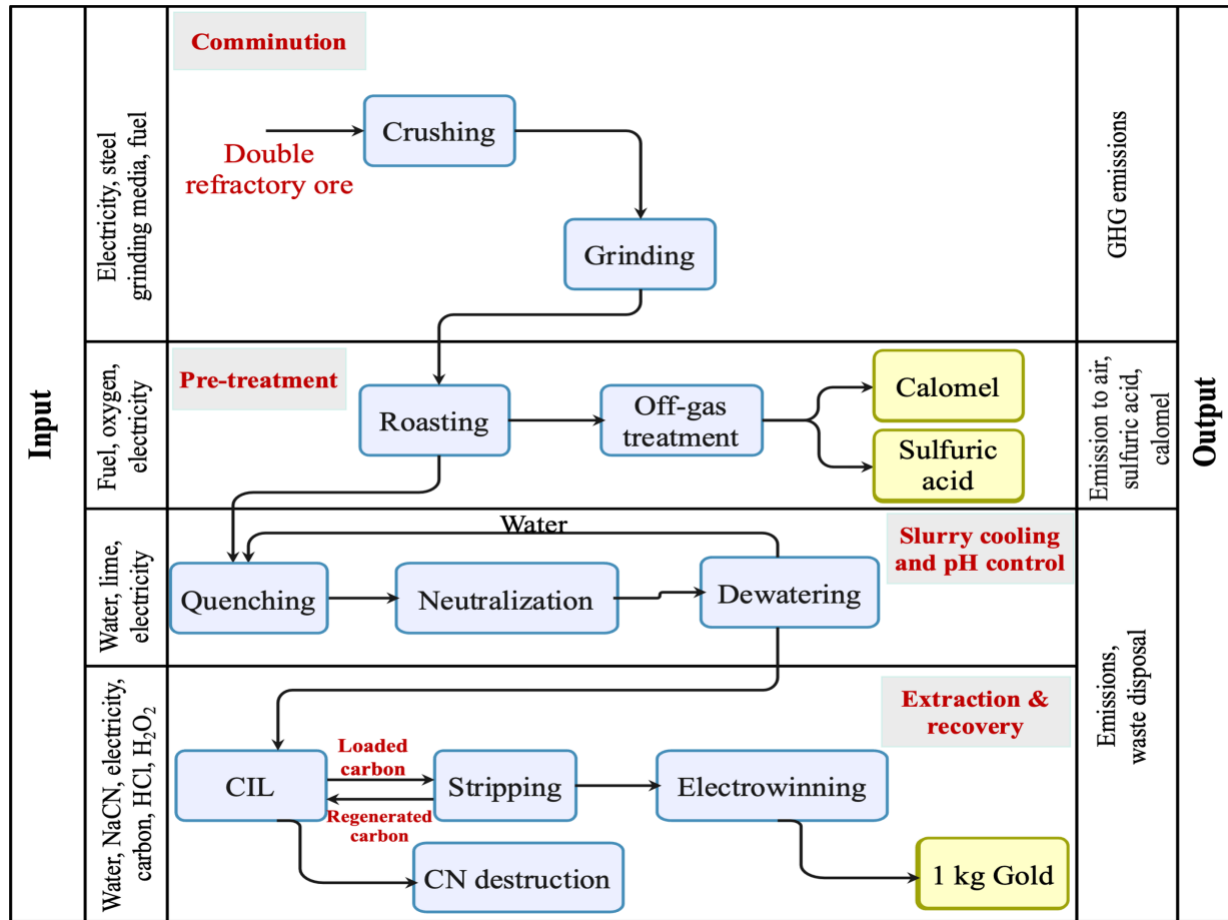


Figure 5. System boundary for the LCA study of roasting process.

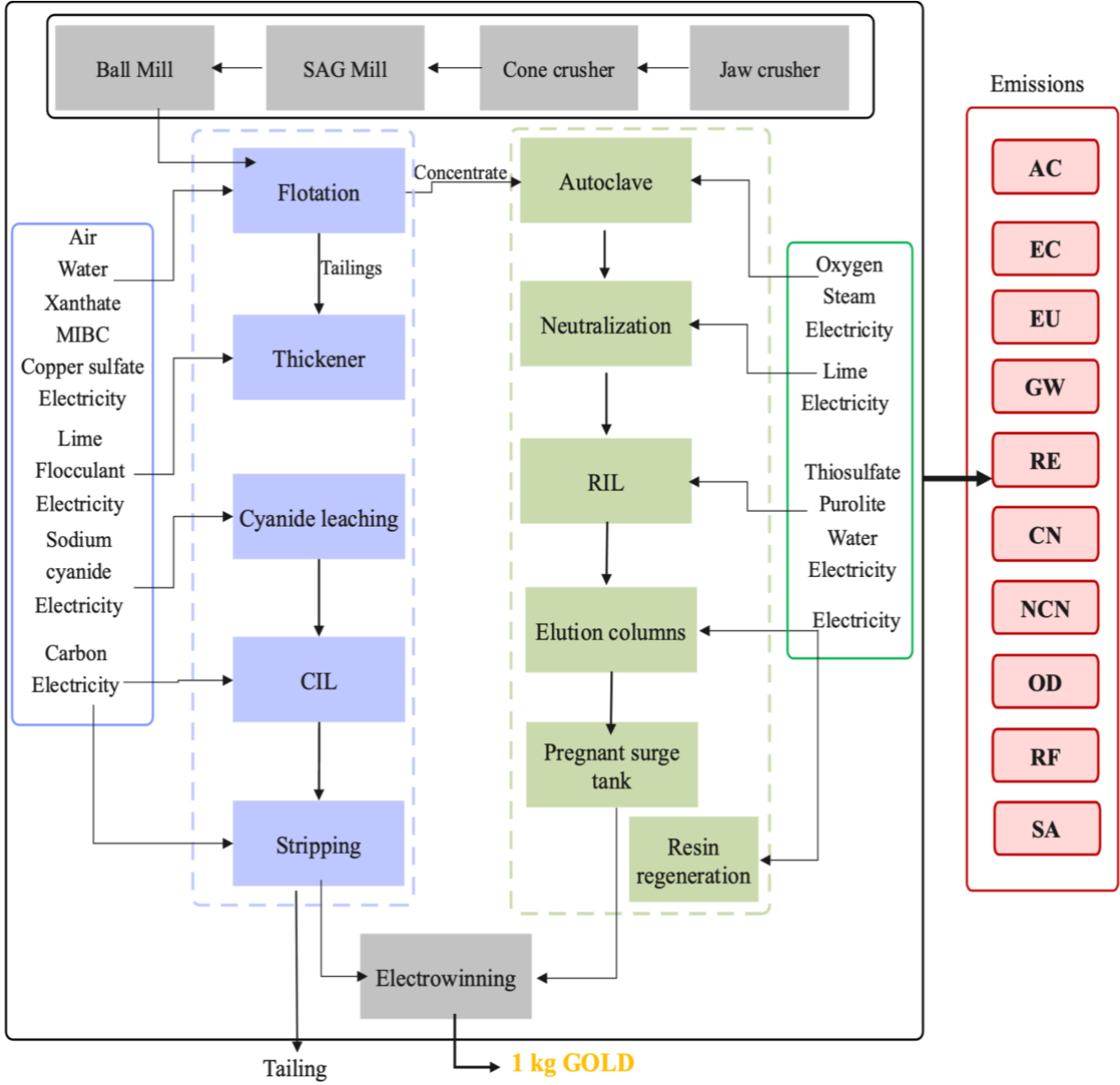


Figure 6. A simplified system boundary for producing one kg of gold from refractory ores.

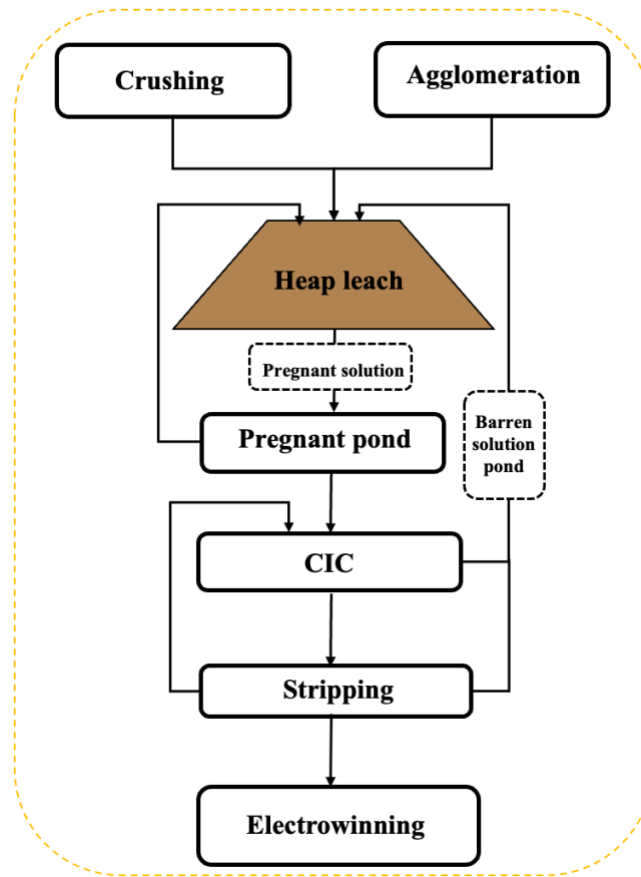


Figure 7. System boundary for heap leaching.

## 5.2 Life cycle inventory (LCI) data

LCI analysis is the second phase of conducting a systematic LCA. This study collected LCI data using various resources such as Carlin Complex technical report, feasibility studies, literature reviews, and gold mining reports. Life cycle inventory analysis was carried out using Simapro v9.4 and Ecoinvent 3.0. As mentioned previously, the main goal of this study is to provide a systematic LCA over various gold processing routes. Life cycle inventory data associated with each process is provided in the following sections.

### 5.2.1 LCI analysis in roasting

Table 2 presents major raw materials, energy input, and wastes for the landfill for the gold ore roasting facility. Emissions to the air were also considered in the inventory data since gaseous emissions of SO<sub>2</sub>, CO, particulate, mercury, and NO<sub>x</sub> accompanied roasting. All the input material, energy consumption, and emissions in Table 2 are calculated based on the functional unit which is 1 kg of gold production. Inventory data for the off-gas treatment is presented in detail in Table 3 in the supporting information including all the raw materials, chemicals, and direct emissions for different gas cleaning systems.

**Table 2.** Life cycle inventory for producing 1 kg of gold from double refractory ores in roasting (Fiddes et al., 2020; Thomas & Buckingham, 1997).

Stage	Input	Value	Unit
Crushing	Electricity	$5.12 \times 10^2$	kWh
Grinding	Electricity	$5.90 \times 10^3$	kWh
	Grinding media	$2.22 \times 10^2$	kg
Roasting	Oxygen	$7.79 \times 10^3$	kg
	Fuel	$2.22 \times 10^3$	MJ
	Electricity	$4.24 \times 10^2$	kWh
Quenching	Water	$1.25 \times 10^2$	m <sup>3</sup>
Neutralization	Lime	$1.45 \times 10^3$	kg
	Electricity	78.40	kWh
Thickener (dewatering)	Electricity	$1.56 \times 10^2$	kWh
Carbon in leach (CIL)	Electricity	31.70	kWh
	Water	3.69	m <sup>3</sup>
	Sodium cyanide	56.62	kg
	Activated carbon	3.77	kg
Carbon stripping	Sodium hydroxide	0.37	kg
	Hydrochloric acid	8.46	kg
CN destruction	Soda ash	26.34	kg
	Hydrogen peroxide	46.71	kg
	Sulfuric acid	106.46	kg
	Lime	15.55	kg
Electrowinning	Electricity	3.1	kWh
<b>Output</b>			
Emissions	Particulate	0.29	kg
	Mercury	0.01	kg
	Carbon monoxide	3.81	kg
	Sulfur dioxide	2.04	kg
	Nitrogen oxide	2.10	kg

**Table 3.** Major life cycle inventory data for the off-gas treatment stages (Thomas and Cole, 2016; Tomatis et al., 2019; van Caneghem et al., 2016).

Off-gas stage	Input	Value	Unit
<b>Gas quenching</b>	water	2.10E+02	kg
<b>WESP</b>	Electricity	1.09E+01	MJ
<b>Mercury scrubber</b>	Input		
	Hg vapor	5.60	kg
	HgCl <sub>2</sub>	7.58E-03	kg
	water	5.66E+02	kg
	Output		
	Hg <sub>2</sub> Cl <sub>2</sub>	4.82E+00	kg
<b>SO<sub>2</sub> scrubber</b>	Input		
	SO <sub>2</sub>	2.88E+03	kg
	Na <sub>2</sub> CO <sub>3</sub>	2.38E+02	kg
	Water	8.09E-04	kg
	Lime	3.33E+03	kg
	Electricity	5.73E+00	MJ
	Output		
	Sulfuric acid	5.29E+03	kg
	CO <sub>2</sub>	1.98E+03	kg
	SO <sub>2</sub>	2.04E+00	kg
<b>CO removal</b>	Input		
	Total CO	1.73E+02	kWh
	Natural gas	6.70E-03	m <sup>3</sup>
	Electricity/heat	1.02E-02	kg
	Output		
	CO	3.82E+00	kg
	CO <sub>2</sub>	2.66E+02	kg
<b>NO<sub>x</sub> reduction</b>	Input		
	Total NO <sub>x</sub>	1.73E+01	kg
	NO <sub>x</sub> removed	1.52E+01	kg
	Natural gas	5.91E+04	kg
	NH <sub>3</sub>	9.79E+00	kg
	Electricity	9.01E+02	MJ
	steel	9.30E-01	kg
	Silica/Alumina	5.55E+00	kg
	TiO <sub>2</sub>	1.58E-02	kg
	Output		
N <sub>2</sub>	1.56E+01	kg	
NO <sub>x</sub>	2.06E+00	kg	

### 5.2.1.1 Assumptions

The challenge in this LCA study was the lack of available industrial information about processing methods utilized for double refractory ore and data gathering was employed using different sources. Thus, the following assumptions were considered in this study for conducting the LCA study:

- ore grade: 7 g Au/t
- grinding method: dry grinding
- pre-treatment method: roasting
- extraction and recovery process: CIL, carbon stripping, and electrowinning
- solid to liquid ratio in quenching, thickener, and CIL tanks were 20%, 48%, and 42%
- Roasting plant by-product: calomel and sulfuric acid
- doré contains 99% gold
- off-gas handling system and CN destruction were also considered as part of the LCA study.

### 5.2.1.2 Allocation

As mentioned in previous sections, in addition to gold production from double refractory ore, the roasting plant generates calomel and sulfuric acid. This indicates that a portion of the environmental impacts of gold recovery from double refractory ore should be allocated to calomel and sulfuric acid as by-products and the goal is to compare the environmental impacts for different outputs (Li et al., 2019; Vahidi et al., 2016; van Genderen et al., 2016). Mass and economic allocation are the two methods for environmental impact allocation in

a multi-product system. Since there is a significant difference between the price of gold and the co-products, economic allocation is used for this study (Norgate & Haque, 2012).

### 5.2.2 LCI analysis in autoclave

Table 4 shows the major raw material and energy inputs and emissions for producing one kg of gold. As seen in Figure 6 for the system boundary, there are two pathways and scenarios for producing gold from refractory ores. The first scenario which is the RIL pathway (with purple color) includes ore concentration using flotation followed by autoclave, thiosulfate leaching, and elution columns. The second scenario called the CIL pathway (green color), includes flotation tailings followed by cyanide leaching and stripping. Both scenarios start with crushing and grinding and end with electrowinning which were considered in two scenarios.

**Table 4.** Life cycle inventory data for producing 1 kg of gold from refractory ores

<b>Input</b>	<b>Value</b>	<b>Unit (/kg Au)</b>
<b>Crushing</b>		
Jaw crusher	5.99E+02	kWh
Cone crusher	1.86E+03	kWh
<b>Grinding</b>		
SAG mill	1.38E+04	kWh
Ball Mill	1.27E+04	kWh
Grinding media	5.24E+02	kg
<b>Flotation</b>		
Collector-Xanthate	1.95E+02	kg
Activator (CuSO <sub>4</sub> )	9.99E-04	kg
Electricity	5.39E+03	kWh
Frother (MIBC)	4.00E+01	kg
Flocculant (Magna Flocc 10)	4.53E-01	kg
<b>CIL</b>		
Lime	3.00E+03	kg
Sodium cyanide	2.00E+02	kg
Electricity	7.38E+01	kWh
Activated carbon	1.20E+01	kg
<b>Stripping</b>		
Electricity	2.29E-01	kWh
<b>Autoclave</b>		
Oxygen	2.16E+03	kg
Steam	2.90E+03	kWh
Electricity	4.20E+02	kWh
<b>RIL</b>		
Thiosulfate	4.45E+02	kg
Electricity	1.50E+00	kWh
Water	1.75E-01	m <sup>3</sup>
Copper sulfate	2.11E+00	kg
<b>Thiosulfate regeneration</b>		
Sodium sulfide	3.44E+02	kg
Electricity	2.98E+04	kWh
<b>Resin regeneration</b>		
electricity	4.77E+03	kWh
<b>Gold elution</b>		
Sodium sulfite	8.16E-01	kg
Sodium hydroxide	5.18E-02	kg
Electricity	4.74E-01	kWh
<b>Electrowinning</b>		
Electricity	3.1E+00	kWh
HCl	4.90E-01	kg

### 5.2.2.1 Limitations

There are some limitations of the current study that might cause a negative effect on the reliability of the results and outcomes. Firstly, few studies were available describing the input flows to the autoclave. Therefore, major data for the pressure oxidation including steam and oxygen were gathered from different sources with validation to make sure that the collected data is reasonable. Additionally, for many processes, surrogates are commonly used due to the lack of available information (Vahidi et al., 2016). For instance, the electricity consumption of various stages such as RIL, resin regeneration, and electrowinning was calculated based on surrogate processes. Moreover, a critical limitation in this study was the availability of data within Sima Pro, Ecoinvent 3 for the input materials such as xanthate, thiosulfate, and methyl isobutyl carbinol (MIBC). The life cycle impact of missing input materials was calculated by manually constructing the missing datasets in Sima Pro. Furthermore, since there was no inventory data in Ecoinvent 3 for MIBC, methyl isobutyl ketone (MIBK) has been selected for MIBC environmental impact assessment. The manufacturing processes, chemical reactions, and assumptions made for the xanthate and thiosulfate are mentioned in the supplementary data.

### 5.2.2.2 Xanthate production

Xanthate salts are produced as a product of the reactions between sodium or potassium hydroxide and alcohol and carbon disulfide. Equation 4 shows the reaction between sodium hydroxide with carbon disulfide and ethanol to form sodium ethyl xanthate. The system boundary for xanthate production can be seen in Figure 8. Table 5 represents the raw materials, energy, and chemical consumption in the process of xanthate production. The

final environmental impact assessment results for producing 1 kg of xanthate are also indicated in Table 6.

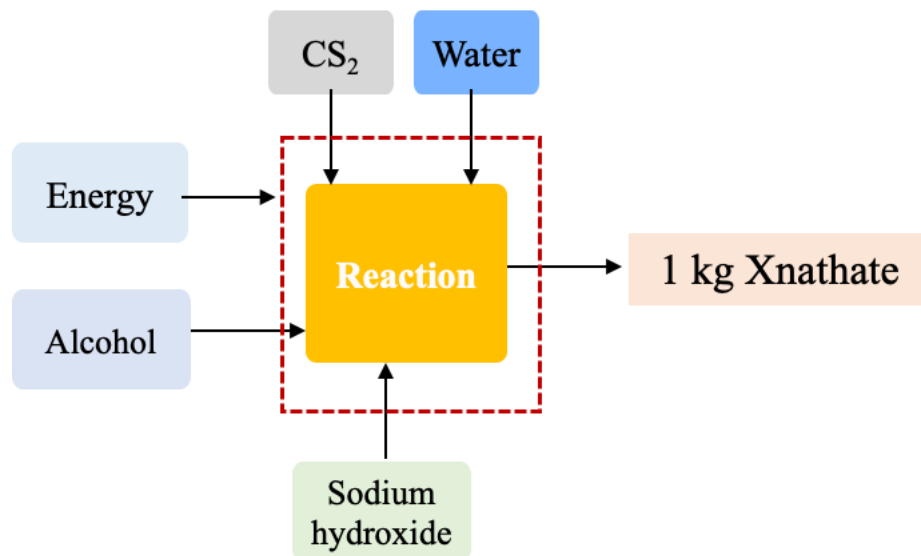
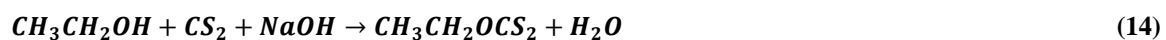


Figure 8. System boundary for xanthate production.

Table 5. Consumption of raw materials and energy flow for xanthate production (1 kg).

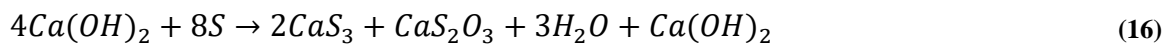
Input materials/energy	Value	Unit
Sulfur	9.00E-01	MJ
Charcoal	3.32E-01	kg
Fuel	1.03E+00	kg
ethanol	6.16E-01	kg
Sodium hydroxide	2.86E-01	kg

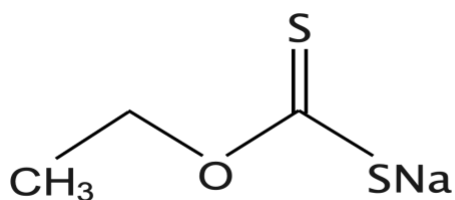
**Table 6.** Life cycle impacts for producing 1 kg of xanthate using the TRACI method.

Impact Category	Unit	Xanthate (1 kg)
Acidification	kg SO <sub>2</sub> eq	1.24E-02
Ecotoxicity	CTUe	3.31E+01
Eutrophication	kg N	7.02E-03
Global warming	kg CO <sub>2</sub> eq	2.80E+00
Respiratory effects	kg PM <sub>2,5</sub> eq	2.61E-03
Carcinogenics	CTUh	1.36E-07
Non-carcinogenics	CTUh	5.35E-07
Ozone depletion	kg CFC 11 eq	2.09E-07
Resources & Fossil fuel depletion	MJ surplus energy	9.25E+00
Smog	kg O <sub>3</sub> eq	1.54E-01

### 5.2.2.3 Thiosulfate production

The chemical symbol for thiosulfate anion is  $S_2O_3^{2-}$  which is shown in Figure 9. Different pathways have been reported in literature reviews for thiosulfate production. It can be produced from elemental sulfur and sulfite at an elevated temperature (Oraby, 2009). In addition, thiosulfate can be produced as a product of the reactions between sulfur, calcium sulfite, and hydroxide, as described in Equations 5 (Hajjatie et al., 2006).





**Figure 9.** Chemical structure of sodium ethyl xanthate.

Few details on the current operations are available in the literature, but some leaching conditions can be summarized from the information contained in patents. Calcium thiosulfate has been selected as their lixiviant choice over cyanide, ammonium thiosulfate, chloride, and thiourea (Daenzer & Eng, 2008). Life cycle inventory data and impact analysis for producing one kg of CaTS have been provided in Table 7 and Table 8.

**Table 7.** Life cycle inventory data for producing 1 kg of thiosulfate.

materials/energy	Value	Unit
Oxygen	1.96E-01	m <sup>3</sup>
Sulfur	4.44E-01	kg
Lime	4.04E-01	kg
Water	3.08E-01	kg
Flocculant (polyacrylamide)	6.00E-08	kg
Acetic acid	3.00E-02	kg
Calcium thiosulfate	2.63E-01	kg
<b>Output</b>		
Calcium hydroxide	1.28E-01	kg
Calcium sulfide	2.50E-01	kg

**Table 8.** Total environmental impacts for thiosulfate production (1 kg).

Impact Category	Unit	Oxygen	Sulfur	Lime	Water	Flocculant (polyacrylamide)	Acetic acid	Total
Acidification	kg SO <sub>2</sub> eq	1.09E-04	4.39E-03	9.16E-05	1.43E-06	9.13E-10	2.27E-04	1.83E-02
Ecotoxicity	CTUe	4.95E-01	4.39E-01	7.34E-02	1.09E-03	1.83E-06	6.88E-01	6.44E+00
Eutrophication	kg N	8.34E-05	8.48E-05	3.73E-05	6.19E-07	9.57E-10	1.38E-04	1.31E-03
Global warming	kg CO <sub>2</sub> eq	2.40E-02	8.17E-02	1.64E-02	2.12E-04	1.93E-07	4.65E-02	6.41E-01
Respiratory effects	kg PM <sub>2,5</sub> eq	3.72E-05	2.78E-04	2.29E-05	3.54E-07	9.82E-11	4.53E-05	1.46E-03
Carcinogenics	CTUh	1.92E-09	2.41E-09	7.98E-10	5.54E-11	1.01E-14	3.80E-09	3.41E-08
Non-carcinogenics	CTUh	5.92E-09	1.37E-08	2.69E-09	8.13E-11	3.04E-14	1.14E-08	1.28E-07
Ozone depletion	kg CFC 11 eq	9.42E-10	1.02E-08	1.46E-09	1.69E-11	7.71E-15	1.33E-08	9.84E-08
Resources & Fossil fuel depletion	MJ surplus energy	1.70E-02	1.17E+00	1.89E-02	1.73E-04	5.22E-07	1.73E-01	5.23E+00
Smog	kg O <sub>3</sub> eq	1.37E-03	4.48E-03	1.26E-03	1.41E-05	7.73E-09	2.92E-03	3.81E-02

## 6. Result and discussion

### 6.1 LCIA results in roasting

#### 6.1.1 Environmental performance results of the off-gas treatment

Various chemical reactions occur during the roasting of double refractory ore, resulting in significant detrimental emissions that need separate pre-treatment processes before releasing to the atmosphere (Thomas & Cole, 2016). The processes include WESP, mercury scrubber, sulfur dioxide scrubber, CO, and NO<sub>x</sub> removal. Table 3 represents the inventory data for the abovementioned treatment stages. All the input materials, reagents, and energy consumption are listed based on the functional unit. Total environmental impact assessment results based on the TRACI method are presented in Table 9. LCIA results showed that the full potential impacts of all stages on climate change and acidification were  $6.85 \times 10^3$  kg CO<sub>2</sub>-eq., and  $3.10 \times 10^3$  kg SO<sub>2</sub>-eq. Furthermore, The potential environmental burden on ecotoxicity, eutrophication, carcinogenics and non-carcinogenics, ozone depletion, resources, and fossil fuel and smog air were  $8.69 \times 10^3$  CTUe, 5.51 kg N-eq, 1.22 kg PM<sub>2.5</sub>-eq,  $1.20 \times 10^{-1}$  CTUh,  $1.19 \times 10^{-3}$  CTUh,  $4.94 \times 10^{-4}$  kg CFC 11-eq,  $1.14 \times 10^4$  MJ energy and  $1.21 \times 10^2$  kg O<sub>3</sub>- eq.

NO<sub>x</sub> reduction unit had the greatest value for global warming among all the treatment stages. The higher value of CO<sub>2</sub> eq. in the NO<sub>x</sub> reduction unit compared to other stages can be attributed to the production of the catalyst needed for NO<sub>x</sub> reduction, electricity consumption, NH<sub>3</sub>, and the heat required for the process. These impacts are represented as indirect emissions generated by raw material inventory and energy consumption.

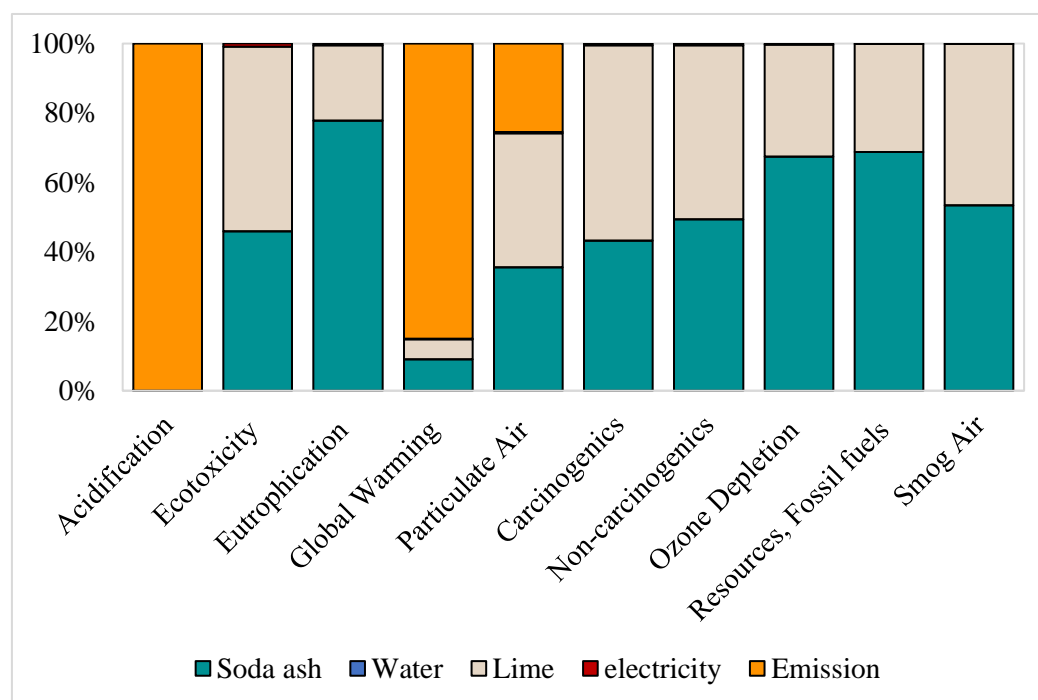
**Table 9.** Total environmental impact assessment results in different off-gas treatment stages.

TRACI/Input	Value (/kg Au)				
	WESP <sup>1</sup>	Hg scrubber	SO <sub>2</sub> scrubber	CO removal	NO <sub>x</sub> reduction
Acidification [kg SO <sub>2</sub> -eq.]	1.85E-02	2.66E-03	3.10E+03	7.11E-06	5.96E+00
Ecotoxicity [CTUe]	6.64E+01	1.76E+03	1.14E+03	1.97E-02	5.73E+03
Eutrophication [kg N- eq.]	4.11E-02	1.17E-03	1.42E+00	1.10E-05	4.05E+00
Global warming [kg CO <sub>2</sub> - eq.]	6.24E+00	3.97E-01	2.32E+03	2.66E+02	4.25E+03
Respiratory effects [kg PM <sub>2,5</sub> - eq.]	1.48E-02	6.63E-04	4.90E-01	1.36E-03	7.11E-01
Carcinogenics [CTUh]	4.87E-07	1.20E-01	1.17E-05	1.44E-10	5.51E-05
Non-carcinogenics [CTUh]	1.71E-06	1.02E-03	4.42E-05	4.88E-10	1.30E-04
Ozone depletion [kg CFC 11- eq.]	6.09E-07	3.55E-08	3.71E-05	4.35E-10	4.60E-04
Fossil fuel depletion [MJ surplus energy]	5.32E+00	3.24E-01	5.03E+02	8.09E-03	1.09E+04
Smog [kg O <sub>3</sub> - eq.]	1.80E-01	2.65E-02	2.24E+01	8.14E-05	9.83E+01

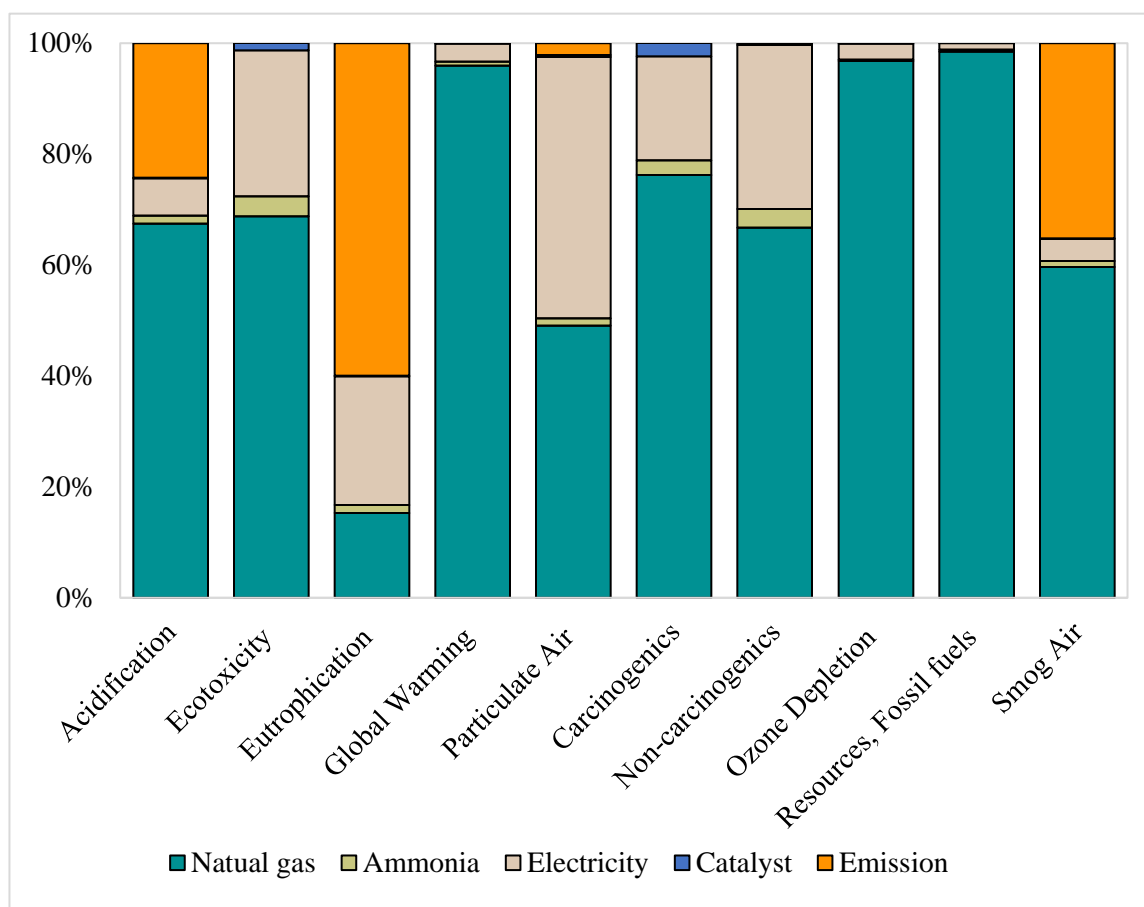
Table 10 represents the environmental impacts of indirect and direct emissions in the mercury scrubber unit. Indirect emissions were responsible for almost all the impact categories except ecotoxicity, carcinogenic, and non-carcinogenics, in which direct emission of mercury showed a significant contribution. The contributions of all the inventories and direct emissions in SO<sub>2</sub> scrubber and NO<sub>x</sub> removal are also shown in Figure 10 and Figure 11.

**Table 10.** Environmental impact assessment for direct and indirect emission of Hg scrubber.

TRACI/Input	Indirect emission	Direct emission
Acidification [kg SO <sub>2</sub> - eq.]	3.67E-05	0
Ecotoxicity [CTUe]	1.25E-01	1.75E+03
Eutrophication [kg N- eq.]	2.78E-05	0
Global warming [kg CO <sub>2</sub> - eq.]	7.61E-03	0
Respiratory effects [kg PM <sub>2,5</sub> - eq .]	1.13E-05	0
Carcinogenics [CTUh]	6.96E-10	1.20E-01
Non-carcinogenics [CTUh]	2.36E-09	1.02E-03
Ozone depletion [kg CFC 11- eq.]	4.42E-09	0
Fossil fuel depletion [MJ surplus energy]	5.80E-03	0
Smog [kg O <sub>3</sub> - eq.]	4.72E-04	0

**Figure 10.** Contribution of raw materials, energy consumption and direct emission in SO<sub>2</sub> treatment stage.

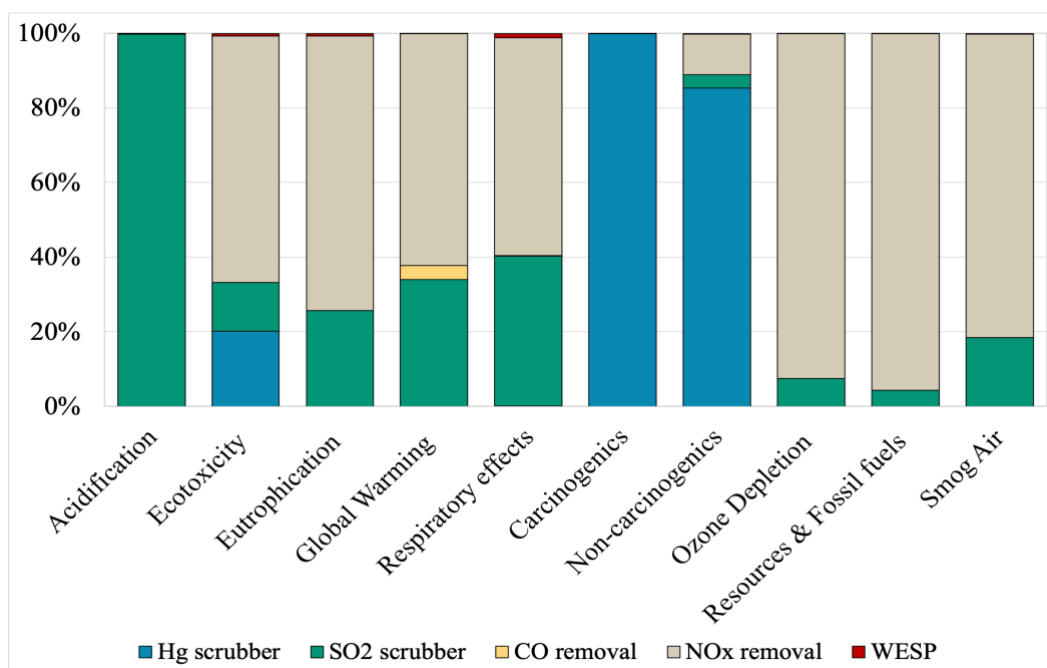
Direct emissions containing sulfur compounds were responsible for the sulfur dioxide removal unit's overall acidification and global warming impact categories (Munyongani et al., 2017). Chemical reagents such as soda ash significantly contributed significantly to the eutrophication impact category. However, for the NO<sub>x</sub> reduction unit, natural gas was the dominant contributor in the categories of acidification and GHG emissions as seen in Figure 11.



**Figure 11.** Indirect and direct contribution to the overall environmental impacts in NO<sub>x</sub> reduction unit.

The highest contribution of natural gas in impact categories is caused by the combustion of natural gas for heat generation in the units (van Caneghem et al., 2016). Direct process

emissions, energy, and raw material contribution to the gas handling system after roasting are observed in Figure 12, where mercury scrubber, SO<sub>2</sub> scrubber, and NO<sub>x</sub> removal were the dominant stages that contributed to almost all the environmental impact categories. For instance, mercury removal contributed most to the categories of carcinogenics and non-carcinogenics due to the emissions of vapor mercury into the atmosphere (Miller, 2005). As seen in Figure 12, sulfur dioxide scrubber and NO<sub>x</sub> removal were responsible for about 36% and 62% of the total CO<sub>2</sub> eq, respectively. Results show that although SO<sub>2</sub> scrubber and NO<sub>x</sub> reduction units reduce the amount of sulfur dioxide emission, they are still energy intensive and produce significant GHG emissions, sulfur dioxide, and nitrogen oxide emissions to the atmosphere. Furthermore, it can be concluded that although treatment units at the gas handling system remove emissions, they utilize electric power and different reagents such as lime and soda ash for the treatment, which can result in impacts on human health and the environment by different emissions releasing to the air as airborne emissions (Munyongani et al., 2017).



**Figure 12.** Contributions of treatment processes and emissions for gas handling system using TRACI.

### 6.1.2 Total environmental impacts of gold production in the roasting process

In this study, the environmental burdens associated with life cycle stages in a gold roasting process plant were explored. Table 11 presents the total environmental impacts of all stages for producing 1 kg of gold using the TRACI method. The potential environmental impacts of global warming and acidification were  $1.22 \times 10^4$  kg CO<sub>2</sub>-eq and  $3.12 \times 10^3$  kg SO<sub>2</sub>-eq. Table 11 shows the LCIA results for the remaining categories. The heat map of the TRACI-characterized environmental impacts of all the stages in a roasting plant can be seen in Table 11. Results indicated that the electrowinning and stripping stages had a lower environmental footprint in all the impact categories. The potential impact of grinding, roasting, and off-gas treatment stages on GHG emissions were  $4.25E+03$ ,  $2.21E+02$ , and  $6.84E+03$  CO<sub>2</sub>- eq, respectively.

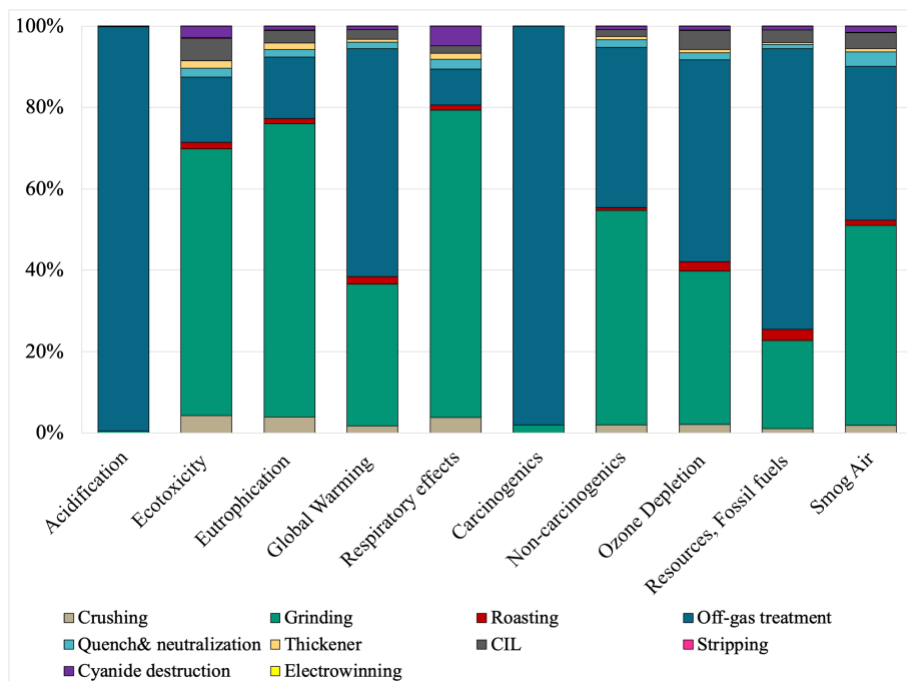
Table 11. Environmental impact assessment results in each life cycle stage.

TRACI	Crushing	Grinding	Roasting	Off-gas Treatment	Quench& Neutralization	Thickener	CIL	Stripping	Cyanide Destruction	Electrowinning	Total
Acidification [kg SO <sub>2</sub> -eq.]	6.18E-01	1.44E+01	3.49E-01	3.10E+03	1.03E+00	2.53E-01	1.12E+00	2.65E-02	3.73E-01	3.23E-03	3.12E+03
Ecotoxicity [CTUe]	2.31E+03	3.52E+04	8.96E+02	8.62E+03	1.18E+03	9.48E+02	3.00E+03	8.50E+01	1.50E+03	1.21E+01	5.38E+04
Eutrophication [kg N-eq.]	1.43E+00	2.62E+01	4.70E-01	5.46E+00	6.79E-01	5.87E-01	1.13E+00	2.18E-02	3.52E-01	7.49E-03	3.64E+01
Global Warming [kg CO <sub>2</sub> -eq.]	2.15E+02	4.25E+03	2.21E+02	6.84E+03	1.89E+02	8.81E+01	2.88E+02	5.91E+00	9.51E+01	1.12E+00	1.22E+04
Respiratory effect [kg PM <sub>2,5</sub> -eq.]	5.12E-01	1.03E+01	1.74E-01	1.20E+00	3.31E-01	2.10E-01	2.46E-01	4.96E-03	6.50E-01	2.68E-03	1.36E+01
Carcinogenic [CTUh]	1.58E-05	2.41E-03	6.59E-06	1.20E-01	2.86E-05	6.49E-06	2.29E-05	4.69E-07	2.04E-05	8.28E-08	1.23E-01
Non-carcinogenic [CTUh]	5.84E-05	1.59E-03	2.17E-05	1.19E-03	5.46E-05	2.39E-05	5.21E-05	1.35E-06	2.49E-05	3.05E-07	3.02E-03
Ozone Depletion [kg CFC 11-eq.]	2.11E-05	3.78E-04	2.32E-05	4.97E-04	1.64E-05	8.64E-06	4.66E-05	1.45E-06	9.32E-06	1.10E-07	1.00E-03
Resources, Fossil fuels [MJ surplus energy]	1.83E+02	3.59E+03	4.62E+02	1.14E+04	1.75E+02	7.51E+01	5.10E+02	1.05E+01	1.46E+02	9.58E-01	1.66E+04
Smog Air [kg O <sub>3</sub> -eq.]	6.02E+00	1.57E+02	4.15E+00	1.21E+02	1.15E+01	2.47E+00	1.24E+01	3.15E-01	4.91E+00	3.15E-02	3.19E+02

Based on LCIA results shown in Table 11, grinding and off-gas treatment were the dominant contributors in almost all the impact categories. Figure 13 shows the contribution of dominant processes to TRACI impact categories in gold production by roasting. According to Figure 13, the off-gas treatment process was responsible for almost all the SO<sub>2</sub> emissions for the acidification category. This result shows that although a gas handling system using an SO<sub>2</sub> scrubber can reduce sulfur dioxide and sulfur trioxide emissions, it still shows emissions to the air since it uses electricity and other reagents. Furthermore, it can be seen that the dominant processes that contributed to the environmental impact were grinding and off-gas treatment compared to other stages at the gold production facility.

For the grinding stage, electricity consumption for grinding the ore and obtaining the target particle size (74 microns) had a significant impact in almost all the impact categories except acidification and carcinogenics, which were dominated by the off-gas treatment stage. For global warming, the grinding stage and off-gas treatment accounted for about 36% and 56.3% of the total carbon dioxide equivalent. Since the dry grinding method is used at the Goldstrike Mine facility, fuel (natural gas) is used to dry the ore before the roaster. High values of electricity consumption at the grinding stage caused a higher amount of greenhouse gas emissions with a value of  $4.24 \times 10^3$  kg CO<sub>2</sub> eq. Furthermore, the off-gas treatment unit had a significant contribution to direct emissions of sulfur dioxide and carbon monoxide to the air, contributing to acidification and global warming categories, respectively. In addition, crushing and CIL stages showed smaller contributions being the

largest in the ecotoxicity impact category. Contributions of other stages were insignificant compared to the grinding and off-gas treatment stages which resulted in smaller impacts that are not visible in the contribution graph.



**Figure 13.** Contributions of dominant processes in gold production at roasting facility.

Furthermore, for the carcinogenics category, the impact from off-gas treatment accounted for almost 98% of the total human toxicity-cancer category. Direct emissions to the air, especially mercury vapor emissions from the mercury scrubber treatment stage, were the main contributor to the carcinogenics category. As mentioned in the inventory data in Table 3, 0.144 kg of mercury (vapor) is released to produce 1 kg of gold at the roasting facility in Carlin Complex, which can directly influence human health. The total LCA results for each stage are listed in Table 11, where the environmental impacts associated with input material, reagents, electricity, and direct emissions of all the stages with the exact values can be observed.

### 6.1.3 Economic allocation

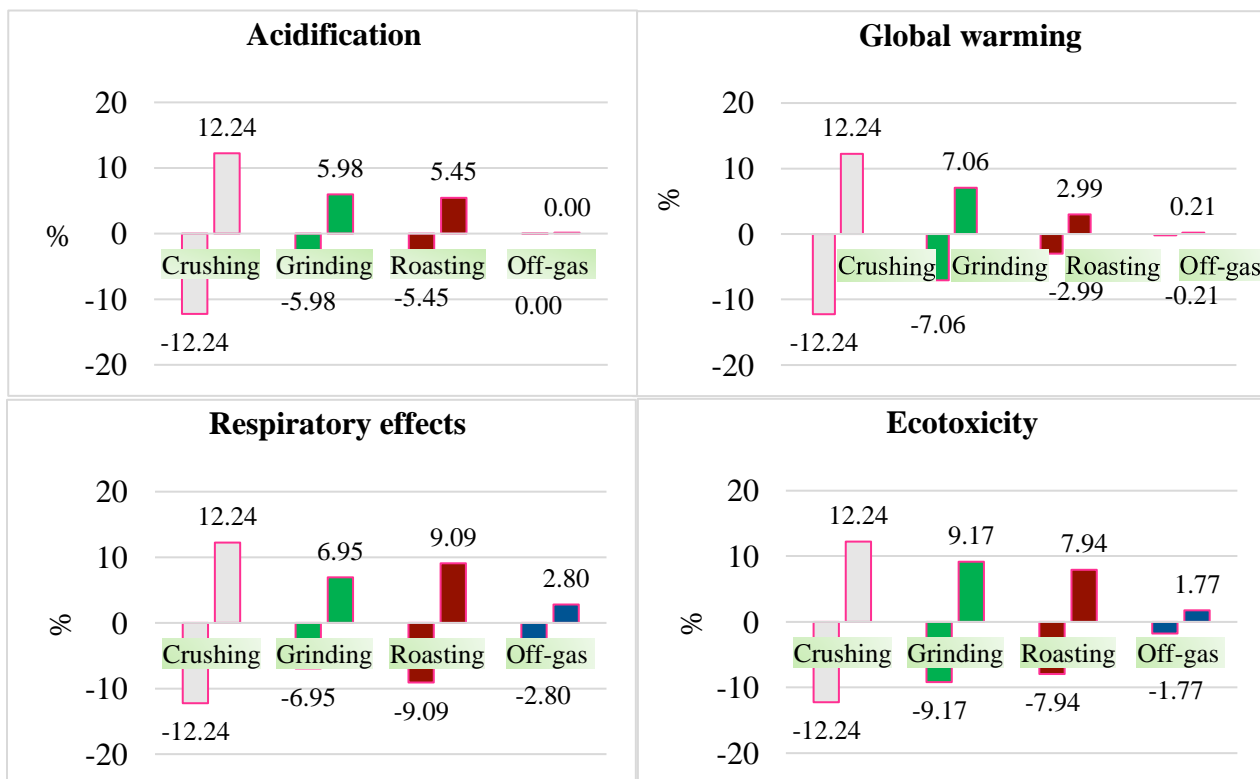
Sulfuric acid and calomel are two products that are generated during the roasting process. To determine the environmental impacts of each product, the economic allocation was adopted in this study (Vahidi et al., 2016). Given the economic-based allocation results in Table 12, the highest environmental impact was obtained for gold production at the roaster facility due to the high economic value of gold compared to other products in the system. The allocation method can affect the LCA results of the process. For instance, Norgate et al. applied mass and economic allocation in their study (Norgate & Haque, 2012). The results showed higher environmental impacts in economic allocation compared with mass allocation due to the higher economic value of gold relative to silver.

**Table 12.** Environmental impact assessment results based on economic allocation.

TRACI	Gold	Sulfuric acid	Calomel
Acidification [kg SO <sub>2</sub> - eq.]	3.01E+03	1.13E+02	9.59E-01
Ecotoxicity [CTUe]	5.18E+04	1.94E+03	1.65E+01
Eutrophication [kg N- eq.]	3.50E+01	1.31E+00	1.12E-02
Global warming [kg CO <sub>2</sub> - eq.]	1.17E+04	4.41E+02	3.74E+00
Respiratory effects [kg PM <sub>2,5</sub> - eq.]	1.31E+01	4.93E-01	4.19E-03
Carcinogenics [CTUh]	1.18E-01	4.44E-03	3.77E-05
Non-carcinogenics [CTUh]	2.91E-03	1.09E-04	9.28E-07
Ozone depletion [kg CFC 11- eq.]	9.65E-04	3.62E-05	3.08E-07
Fossil fuel depletion [MJ surplus energy]	1.60E+04	6.00E+02	5.10E+00
Smog [kg O <sub>3</sub> - eq.]	3.08E+02	1.15E+01	9.81E-02

#### 6.1.4 Sensitivity analysis

Since the data for this study were collected from different sources, a sensitivity analysis was employed on the main contributors in this study to address uncertainty (Vahidi & Zhao, 2018; Volk et al., 2023; Zhou et al., 2023). A change in sensitive input material, such as electricity consumption, can significantly influence the LCA results (Vahidi & Zhao, 2018). As shown in Figure 14 (a), a 10% change in electricity consumption on dominant processes was considered. Sensitivity results demonstrate that a 10% change in electricity consumption can decrease GHG emissions (Chen et al., 2021) by 10% generated by the crushing stage. According to Figure 14, it can also be concluded that a 10% change in electricity can lead to 7.06% and 2.99% environmental benefits in global warming generated by grinding and roasting stages, respectively.



**Figure 14.** Sensitivity analysis on electricity for dominant processes to produce 1 kg gold at roasting facility.

As seen in Figure 14, the off-gas treatment stage had the lowest variation for global warming and acidification categories proving that the majority of global warming and acidification categories in the off-gas treatment stage are generated by the emissions to the air. Similar observations for the rest categories and contributors can also be derived from the sensitivity results. For instance, for respiratory effects and ecotoxicity impact categories, all the processes had a significant variation except off-gas treatment, dominated mainly by the direct emissions from SO<sub>2</sub>, CO, mercury, and NO<sub>x</sub>. Considering the sensitivity analysis results, environmental regulations and actions should be considered to achieve GHG emissions reduction. In this study, electrical power is transmitted to Carlin Complex by NV energy via energy transmission lines. Greener sources of electricity can considerably lead to environmental benefits in terms of less GHG emissions (Vahidi & Zhao, 2018). In this regard, Carlin Complex planned to progress in the sustainable gold production process by converting the power plant from a coal-fired to a natural gas and solar facility. This conversion will enable the facility to reduce carbon emissions by as much as 50%.

## 6.2 LCIA results in autoclave

This section will discuss the environmental impact evaluation results of the RIL and CIL pathways as well as the total LCIA results. Firstly, the environmental performance of the CIL and RIL pathways with the absolute values of the impact categories will be shown. Then, the contributions of each stage in separate pathways will be compared. Finally, the total environmental footprint for producing one kg of gold for the overall process is calculated.

### 6.2.1 Life cycle impact analysis for RIL and CIL pathways

The environmental burdens associated with RIL and CIL pathways for producing one kg of gold have been listed in Table 13 and Table 14. Table 13 shows the environmental impacts of all the stages, including comminution, flotation, autoclave, RIL, resin and thiosulfate regeneration, and elution column. While Table 14 represents the environmental impacts associated with gold extraction from flotation tailing. The LCIA results in Table 14 show the total environmental impacts of all the CIL pathway stages, including comminution, flotation, cyanide leaching, and stripping. Tailing treatment was out of our goal and was not considered in the calculation. From the results, the potential global warming for producing one kg of gold through the RIL pathway is  $1.81 \times 10^4$  kg CO<sub>2</sub>-eq while it was  $1.27 \times 10^4$  kg CO<sub>2</sub>-eq. Comparing the LCA results of Table 13 and Table 14 shows that gold production through the RIL scenario has a higher environmental impact than the CIL pathway in terms of global warming and other impact categories such as acidification and ecotoxicity.

From the results, it is clear that using a pretreatment method such as autoclave results in higher environmental impacts since this stage needs steam, electricity, and oxygen to oxidize the ore. If the ore contains sufficient sulfide for oxidation in the POX circuit, the process in the autoclave will be autothermal and no external heat source and steam is required. However, the sulfide grade in this study was low, and adding steam to the autoclave was necessary to raise the operating temperature (Mason, 1990). Furthermore, the potential impact on acidification for the first scenario was 68.4 kg SO<sub>2</sub> eq while it was reported 48.2 kg SO<sub>2</sub> eq in the CIL pathway. This indicates that the autoclave stage in the RIL pathway can be responsible for a significant amount of acidification. The total

ecotoxicity impact category is also higher in the first scenario, with a value of  $1.65 \times 10^5$  CTUe, compared to  $1.50 \times 10^5$  CTUe in the second scenario.

**Table 13. Environmental impacts associated with RIL pathway for one kg gold production.**

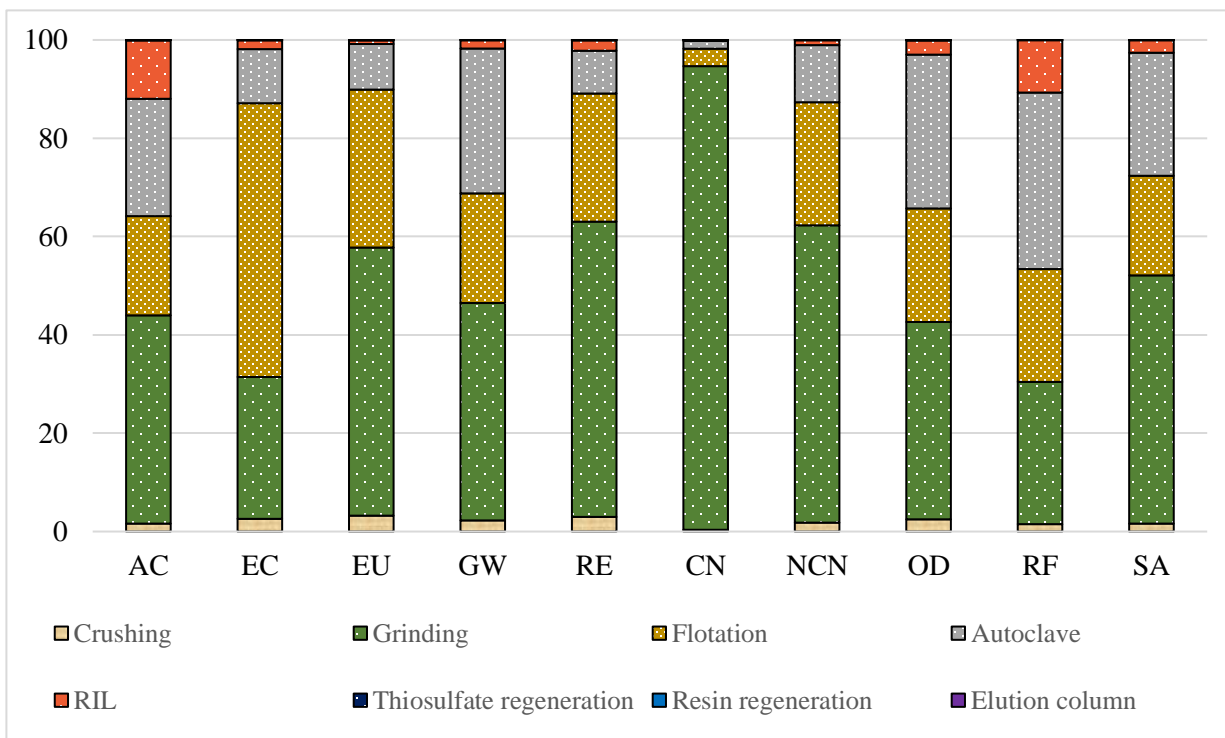
Impact Category	Unit	Crushing	Grinding	Flotation	Autoclave	RIL	Thiosulfate regeneration	Resin regeneration	Elution column	Total
AC	kg SO <sub>2</sub> eq	1.11E+00	2.90E+01	1.38E+01	1.46E+01	7.32E+00	1.55E-02	4.30E-03	2.82E-02	6.59E+01
EC	CTUe	4.14E+03	4.62E+04	8.93E+04	1.59E+04	2.58E+03	5.79E+01	1.61E+01	2.42E+01	1.58E+05
EU	kg N	2.56E+00	4.33E+01	2.55E+01	6.62E+00	5.28E-01	3.59E-02	9.96E-03	1.14E-02	7.85E+01
GW	kg CO <sub>2</sub> eq	3.84E+02	7.52E+03	3.79E+03	4.51E+03	2.57E+02	5.38E+00	1.49E+00	2.22E+00	1.65E+04
RE	kg PM <sub>2,5</sub> eq	9.16E-01	1.85E+01	8.03E+00	2.41E+00	5.85E-01	1.28E-02	3.56E-03	5.01E-03	3.05E+01
CN	CTUh	2.83E-05	7.49E-03	2.82E-04	1.13E-04	1.37E-05	3.97E-07	1.10E-07	1.64E-07	7.93E-03
NCN	CTUh	1.04E-04	3.49E-03	1.45E-03	6.04E-04	5.16E-05	1.46E-06	4.06E-07	8.58E-07	5.70E-03
OD	kg CFC 11 eq	3.77E-05	6.10E-04	3.51E-04	4.28E-04	3.95E-05	5.28E-07	1.47E-07	5.93E-07	1.47E-03
RF	MJ surplus energy	3.28E+02	6.31E+03	5.01E+03	7.05E+03	2.09E+03	4.59E+00	1.27E+00	2.80E+00	2.08E+04
SA	kg O <sub>3</sub> eq	1.08E+01	3.36E+02	1.35E+02	1.50E+02	1.53E+01	1.51E-01	4.19E-02	1.02E-01	6.48E+02

**Table 14. Life cycle impact assessment results in CIL pathway for producing one kg gold.**

Impact Category	Unit	Crushing	Grinding	Flotation electricity	Flotation reagents	CIL	Stripping	Total
AC	kg SO <sub>2</sub> eq	1.11E+00	2.90E+01	8.75E+00	5.09E+00	4.30E-01	2.32E-04	4.43E+01
EC	CTUe	4.14E+03	4.62E+04	3.27E+04	5.67E+04	1.01E+03	2.74E-04	1.41E+05
EU	kg N	2.56E+00	4.33E+01	2.03E+01	5.29E+00	3.63E-01	3.33E-04	7.17E+01
GW	kg CO <sub>2</sub> eq	3.84E+02	7.52E+03	3.04E+03	7.65E+02	1.04E+02	3.03E-04	1.18E+04
RE	kg PM <sub>2,5</sub> eq	9.16E-01	1.85E+01	7.25E+00	8.05E-01	8.09E-02	3.10E-04	2.75E+01
CN	CTUh	2.83E-05	7.49E-03	2.24E-04	5.84E-05	7.73E-06	3.38E-05	7.84E-03
NCN	CTUh	1.04E-04	3.49E-03	8.27E-04	6.22E-04	1.75E-05	1.92E-04	5.25E-03
OD	kg CFC 11 eq	3.77E-05	6.10E-04	2.98E-04	5.36E-05	1.66E-05	3.46E-04	1.36E-03
RF	MJ surplus energy	3.28E+02	6.31E+03	2.59E+03	2.42E+03	1.86E+02	2.58E-04	1.18E+04
SA	kg O <sub>3</sub> eq	1.08E+01	3.36E+02	8.52E+01	5.02E+01	4.97E+00	2.06E-04	4.87E+02

### 6.2.2 Process contribution in RIL and CIL pathways

The contribution of various stages for both scenarios has been depicted in Figure 15 and Figure 16. The functional unit is one kg of gold production and stages contributions are calculated based on one kg of gold recovery through two different pathways. Looking at the process contributions in Figure 15 and Figure 16, it is evident that grinding was the dominant contributor to almost all the impact categories except ecotoxicity. For instance, for global warming, electricity consumption was responsible for 44.2% and 59.1% of the total carbon footprint in the RIL and CIL scenarios, respectively.

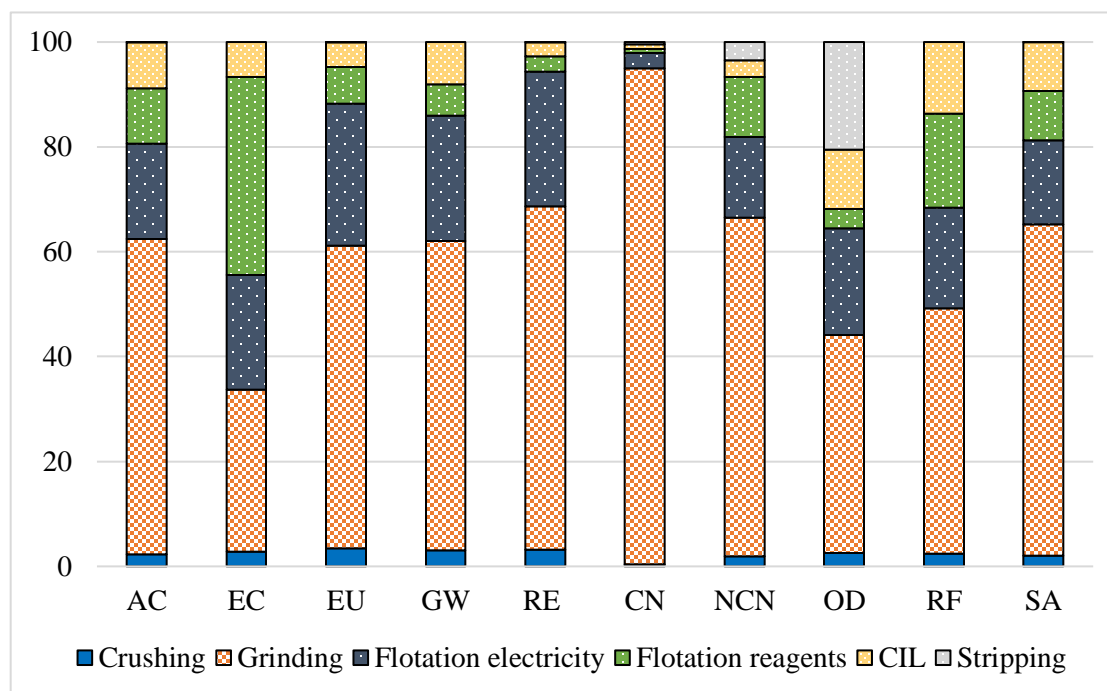


**Figure 15.** Environmental impact contribution of various stages in RIL pathway for producing 1 kg gold.

Electricity consumption was the dominant contributor in the grinding stage and made the greatest contribution which can be related to the ore work index that represents the work

required to reduce the ore. The finer particle size of the ore requires more electricity and a higher work index (kWh/ton) (Gupta & Yan, 2016).

Furthermore, flotation contributed to the TRACI impact categories, being the dominant contributor to ecotoxicity for both pathways. Flotation reagents played a key role in the overall impact categories and were responsible for almost 30.90% of the EC category in the CIL scenario. Chemical reagents such as xanthate can be metabolized in humans and animals to CS<sub>2</sub>.



**Figure 16.** Raw material and input flow contribution to TRACI impact categories in CIL pathway for producing one kg gold.

Flotation tailings typically contain solid content of about 30%. Tailings may be collected in settling tanks during some processes to produce wastewater with low xanthate concentrations. The tailings slurry may include sodium ethyl xanthate concentrations that

are harmful to aquatic life (Bach et al., 2016). Furthermore, methyl isobutyl carbinol (MIBC), a hazardous chemical employed as a frother in the gold mining industry, has been shown in reviews and records to have possible effects on humans. Exposure to MIBC is possible both at the facilities where this chemical substance is manufactured MIBC manufacturing facility or in the various industrial facilities that use this material (Product Safety Assessment DOWTM Methyl Isobutyl Carbinol, 2009). The contribution of other stages can be seen in the contribution figures.

### 6.2.3 Comparison of sodium cyanide and thiosulfate environmental impact

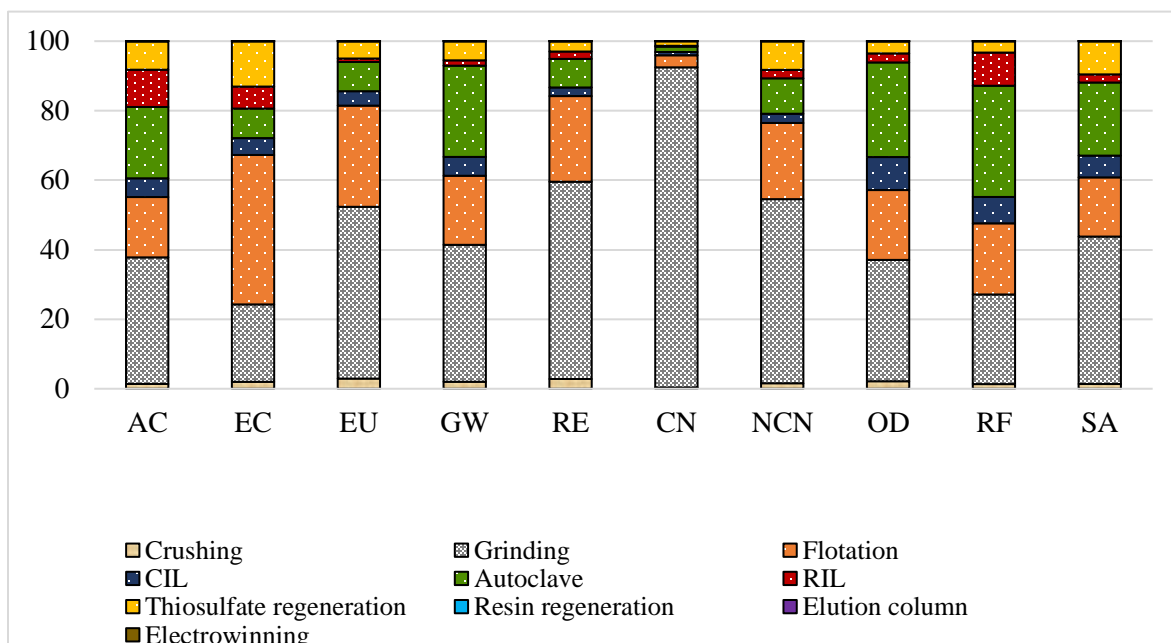
There was no inventory for thiosulfate in the Ecoinvent inventory and TRACI impact categories were calculated based on the production reaction of calcium thiosulfate. The LCIA results of TRACI impact categories for producing one kg of thiosulfate and sodium cyanide are represented in Table 15. Analysis of the LCIA results showed that environmental impacts were higher for almost all the impact categories using sodium cyanide as the main leaching lixiviant compared to thiosulfate lixiviant. As seen in Table 15, global warming generated by thiosulfate production was almost six times lower than the same impact for cyanide production. The category of carcinogenics is ten times higher in sodium cyanide which is attributed to the toxicity of sodium cyanide. Other impact categories and the comparison of these two main lixiviants can be seen in Table 15.

**Table 15.** Environmental impact comparison between sodium cyanide and thiosulfate production.

<b>Impact category</b>	<b>Unit</b>	<b>Thiosulfate (1 kg)</b>	<b>Sodium cyanide (1 kg)</b>
Acidification	kg SO <sub>2</sub> eq	1.83E-02	1.68E-02
Ecotoxicity	CTUe	6.44E+00	4.57E+01
Eutrophication	kg N	1.31E-03	1.57E-02
Global warming	kg CO <sub>2</sub> eq	6.41E-01	4.34E+00
Respiratory effects	kg PM <sub>2,5</sub> eq	1.46E-03	2.91E-03
Carcinogenics	CTUh	3.41E-08	3.37E-07
Non-carcinogenics	CTUh	1.28E-07	7.17E-07
Ozone depletion	kg CFC 11 eq	9.84E-08	7.63E-07
Resources & Fossil fuel depletion	MJ surplus energy	5.23E+00	8.43E+00
Smog air	kg O <sub>3</sub> eq	3.81E-02	1.89E-01

#### 6.2.4 Process contributions to the overall environmental impacts

The total environmental impact of gold production is shown in Table 16 which includes all processes, beginning with comminution, concentration, gold extraction from tailing using CIL, and gold extraction from flotation concentrate using RIL. Results show that the total carbon emission for producing one kg of gold was  $1.91 \times 10^4$  kg CO<sub>2</sub>-eq. Moreover, primary contributor stages that lead to each TRACI impact category are shown in Figure 17 to help understand how processes affect the environmental impact. With a few exceptions of the EC and RF impact categories, grinding was the main contributor, being responsible for 39.4% and 36.4% of the global warming and acidification categories, respectively (Norgate & Haque, 2012).



**Figure 17.** Major contributor stages to the total environmental impacts for one kg gold production.

NV Energy supplies electricity to the Carlin Complex in Nevada. According to reports, Nevada Gold Mine is constructing a power plant that would employ 14 reciprocating gas-fired engines to generate 115 MW of electricity for the Goldstrike Mine. The power plant will also contain a 1 MW solar panel. This plan will allow the facility to generate power from natural gas which enables the facility to reduce carbon emissions (Fiddes et al., 2020). Furthermore, according to the contribution graph, autoclaves showed a significant contribution to global warming, acidification, ozone depletion, and resources and fossil fuels. Pressure oxidation emissions mainly originate from oxygen and steam production which contribute approximately 1.55% and 26.5% of the total carbon emissions.

**Table 16.** Total environmental footprints of gold production from refractory ores for producing one kg of gold.

Impact Category	Unit	Crushing	Grinding	Flotation	CIL	Autoclave	RIL	Thiosulfate regeneration	Resin regeneration	Gold elution	Electrowinning	Total
Acidification	kg SO <sub>2</sub> eq	1.11E+00	2.90E+01	1.38E+01	4.30E-01	1.46E+01	7.68E+00	5.85E+00	4.30E-03	2.82E-02	5.39E-03	7.25E+01
Ecotoxicity	CTUe	4.14E+03	4.62E+04	8.93E+04	1.01E+03	1.59E+04	1.18E+04	2.43E+04	1.61E+01	2.42E+01	2.04E+01	1.93E+05
Eutrophication	kg N	2.56E+00	4.33E+01	2.55E+01	3.63E-01	6.62E+00	7.93E-01	3.90E+00	9.96E-03	1.14E-02	1.18E-02	8.30E+01
Global warming	kg CO <sub>2</sub> eq	3.84E+02	7.52E+03	3.79E+03	1.04E+02	4.51E+03	2.65E+02	9.41E+02	1.49E+00	2.22E+00	1.80E+00	1.75E+04
Respiratory effects	kg PM <sub>2,5</sub> eq	9.16E-01	1.85E+01	8.03E+00	8.09E-02	2.41E+00	6.23E-01	8.60E-01	3.56E-03	5.01E-03	4.23E-03	3.14E+01
Carcinogenics	CTUh	2.83E-05	7.49E-03	2.82E-04	7.73E-06	1.13E-04	1.81E-05	9.67E-05	1.10E-07	1.64E-07	1.32E-07	8.03E-03
Non-carcinogenics	CTUh	1.04E-04	3.49E-03	1.45E-03	1.75E-05	6.04E-04	1.45E-04	4.88E-04	4.06E-07	8.58E-07	4.99E-07	6.30E-03
Ozone depletion	kg CFC 11 eq	3.77E-05	6.10E-04	3.51E-04	1.66E-05	4.28E-04	4.08E-05	5.44E-05	1.47E-07	5.93E-07	1.94E-07	1.54E-03
Resources & Fossil fuel depletion	MJ surplus energy	3.28E+02	6.31E+03	5.01E+03	1.86E+02	7.05E+03	2.10E+03	7.16E+02	1.27E+00	2.80E+00	1.56E+00	2.17E+04
Smog air	kg O <sub>3</sub> eq	1.08E+01	3.36E+02	1.35E+02	4.97E+00	1.50E+02	1.67E+01	6.80E+01	4.19E-02	1.02E-01	5.39E-02	7.22E+02

### 6.3 Environmental impact of heap leaching process

#### 6.3.1 Pad construction

The environmental footprints of each material/energy flow in pad construction are presented in Table 17. From the results, it can be concluded that diesel consumption and sand usage dominated all the impact categories. The higher contribution of diesel can be related to diesel consumption in vehicles used in the pad construction stage. These vehicles include trucks, loaders, and dozers and are used to excavate land fields and to move materials during the pad construction.

Given the large quantity of geomembrane liner used in the heap leach pad building stage, this material's considerable contribution is a result of both its high utilization and a manufacturing process that consumes an extensive amount of energy. Additionally, geomembrane liners are made using organic substances, such as polymers and resins, whose synthesis consumes a lot of energy (environment et al., n.d.).

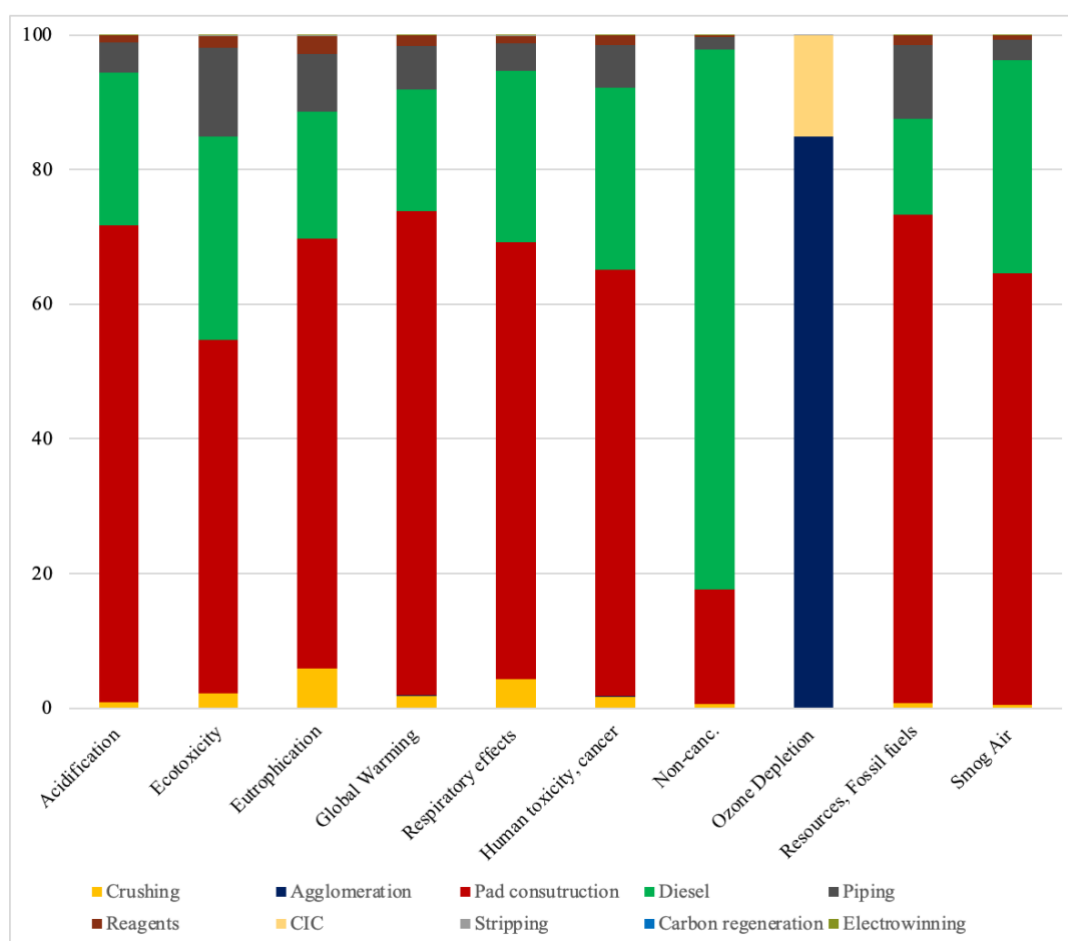
**Table 17.** Environmental impact assessment result for pad construction.

Impact Category	Unit	Geomembrane				
		Clay	ane	Geotextile	Sand	Diesel consumption
Acidification	kg SO <sub>2</sub> eq	5.72E-01	3.79E-02	5.51E-01	1.80E+00	9.45E-01
Ecotoxicity	CTUe	2.08E+02	7.76E+01	1.38E+03	1.55E+03	1.85E+03
Eutrophication	kg N	5.50E-02	1.50E-02	3.60E-01	4.73E-01	2.65E-01
Global warming	kg CO <sub>2</sub> eq	7.56E+01	3.84E+00	1.54E+02	2.52E+02	1.22E+02
Respiratory effects	kg PM <sub>2,5</sub> eq	9.19E-02	4.81E-03	1.23E-01	2.29E-01	1.77E-01
Carcinogenics	CTUh	1.05E-05	3.09E-07	1.05E-05	1.42E-05	1.52E-05
Non-carcinogenics	CTUh	2.28E-05	1.04E-06	2.41E-05	5.47E-05	4.82E-04
Ozone depletion	kg CFC 11 eq	1.17E-05	9.03E-06	2.83E-05	2.39E-05	2.18E-05
Resources & Fossil fuel depletion	MJ surplus energy	9.19E-02	4.81E-03	1.23E-01	2.29E-01	1.77E-01
Smog air	kg O <sub>3</sub> eq	1.12E+01	3.13E-01	7.57E+00	3.10E+01	2.48E+01

### 6.3.2 Total environmental impacts of heap leaching process

Total environmental impacts associated with heap leaching for producing one kg of gold are presented in Table 18. The LCA results include all the stages involved in heap leaching, such as crushing, agglomeration, pad construction, CIC, stripping, and electrowinning. As seen in Table 18, the potential impact on climate change was 675 kg CO<sub>2</sub>. The contribution of various stages is also shown in Figure 18. Based on the contribution graph, pad construction and diesel consumption were the dominant contributors to all the impact categories. The contribution of other stages, such as crushing, agglomeration, piping, CIC,

and stripping, was insignificant compared to pad construction and diesel consumption. Crushing and chemical reagents used in gold extraction significantly contributed to eutrophication. The notable environmental role of electricity can be illustrated by its consumption in the pumping system. Various pumping stations are installed around the heap area or ponds to flow the lixiviant in the leaching circuit, transfer PLS, or raffinate from ponds to the plant or vice versa (Sorensen et al., 2020).



**Figure 18** Contribution of different stages in heap leaching.

**Table 18.** Life cycle assessment results for producing one kg of gold from the heap leaching process.

Impact Category	Unit	Crushing	Agglomeration	Pad construction	Diesel	Piping	Reagents	CIC	Stripping	Carbon regeneration	Electrowinning	Total
Acidification	kg SO <sub>2</sub> eq	3.55E-02	2.25E-03	2.96E+00	9.45E-01	1.91E-01	4.08E-02	2.66E-04	1.40E-03	1.33E-04	2.13E-04	4.18E+00
Ecotoxicity	CTUe	1.33E+02	4.76E+00	3.21E+03	1.85E+03	8.09E+02	1.10E+02	9.94E-01	4.82E+00	4.97E-01	7.95E-01	6.13E+03
Eutrophication	kg N	8.23E-02	1.41E-03	9.03E-01	2.65E-01	1.21E-01	3.78E-02	6.16E-04	1.04E-03	3.08E-04	4.92E-04	1.41E+00
Global warming	kg CO <sub>2</sub> eq	1.23E+01	7.72E-01	4.85E+02	1.22E+02	4.36E+01	1.05E+01	9.23E-02	2.62E-01	4.62E-02	7.39E-02	6.75E+02
Respiratory effects	kg PM <sub>2.5</sub> eq	2.94E-02	3.16E-04	4.49E-01	1.77E-01	2.85E-02	7.12E-03	2.20E-04	3.45E-04	1.10E-04	1.76E-04	6.92E-01
Carcinogenics	CTUh	9.10E-07	6.20E-08	3.54E-05	1.52E-05	3.48E-06	8.11E-07	6.81E-09	2.66E-08	3.40E-09	5.45E-09	5.59E-05
Non-carcinogenics	CTUh	3.35E-06	1.06E-07	1.03E-04	4.82E-04	1.13E-05	1.73E-06	2.51E-08	9.11E-08	1.25E-08	2.01E-08	6.01E-04
Ozone depletion	kg CFC 11 eq	1.21E-06	4.44E-01	7.29E-05	2.18E-05	1.84E-06	1.83E-06	7.87E-02	1.44E-07	4.53E-09	7.24E-09	5.23E-01
Resources & Fossil fuel depletion	MJ surplus energy	1.05E+01	4.32E-08	1.03E+03	2.04E+02	1.56E+02	2.03E+01	9.06E-09	2.39E-01	3.94E-02	6.30E-02	1.42E+03
Smog air	kg O <sub>3</sub> eq	3.46E-01	4.68E-02	5.00E+01	2.48E+01	2.40E+00	4.61E-01	2.59E-03	1.70E-02	1.29E-03	2.07E-03	7.81E+01

## 7. Conclusion

This master's thesis evaluated the environmental burdens associated with gold production from different ore types requiring more complex processing routes. Gold mining has been a crucial part of Nevada's economy; however, its environmental impact has been understudied. With growing concerns over climate change, it seemed like an appropriate time to start studying the impact of one of the essential sectors of the state's economy. Therefore, this study investigated the environmental footprints of gold processing routes, including roasting, autoclave, flotation, and heap leaching. This study also identified key factors contributing to the total environmental impacts.

The pressure oxidation process associated with processing refractory ores resulted in higher environmental impact categories mainly due to the highest electricity consumption in the grinding stage and autoclave. Two pathways based on thiosulfate leaching and cyanide leaching were evaluated for their environmental footprints. The results have shown that the grinding stage is the dominant contributor to GHG emissions of gold recovery from refractory ores and was responsible for 39.4% of the overall carbon emissions. This is due to the high amount of energy consumption in grinding to grind the ore to fine particle size. Flotation and autoclave are the following great contributors to the TRACI impact categories in processing refractory ores. Flotation demonstrated its most significant contribution in the ecotoxicity impact category due to the large consumption of input materials, specifically chemical reagents such as xanthate, which was selected as a collector in flotation.

From the LCIA results using the TRACI method, grinding and off-gas treatment were the

dominant contributors to almost all the impact categories. This indicates that these stages need more attention and actions toward environmental regulations by using green electricity sources and additional treatment processes to achieve the goal of GHG emissions reduction. For grinding, low-energy intensive technologies such as high pressure grinding rolls can also be a better alternative to conventional grinding technologies for saving the energy and economy. Additionally, the high value of electricity consumption and substantial gaseous emissions were the main contributors to the grinding and off-gas treatment stages.

The heap leaching process showed its highest environmental impacts in the pad construction stage due to using polymer materials such as geomembrane liners and diesel consumption to transfer materials. However, despite the high electricity consumption by crushers in the ore size reduction stage, the contribution of this stage could have been more significant. Generally, the main driving force for process alternatives and implementing improvements is the need to treat lower-grade ores with complex mineralogy, coupled with the increasing environmental requirement in mining operations. The findings of this study may be utilized as a complete resource by stakeholders to compare the effects of gold mining activities and make better environmental decisions.

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