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Evaluating the Environmental Footprint: An LCA Study of a Pilot System Treating Potassium Mining Wastewater

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Abstract

Potassium mining activities result in the discharge of highly saline wastewaters, creating severe environmental impacts in water and soil. This study evaluates the environmental performance of a novel pilot system developed in the framework of the LIFE Brine-Mining project. The system comprises membrane, precipitation and thermal technologies, recovering high-purity water and five valuable resources from it: magnesium hydroxide, calcium carbonate, calcium sulfate, sodium chloride, and potassium chloride. A cradle-to-grave Life Cycle Assessment (LCA) was performed following the standards ISO14040 and EN15804 and using 1 m^3 of potassium wastewater as functional unit. The LCA results indicated that the novel system environmental impact is mainly affected by the use of chemicals (20.63×10^0 kg/FU) during its operation and energy consumption (1.39×10^1 kWh/FU). The chemical use dominates areas like the Abiotic Depletion, and the Eutrophication Potential, and the Water Depletion Potential. The novel pilot system was compared with another novel configuration that treated a brine from coal mining activities and with a conventional method of potassium brine management, which is the disposal in underground old mines. The potassium brine treatment system exhibited lower environmental impact than the coal mine brine system, and outperformed compared to the conventional disposal method.

Keywords: potassium mine wastewater; brine; resource recovery; LCA; sensitivity analysis; industrial effluents; desalination

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1. Introduction

Potassium is considered one of the main nutrients for plant growth [1]. In fertilizers, potassium is commonly present in the form of potassium chloride, potassium sulfate, and potassium nitrate [2]. The major potassium-producing countries are Canada, the USA, Russia, Germany, Belarus, Spain, the United Kingdom, China, and Brazil [3]. The global potash market is continuously growing. The market size was estimated at around USD 62.37 billion in 2024, and it is expected to grow at a compound annual rate (CAGR) of 5.3% from 2025 to 2032, due to the increasing global population. Out of all the types of potassium products in the market, potassium chloride dominated the global market with a revenue share of 53% in 2024. Among all the different sectors in which potassium can be applied, agriculture had by far the largest field of application, with a revenue share of 93.1% in 2024 [4]. Potash brine comes from underground deposits containing high concentrations of potassium salts. Potash deposits are formed through a combination of geological and climatic processes. Most major deposits originated from the evaporation of ancient seas or saltwater inland bodies millions of years ago. Prolonged evaporation caused dissolved salts to precipitate, crystallize and settle at the bottom of the basins [5]. Over time, groundwater and natural geological processes dissolved these salt layers and created potash-rich brines. Potash is drilled from very deep points under the ground, around 1400 m [6].

Although mines have adopted brine management measures, like discharge in evaporation ponds, backfilling discharge, and landfill application, these solutions still face challenges [7].

The disposal of brine into the land and waterways causes the salinization of soil and freshwater, contributes to ground subsidence, and leads to biological degradation. In rivers and lakes, the water quality is affected and the aquatic ecosystem is destroyed [6]. Landscape modification, noise from the mine operation, and changes in wildlife habitat are some more adverse impacts of potash mining operations [8].

Many methods are used for the treatment of saline wastewaters, both biological and physicochemical [9]. In biological methods, pollutants are removed from saline wastewaters through the metabolism of the microorganisms. Activated sludge can effectively treat salinity with a TDS equal to 4000 mg/L, but above that threshold, the efficiency decreases [10]. The physicochemical methods include membrane-based technologies, such as nanofiltration, electrodialysis, reverse osmosis, and membrane distillation [11]. Overall, for the treatment of saline wastewaters, a combination of conventional and novel technologies is required, while the specific characteristics of the wastewater to be treated and the system energy efficiency are important parameters that need to be taken into consideration [12].

The desalination technologies today are well developed, but they also have some drawbacks, such as the generation of byproducts, high energy demand, and the management of the used membranes [13]. Furthermore, the emissions of greenhouse gases (GHGs) from fossil fuel-powered desalination plants have a detrimental effect on the environment and contribute to global warming by emitting CO_2 [14]. Therefore, the environmental sustainability of desalination technologies should be assessed through comprehensive environmental studies. The most commonly used environmental tool for sustainability evaluation is the LCA, as it can assess a product's environmental impact by reviewing all the stages of its life, from raw material extraction to its disposal [15,16]. Another advantage of the LCA study is the identification of areas that need to be improved in terms of energy consumption, emissions, water use and waste generation [17]. Therefore, through a holistic approach, LCA has the ability to guide the sustainable development of a product or a technology [18,19]. The number of LCA studies on desalination technologies has grown since 2004, but most of them have focused on the use of reverse osmosis, while there is a limited number on thermal desalination processes [20]. Recently, an LCA study was incorporated to evaluate the environmental performance of hydrogen production technologies using wastewater as a feedstock, covering both conventional and emerging methods, such as steam methane reforming, electrolysis, microbial electrolysis cells, and thermochemical processes like aqueous phase reforming and hydrothermal liquefaction [21].

The goal of this study is to assess the environmental impact of a novel system treating potassium mining wastewater. An LCA study was employed, covering all the relevant life cycle stages of the process, from raw material extraction to end-of-life disposal. The following sections include a description of the pilot system units, the life cycle inventory, and the results of the LCA for the novel pilot system. The system was also compared with another desalination system, which treated coal mine wastewater, and with a common method of brine management, which is underground disposal. A sensitivity analysis was performed to highlight potential areas for environmental footprint improvement of the pilot system during both construction and operation phases.

2. Materials and Methods

2.1. Description of the Pilot System

The potassium mining wastewater that was treated by the project pilot system was very saline, as it was characterized by a Total Dissolved Solids content equal to 18%. Table 1 presents the potash mining brine composition.

Table 1. Potash mine wastewater composition.

Potash Mine Wastewater		
Na^{+}	58,758	mg/L
K^{+}	18,280	mg/L
Mg^{2+}	3539	mg/L
Ca^{2+}	990	mg/L
Cl^{-}	117,240	mg/L
SO_4^{2-}	4820	mg/L

As demonstrated in Figure 1, the system's first technology step is ultrafiltration, which removes suspended solids from the inlet brine, reducing its turbidity. After the ultrafiltration, two sequencing precipitation units are placed, which precipitate magnesium as magnesium hydroxide ($Mg(OH)_2$) and calcium as calcium carbonate ($CaCO_3$). The effluent from the second precipitation reactor is neutralized and then flows into nanofiltration for the separation of monovalent from divalent ions. The divalent ion-rich stream flows into the third precipitation reactor, in which sulfates are precipitated as calcium sulfate ($CaSO_4$). The monovalent ion-rich stream flows into the final technology of the pilot system, which comprises a crystallizer and a dryer. From the combination of the two systems, pure NaCl in a solid form is recovered, as well as clean water. The boundaries of the system on which LCA was applied are demonstrated in Figure 1.

2.2. Pilot System Units

The ultrafiltration unit of the pilot system is equipped with a filtration tank, pumps, a blower, valves, and a control cabinet. The membranes consist of silicon carbide (SiC). The wastewater was continuously fed to the membrane while filtration was taking place. Backwash and air blowing were used to clean the membranes, and if necessary, NaOCl, HCl, and NaOH were also used for the cleaning.

The first precipitation unit received the ultrafiltration permeate and precipitated magnesium as magnesium hydroxide with the addition of NaOH. To clean it, the precipitation unit was drained and then cleaned with water.

The second precipitation unit received the effluent from the first precipitation unit and precipitated calcium as calcium carbonate with the addition of Na_2CO_3. To clean it, the precipitation unit was drained and then cleaned with water.

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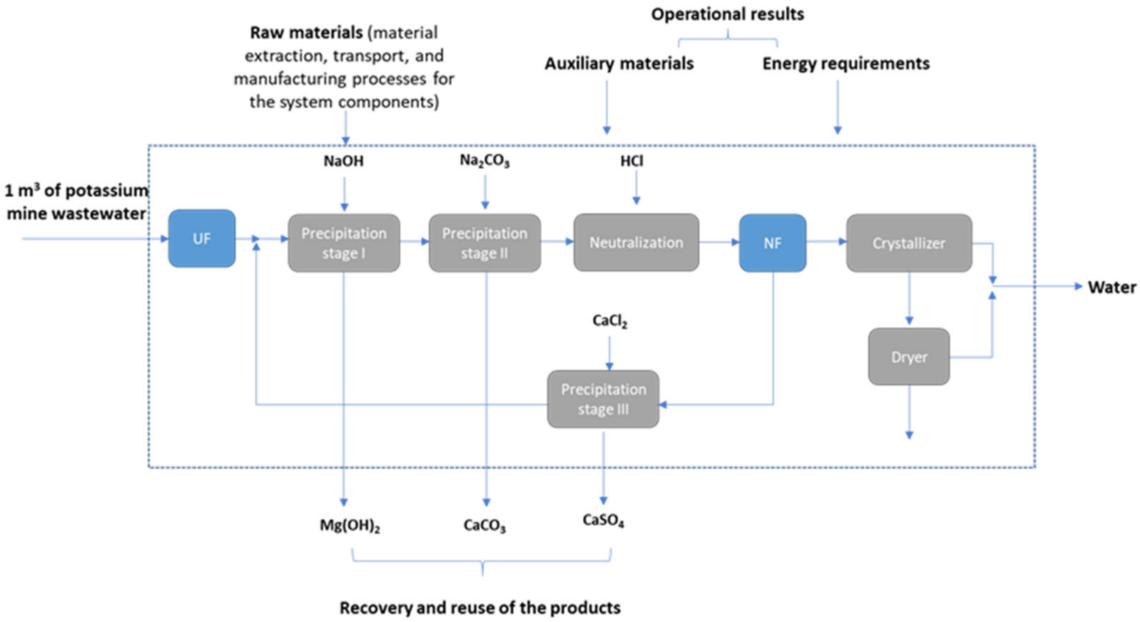

Figure 1. Process flow diagram of innovative desalination system—LCA system boundaries.

The effluent from the second precipitation unit was basic, with a pH value of around 10, due to the addition of NaOH and Na_2CO_3 in the previous steps. Therefore, before it flowed into the nanofiltration unit for the separation of the monovalent from divalent ions, the effluent had to be neutralized in a dedicated unit with the addition of hydrochloric acid, to reduce its pH value to 7.

Through nanofiltration, the neutralized effluent was separated into two different flows through membranes. The first flow, also called nanofiltration permeate, was rich in monovalent ions, mainly sodium ions (Na) and chlorides (Cl). The second flow, also called nanofiltration concentrate, was rich in divalent ions, mainly sulfates. The nanofiltration concentrate flowed into the third precipitation unit, where the sulfates precipitated as calcium sulfate ($CaSO_4$) with the addition of calcium chloride ($CaCl_2$).

The TDS content of the nanofiltration permeate was around 19%, consisting mainly of sodium chloride. The effluent was treated in a crystallizer, which recovered clean water and sodium chloride with 99.9% purity. The water content of this stream was around 30%. For further drying, a dryer was used for the recovery of solid salt, with a water content equal to 10%. Figure 2 demonstrates the inflows and the outflows of the precipitation units, the neutralization, the nanofiltration, the crystallizer, and the dryer. As it is shown, the inflows of the precipitation units are NaOH (unit I), Na_2CO_3 (unit II), $CaCl_2$ (unit III), the inflow (each precipitation unit has a different inflow), and energy. The outflows of the precipitation units are $Mg(OH)_2$ (unit I), $CaCO_3$ (unit II), and $CaSO_4$ (unit III). The inflow of the neutralization unit is the effluent from the second precipitation unit, with HCl to neutralize the solution and energy. The outflow is the neutralization effluent. The inflows of the nanofiltration unit are the neutralization effluent and energy. The outflows are the nanofiltration concentrate, which heads to the third precipitation tank (Figure 1), and the nanofiltration effluent, which heads to the crystallizer. The crystallizer input is the nanofiltration effluent and energy. The crystallizer outputs are clean water and pure NaCl with 30% water content. The dryer input is pure NaCl with 30% water content and energy. The dryer outflows are clean water and pure NaCl with 10% water content.

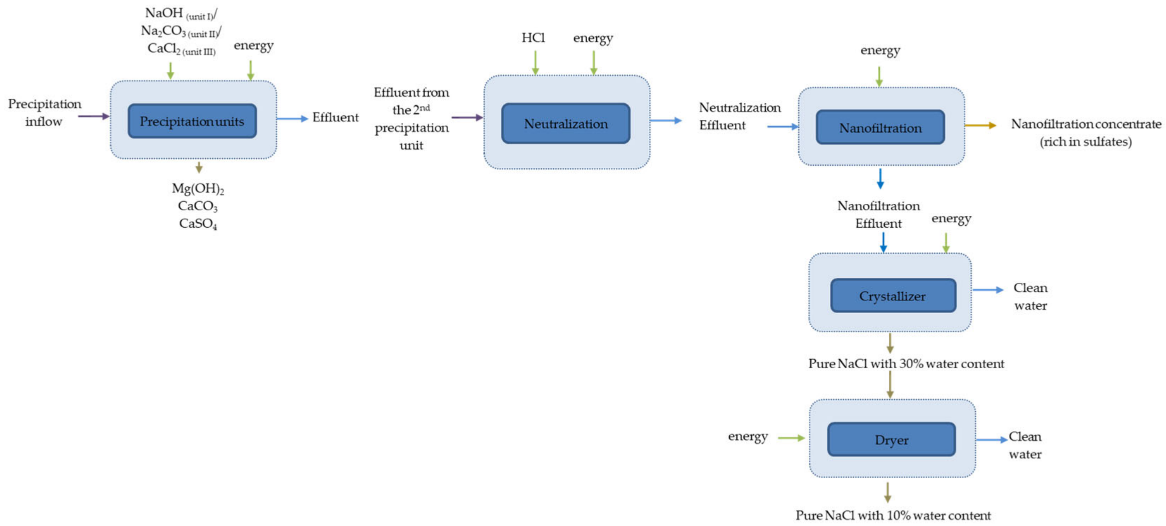

Figure 2. Precipitation units, neutralization, nanofiltration, crystallizer, and dryer inflows and outflows.

2.3. Life Cycle Assessment (LCA)

The LCA study is a standardized method consisting of four stages: (a) definition and scope, (b) life-cycle inventory (LCI), (c) life-cycle impact assessment (LCIA), and (d) interpretation [22]. For its completion, both primary and secondary data were collected.

Primary data were collected from the pilot system operation, while secondary data were derived from the ecoinvent database. Key results were interpreted to identify critical areas of the system that most contribute to the environmental burdens. The LCA study followed the context provided by ISO14040 [23] and EN15804 standards, which ensure that the environmental impacts are assessed consistently [23,24].

The scope of the LCA study was to identify the system environmental hot spots and then compare their overall environmental impact with that of a corresponding desalination system and an alternative wastewater management method.

The functional unit of the system was defined as 1 m^3 of potassium mining wastewater, and it was assumed that the pilot system has a life span of 20 years. The LCA study followed a cradle-to-grave approach, covering the entire life cycle from raw material extraction to end-of-life stages. Specifically, the system boundaries encompass the stages indicated in Table 2.

Table 2. LCA stages.

Stages	Specific Description of Each Stage
A1	Extraction of raw materials
A2	Transport to manufacturing
A3	Manufacturing
B1	Emissions from the system/chemicals/auxiliary materials
B6	Energy use
C1	Disassembly and demolition
C2	Transport to waste disposal
C3	Waste handling
C4	Final handling
D	Impact outside the life cycle

Stages A1–A3 cover the processes associated with the pilot system construction.

Stage A1 includes the extraction of raw materials necessary for the system components, such as stainless steel, plastics, membranes, pipes, pumps and any other equipment used in the system technologies. Stage A2 refers to the transportation of these materials from various countries to the pilot system site. Stage A3 includes the manufacturing and packaging processes of the different components.

Stages B1 and B6 represent the operational life of the system. Stage B1 includes emissions and materials use during operation. It focuses mainly on the consumption of chemicals such as NaOH, Na_2CO_3, HCl, and $CaCl_2$. Stage B6 represents the energy consumption during the system operation, mainly the electricity use.

Stage D refers to the environmental benefits outside the system boundary through resource recovery. The pilot system enables the recovery of water and of valuable resources, such as $Mg(OH)_2$, $CaCO_3$, $CaSO_4$, and NaCl. The recovered resources reduce the need for material production and thus contribute positively to the system's environmental performance.

2.4. Life Cycle Inventory

Based on the breakdown of each technology into its components, the Life Cycle Inventory of the pilot system was formed. For each technology, named as a sector, e.g., ultrafiltration, precipitation reactors, the inventory encompasses a list of all the corresponding components, the quantity of each component, their mass, and the raw materials used for their production (see Tables 3–9).

Stage A1—extraction of raw materials.

Table 3. Stage A1—extraction of raw materials.

LCA Stages		Unit	Products	Number	Materials	Mass	Unit	per FU	Unit
A1: Raw materials	Raw materials	Ultrafiltration	Degassing valve	1	PVC	0.5	kg	6.68×10^{-6}	kg/FU
	Raw materials		Control cabinet	1		30	kg	2.00×10^{-4}	kg/FU
	Raw materials		Filtration/ backwash pump	1	PP/PE	20	kg	4.01×10^{-4}	kg/FU
	Raw materials		Pressure indicator	1	SS	1	kg	6.68×10^{-6}	kg/FU
	Raw materials		Ventilation valve drain pipe	1	PVC	0.5	kg	6.68×10^{-6}	kg/FU
	Raw materials		Level switch	2	Plastic	0.25	kg	3.34×10^{-6}	kg/FU
	Raw materials		Flow indicator	1	ETFE	025	kg	5.56×10^{-7}	kg/FU
					PA 6T	0.25	kg	5.56×10^{-7}	kg/FU
					EPDM	0.25	kg	5.56×10^{-7}	kg/FU
	Raw materials		Feed pump	1	PP/PE	10	kg	2.00×10^{-4}	kg/FU
	Raw materials		Sprinkler pump	1	PP/PE	2	kg	4.01×10^{-5}	kg/FU
	Raw materials		Drain pump	1	PP/PE	10	kg	2.00×10^{-4}	kg/FU
	Raw materials		Inlets (e.g., for raw water, NaOCl)	3	PVC	2	kg	4.01×10^{-5}	kg/FU
	Raw materials		Siemens TDE panel	1	PP/PE	5	kg	3.34×10^{-5}	kg/FU
	Raw materials		Ceramic UF membranes	1	Ceramic	100	kg	4.67×10^{-3}	kg/FU
	Raw materials		PVC pipes	1	PVC	10	kg	6.68×10^{-5}	kg/FU
	Raw materials		PVC valves	5	PVC	5	kg	3.34×10^{-4}	kg/FU
	Raw materials		Permeate and feed tanks	2	PP	300	kg	8.01×10^{-3}	kg/FU
	Raw materials	Insulated container	Air conditioning	1		40	kg	5.34×10^{-4}	kg/FU
	Raw materials		Insulated container	1	SS	2380	kg	1.59×10^{-2}	kg/FU
	Raw materials	Nanofiltration	Feed pump	1	SS316	10	kg	2.00×10^{-4}	kg/FU
	Raw materials		20-micron filter	1	PP	0.5	kg	3.34×10^{-4}	kg/FU

Table 3. *Cont.*

LCA Stages		Unit	Products	Number	Materials	Mass	Unit	per FU	Unit
A1: Raw materials	Raw materials	Nanofiltration	SS valves	4	SS	10	kg	5.34×10^{-4}	kg/FU
	Raw materials		Skid structure	1	SS	100	kg	1.34×10^{-3}	kg/FU
	Raw materials		PVC valves	6	PVC	1	kg	8.01×10^{-5}	kg/FU
	Raw materials		Control cabinet	1	PVC/Al	50	kg	3.34×10^{-4}	kg/FU
	Raw materials		5-micron filter	1	PP	0.5	kg	3.34×10^{-4}	kg/FU
	Raw materials		High-pressure pump (HPP)	1	SS 1.4408	40	kg	8.01×10^{-4}	kg/FU
	Raw materials		NF membranes	5	PA	25	kg	5.84×10^{-3}	kg/FU
	Raw materials		Flow transmitter	3	ETFE; PA 6T; EPDM	0.25	kg	1.00×10^{-5}	kg/FU
	Raw materials		Pressure transmitter	10	SS316L	0.5	kg	1.34×10^{-4}	kg/FU
	Raw materials		Conductivity transmitter	2	SS316L	0.5	kg	1.34×10^{-5}	kg/FU
	Raw materials		Temperature transmitter	2	SS316L	0.5	kg	6.68×10^{-6}	kg/FU
	Raw materials		SS piping	1	SS	20	kg	1.34×10^{-4}	kg/FU
	Raw materials		PVC piping	1	PVC	20	kg	1.34×10^{-4}	kg/FU
	Raw materials	Insulated container	Air conditioning	1		40	kg	5.34×10^{-4}	kg/FU
	Raw materials		Raw container	1	Corton steel	3800	kg	2.54×10^{-2}	kg/FU
	Raw materials	Buffer Tanks	Tank 1000 L	1	PP	100	kg	1.34×10^{-3}	kg/FU
	Raw materials		Tank 2000 L	1	PP	150	kg	2.00×10^{-3}	kg/FU
	Raw materials		Tank 3000 L	1	PP	200	kg	2.67×10^{-3}	kg/FU
	Raw materials		Tank 60 L dosing	2	PE	25	kg	6.68×10^{-4}	kg/FU
	Raw materials		Catchment tank 80 L	2	PE	50	kg	1.34×10^{-3}	kg/FU
	Raw materials	4 m^3 crystallizer	Clean water collection tank	1	Plastic	50	kg	3.34×10^{-4}	kg/FU
	Raw materials		Crystallization shell	1	Stainless steel	200	kg	1.34×10^{-3}	kg/FU
	Raw materials		Vacuum pump (inc. booster)	1	Stainless steel	4	kg	8.01×10^{-5}	kg/FU
	Raw materials		Submersible pump	1	Stainless steel	10	kg	2.00×10^{-4}	kg/FU
	Raw materials		Water pump	1	Stainless steel	10	kg	2.00×10^{-4}	kg/FU
	Raw materials		Compressor with hot and cold radiators	1	Stainless steel	15	kg	2.00×10^{-4}	kg/FU
	Raw materials		Hydrocyclone	1	Stainless steel	30	kg	2.00×10^{-4}	kg/FU
	Raw materials		Flow, pressure, temperature, level sensors connected to control panel	6	Stainless steel	1.5		2.40×10^{-4}	kg/FU
	Raw materials		Control panel	1	PVC/Al	20	kg	1.34×10^{-4}	kg/FU
	Raw materials	Dryer	Heating bath	1	Stainless steel	100	kg	6.68×10^{-4}	kg/FU
	Raw materials		Heater 4 kW	1	Stainless steel	8	kg	5.34×10^{-5}	kg/FU
	Raw materials		Vacuum pump	1	Stainless steel	4	kg	8.01×10^{-5}	kg/FU
	Raw materials		Water collection tank	1	Plastic	50	kg	3.34×10^{-4}	kg/FU

Table 3. *Cont.*

LCA Stages		Unit	Products	Number	Materials	Mass	Unit	per FU	Unit
A1: Raw materials	Raw materials	Dryer	Shneck Engine 3 ph 380 V	1	Metal	6	kg	4.01×10^{-5}	kg/FU
	Raw materials		Flow transmitter	1	ETFE; PA 6T; EPDM	0.25	kg	3.34×10^{-6}	kg/FU
	Raw materials		Valves	15	Stainless steel	1	kg	2.00×10^{-4}	kg/FU
	Raw materials		SS Spiral	1	Stainless steel	40	kg	2.67×10^{-4}	kg/FU
	Raw materials		Control panel	1	PVC/Al	20	kg	1.34×10^{-4}	kg/FU
	Raw materials		Hot water recirculation pump	1	stainless steel	3	kg	6.01×10^{-5}	kg/FU
	Raw materials	Precipitation units	IBC tanks	4	Plastic and iron	65	kg	8.68×10^{-4}	kg/FU
								8.68×10^{-4}	kg/FU
								1.30×10^{-3}	kg/FU
	Raw materials		Reactors	6	Plastic and iron	65	kg	1.30×10^{-3}	kg/FU
	Raw materials		Insulated container	1	SS	2300	kg	1.54×10^{-2}	kg/FU
	Raw materials		Dosing pumps	4	SS and PP	5	kg each	4.01×10^{-4}	kg/FU
								6.68×10^{-5}	kg/FU
	Raw materials		Online measurement system	1	PVC and Al	20	kg	6.68×10^{-5}	kg/FU
	Raw materials		Cables	15	Copper, PVC	40	kg/km	4.01×10^{-3}	kg/FU
	Raw materials		Pumps	3	Duplex SS	67	kg	4.03×10^{-3}	kg/FU
	Raw materials		SS piping	1	SS	30	kg	2.00×10^{-4}	kg/FU
	Raw materials		PVC piping	1	PVC	20	kg	1.34×10^{-4}	kg/FU
A1: Packaging of RM	Packaging of RM	Nylon (pallet wrap)	Nylon (pallet wrap)	-	-	2.5	kg	1.67×10^{-5}	kg/FU
		pallet	pallet	-	-	10	items	6.68×10^{-5}	items/Fu

Stage A2—Transport to manufacturing.

Table 4. Stage A2—Transport to manufacturing.

LCA Stages		Unit	Products	Mass	Unit	per FU	Unit
A2	Transportation	Germany	Lorry	734	km	4.97×10^{-3}	tn·km/FU
	Transportation	UK	Vessel	26	km	1.45×10^{-3}	tn·km/FU
	Transportation	UK	Lorry	26	km	7.18×10^{-3}	tn·km/FU
	Transportation	Netherlands	Lorry	9407.75	km	9.36×10^{-2}	tn·km/FU
	Transportation	France	Lorry	81	km	2.91×10^{-3}	tn·km/FU
	Transportation	Spain	Lorry	11	km	1.70×10^{-3}	tn·km/FU
	Transportation	Switzerland	Lorry	450.5	km	7.35×10^{-3}	tn·km/FU
	Transportation	Turkey	Lorry	0.5	km	1.78×10^{-5}	tn·km/FU
	Transportation	Cyprus	Lorry	315.75	km	1.41×10^{-3}	tn·km/FU
	Transportation	Cyprus	Vessel	315.75	km	2.23×10^{-2}	tn·km/FU
	Transportation	China	Lorry	206	km	7.54×10^{-4}	tn·km/FU
	Transportation	China	Vessel	206	km	3.31×10^{-2}	tn·km/FU
	Transportation	Poland	Lorry	23	km	6.93×10^{-5}	tn·km/FU

Stage A3—Manufacturing.

Table 5. Stage A3—Manufacturing.

LCA Stages		Unit	Products	Mass	Unit	per FU	Unit
A3	Packaging of RM waste	Nylon (pallet wrap)	-			1.67×10^{-5}	kg/FU
	Packaging of RM waste	pallet	-			2.00×10^{-3}	kg/FU
	Transportation of packaging of RM waste	Transportation of waste	Lorry	300	km	6.06×10^{-4}	tn·km/FU

Stage B1—Emissions from the system.

Table 6. Stage B1—Emissions from the system.

LCA Stages		Unit	Products	Mass	Unit	per FU	Unit
B1	Transportation—Material use and packaging materials	Poland	Lorry	500	km	1.03×10^{1}	tn·km/FU
	Material use	NaOH	-	-	-	5.23×10^{0}	kg/FU
	Material use	Na_2CO_3	-	-	-	2.14×10^{0}	kg/FU
	Material use	HCl	-	-	-	8.80×10^{0}	kg/FU
	Material use	$CaCl_2$	-	-	-	4.46×10^{0}	kg/FU
	Packaging materials	Sack	-	1290	items	4.33×10^{-3}	kg/FU
	Packaging materials	Pallet	-	5	items	1.00×10^{-3}	items/Fu

Stage B.6—Energy consumption.

Table 7. Stage B.6—Energy consumption.

LCA Stages		Unit	per FU	Unit
B6	Energy	Electricity	1.39×10^{1}	kWh/FU

Stages C—Dismantling, transportation for disposal, waste treatment, final disposal.

Table 8. Stages C—Dismantling, transportation for disposal, waste treatment, final disposal.

LCA Stages		Unit	Mass	Unit	per FU	Unit
C1	Energy	Diesel for demolition machinery	-	-	-	-
C2	Transport	Transportation of each system unit	200	km	2.25×10^{-2}	tn·km/FU
C3	Waste processing	Treatment of steel	-	-	2.16×10^{-2}	kg/FU
C3	Waste processing	Treatment of electric equipment	-	-	5.41×10^{-2}	kg/FU
C3	Waste processing	Treatment of plastic	-	-	2.16×10^{-2}	kg/FU
C3	Waste processing	Treatment of aluminum scrap	-	-	1.08×10^{-2}	kg/FU
C3	Waste processing	Treatment of paper sack	-	-	4.33×10^{-3}	kg/FU
C3	Transport	Transportation of materials for disposal	200	km	1.10×10^{-2}	tn·km/FU
C4	Disposal	Landfill of plastic treatment	-	-	3.24×10^{-2}	kg/FU
C4	Disposal	Landfill of plastic treatment	-	-	2.16×10^{-2}	kg/FU
C4	Waste processing	Treatment of pallet	-	-	1.00×10^{-3}	kg/FU

Stage D—Reuse/recycling.

Table 9. Stage D—Reuse/recycling.

LCA Stages		Unit	per FU	Unit
D	Reuse/Recycling	Recovery of water	6.79×10^{2}	kg/FU
D	Reuse/Recycling	Recovery of NaCl	1.28×10^{2}	kg/FU
D	Reuse/Recycling	Recovery of $Mg(OH)_2$	7.53×10^{0}	kg/FU

Table 9. *Cont.*

LCA Stages		Unit	per FU	Unit
D	Reuse/Recycling	Recovery of $CaCO_3$	2.02×10^0	kg/FU
D	Reuse/Recycling	Recovery of $CaSO_4$	5.47×10^0	kg/FU
D	Reuse/Recycling	Recovery of KCl	2.95×10^1	kg/FU

3. Results

3.1. Life Cycle Impact Assessment

Figure 3 presents the Life Cycle Impact Assessment for the treatment of potassium mining wastewater and provides the relative contribution of the operational factors, mainly the chemical use and the energy consumption, in the different environmental impact categories. As demonstrated in Figure 3, the main contributor to all the environmental impact categories is the use of chemicals in the pilot system, followed by energy consumption. Global Warming Potential (GWP) refers to an increase in the average global temperature due to greenhouse gas emissions [25]. It is affected by the use of chemicals, with 65% in the novel pilot system, and also 25% from its energy consumption. Ozone Depletion (ODP) refers to the estimated impact of a substance on the depletion of the ozone layer [26]. In the novel pilot system, the Ozone Depletion Potential is generally low, equal to 1.09×10^{-7} Kg CFC 11 eq. The main contribution to it is the use of chemicals, at around 70%.

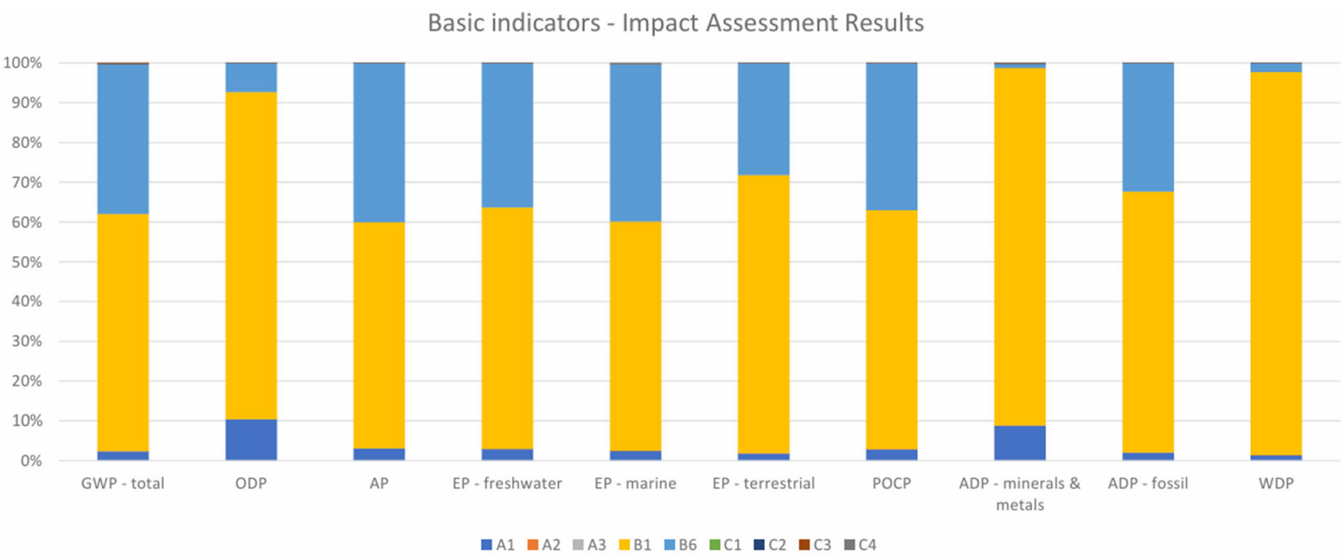

Figure 3. Impact assessment results for the treatment of the potassium mining wastewater.

The Acidification Potential (AP) refers to the possibility that the system contributes to environmental acidification [27], and it is 55% dominated by the system energy consumption, followed by contributions from the use of chemicals. Freshwater (EP-freshwater), Marine (EP-marine), and Terrestrial (EP-terrestrial) Eutrophication Potentials are mainly affected by the use of chemicals, and secondarily by the system's energy consumption. The use of chemicals contributes around 50% to the Freshwater Eutrophication, 50% to Marine Eutrophication, and 70% to Terrestrial Eutrophication. The Photochemical Ozone Creation Potential (POCP), which is a measure of the formation of ground-level ozone, a major component of smog, from various pollutants [28], is mainly affected by the chemical consumption of the pilot system, and secondarily by its energy use. The Abiotic Depletion Potential (ADP) represents the depletion of non-renewable resources, such as minerals and metals (ADP-minerals and metals), as well as fossil fuels (ADP-fossil) [29]. The contribution of the use of chemicals to the ADP of minerals and metals is around 90%, and to the ADP

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of fossil fuels is around 60%. Water Depletion Potential (WDP) aims to assess the potential impact of water consumption on the availability of water resources for both humans and ecosystems [30,31], and is affected by chemical use at around 65–70%.

3.2. Comparison of the Novel Pilot System Configuration with Other Desalination Systems

The novel pilot system configuration was set for the treatment of potassium wastewater characterized by 18% TDS content. The energy consumption of this system is equal to 15 kWh/m^3. Figure 1 presents the process flow diagram of the pilot system configuration for the treatment of the potassium wastewater.

The system was only compared with another system of the Brine-Mining project, as no LCAs were found in the literature for high-salinity wastewater treatment systems achieving high-purity water recovery, almost zero-liquid discharge, and the recovery of marketable salts. Tsalidis et al. (2022) [32] assessed the environmental performance of a novel coal mine brine treatment technique in the framework of the project Zero-Brine, but the TDS content was quite low, around 3.8%.

In the framework of the LIFE project, titled Brine-Mining, the same technologies were used for the treatment of a coal mine wastewater with a salinity of 8%. For the treatment of this wastewater, a different configuration was used. The configuration employed four (4) membrane technologies: an ultrafiltration, a nanofiltration, an electrodialysis, and a reverse osmosis; and three (3) precipitation units: an evaporator, a crystallizer, and a dryer. Four (4) salts were recovered from this configuration. The system energy consumption is equal to 44 kWh/m^3. Figure 4 presents the system configuration for the treatment of the saline coal mine wastewater. As is demonstrated in Figure 4, the raw brine goes through an ultrafiltration unit for the removal of suspended solids. The permeate from the ultrafiltration heads to the first precipitation unit. There, NaOH is added for the precipitation of $Mg(OH)_2$. The effluent from the first precipitation unit is added to the second precipitation unit. There, Na_2CO_3 is added and $CaCO_3$ is precipitated. The effluent from the second precipitation unit travels to a neutralization unit, in which HCl is added to neutralize the effluent pH value. The neutralization effluent undergoes nanofiltration to remove sulfate and any remaining calcium and magnesium from the effluent. The nanofiltration effluent moves towards the electrodialysis unit, while the nanofiltration concentrate goes to the third precipitation unit, in which $CaCl_2$ is added for the precipitation of $CaSO_4$. From the electrodialysis, a partly diluted effluent and a concentrated stream are produced. The partly diluted effluent goes through reverse osmosis, where clean water is produced. The concentrated stream, which is rich in sodium (Na) and chlorides (Cl), moves forward to a MED evaporator where it is concentrated. The MED produces clean water, and the MED concentrate then flows into the crystallizer from which clean water and NaCl of high purity are produced.

The potassium wastewater was characterized by a TDS content equal to 18%, while the coal mine wastewater TDS content was 8%.

Table 10 presents a comparative Life Cycle Assessment of the two pilot systems. The first one treats saline coal mine brine, and the second treats potassium mine brine.

Table 10. Comparison of the two pilot systems treating saline wastewaters, based on the LCA results.

Impact Categories	Unit	Novel Pilot System for the Treatment of Saline Coal Mine Brine (L650)	Novel Pilot System for the Treatment of Potassium Mine Brine (KCl)
GWP—total	Kg CO_2 eq.	7.42×10^{1}	4.09×10^{1}
ODP	Kg CFC-11 eq.	1.18×10^{-6}	1.05×10^{-6}
AP	mol H^+ eq.	5.55×10^{-1}	2.89×10^{-1}

Table 10. *Cont.*

Impact Categories	Unit	Novel Pilot System for the Treatment of Saline Coal Mine Brine (L650)	Novel Pilot System for the Treatment of Potassium Mine Brine (KCl)
EP-freshwater	Kg P eq.	4.04×10^{-2}	2.17×10^{-2}
EP-marine	Kg N eq.	7.62×10^{-2}	4.07×10^{-2}
EP-terrestrial	mol N eq.	9.13×10^{-1}	5.87×10^{-1}
POCP	Kg NMVOC eq.	2.30×10^{-1}	1.26×10^{-1}
ADP-minerals and metals	Kg Sb eq.	1.27×10^{-3}	8.88×10^{-4}
ADP-fossil	MJ	9.31×10^{2}	5.50×10^{2}
WDP	m^3	1.99×10^{1}	2.15×10^{1}

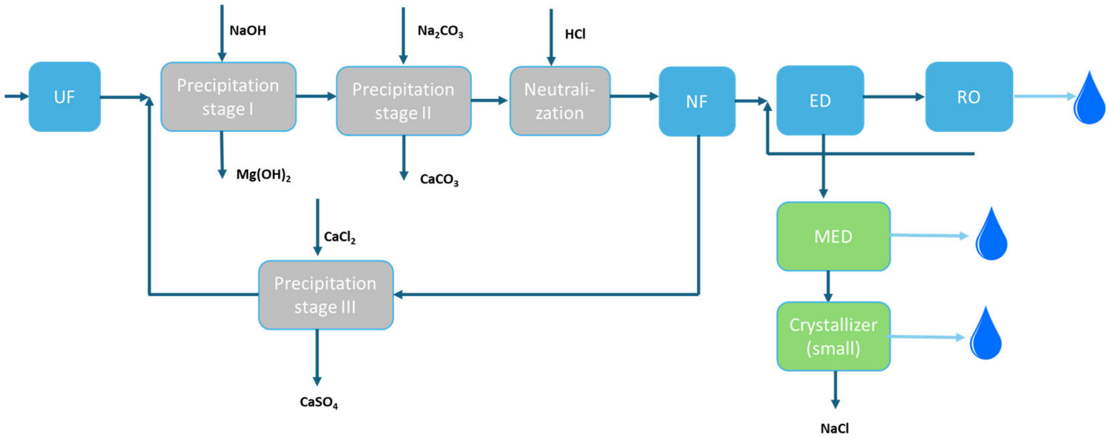

Figure 4. Process flow diagram of the pilot system configuration for the treatment of the coal mine wastewater.

The potassium mine brine system generally exhibits lower environmental impact than the coal mine brine system. The Global Warming Potential of the coal mine brine system (7.42×10^1 Kg CO_2 eq.) is higher than the other system (4.09×10^1 Kg CO_2 eq.). The main driver for this difference is the three-times-higher energy consumption of the coal mine brine system than the potassium mine brine configuration.

Both systems have a very low Ozone Depletion Potential, exhibiting minimal impact on the ozone layer. The slight difference in the two values, with the coal mine brine ODP being higher (1.18×10^{-6} Kg CFC-11 eq.) than the corresponding value of the potassium mining brine system (1.05×10^{-6} Kg CFC-11 eq.), is negligible.

The Acidification Potential of the coal mine brine system (5.55×10^{-1} mol H^+ eq.) is nearly double that of the potassium mining brine system (2.89×10^{-1} mol H^+ eq.), suggesting a greater contribution to acidification rain and similar impacts. The different impact of the two systems is linked to the use of chemicals and energy consumption. However, the mass of the chemicals used is similar for the two systems; as for the coal mine brine system, the use of chemicals was 20.86 kg/h, while for the potassium mining brine, equal to 17.63 kg/h. So, it is more likely that this difference is attributed to the much higher energy consumption of the coal mine brine system than the other system.

In all types of Eutrophication Potential, the coal mine brine system exhibits higher impact than the potassium mine brine system. The Freshwater Eutrophication Potential indicates higher possibility for release of phosphorus into water bodies, while the Marine Eutrophication Potential indicates the release of nitrogen into marine environments. The excessive flow of nitrogen and potassium, can lead to oxygen depletion and algal growth [33]. Therefore, the difference between the two systems impact in the Eutrophication Potential is mainly attributed to the difference in their energy consumption. The Photochemical Ozone Creation Potential of the coal mine brine system (2.30×10^{-1} Kg NMVOC eq.) is higher than the potassium mining brine system (1.26×10^{-1} Kg NMVOC eq.), exhibiting greater contribution to the release of volatile organic compounds that end up in the formation of smog. The difference is mainly attributed to the higher energy use that generally provokes higher emissions.

The coal mine brine Abiotic Depletion Potential referring to minerals and metals (1.27×10^{-3} Kg Sb eq.) is higher than the potassium mining brine system (8.88×10^{-4} Kg Sb eq.), indicating greater consumption of minerals and metals resources. The corresponding Abiotic Depletion Potential referring to fossils for the coal mine brine system (9.31×10^{2} MJ) is higher than the potassium mining brine system (5.50×10^{2} MJ), indicating greater reliance on fossil fuels for the coal mine brine treatment process than the potassium mining process.

The Water Depletion Potential of the coal mine brine system (1.99×10^{1} m^3) is lower than the corresponding value (2.15×10^{1} m^3) for the potassium mining brine system. This is a significant exception to the general condition of lower impact of the potassium mine brine system compared to the coal mine brine treatment system, indicating that the potassium mine brine system may be more water-demanding. However, the difference between the two systems is slightly different.

From the comparison of the two systems, it is shown that the three times higher energy consumption of the coal mine brine system contributes to its higher Global Warming Potential, Eutrophication Potential, Acidification Potential, Photochemical Ozone Creation Potential, and Abiotic Depletion Potential. Both systems have very small Ozone Depletion Potential, while the Water Depletion Potential is the only exception, as it is higher for the potassium mine brine system than the coal mine brine system.

3.3. Sensitivity Analysis

A sensitivity analysis was conducted to assess the changes in the auxiliary equipment used and its respective impact on the Global Warming Potential. Two different scenarios were investigated. Tables 4 and 5 present the sensitivity analysis for the potassium mine brine system for the Global Warming Potential. More in specific, Table 11 presents the results of the sensitivity analysis evaluating how changes in material consumption influence the total Global Warming Potential (GWP) of the potassium mine brine treatment across all life cycles, and Table 12 presents the sensitivity analysis results for the fossil-based Global Warming Potential (GWP-fossil) of the potassium mine brine treatment system. In both cases, two scenarios are evaluated: The first scenario is a 10% decrease in the materials used, and the second scenario is a 10% increase in the materials used.

First scenario—10% decrease in materials consumption: a 10% decrease in material consumption results in a slight decrease in the total Global Warming Potential from 4.09×10^{1} to 3.86×10^{1} Kg CO_2 eq. All stages, except B6, which is the electricity consumption, indicated a 9.1% decrease for the GWP.

Second scenario—10% increase in material consumption: a 10% increase in material consumption results in a slight increase in the total Global Warming Potential to 4.37×10^{1} Kg CO_2 eq. All stages, except the electricity consumption, indicated a 11.1% increase for the GWP.

The sensitivity analysis indicated that the material consumption significantly affects the system's environmental impact.

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Table 11. Sensitivity analysis for various scenarios (GWP-total).

Scenarios	Reference Unit	A1	A2	A3	B1	B6	C1	C2	C3	C4	Total
Baseline	GWP—total ($Kg\ CO_2$ eq.)	9.57×10^{-1}	3.16×10^{-2}	1.46×10^{-4}	2.44×10^{1}	1.54×10^{1}	0.00×10^{0}	4.36×10^{-3}	7.89×10^{-2}	1.15×10^{-3}	4.09×10^{1}
10% decrease in material consumption	GWP—total	8.70×10^{-1}	2.87×10^{-2}	1.33×10^{-4}	2.22×10^{1}	1.54×10^{1}	0.00×10^{0}	3.96×10^{-3}	7.17×10^{-2}	1.05×10^{-3}	3.86×10^{1}
10% increase in material consumption	($Kg\ CO_2$ eq.)	1.06×10^{0}	3.51×10^{-2}	1.62×10^{-4}	2.71×10^{1}	1.54×10^{1}	0.00×10^{0}	4.84×10^{-3}	8.77×10^{-2}	1.28×10^{-3}	4.37×10^{1}
Baseline 10% decrease in material consumption	GWP—total	−9.1%	−9.1%	−9.1%	−9.1%	0.0%	-	−9.1%	−9.1%	−9.1%	−5.7%
10% increase in material consumption	($Kg\ CO_2$ eq.)	11.1%	11.1%	11.1%	11.1%	0.0%	-	11.1%	11.1%	11.1%	6.9%

Table 12. Sensitivity analysis for various scenarios (GWP-fossil).

Scenarios	Reference Unit	A1	A2	A3	B1	B6	C1	C2	C3	C4	Total
Baseline	GWP—fossil ($Kg\ CO_2$ eq.)	9.57×10^{-1}	3.16×10^{-2}	1.46×10^{-4}	2.39×10^{1}	1.54×10^{1}	0.00×10^{0}	4.35×10^{-3}	7.83×10^{-2}	1.07×10^{-3}	4.04×10^{1}
10% decrease in material consumption	GWP—total	8.70×10^{-1}	2.87×10^{-2}	1.32×10^{-4}	2.17×10^{1}	1.54×10^{1}	0.00×10^{0}	3.96×10^{-3}	7.12×10^{-2}	9.73×10^{-4}	3.81×10^{1}
10% increase in material consumption	($Kg\ CO_2$ eq.)	1.06×10^{0}	3.51×10^{-2}	1.62×10^{-4}	2.66×10^{1}	1.54×10^{1}	0.00×10^{0}	4.84×10^{-3}	8.71×10^{-2}	1.19×10^{-3}	4.32×10^{1}
Baseline 10% decrease in material consumption	GWP—total	−9.1%	−9.1%	−9.1%	−9.1%	0.0%	-	−9.1%	−9.1%	−9.1%	−5.7%
10% increase in material consumption	($Kg\ CO_2$ eq.)	11.1%	11.1%	11.1%	11.1%	0.0%	-	11.1%	11.1%	11.1%	6.9%

3.4. System Comparison with Underground Disposal Method (Wastewater from Potassium Extraction)

Wastewater coming from mining operations can undergo various forms of treatment or management systems. One common method, depending on the composition of the wastewater, is the disposal of the wastewater in old underground mines that are not used. This method will be described as 'underground disposal' throughout this research work.

A Life Cycle Assessment (LCA) was performed to assess the impact of the potassium wastewater underground disposal. The main activity comes from energy use in pumps and soil contamination. The purpose of this LCA was to compare the potassium mining brine system with the underground disposal, which is the current implemented method. To make the two systems comparable, the production of salt products (NaCl, $CaSO_4$, $Mg(OH)_2$, $CaCO_3$, NaCl) in the pilot system was taken into consideration. The functional unit is 1 m^3 of wastewater. The results of the LCIA are demonstrated in Table 13, which presents a comparative Life Cycle Impact Assessment between the innovative pilot system treating potassium mining wastewater and the conventional management method of underground disposal.

Table 13. Comparison of the novel pilot system for the treatment of potassium wastewater with the conventional method.

Indicator	Unit	Conventional Treatment Method	Innovative Pilot System
GWP—fossil	Kg CO_2 eq.	4.07×10^{1}	4.04×10^{1}
GWP—biogenic	Kg CO_2 eq.	0.00×10^{0}	0.00×10^{0}
GWP—luluc	Kg CO_2 eq.	3.10×10^{-2}	2.95×10^{-2}
GWP—total	Kg CO_2 eq.	2.94×10^{2}	4.09×10^{1}
ODP	Kg CFC 11 eq.	5.00×10^{-7}	1.05×10^{-6}
AP	mol H^+ eq.	2.11×10^{-1}	2.89×10^{-1}
EP—freshwater	Kg P eq.	$3.08E \times 10^{-2}$	2.17×10^{-2}
EP—marine	Kg N eq.	2.39×10^{-1}	4.07×10^{-2}
EP—terrestrial	mol N eq.	3.60×10^{-1}	5.87×10^{-1}
POCP	Kg NMVOC eq.	1.97×10^{-1}	1.26×10^{-1}
ADP—minerals and metals	Kg Sb eq.	3.34×10^{-3}	8.88×10^{-4}
ADP—fossil	MJ	3.74×10^{2}	5.50×10^{2}
WDP	m^3	5.06×10^{1}	2.15×10^{1}
Potential Comparative Toxic Unit for ecosystems (ETP-fw)	CTUe	6.24×10^{1}	3.31×10^{2}
Potential Comparative Toxic Unit for humans—non-cancer effects (HTP-nc)	CTUh	7.77×10^{-8}	7.16×10^{-7}
Potential Comparative Toxic Unit for humans—cancer effects (HTP-c)	CTUh	2.31×10^{-8}	1.29×10^{-7}
Potential Human exposure efficiency relative to U235 (IRP)	kBq U235 eq.	3.85×10^{-1}	8.37×10^{-1}
Potential incidence of disease due to PM emissions (PM)	Disease Incidence	7.52×10^{-7}	7.20×10^{-7}
Potential Soil quality index (SQP)	Dimensionless	8.25×10^{2}	7.98×10^{1}

The potassium mine brine system, while having a higher impact in some categories, demonstrates important advantages compared to the conventional underground disposal method for most of the impact indicators.

The conventional treatment method has a significantly higher Global Warming Potential (2.94×10^{2} Kg CO_2 eq.) than the novel pilot system (4.09×10^{1} Kg CO_2 eq.), even though the system has slightly higher fossil GWP. This indicates that other factors, such as the energy used for pumping in underground disposal, have a greater impact on the conventional method of treatment.

The Ozone Depletion Potential of the conventional method (5.00×10^{-7} Kg CFC 11 eq.) is lower than the potassium mine brine system (1.05×10^{-6} Kg CFC 11 eq.); however, both values are quite low, indicating low environmental detrimental. The Acidification Potential of the conventional treatment method (2.11×10^{-1} mol H^+ eq.) is also lower than the brine treatment system (2.89×10^{-1} mol H^+ eq.), indicating less contribution to acid rain and similar phenomena, and it is probably attributed to the use of chemicals in the potassium mine brine system.

The Eutrophication Potential of all types (Freshwater, Marine, Terrestrial) is higher for the conventional method compared to the brine treatment system, indicating that the conventional method creates remaining solid substances that can contribute to nutrient pollution in land and waterways. Also, the Photochemical Ozone Creation Potential of the conventional method (1.97×10^{-1} Kg NMVOC eq.) is higher than the brine treatment system (1.26×10^{-1} Kg NMVOC eq.), indicating that this method contributes more to smog creation.

As for the Abiotic Depletion Potential, a special kind of contribution has been observed: even though the conventional method exhibits higher ADP for minerals and metals (3.34×10^{-3} Kg Sb eq.) than the potassium mine brine system (8.88×10^{-4} Kg Sb eq.), it exhibits lower ADP for fossils (3.74×10^{2} MJ) than the system (5.50×10^{2} MJ). This is attributed to the fact that the infrastructure for the conventional underground disposal method requires metals, while the pilot system's energy consumption drives its fossil fuel depletion.

As for the Water Depletion Potential, the conventional method is more water-intensive (5.06×10^{1} m^3) than the potassium mine brine system (2.15×10^{1} m^3). The higher WDP in the conventional system is mainly due to the complete loss of water during the underground disposal, while, on the other hand, from the pilot system, clean water is recovered.

The pilot system seems to have a higher potential to cause cancer and non-cancer-related health effects compared to the conventional method. This is potentially attributable to the use of chemicals in the brine treatment system.

The conventional method's Ionizing Radiation Potential (3.85×10^{-1} kBq U235 eq.) is lower than that of the potassium brine system (8.37×10^{-1} kBq U235 eq.). The IRP is primarily connected to energy consumption; therefore, the Brine-Mining system has a higher impact in this category.

The conventional method's Particulate Matter Formation is higher (7.52×10^{-7} Disease Incidence) than that of the brine treatment system (7.20×10^{-7}). The formation of particulate matter is linked both to energy consumption and to industrial processes that release particles. The pilot system has a higher energy demand than the conventional system, but the conventional method of discharging wastewater underground can potentially lead to the mobilization of existing particulate matter in soil, which can end up in the air.

The conventional method's Soil Quality Potential is equal to 8.25×10^{-2}, suggesting that it has a very detrimental impact on soil quality, compared to the pilot system's corresponding value (7.98×10^{1}). This is attributed to the direct discharge of wastewaters in underground mines.

From the comparison of the two systems, it seems that while the brine treatment system has some drawbacks related to chemical use and energy consumption, it is a more sustainable solution for potassium mining wastewater compared to underground disposal, which poses a threat to soil, water, and air quality.

4. Discussion

The environmental impact of a novel pilot system to treat potassium mining brine was assessed through an LCA study. From the LCA analysis, it was shown that the main environmental burden of the system is attributed to the operation phase, rather than to the construction or demolition phase. The production of raw materials during the construction phase contributed only marginally to the ODP and ADP (less than 10% in each of these two indicators). It was also proven that the system's environmental impact is mainly affected by the energy consumption and the use of chemicals for its operation. Each environmental impact category is affected by the following two factors to different proportion: the use of chemicals contributes 65% to the Global Warming Potential, while the energy consumption to 25%. Regarding the Ozone Depletion Potential, chemical use contributes 70%, while energy consumption is a minor factor. The chemical consumption influenced the Eutrophication Potential by almost half, except for terrestrial eutrophication, which contributed 70%. The Photochemical Ozone Creation Potential and the Abiotic Depletion Potential are all dominated by chemical use. The ADP for minerals and metals is 90%, while the ADP for fossil fuels is 60%. The energy consumption contributes to the Acidification Potential by 55%, while its contribution to the Water Depletion Potential is 65–70%.

The potassium mine brine system was compared to another desalination system that treated coal mine brine. The coal mine brine was characterized by half the salinity (8% TDS) of the potassium brine (18% TDS), while both systems recovered valuable salts of high purity from the saline wastewaters treatment.

The environmental impact of the two systems was assessed, proving that the potassium brine system has a lower environmental impact compared to the coal mine brine system, especially for Global Warming, Acidification, Eutrophication, and the Photochemical Ozone Creation Potential. The difference in the environmental impact of the two systems is attributed to the higher energy consumption of the coal mine brine system compared to the potassium mine brine. The main reason for this difference is the higher energy consumption of the coal mine brine system, which includes two more technologies than the potassium brine system, the electrodialysis and the RO, which are quite energy-intensive. In some other categories, both systems exhibit similar impacts, such as in the Abiotic Depletion Potential for minerals and metals. Overall, the potassium mine brine system is more sustainable, except for its impact on the Water Depletion Potential, as it requires slightly more water than the coal mine brine system.

The novel pilot system for the potassium brine treatment was also compared to the conventional method, which is the disposal of potassium mine brine in underground mines. The pilot system demonstrates lower environmental impact in areas such as Global Warming, Acidification, Eutrophication, Water Depletion, and Soil Quality compared to underground disposal, but has a higher impact on the Abiotic Depletion Potential for minerals and metals, and Ionizing Radiation Potential, mainly due to the novel system's energy demand. Overall, the novel system is a more sustainable solution for potassium mine brine treatment than the underground disposal.

5. Future Research Work

Based on this study, future research should focus on the optimization of the pilot system's operational phase. The main focus should be on a reduction in chemical consumption and energy demand, as these two stages were identified as the main contributors to the environmental impact of the system. Additionally, future work can explore the system's scale-up and long-term operational performance to enhance its sustainability.

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Conflicts of Interest: Author Dionysia Diamantidou was employed by the company LENNTECH. Author Christina Xenogianni was employed by the company THERMOSSOL. Author Kallirroi Panteleaki was employed by the company SEALEAU. Author Dmitry Ponomarenko was employed by the company NEVIS. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AP	Acidification Potential
CAGR	Compound Annual Growth Rate
EP	Eutrophication Potential
GWP	Global Warming Potential
IRP	Ionizing Radiation Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ODP	Ozone Depletion Potential
PE	Polyethylene
POCP	Photochemical Ozone Creation Potential
PP	Polypropylene
PVC	Polyvinyl chloride
TDS	Total Dissolved Solids
USD	United States Dollar
WDP	Water Depletion Potential

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