

## Research article

# Extensive comparison of methods for removal of organic halogen compounds from pharmaceutical process wastewaters with life cycle, PESTLE, and multi-criteria decision analyses

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## ABSTRACT

Recycling and disposing wastewater from the pharmaceutical industry are of utmost importance in mitigating chemical waste generation, where unmanaged hazardous waste fluxes could cause massive environmental damage. Air stripping, steam stripping, distillation, and incineration offer significant emission reduction potentials for pharmaceutical applications; however, selecting specific process units is a complicated task due to the high number of influencing screening criteria. The mentioned chemical processes are modelled with the Aspen Plus program. This study examines the environmental impacts of adsorbable organic halogens (AOX) containing pharmaceutical process wastewater disposal by conducting life cycle impact assessments using the Product Environmental Footprint (PEF), IMPACT World + Endpoint V1.01, and Recipe 2016 Endpoint (H) V1.06 methods. The results show that the distillation-based separation of AOX compounds is characterized by the most favourable climate change impact and outranks the PEF single score of air stripping, steam stripping, and incineration by 6.3%, 29.1%, 52.0%, respectively. The energy-intensive distillation technology is further evaluated by considering a wide selection of energy sources (i.e., fossil fuel, nuclear, solar, wind onshore, and wind offshore) using PESTLE (Political, Economic, Social, Technological, Legal, Environmental) analysis combined with multi-criteria decision support to determine the most beneficial AOX disposal scenario. The best overall AOX regeneration performance and lowest climate change impact ( $7.25 \times 10^{-3}$  kg CO<sub>2</sub>-eq (1 kg purified wastewater)<sup>-1</sup>) are obtained by supplying variable renewable electricity from onshore wind turbines, reaching 64.87% carbon emission reduction compared to the baseline fossil fuel-based process alternative.

## Credit author statement

**Ms. Huyen Trang Do Thi:** Conceptualization, Methodology, Writing- Original draft preparation. **Dr. Daniel Fozer, PhD:** Investigation, Writing- Reviewing and Editing. **Dr. Andras Jozsef Toth, PhD:** Corresponding author: Supervision, Writing- Reviewing and Editing, Funding acquisition.

## 1. Introduction

The chemical industry has a massive ecological problem with organic solvents used for synthesis and purification ending up as highly toxic wastes. Solvents have positively impacted the global economy as they

have been widely used for paints, pharmaceuticals, personal care and cosmetics, adhesives, household care, and other applications. However, due to their extensive use, human bodies are exposed to solvents directly through consumer products daily. The on- and off-site emissions of carcinogenic solvents into natural water resources could fatally affect the metabolic system of living bodies; thus, the application of such compounds should be replaced by suitable green alternatives (Janicka et al., 2022; Kumaravel et al., 2021; Prasad et al., 2022). However, in many cases, conventional solvents cannot be avoided or replaced by more environmentally friendly substances. The emission of such compounds into the sewage system or rivers must be prevented using removal and regeneration technologies.

Pharmaceutical production faces environmental challenges due to

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complex technologies, raw material usage, and limited recycling (Gupta et al., 2018). Active ingredient production generates significant environmental burdens through high water demand and wastewater production. Main environmental loads include excessive use of organic and chlorinated solvents, organic substances, inorganic salt, ammonia-ammonium ion, metals, and adsorbable organic halogens emissions. The emission of these compounds negatively affects air and water quality, and biodiversity (Patneedi and Prasadu, 2015; Samal et al., 2022).

The adsorbable organic halogens (AOX) consist of all organic compounds that can be adsorbed on activated carbon after being halogenated, including chlorinated, brominated, and iodized (Müller, 2003). A large number of AOX solvents are classified as persistent organic pollutants as they cannot degrade naturally in the environment. Without removal, these persistent compounds can build up in watercourses, enter the food chain, and accumulate in animal tissues (Savant et al., 2006). The toxicity of AOX also poses a potential long-term risk to the environment, ecosystem safety, and human health (De Vera et al., 2015; Gellert, 2000; Gribble, 2015; Jörundsdóttir et al., 2010). Carcinogenicity, mutagenicity, acute toxicity, and chronic toxicity are some harmful effects associated with AOX. AOX can be degraded by various physical, chemical, electrochemical, physicochemical, and biological methods. The degradation of AOX by biological methods can be promoted by a variety of dehalogenation bacteria, fungi, or enzymes, which are widely used on a large scale because of their low cost and technological maturity (Fulthorpe and Allen, 1995; Sharma et al., 2014). The AOX removal efficiency of these methods is between 50 and 80% (Kumar Singh et al., 2020), while the efficiency of physical or chemical methods is approximately 90–95%. Physical processes like adsorption, coagulation, and flocculation offer ease of use and adaptability, but these methods require adsorbent regeneration and excess sludge disposal (Xu et al., 2021).

Chemical treatments offer strong hydraulic impact resistance and can effectively remove AOX with complex structures. Numerous model compounds, such as polychlorinated biphenyls, have been found to degrade refractory AOX (Qin et al., 2018). Physicochemical treatments involve the use of chemicals to alter colloidal particles' physical state to become more stable and coagulable for further processing. Several physicochemical methods exist for removing AOX, including adsorption (Qu et al., 2009; Zhang et al., 2019), extraction (Fatima et al., 2022; Prasad et al., 2022; Zhang et al., 2022), wet oxidation (Baycan et al., 2005), evaporation (Tóth et al., 2022), stripping (Bell et al., 1993), distillation (Li et al., 2019), membrane filtration (nanofiltration (NF), and reverse osmosis (RO)) (M Mänttari and Nyström, 2007; Vinder and Simonič, 2012), and incineration (Tóth et al., 2022).

Despite the availability of various technologies for treating chemical process wastewater, only a handful are commonly used, including stripping, distillation, and incineration (Toth et al., 2022). These methods are typically applied to process wastewater with high efficiency in the industry. Stripping is a wastewater treatment method to separate VOCs and inorganic contaminants (Başakçılardan-Kabakci et al., 2007). Solid contaminants can cause fouling and contamination in the process. Additional purification methods are often necessary due air stripping has limitations as gases and vapors are released into the atmosphere (Toth and Mizsey, 2015). Distillation is a standard treatment technology, but separating azeotropic mixtures is challenging and consumes a large amount of energy (Arlt, 2014; Ge et al., 2021). Incineration converts waste into heat and electricity but is not environmentally recommended because it releases toxic chemicals and pollutants (Frederik Neuwahl et al., 2019; Moharir et al., 2019).

Life Cycle Assessment (LCA) is increasingly applied to identify technological hotspots and support environmental decision-making (Burgess and Brennan, 2001). The usability of LCA is already demonstrated in designing environmentally friendly approaches for solvent waste treatment (Raymond et al., 2010) and recovering halogenated organic compounds (Savelski et al., 2017). The environmental impacts

(i.e., human health, ecosystem, and resources) of isobutanol-contaminated wastewater purification were improved by 50% by analyzing pervaporation systems and pervaporation-assisted hybrid distillation with heat integration with the ReCiPe and IMPACT 2002+ life cycle impact assessment methods (Andre et al., 2018). A comparison of spray incineration and supercritical water oxidation (SCWO) has been conducted at the University of Tokyo using endpoint modelling (Kikuchi et al., 2011). Spray incineration is obtained to have a lower environmental impact than supercritical water oxidation, but SCWO was recommended because spray incineration may contribute to the emission of dioxins and particulates.

Amelio et al. (2014) analysed the treatment of organic solvents with distillation and incineration and suggested component-specific treatment strategies based on life cycle impacts. Solvent mixtures containing methanol, ethanol, xylene, methyl ethyl ketone, and isopropanol were advised to be incinerated due to the lack of environmental benefits gained from their recovery. In the case of THF, acetonitrile, benzaldehyde, butyl acetate, and benzyl alcohol-containing solvent mixtures, better emission reduction was obtained by applying distillation.

The PESTLE (Political, Economic, Social, Technological, Legal, Environmental) analysis provides a multi-angle perspective to assess the weaknesses and benefits of technologies. The PESTLE framework was applied in diverse fields to support decision-making, such as economics (Marinova and Bitri, 2021; Werth et al., 2020), industry (Bhuyan et al., 2022; Fonseca et al., 2022), science-technology (Loddo et al., 2020), energy (Achinas et al., 2019; Ghaboulia Zare et al., 2022), agriculture (Mihailova, 2020), social (El Khateeb and Shawket, 2022), waste management (Iacovidou and Zorpas, 2022; Zorpas, 2020), water management (Fonseca et al., 2022), infrastructure development (Kumar et al., 2021; Tleuken et al., 2022), and health care (Ahsan Ali Siddiqui, 2021; Thakur, 2021), etc. Gul et al. evaluated the barriers to wastewater utilization using the PESTLE framework assisting in the planning, marketing, implementing, and managing of wastewater treatment projects (Gul et al., 2021).

The pharmaceutical industry generates a large amount of adsorbable organic halogens contaminated wastewater; however, little research has been conducted on AOX in pharmaceutical wastewater, and the environmental performance of AOX removal technologies hasn't been investigated in detail. Exploring the presence and removal of AOX in pharmaceutical wastewater is essential for devising measures to curb their extensive proliferation. To fill this research gap, the paper is dedicated to examining and comparing the gate-to-gate environmental impacts of robust AOX removal technologies, i.e., air stripping, steam stripping, distillation, and incineration. The environmental aspects of AOX-containing solvent waste management are extended by investigating the effects of alternative energy sources by applying Political, Economic, Social, Technological, and Legal points of view. Multi-criteria decision analysis ranking method indicates that the distillation-based AOX removal combined with onshore wind turbines has the highest environmental impact reduction potential.

## 2. Data and methodology

### 2.1. The specification of the wastewater treatment technologies

#### 2.1.1. Air stripping

Stripping is a commonly used process wastewater treatment method to separate volatile organic compounds (VOCs). The process involves the transfer of volatile organic and/or inorganic compounds from the liquid to the gas phase by contacting the wastewater with a large amount of hot gas or steam. The life cycle inventory of wastewater stripping was compiled based on the work of Toth and Mizsey (2015). The air stripping block consists of three main units (as illustrated in Fig. S1 of the Supporting information part).

1. The stripping column is where the halogens' desorption occurs.

Wastewater is delivered to the top of the stripping column at a flow rate of 20 m<sup>3</sup>/h. A ventilator at the bottom of the stripping column provides a counter-current air flow rate of 2000 m<sup>3</sup>/h. The packed stripping column is 10 m high and 1 m in diameter and contains a polypropylene Polyhedral Hollow Ball packing. After discharge, there are essentially zero AOX components in the water phase of the channelled mixture, which are removed with the overhead product in the air stream.

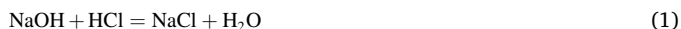
2. The KATOX-catalytic oxidation, where the hydrocarbons are oxidized.

The polluted air stream leaving the stripping column, i.e., the mixture concentrated in the pollutants, is fed through a droplet separator into the catalytic oxidation (KATOX) unit. The excess air required for the operation of KATOX is provided by a separate ventilator, which delivers an additional air flow rate of 500 m<sup>3</sup>/h. An electrical preheater is used to heat the catalyst to 500 °C, at which temperature oxidation starts. The catalyst is manufactured from Pt–Ir. However, it only needs to be operated at the start-up stage since the heat released during the combustion of the pollutant gases provides the required 500 °C for oxidation; the system is indeed partially thermally self-sustaining. The energy demand of the heating unit is 118 kW h and 422 kW h with and without heat integration. The contaminants in the gas stream heated by the electric heater are decomposed into H<sub>2</sub>O, CO<sub>2</sub>, Cl<sub>2</sub>, HCl and chlorinated hydrocarbons. According to information from the pharmaceutical company, the effectiveness of KATOX is at least 70% (Major, 2008).

3. The gas cleaner with sodium hydroxide, where the oxidized material is neutralized by chemisorption.

In the first unit of the gas cleaner model, the mixture, mainly containing acid hydrochloric acid vapour and chlorine gas, exiting the catalytic oxidation unit is cooled from about 250 °C to about 130 °C in the quench tank in front of the packed gas cleaner column. The gas stream containing oxidized contaminants enters the lowest theoretical plate of the gas cleaner column and the 1 wt% sodium hydroxide scrubbing liquid enters the uppermost theoretical plate in counter current. Based on industrial data, the gas scrubbing column is 6 m high and 63 cm in diameter, with a polypropylene Polyhedral Hollow Ball charge.

The gas scrubbing column is where the hydrochloric acid vapors and chlorine gases are neutralized by chemisorption, according to the following reaction (Eq. (1)):



The overhead product of the gas cleaner is clean air. The bottom product contains the salt generated during neutralization reactions. To reduce the use of alkali, 90% of the bottom product is recirculated, and 10% is discharged. Disposal of this latter effluent will have to be ensured in the future, as its discharge into the sewerage system will incur high fines due to its high salt content.

### 2.1.2. Steam stripping

Steam stripping is a simpler alternative to air stripping used to recover less volatile pollutants. The processing unit consists of a single charged stripping column. When steam is used instead of air, volatile components are not released into the atmosphere but are condensed and treated.

In the case of the steam stripping model, the wastewater reaches the top of the column at a flow rate of 20 m<sup>3</sup>/h and the bottom in a counter-current way at a flow rate of 0.42 m<sup>3</sup>/h. The packed stripping column contains a 6 m high, 0.6 m diameter polypropylene Polyhedral Hollow Ball packing. The inlet effluent is heated to 95 °C using the heat of the bottom product by a heat exchanger. This results in energy integration in the system, whereby the heat invested can be recovered so that 296 kW h of energy had to be invested for the operation instead of 306 kW h. The

flowsheet of steam stripping process can be found in the Supporting information (Fig. S2).

### 2.1.3. Distillation

The distillation column model has been used for optimization in Aspen Plus software V10. The same input flow was examined as in the case of stripping processes. According to the model results, the distillation column has the best efficiency using the following configuration: the inlet stream was fed to the 10th plate at 30 °C and 1 bar pressure; 20 plates were arranged in the distillation column, and the reflux ratio was set to 10. This setting resulted from the objective to minimize the required heat duty while maintaining an efficient AOX bottom product of less than 8 ppm and maximizing the concentration of dichloromethane in the distillate based on the observed compositions. The feed methanol concentration was 0.44 wt% at 30 °C. The target bottom and distillate product streams reached 0.10 wt% methanol mass fraction at 98.7 °C and 41.11 wt% at 70 °C, respectively. Based on the distillation column and heat exchanger heat requirements, condenser and reboiler duties were –72 MJ/h and 1233 MJ/h. The UNIQUAC thermodynamic model was applied to the distillation process.

### 2.1.4. Incineration

Combustion reactions were assumed to take place in ideal conditions, where the CO<sub>2</sub> emission ( $7.70 \times 10^{-3}$  kg CO<sub>2</sub> (1 kg purified wastewater)<sup>–1</sup>) and the amount of supplied heat ( $8.82 \times 10^{-2}$  MJ (1 kg purified wastewater)<sup>–1</sup>) were estimated based on literature data (Randall Seeker, 1991), (Kharasch, 1920), (Raymond et al., 2010).

## 2.2. Life cycle assessment modelling framework

### 2.2.1. Goal and scope

Life Cycle Assessment (LCA) was performed to quantify the environmental burdens associated with four applied AOX-containing wastewater treatment technologies: (1) distillation, (2) air stripping, (3) steam stripping, and (4) incineration. Fig. 1 illustrates the system boundary for AOX containing solvent treatment process. The LCA modelling was carried out by using the SimaPro V9.3.0.3 software and Ecoinvent V3.8 database. Three impact assessment methods were used for the evaluation: (i) Environmental Footprint (EF) method, (ii) IMPACT World + Endpoint V1.01, and (iii) ReCiPe 2016 Endpoint (H) V1.06. The study's scope covered the process's operation phase, which included the chemical inputs and energy demands, referred to as a "gate-to-gate" analysis. The functional unit (FU) was defined as 1 kg of wastewater treated with a composition of AOX below 8 ppm and COD below 1000 mgO<sub>2</sub>/L. These emission values are discharge limits, found in Ministry of the Environment Regulation 28/2004 (XII. 25.) (2004).

### 2.2.2. Life cycle inventory

The overall mass balance is presented in Table 1, the life cycle inventory is summarized in Table S1 in the Supporting information. The pharmaceutical factory effluent composition data was obtained from the monitoring results submitted to Budapest Sewage Works Ltd. By the Department of Environmental Protection of the pharmaceutical factory (ALÜCS, 2007). It is also monitored by the Central Danube Valley Environmental, Ecological, and Hydrological Inspectorate. The main characteristics of averaged pharmaceutical wastewater effluent were: a pH 7; COD 4900 mgL<sup>–1</sup>; BOD<sub>5</sub> 2890 mgL<sup>–1</sup>; total salt 6200 mgL<sup>–1</sup>; the average ratio of COD/BOI<sub>5</sub>/N/P was 1441/850/40/1 (Oláh et al., 2021). A global energy mix composition was considered in the life cycle analysis.

### 2.2.3. Life cycle impact assessment

EF 3.0 Method.

The European Commission recommends the Environmental Footprint (EF) method for measuring and communicating environmental performance over the life cycle of all kinds of products and organizations

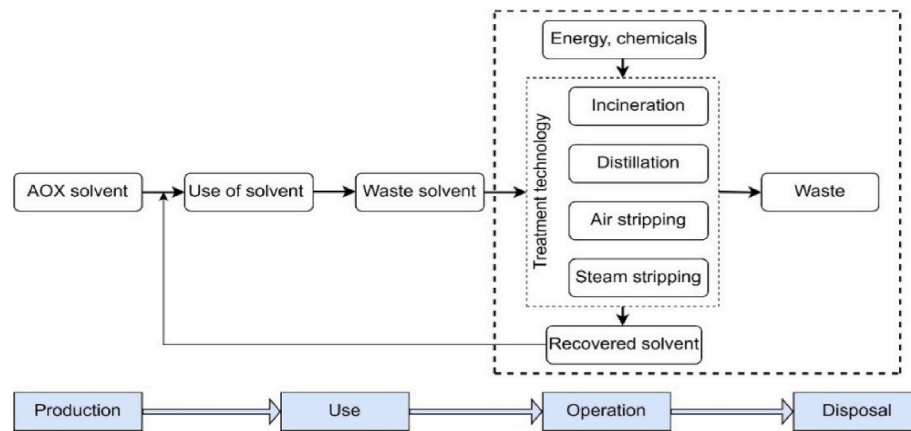


Fig. 1. The system model of the AOX containing solvent assessment using the LCA method. (The system boundary is indicated by dashed lines.)

Table 1

Life cycle inventory data.

Materials for 1 kg production	Input [kg]	Output [kg]			
		Air stripping <sup>b</sup>	Steam stripping <sup>b</sup>	Distillation	Incineration (CO <sub>2</sub> ) <sup>c</sup>
Water	9.94E-01	9.97E-01	9.96E-01	9.99E-01	–
Methanol	4.43E-03	3.25E-03	4.32E-03	1.00E-03	6.80E-03 <sup>e</sup>
Dichloromethane <sup>d</sup>	1.02E-03	3.24E-34	2.71E-19	5.36E-13	5.30E-04
Isobutanol	6.63E-05	1.03E-33	6.36E-05	2.01E-09	1.57E-04
Acetone	2.90E-05	3.43E-34	2.80E-05	5.36E-13	5.91E-05 <sup>e</sup>
Isopropanol	2.18E-05	1.22E-34	2.10E-05	1.53E-10	3.29E-05 <sup>e</sup>
Ethanol	1.11E-05	4.28E-11	1.08E-05	1.95E-08	1.60E-05 <sup>e</sup>
Toluene	1.70E-05	2.83E-34	2.83E-27	1.16E-21	4.17E-05 <sup>e</sup>
Trichloroethylene <sup>d</sup>	7.17E-06	6.42E-34	1.02E-33	3.70E-21	2.40E-06
1,2-Dichloroethane <sup>d</sup>	3.90E-07	1.05E-33	1.36E-17	1.54E-21	3.47E-07
Chloroform <sup>d</sup>	2.67E-07	2.00E-33	8.93E-24	3.76E-22	9.86E-08
Tetrachloroethylene <sup>d</sup>	3.50E-08	1.32E-33	3.44E-25	1.91E-22	1.86E-08
Carbon tetrachloride <sup>d</sup>	4.00E-09	3.06E-34	8.29E-34	1.06E-21	1.14E-09
Other compounds	8.01E-06	5.88E-33	6.84E-07	3.55E-09	2.37E-05

<sup>a</sup> Adapted from (ALÜCS, 2007).

<sup>b</sup> Adapted from available studies by Major (2008).

<sup>c</sup> Calculated from combustion reaction.

<sup>d</sup> AOX compounds in the effluent.

<sup>e</sup> Adapted from available studies by Raymond et al. (2010).

Directorate-General for Environment (European Commission, 2021a,b). The EF 3.0 method is the latest version available with updated human toxicity, ecotoxicity, and land use impact categories. This method incorporates 28 impact categories relating to climate change, human toxicity, ecotoxicity, and resource use. The current analysis focuses on agents that affect climate change, human carcinogenic toxicity, and ecotoxic effects of freshwater. The Comparative Toxic Unit for human-CTUh is the unit of toxicity impact for humans, which is expressed in cases per kilogram of chemical emitted per unit mass as the increase in morbidity in the total global human population of about 6.9 billion people. By expressing PAF. m<sup>3</sup>. year/kg, the CTUe quantifies how toxic chemicals affect ecosystems by incorporating the number of Potentially Affected Fraction (PAF) over time (Saouter et al., 2018). Climate change impact is measured by Global Warming Potential, which is the amount of greenhouse gases (GHGs) generated over a time horizon of 100 years, in kilograms of CO<sub>2</sub> equivalent (SimaPro, 2023).

#### 2.2.4. IMPACT World+

Implementing IMPACT World + V1.01 will compile and update IMPACT 2002+, LUCAS, and EDIP methods, which are available as midpoint and endpoint (damage level) with worldwide scope. Most of the regional impact category indicators are geographically determined, and each long-term impact category is subdivided into short-term, excess emissions over 100 years, and long-term impairments. The

proposed revision of IMPACT World + includes two damage categories: the health of humans and the quality of ecosystems (Bulle et al., 2019). The measurement of human health damage is the Disability Adjusted Life Years (DALYs), representing the number of lost years of a fully healthy life. The indicator of ecosystem quality is given in Potentially Disappeared Fraction (PDF). m<sup>2</sup>. year, defined as the proportion of potentially extinct species due to environmental pressures in certain regions and time periods.

#### 2.2.5. ReCiPe 2016

The ReCiPe 2016 V1.06 covers eighteen midpoint impact categories (problem-oriented) and three endpoint impact categories (harm-oriented) on three global perspectives: hierarchical (H), egalitarianism (E), and individualism (I). These midpoint impact factors are grouped under three endpoint criteria at the extreme endpoint level: resource scarcity, human health, and ecosystems (Catalán and Sánchez, 2020; Cortesi et al., 2022; Mikosch et al., 2022). The unit of measurement for resource scarcity, human health, and ecosystem endpoint characterization factors are expressed in USD 2013, DALYs, and species year, respectively. The scarcity of resources is represented as the excess cost of future resource production, assumed to be constant annual production over an infinite time horizon, with a 3% discontinuity rate (SimaPro, 2023). The human health damage from different environmental stressors is estimated in terms of mortality and morbidity changes. The measure of ecosystem



quality is the relative local species loss across all ecosystems in marine, freshwater, and terrestrial, time, and space integrated. In this study, ReCiPe 2016 Endpoint (H) V1.06 is implemented with a hierarchical perspective using the most common policy principles with respect to a timeframe and other issues.

### 2.2.6. Uncertainty analysis

Uncertainty analysis is not generally undertaken in LCAs, even though considerable attention has been paid to the classification, determination of sources, and addressing methodological aspects of uncertainty expression. Uncertainty arises due to a lack of information, such as when data are unavailable, inaccurate, or imprecise (Guo and Murphy, 2012). On the LCI level, openly accessible LCA databases contain only the average stock data without uncertainty information. During the Life Cycle Inventory Assessment (LCIA) phase, the wide range of methods available for uncertainty analysis was overviewed by (Björklund, 2002). Among them, Monte Carlo simulation has been the most commonly proposed. Nowadays, Monte Carlo Simulations (MCS) have been incorporated into commercial LCA software such as SimaPro, but are still only used in a few LCA studies. In this paper, uncertainty analysis is performed using the SimaPro V9.3.0.3 software. MCS was conducted in 10,000 simulation runs applying 95% confidence level to quantify the uncertainty measures.

### 2.3. PESTLE factors combined with multi-criteria decision analysis

PESTLE is a mnemonic for Political, Economic, Social, Technological, Legal, and Environmental factors. The PESTLE framework provides a birds-eye perspective on the whole technology space that can be used to evaluate and compare the potentials of competing processes. The tool offers oversight of macro- and micro-environmental factors that corporations and stakeholders must consider in decision-making. PESTLE analysis requires a large amount of data for evaluations. The rapidly changing pace of data makes it more and more difficult to predict future trends that affect technology. The process needs to be repeated regularly to be effective. The PESTLE analysis of the process wastewater treatment is summarized in Fig. 2.

Multi-criteria decision analysis (MCDA) was used to compare and rank distillation scenarios using PESTLE sub-criteria. The MCDA was carried out by using the TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution) method. The concept of the classic TOPSIS procedure can be implemented in the following consecutive steps (Balioti et al., 2018).

**Step 1.** Constructing the normalized and weighted normalized decision matrices from the decision matrix (as defined in Eqs. (2) and (3)):

$$v_{ij} = w_j n_{ij}, \text{ with } \sum_{j=1}^n w_j = 1 \quad (2)$$

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (3)$$

**Step 2.** Determining the positive ( $A^+$ ) and negative ideal solutions ( $A^-$ ):

$$A^+ = (v_1^+, v_2^+, \dots, v_n^+) \quad (4)$$

$$A^- = (v_1^-, v_2^-, \dots, v_n^-) \quad (5)$$

**Step 3.** Calculating the closeness of the positive ideal solution:

$$R_i = \frac{\sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}}{\sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} + \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2}}, \text{ where } 0 \leq R_i \leq 1 \quad (6)$$

**Step 4.** Ranking the order of preference by choosing the alternative closest to 1.

Where:

$x_{ij}$  is the value of  $i$ -alternative with respect to  $j$ -criterion, for  $i = 1, 2, \dots, m; j = 1, 2, \dots, n$

$n_{ij}$  is a normalized value

$W_j$  is the weight of the  $j$ th criterion.

$v_{ij}$  is a weighted normalized value

$v_1^+, v_2^+, v_n^+$  are the maximum values of the benefit criteria and the minimum value of the cost criteria

$v_1^-, v_2^-, v_n^-$  are the maximum values of the cost criteria and the minimum value of the benefit criteria.

$R_i$  is the relative closeness to the Ideal Solution of the  $i$ th alternative.

Decerns (Decision Evaluation in Complex Risk Network system)

MCDA V1.5 software (Sullivan et al., 2009; Yatsalo et al., 2015) was applied to perform the MCDA of the distillation process considering various energy supply scenarios.

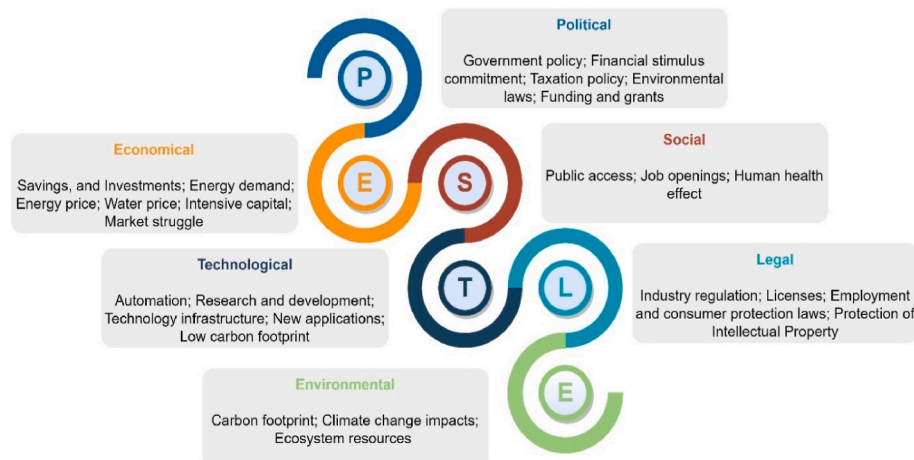


Fig. 2. The scope of the PESTLE analysis applied for process wastewater treatment.

### 3. Results and discussion

#### 3.1. Life cycle analysis of process wastewater treatment by air stripping, steam stripping, distillation, and incineration methods

The life cycle impact assessment results are summarized in Tables S2–4 of the Supporting information: EF 3.0 method (adapted) in Table S2, IMPACT World + Endpoint in Table S3 and ReCiPe 2016 Endpoint (H) in Table S4. The results show that the incineration process has the highest impact, followed by steam stripping, air stripping, and distillation. Considering only the separation efficiency of technologies, distillation can achieve an 82% reduction in pollutant discharge that is followed by air stripping (approx. 42%) and steam stripping (approx. 21%).

The categories of human health and toxicity impacts investigated processes are shown in Fig. 3. Based on the ReCiPe 2016 Endpoint (H) method shown in Fig. 3a, distillation has the lowest impact on human health ( $2.29 \times 10^{-8}$  DALY), followed by air stripping, steam stripping, and incineration with values of  $2.58 \times 10^{-8}$ ,  $4.07 \times 10^{-8}$ , and  $5.96 \times 10^{-8}$  DALY, respectively. Based on the IMPACT World + Endpoint method, as illustrated in Fig. 3b, the number of days spent in disease is only  $6.21 \times 10^{-5}$  days  $\text{FU}^{-1}$  by applying distillation. This value is increased in the case of air stripping ( $6.39 \times 10^{-5}$  days  $\text{FU}^{-1}$ ), steam stripping ( $7.19 \times 10^{-5}$  days  $\text{FU}^{-1}$ ) and incineration ( $9.56 \times 10^{-5}$  days  $\text{FU}^{-1}$ ). Fig. 3c illustrates that the AOX removal based on distillation is characterized by 1.08, 1.46, and 7.37 times lower human toxicity impact compared to air stripping, steam stripping, and incineration, respectively. The human toxicity effect of incineration increased significantly

compared to the other three technologies, showing the severe influence, causing non-cancer or cancer agents to humans.

Table S4 and Fig. 3d show that incineration and steam stripping leave a lot of carcinogenic substances in the wastewater, resulting in less desirable AOX removal process alternatives. It is obtained that distillation, air stripping, steam stripping, and incineration are characterized by carcinogenic toxicity values of  $2.78 \times 10^{-10}$ ,  $3.00 \times 10^{-10}$ ,  $4.11 \times 10^{-10}$ , and  $4.16 \times 10^{-10}$  DALY  $\text{FU}^{-1}$ , respectively. The energy and materials contribution to human carcinogenicity are listed in Table S5 of the Supporting information. Energy, methanol, dichloromethane, and isobutanol are mainly responsible for carcinogenicity. Dichloromethane is one of the AOX compounds. The ReCiPe 2016 Endpoint (H) modelling results indicate that methanol, dichloromethane, and isobutanol contribute to 27.20%, 53.50%, and 2.12% of human carcinogenicity, respectively. Methanol and isobutanol are present in the feed stream at 0.443% and 0.066% by weight, while the AOX compounds are present in a concentration of 0.102 wt%. The simulation results show that specific energy consumption contributes significantly to the human carcinogenic toxicity impact. Energy consumption is responsible for 18.1%, 24.2%, 44.9%, and 56.9% of human carcinogenic toxicity in the case of distillation, air stripping, steam stripping, and incineration.

In Fig. 4, the examined processes are classified according to their impact on ecosystem quality. As shown in Fig. 4a, the ecosystem quality of distillation, air stripping, steam stripping, and incineration is  $9.75 \times 10^{-3}$ ,  $1.12 \times 10^{-2}$ ,  $1.83 \times 10^{-2}$ ,  $3.28 \times 10^{-2}$  PDF.  $\text{m}^2$ . yr, respectively. Meaning that if wastewater is separated by distillation,  $9.75 \times 10^{-3}$  species are lost per functional unit per year. Thus, the ecosystem impact of the distillation technology is 1.15, 1.88, and 3.36 times smaller than

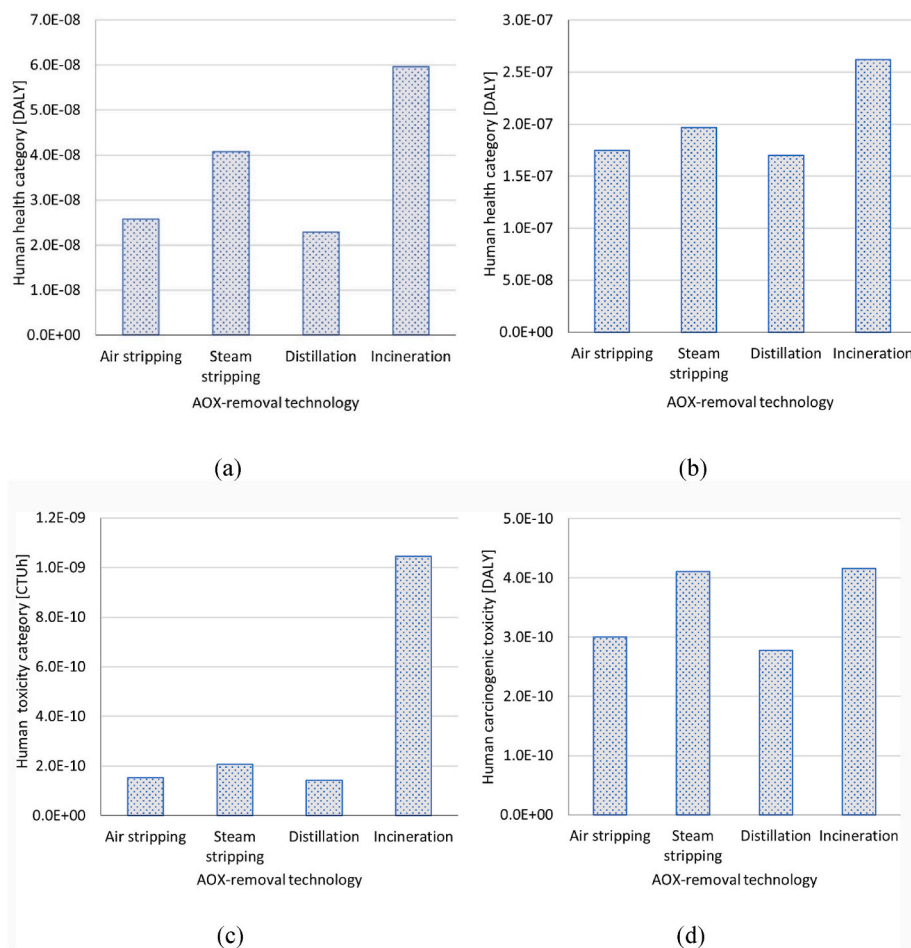


Fig. 3. Human health based on (a) ReCiPe 2016 Endpoint (H) method and (b) IMPACT method; (c) Human toxicity based on EF 3.0 method (adapted); (d) Human carcinogenic toxicity based on ReCiPe 2016 Endpoint (H) method of the investigated alternatives.

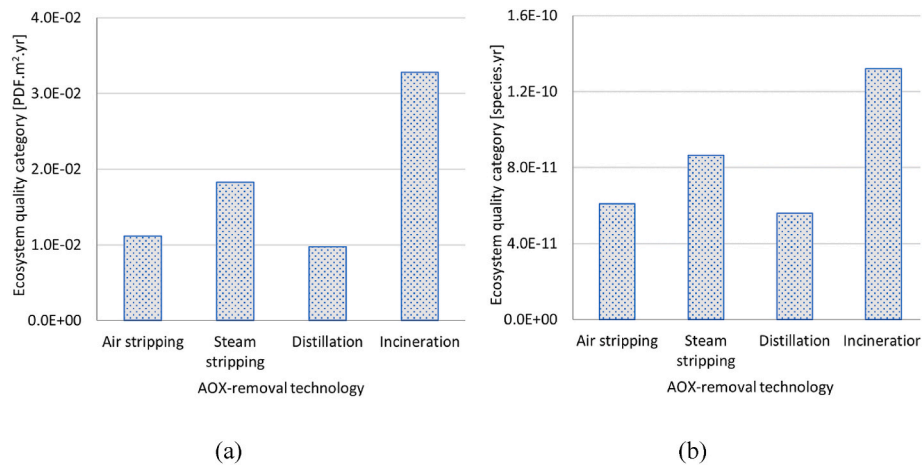


Fig. 4. Ecosystem quality based on (a) IMPACT World + Endpoint and (b) ReCiPe 2016 Endpoint (H) method of the investigated alternatives.

air stripping, steam stripping, and incineration. If process wastewater was not purified,  $1.09 \times 10^{-1}$  species could be lost in a year. AOX compounds account for 24% of this high degradation. If distillation is used, the harmful amount is reduced by 91% compared to AOX-rich

wastewater.

Climate change impact in the operation phases of investigated technologies was calculated based on the EF, as shown in Table S2. The results show that the distillation process produces the lowest pollution of

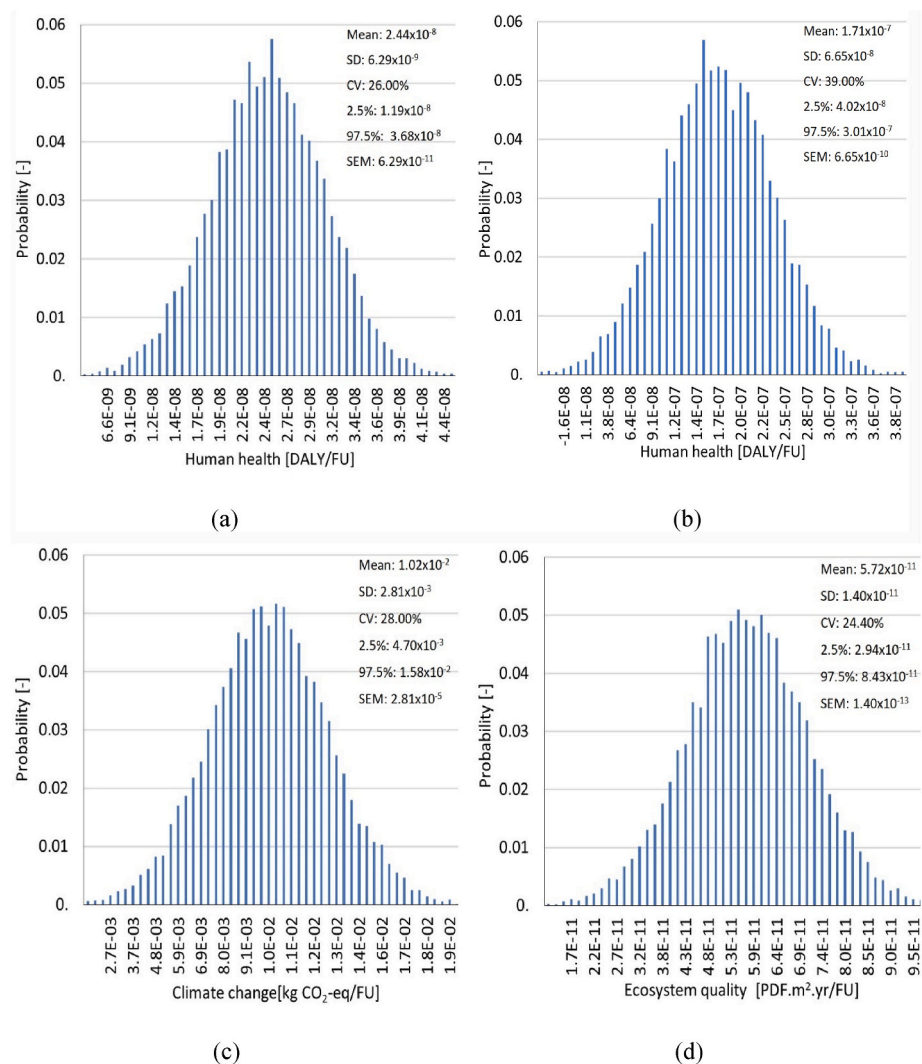


Fig. 5. Monte Carlo analysis of distillation based on (a) ReCiPe 2016 Endpoint (H) method - Human health; (b) IMPACT method - Human health; (c) EF 3.0 method - Climate change; (d) ReCiPe 2016 Endpoint (H) method- Ecosystem quality.

the four technologies. It emits  $1.02 \times 10^{-2}$  kg of CO<sub>2</sub>-eq FU<sup>-1</sup>, which is 1.12 times, 1.75 times and 3.16 times less than air stripping, steam stripping, and incineration. The climate change impact is influenced by the energy requirement of AOX separation and the emission of methanol and AOX compounds, including dichloromethane. For example, dichloromethane contributes to 35.6% of total distillation's CO<sub>2</sub> emissions; methanol contributes 29.2%, and electricity consumption accounts for 27.8%. In the case of air stripping, the contribution of dichloromethane, methanol, and electricity to the total CO<sub>2</sub> emissions is 31.7%, 26%, and 35.7%. As for steam stripping, the contribution of the above factors is obtained to be 20.4%, 16.7%, and 58.6%, respectively. Distillation can reduce CO<sub>2</sub> emissions by 82% because the concentration of methanol and AOX compounds in the residue is much lower than in the two stripping processes. Though stripping is more efficient in separating AOX compounds, but methanol is released into the ecosystem with water.

The results of the Monte Carlo Simulation are presented in Fig. 5, using distillation technology based on ReCiPe 2016 Endpoint (H) method and the IMPACT World + Endpoint - Human health category; EF 3.0 - Climate Change category; and ReCiPe 2016 Endpoint (H) method - Ecosystem quality category. In the Supporting information, more tables represent the results of the Monte Carlo Simulation of ReCiPe (2016) Endpoint (H) method (Table S6), IMPACT World + Endpoint method (Table S7), and EF 3.0 method (Table S8). The Coefficient of Variation (CV) indicates normalized dispersion in the category indicator results, SD represents the Standard Deviation, and SEM denotes the Standard Error of the Mean. The human health median from data generated by distillation technology in the MCS based on the ReCiPe 2016 Endpoint (H) method is  $2.44 \times 10^{-8}$  DALY, SD =  $6.29 \times 10^{-9}$ ; and with the IMPACT method is Mean =  $1.71 \times 10^{-7}$ , SD =  $6.65 \times 10^{-8}$ . Fig. 5a, b shows that uncertainty simulations follow a normal distribution using a 95% confidence level. The simulation results with the ReCiPe 2016 Endpoint (H) and IMPACT World + Endpoint LCIA methods are obtained to be in a range of  $1.19 \times 10^{-8}$  to  $3.68 \times 10^{-8}$  DALY, and  $4.02 \times 10^{-8}$  to  $3.01 \times 10^{-7}$  DALY, respectively. Fig. 5c indicates that the climate change impacts characterized by the EF 3.0 method follow a normal distribution with a median value of  $1.02 \times 10^{-2}$  kg CO<sub>2</sub>-eq and SD of  $2.81 \times 10^{-3}$ . The MCS results show that 95% of climate change impacts fall from  $4.70 \times 10^{-3}$  to  $1.58 \times 10^{-2}$  kg CO<sub>2</sub>-eq. The uncertainty results of the Ecosystem Quality impact category show ecosystem quality effects are within the range of  $2.94 \times 10^{-11}$  to  $8.43 \times 10^{-11}$  PDF. m<sup>2</sup>. yr (Fig. 5d).

The goal of the European Union is to become climate neutral by 2050, which implies zero net greenhouse gas emissions for all EU countries, primarily by lower greenhouse gas emissions, green technology investment, and conservation of the natural environment. In addition to wastewater treatment, minimizing waste during production is vital, for example, by reducing inputs or recycling by-products. Today's challenge for the engineering community is to modify existing and operational industrial processes to match increasingly stringent environmental standards. In the long term, the environmental goal is to develop Zero Liquid Discharge, but developing such technologies still requires much future research.

### 3.2. The impact of energy sources on the performance of distillation

Fossil fuels, nuclear, and renewable energy are the three primary sources of energy worldwide, which are traditionally viewed as competitors. For modern societies, replacing crude oil and reducing greenhouse gas emissions are the two most pressing energy-related challenges. PESTLE factors combined with Multi-Criteria Decision Analysis (MCDA) were used to determine an ideal distillation-based scenario for AOX-contaminated wastewater treatment in EU. The PESTLE-based criteria set are discussed below.

#### 3.2.1. Political and legal

The EU's main power source shifted from fossil fuels to renewables for the first time in 2020: 38% of electricity was generated by renewables, 37% by fossil fuels, and 25% by nuclear (European Commission, 2021a,b). A clear binding framework for reaching climate neutrality by 2050 was established with the adoption of the European Climate Law. The 2030 Climate Target Plan enshrines a minimum 55% reduction in greenhouse gas emissions by 2030 and relies on Member States' National Energy and Climate Plans (NECPs). As part of its pioneering "Delivering the European Green Deal" package, which supported the path outlined in the Climate Law, a series of interconnected proposals was presented across the economy with the aim of increasing the ambition for 2030, among others, through setting new targets for greenhouse gas reduction, renewable energy production, and energy efficiency. A complete framework for the deployment of renewable energy, targeting all sectors of the economy, was proposed by the Commission, aiming to increase the EU 2030 renewable energy target from 32 to 40% of the Union's gross final energy consumption. In addition to the planned combined climate-related investments of around EUR 177 billion, approximately EUR 76 billion will be spent on energy efficiency and clean energy investments and reforms in Europe (European Commission, 2022).

The Commission developed an EU Solar Energy Strategy in 2022 to support innovation and deployment of renewable energy. In 2020, renewable energy investments in the EU reached EUR 48.8 billion, up from EUR 32.9 billion in 2019. However, the situation varied across the technologies: onshore wind added 8.4 GW–7.1 GW yearly, offshore wind added 1.5 GW–2.5 GW, and solar PV added 16.3 GW–18.6 GW. The 2020's offshore renewable energy strategy sets the goal of deploying at least 60 GW of offshore wind power and 1 GW of ocean energy by 2030 to achieve 300 GW of offshore wind power and 40 GW of ocean power by 2050 without causing environmental harm while allowing different uses of the sea. As a result, all European sea basins will generate more wind electricity.

In December 2021, a decarbonization package addressed consumer provisions, including gas markets. Consumer choice and active participation will be promoted by the EU Commission's implementation of existing legislation to allow consumers to engage in the market actively. Self-consumers, prosumers, and active consumers are increasingly important constituents of the Renewables Directive and the Electricity Directive. As a result of this legal framework, distributed energy communities and citizen energy communities can cooperate with each other in the development of clean energy. As part of the EU's efforts to promote the use of renewable energy from new installations, the Commission is considering options for establishing a Union-wide green label.

#### 3.2.2. Economical

The Total Annual Cost (TAC) was calculated for a column with optimal parameters. The TAC includes the annual operating and investment costs with a 10-year amortization period. In a year, the equipment operates for 8000 h. The investment cost (IC) estimate for the rectification column was calculated using the Douglas cost equations (Douglas, 1988) in euro (€). The investment costs for the outside, the inside of the column, and the heat exchangers were calculated using Equations (7)–(9). In these equations, inflation is taken into account through the M&S index. In estimating the operating costs (OC), the annual heating cost of the reboiler and the condenser's costs were calculated. The surface area of the heat exchangers was determined using the relationship as shown in Equation (10). Table 2 shows the costs of the column with optimal operation.

$$IC_{\text{column outside}} = \left( \frac{M\&S}{280} \right) * 101,9 * D^{1.066} * H^{0.82} * (2,18 + F_c) \quad (7)$$

$$IC_{\text{column inside}} = \left( \frac{M\&S}{280} \right) * 4,7 * D^{1.55} * H * F_c \quad (8)$$



**Table 2**  
Cost estimation of the distillation process.

IC of column outside [€]	52,500
IC of column inside [€]	351,200
IC of condenser [€]	51,400
IC of reboiler [€]	70,300
OC of cooling [€/year]	7100
OC of heating [€/year]	23,000
Total of OC [€/year]	30,100
Total of IC [€/year]	52,500
TAC [€/year]	82,600

$$IC_{\text{heat exchanger}} = \left( \frac{M\&S}{280} \right) * 101,3 * A^{0.65} * (2,29 + F_c) \quad (9)$$

$$Q = k * A * \Delta T \quad (10)$$

Where,

M&S is the Marshall & Swift equipment cost index, considered in this work has a value of 1773.4 [-]

D is the diameter of column [m].

H is the height of column [m], considering a tray-spacing of 0.6096 m.

$F_c$  is constant [-]. For the outside of the stainless-steel column:  $F_c = 2.25$ , while for the inside:  $F_c = 12.6$ , for the heat exchangers:  $F_c = 5.1$ .

A is the total heat transfer area [ $m^2$ ].

Q is heat transfer [W].

K is heat transfer coefficient [ $W/(m^2 \cdot K)$ ]

$\Delta T$  is taken as the logarithmic temperature difference [K].

The total annual cost of the distillation process is 82,641 €/year, where 36.5% of TAC is attributed to the cost of energy. The prices of electricity depend on the source of energy. Solar power generates electricity at the expense of 0.0114 €/kWh, solar photovoltaics at 0.048 €/kWh, offshore wind at 0.075 €/kWh, onshore wind at 0.033 €/kWh, nuclear at 0.03 €/kWh, and fossil fuels at 0.0076 €/kWh (IRENA, 2022).

### 3.2.3. Social

All factors affecting the market and community socially, including the advantages and disadvantages to the local communities, are considered in the social aspects. ReCiPe 2016 Endpoint (H) and IMPACT World + Endpoint methods were used to examine the social aspect of distillation. Human health is the damage category, which is shown in Fig. S3 in Supporting information. Assuming that fossil fuels have a 100% impact on human health, renewable energy sources are reduced by about 20% based on the Impact World + Endpoint method and almost 40% based on ReCiPe 2016. Accordingly, there is no difference between wind onshore and offshore energy. Wind energy has the least impact on human health, followed by nuclear and solar. A total of  $3.16 \times 10^{-5}$  days is spent with diseases for the whole population based on the IMPACT World + Endpoint method for 1 kg purified wastewater (1 functional unit) by fossil fuel. Nuclear energy suffers from illness for  $2.57 \times 10^{-5}$  days, solar energy for  $2.52 \times 10^{-5}$  days, and wind onshore and wind offshore for  $2.51 \times 10^{-5}$  days.

The combination of renewable energy sources with distillation or other wastewater treatment technologies creates new job opportunities. For technology and solution development and deployment to proceed, all skill levels must be retrained and uptrained in order to accommodate the rapid growth of clean energy innovations. Renewable energy and energy efficiency will drive job creation in relation to the energy transition. Installation and production of solar PV panels are key drivers of jobs in wind energy and solar PV. Solar PV is expected to create up to 140,000 full-time jobs in the EU by 2050, while wind energy will create more than 420,000 (European Commission, 2021a,b).

### 3.2.4. Environmental

The results of the environmental impact of distillation process energy

alternatives have been shown in Table S9 in the Supporting information. As seen in Table S9, the most significant source of carbon emissions is fossil fuels, followed by nuclear power, solar energy, and wind energy. It is obtained that the climate change impact of wind onshore energy is 64.87% lower compared to fossil fuels. Hard coal is the fossil fuel selected for this study.

In addition, environmental impacts are significant in several impact categories in the case of EF 3.0 methods, which are listed in Table S9. In general, fossil fuel accounts for the majority of ecotoxicity of fresh water, climate change, eutrophication of marine, eutrophication of fresh water, photochemical ozone formation, acidification, eutrophication of terrestrial, followed by nuclear, solar, and wind. Solar energy in land use is much worse than other energy sources. As far as ozone depletion, mineral and metal resource use, and water use are concerned, there is no significant difference between energy sources. Notably, a significant difference between nuclear energy and fossil fuels is the amount of ionizing radiation produced. Ionizing radiation from nuclear energy is 23.65 times greater than fossil fuel, and 24.73 times more than renewable energy.

### 3.2.5. Technological

Renewable energy technologies are becoming more attractive for water supply and wastewater treatment applications. Energy generated from renewable sources can be used for conventional and emerging water treatment technologies, such as distillation.

Direct or indirect uses of solar energy (thermal or electrical) can treat wastewater by distillation. Water can be pumped with electricity produced by PV panels. Stabilization ponds, aerated lagoons, and oxidation ditches are the three most common treatment methods with solar energy. Solar distillation systems with small capacities are designed for distances in remote, drought, or semi-drought areas. Preference is given to simple designs that are cost-effective and easier to operate and maintain, using locally available materials, considering the reliability and durability of the installation. Several solar distillation plants with a 1–40  $m^3$ /day capacity are currently operating in Greece, India, the Caribbean islands, and other locations (Delyannis and Belessiotis, 2004).

The wind can also be used to pump water manually using wind pumps or windmills and treat or disinfect water with electrical energy produced by the wind turbine. Electric wind turbines operate at higher wind speeds than mechanical wind pumps.

These windmills operate at between 2.5 and 3.5 m/s, while the average wind speed of an electric wind turbine is 5–6 m/s to make it more competitive with windmills used in water pumping applications. As the size of the wind turbine rotor increases, the initial wind speed becomes higher. Secondly, wind turbines provide many benefits over windmills in versatility and generation of electricity. The turbine installation can be placed in higher wind conditions, and the electricity generated can be fed to the pumping station. The turbine's electricity can be used for storage in batteries or in purification systems. Applications for wind turbines are pumping water, lighting, and water treatment systems (Argaw, 2003).

Also increasingly attractive nowadays are hybrid systems, particularly for remote autonomous systems. The hybrid system can consist of a combination of PV, wind turbines with or without standby, and battery storage.

### 3.3. The results of multi-criteria decision analysis

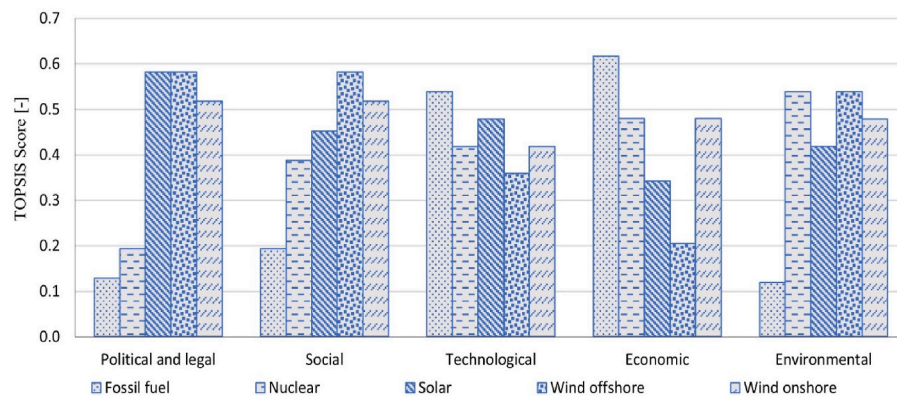
TOPSIS scores of energy scenarios were determined considering the political-legal, economic, social, and technological subfactors based on their assessment specified in Table 3. The results of MCDA are detailed in Fig. 6a and b. According to the results, the most favourable energy source alternatives are wind turbines installed onshore, followed by wind offshore, solar, nuclear, and fossil fuel. Wind energy stands out from multiple perspectives among the investigated energy sources.

The rankings are subjective inputs that reflect the practitioner's

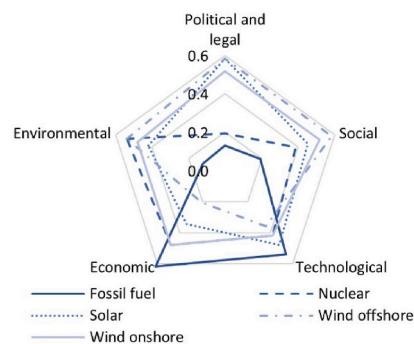
**Table 3**

Classical TOPSIS method alternatives for qualitative criterion ratings. [0,1]-very poor; [1,3]-poor; [3,4]-medium poor; [4,5]-fair, [5,6]-medium good; [6,9]-good; [9,10]-very good.

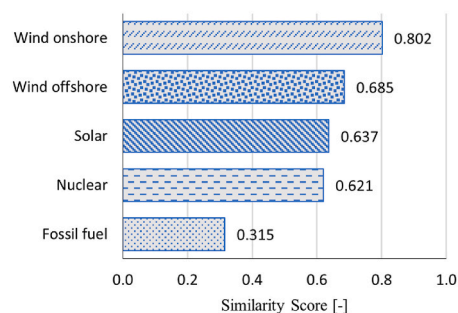
	Political & legal	Economic	Social	Environmental	Technological
Fossil fuel	2	9	3	2	9
Nuclear	3	7	6	9	7
Solar	9	5	7	7	8
Wind offshore	9	3	9	9	6
Wind onshore	8	7	8	8	7



(a)



(b)



(c)

**Fig. 6.** (A) The TOPSIS Score diagram, (b) Radial graph based on PESTLE factors, and (c) Report of the MCDA (A higher score is better).

opinion. Social and environmental factors weighed most heavily in this study, followed by economic factors. The least important factors were political-legal and technological. The weights of the criterion can be found in Table S10 in Supporting information.

The final results of the multi-criteria decision analysis are illustrated in Fig. 6c. With a TOPSIS score of 0.802, distillation combining wind onshore is found to be the most advantageous alternative for the EU region. Solar, wind offshore, and nuclear were followed by wind onshore. Fossil fuels rank the worst out of the alternatives, scoring down to 0.315.

Overall, the use of renewable energy for wastewater treatment has gained considerable attention since 2000 because of its ability to reduce carbon dioxide emissions, provide sanitation and reuse water in remote areas. The availability of renewable energy has increased over the last few decades, making wastewater treatment facilities more likely to utilize it. Using renewable energy for wastewater treatment could be an option if energy grids are down following a natural disaster. Nevertheless, when considering the promotion of renewable technologies for water treatment in urban communities, the system's sustainability, the

potential costs, the promotion from local political and legal, the accessibility of energy sources, the availability of a skilled workforce, and replacement parts must be considered. Applying wastewater treatment technologies from renewable energy sources, including distillation plants, can be extremely costly. The technology requires large amounts of energy, leading to high investment costs, notably for applications in urban. Alternatively, renewable energy sources may give opportunities for increased economic viability in some treatment requirements and locations. For example, there may be cases where grid power is not an alternative source in many developing countries and remote island locations due to significant grid expansion. In these cases, it may be that renewables are the only alternative. Any alternative system should be assessed based on local conditions and the sustainability aspects of the system.

#### 4. Conclusions

The present study examines the performance of air stripping, steam stripping, distillation, and incineration in adsorbable organic halogens

(AOX) removal using life cycle assessment, PESTLE, and multi-criteria decision analyses. While halogen compounds continue to be used in the pharmaceutical industry, more attention should be given to AOX in pharmaceutical wastewater. There needs to be an adequate investigation into the efficacy of AOX removal technologies regarding their environmental impact to assess the sustainability of AOX removal technologies. Distillation is obtained to be the best method in terms of human health, ecosystem quality, and climate change impacts. According to the Environmental Footprint V3.0 method, distillation is less harmful to human toxicity than air stripping, steam stripping, and incineration by 1.08, 1.46, and 7.37 times, respectively. Based on the ReCiPe 2016 Endpoint (H) method, distillation is characterized by the lowest human health ( $2.29 \times 10^{-8}$  DALY (kg purified wastewater) $^{-1}$ ), followed by air stripping, steam stripping, and incineration with values of  $2.58 \times 10^{-8}$ ,  $4.07 \times 10^{-8}$ , and  $5.96 \times 10^{-8}$  DALY (kg purified wastewater) $^{-1}$ , respectively. Distillation technology has a median human health impact of  $2.44 \times 10^{-8}$  DALY, with an SD of  $6.29 \times 10^{-9}$  and a CV of 26.0%. The 95% characterization of human health effects falls within the range of  $1.19 \times 10^{-8}$  to  $3.68 \times 10^{-8}$  DALY. According to the sustainability analyses, the distillation process has proven to be more environmentally efficient than stripping solutions for treating AOX-contaminated process wastewater. A distillation process combined with onshore wind energy has been determined to be the most favourable method based on PESTLE criteria and multi-criteria decision analysis.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

Data will be made available on request.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2023.118593>.

#### Abbreviations

AOX	Adsorbable Organic Halogens
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CTUe	Comparative Toxic Unit for ecosystem
CTUh	Comparative Toxic Unit for human
CV	Coefficient of Variation
DALYs	Disability Adjusted Life Years
EF	Environmental Footprint
FU	Functional Unit
GHGs	Greenhouse Gases
IC	Investment Cost
KATOX	Catalytic Oxidation
LCA	Life Cycle Analysis
LCIA	Life Cycle Inventory Assessment
MCDA	Multi-Criteria Decision Analysis
MCS	Monte Carlo Simulation
NF	Nanofiltration

OC	Operating Cost
PAF	Potentially Affected Fraction
PDF	Potentially Disappeared Fraction
PEF	Product Environmental Footprint
PESTLE	Political, Economic, Social, Technological, Legal, Environmental
RO	Reverse Osmosis
SCWO	Supercritical Water Oxidation
SD	Standard Deviation
SEM	Standard Error of Mean
TAC	Total Annual Cost
TOPSIS	Technique for Order Preference by Similarity to the Ideal Solution
VOCs	Volatile Organic Compounds

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