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Full length article

Assessment of environmental sustainability of drinking water treatments for arsenic removal

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ABSTRACT

To date, few studies that developed a complete Life Cycle Assessment (LCA) are available in literature, but they are limited to non-conventional processes and did not take into consideration the entire drinking water treatment plant (DWTP). Moreover, few data of the environmental impact are currently available for some of the most widely applied technologies such as biological filtration and coagulation. This study aims to overcome this research gap carrying out a LCA in order to identify (i) what is the most impactful process, and (ii) what possible solutions for mitigating the impact can be proposed. Focusing on the treatment for arsenic removal, the results showed that coagulation was the most impactful process mainly due to the electricity consumption while, looking at the entire DWTP, disinfection prevails. In view of potential up-grade, the use of green energy can effectively increase the sustainability.

1. Introduction

Arsenic is a naturally occurring element commonly found in geological formations, particularly in regions characterized by specific geological attributes (Raju, 2022). The arsenic contamination in water sources is mainly due to the dissolution from minerals and rocks, agricultural runoff, and industrial discharges and has determined a significant concern due to its detrimental effects on human and ecosystems (Adeloju et al., 2021; Raju, 2022) In fact, human exposure to elevated levels of arsenic through water consumption has been linked to various health issues, including skin diseases, developmental disorders and various types of cancer (Mohammed Abdul et al., 2015). Moreover, arsenic contamination can also affect the fertility of soils irrigated with polluted water and can damage the plant health (Khanikar and Ahmaruzzaman, 2022; Pawar et al., 2022).

The World Health Organization (WHO) and various national regulatory agencies have established stringent limits for arsenic concentrations in drinking water in order to protect the public health. For instance, the WHO set a guideline value of 10 $\mu g\ l^{-1}$ for the presence of arsenic in drinking water (Khan and Flora, 2023). However, in several countries of the world, such as Bangladesh, Cambodia, China, India, Pakistan (Chunhui et al., 2018; Farooqi et al., 2007; Subhani et al., 2015; Thakur et al., 2019), Argentina, Chile, Mexico, United States (Reyes-Gómez et al., 2015), and, in Europe, Greece, Italy and Spain (Katsoyiannis et al., 2015; Tolkou et al., 2023), the arsenic in groundwater frequently exceeds the limits suggested by the WHO.

For this reason, arsenic removal techniques are essential for reducing the toxicity and health risks determined by arsenic contamination (Alka et al., 2021). Several methods have been developed for arsenic removal (Nicomel et al., 2015), including biological processes (Maity et al., 2021), coagulation (Hu et al., 2012; Katsoyiannis et al., 2017), chemical and electrochemical oxidation (Callegari et al., 2018; Collivignarelli et al., 2019; Sorlini et al., 2023; Tolkou et al., 2023), microfiltration (Usman et al., 2021, 2020), ion exchange (Laatikainen et al., 2016), phytoremediation (Srivastava et al., 2021), and adsorption (Meez et al., 2021; Tolkou et al., 2020). Different combinations between the methods

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Abbreviations: AER, aeration; BF, birm-ferric hydroxide-based sorbent; BIO, biological filtration; COA, coagulation with $feClSO_4$; CSB, canola straw biochar; DIS, disinfection with NaOCl; DWTP, drinking water treatment plant; EP, environmental prices; FIL, filtration; FU, functional unit; GAC, granular activated carbon; GW, global warming; HCT, human carcinogenic toxicity; HnCT, human non-carcinogenic toxicity; LCA, Life Cycle Assessment; OGF, ozonation-greensand-ferric hydroxide-based sorbent; PM, fine particulate matter formation; WaC, water consumption; WHO, world health organization; WTR, water treatment residuals.

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have been also tested (Hering et al., 2017). These techniques aim to reduce the concentration of arsenic in water and soil, and their effectiveness varies depending on the specific conditions and contaminants present (Feng et al., 2023; Mahamallik and Swain, 2023; Rada et al., 2013; Sen et al., 2023; Srivastava et al., 2022).

In order to choose the best solution, it is important to consider factors such as the economic feasibility, sustainability and the safe disposal of treatment residues (Ahmed et al., 2022; Weerasundara et al., 2021). Moreover, like any other treatments, also technologies for arsenic removal determined indirect environmental impacts that can significantly affect ecosystems and human health (Alka et al., 2021). In fact, standard methods for arsenic removal involve chemical agents, such as coagulants, oxidants, disinfectants and energy-intensive processes (e.g., oxidation) (Altowayti et al., 2022). These activities contribute also to greenhouse gas emissions and the generation of chemical waste, which in most cases is loaded with arsenic. Additionally, the extraction, production, and disposal of materials used in these systems further contribute to resource depletion and environmental degradation (Maktabifard et al., 2023). For this reason, in the decision-making process for the selection of the proper technologies for arsenic removal, the economic aspect should not be the only one considered.

The use of a Life Cycle Assessment (LCA) approach can be crucial for comprehensively evaluating the environmental sustainability of arsenic removal systems because it considers the entire life cycle of a product or process, from raw material extraction to end-of-life disposal, offering a holistic perspective on environmental impacts (Paoli et al., 2022). By applying LCA, decision-makers can identify hotspots in the life cycle, prioritize sustainable alternatives, and develop strategies to minimize the overall environmental burden associated with technologies (Baltrocchi et al., 2023; Ferronato et al., 2023). In literature, several examples of LCA application in the field of water treatment for arsenic removal are available (Goyal et al., 2023; Tsangas et al., 2023) (Table S1).

However, in most cases, the studies lacked consider the global sustainability of the processes but focused only on the estimation of global warming potential. For instance, (Norberto et al. (2023) evaluated H_3PO_4-$FeCl_3$ treated canola straw biochar (CSB) for the adsorption of arsenate (As^{5+}) and arsenite (As^{3+}) and highlighted the emissions were equals to -0.298 kg CO_2,eq kg^{-1}_{CSB}, including avoided impacts.

So, based on the authors knowledge, this work represents the first attempt to evaluate the environmental sustainability with a focus on all different midpoints and not only on global warming potential. Only three other study that developed a complete LCA is available in literature, but they are limited to non-conventional processes and did not take into consideration the entire drinking water treatment plant (DWTP). In particular, Hu et al. (2020) studied ozonation-greensand-ferric hydroxide-based sorbent (OGF) and Birm-ferric hydroxide-based sorbent (BF) processes for arsenic and manganese removal. Considering the total volume of water treated using the two systems for ten years (9.5E04 m^3), they found that the impacts of OGF are mainly due to the manufacturing of the sorbent and the disposal of arsenic-contaminated treatment waste but the generated impacts are lower than BF. Goyal et al. (2023) analysed the increase of environmental sustainability in using iron impregnated granular activated carbon (GAC-Fe) instead of conventional activated carbon. The functional unit (FU) considered the treatment of 1 m^3 of contaminated groundwater having an initial arsenic concentration of 0.2 mg l^{-1} showing that the treatment with GAC-Fe emitted 1.85 kg CO_2,eq vs. 2.67 kg CO_2,eq emitted with the conventional ones. Finally, Goyal and Mondal (2022) estimated the emissions of adsorption with aluminum hydroxide/oxide nanoparticles and electrocoagulation processes for the removal of arsenic and fluoride. Their results highlighted that they emitted 35.25 $kgCO_2$,eq and 4.5 $kgCO_2$,eq, respectively, for the treatment of 720 L contaminated groundwater with an initial arsenic concentration of 0.5 mg l^{-1}.

The research is investigating the effect of novel approaches such as the use of engineered adsorbents and membrane technologies (Carnevale et al., 2024; Dilpazeer et al., 2023). However, to date, in most of cases the removal of arsenic from groundwater was carried out through conventional processes (such as biological and sand filtration, and coagulation (Hering et al., 2017)) but for these technologies the literature lacks of data.

This study aims to evaluate the environmental sustainability of a DWTP designed to remove arsenic from groundwater in order to identify the most impactful process for arsenic removal and what possible solutions for mitigating the impact of the entire DWTP can be proposed. The reported outcomes are intended to be useful for the scientific community and the technical stakeholders and to the best of our knowledge, these is the first data set provided in literature to assess the whole drinking water treatment process for arsenic removal.

2. Materials and methods

2.1. Goal and scope definition

A real DWTP designed for removing arsenic from groundwater with conventional treatments was considered in the analysis. The plant was in northern Greece and treated groundwater with concentrations of arsenic (20 μg l^{-1}) and manganese (235 μg l^{-1}) higher than the legislation limit. The detailed characteristics of the groundwater are available in Table S2. The scheme of the plant is composed by five main treatment phases, namely: aeration (AER), up-flow biological filtration (BIO), coagulation with $FeClSO_4$ (COA), final down-flow filtration (FIL), and disinfection with NaOCl (DIS).

This study wants to answer two different research questions (RQ):

RQ1. what is the most impactful process for arsenic removal?

RQ2. what possible solutions for mitigating the impact of the entire DWTP can be proposed?

The analysis was carried out following the LCA methodology according to the standards ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b). SimaPro v9.6 (Goedkoop et al., 2016) and Ecoinvent v3.9.1 database (Wernet et al., 2016) were used for the analysis. Simapro software was chosen for its consistency, functional graphical interface, and effective uncertainty analysis (Ormazabal et al., 2014) while Ecoinvent database is recognised as the largest unit-process LCI database worldwide. Its structure allows users to trace the impacts of their products throughout the supply chain and understand their results (Wernet et al., 2016).

The environmental profile was evaluated with the impact assessment method ReCiPe 2016 v1.07, while the global warming potential was assessed with the method IPCC 2021 GWP100 v1.02. ReCiPe2016 provides a state-of-the-art method for converting inventory data to environmental impact scores on midpoint and endpoint levels (17 midpoint and 3 endpoint categories) (Huijbregts et al., 2017). Finally, IPCC 2021 GWP100 ensures the use of the most recent scientific data on climate change, facilitates comparability between studies, and aligns with internationally recognized standards. This method provides a view of greenhouse gas impacts over 100 years (Arias et al., 2021). It should be noted that, although these methods cover most impact categories, other studies developed with different impact assessment methods may not be easily comparable. The environmental profile is reported in mPt, where Point (Pt) is a measurement unit representative of one-thousandth of the yearly environmental load of the average European inhabitant (Paoli et al., 2022). Furthermore, the results of global warming potential are shown in kg CO_2 eq measurement unit.

Two different LCAs have been carried out to answer the work's aims. Depending on the aim of the analysis, two diverse FUs have been chosen. To answer RQ1, a first analysis (LCA-1) in which 1 mg of arsenic was removed from groundwater was defined as FU was carried out (Fig. 1). Moreover, in order to define the comprehensive impact of the DWTP and suggest potential mitigation scenarios (RQ2), another analysis was

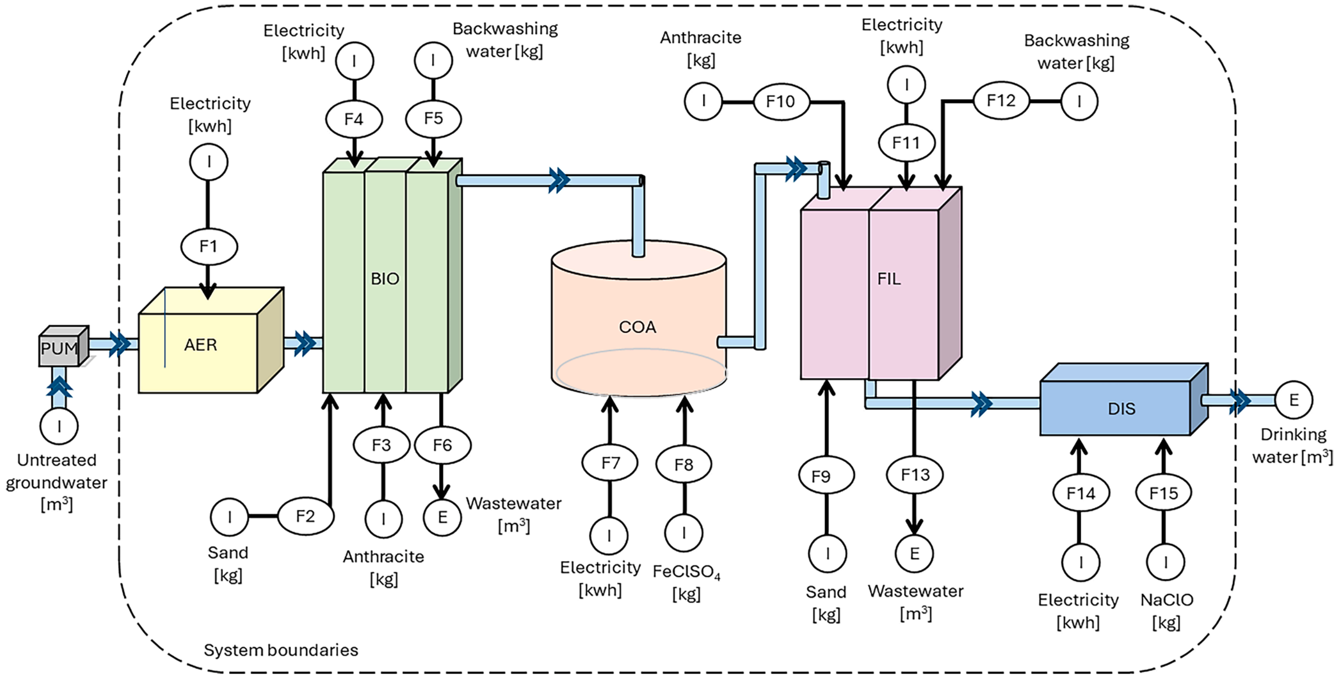

Fig. 1. System boundaries (SBs) for the LCA-1 and LCA-2 analysis.

carried out, defining 1 m^3 of polluted water as FU (LCA-2).

2.2. *Life cycle inventories (LCIs)*

Primary data referred to the specific DWTP has been used in the LCA. However, where primary data are not available (e.g., electrical consumptions), literature data was used (Table S3). Data referred to this specific DWTP were used while when not available (e.g., for average electrical consumption) literature was used. The total water supply rate of the DWTP was 70 m^3 h^{-1}, and treatments were carried out in five main phases. Firstly, the water was subjected to AER to achieve complete saturation (8.2 mgO2 l^{-1}) from an initial dissolved oxygen concentration of 3.7 mgO_2l^{-1} (Katsoyiannis and Katsoyiannis, 2006) while the electricity required for this phase was assumed equal to 0.003 kWh m^{-3} (Plappally and Lienhard V, 2012; Wakeel et al., 2016). Then, the water was fed to BIO consisting in three open columns operating in parallel and filled with sand and anthracite (total volume: 13.5 m^3). The first layer (40 % of volume) consists of sand with 0.4–0.8 mm grains, a porosity equals to 42 % and an average density of 2600 kg m^{-3}. The second layer (60% of volume) consists of anthracite with 0.8–1.6 mm grains, a porosity of 49% and an average density of 1400 kg m^{-3}. Backwashing in BIO occurs once daily in one filter while the operation in the other two filters continues. In this way, every filter is backwashed every three days. Since some filling materials were lost during every backwashing, the replacement ratio was calculated to be 0.3 % in mass after each cycle. The backwashing was operated at a flow rate of 113 m^3 h^{-1} for 4 min, and the spent water was subsequently sent in the sewer system. The electrical consumption to perform backwashing was calculated to be 0.023 kWh m^{-3} based also on studies from literature (Bukhary et al., 2020a, 2020b)). Then, treated water flows to COA in which $FeClSO_4$ was dosed in concentration of 13 mL m^{-3}. The electrical consumption for the mixing of the reactor was calculated to be equals to 0.095 kWh m^{-3} (Bukhary et al., 2020a, 2020b). After that, a filtration on a two-layer FIL operating in down-flow mode occurred (total volume: 10.5 m^3). The upper and lower layers consist of anthracite (55 % of volume) and sand (45 % of volume), respectively with the same characteristics as in BIO. The backwashing occurred every 18 h and was performed in up-flow mode with an electrical consumption of 0.092 kWh m^{-3} (Bukhary et al., 2020a, 2020b). Considering that some filling materials were lost during every backwashing, the replacement ratio was assumed to be 0.1 % in mass after each cycle. The spent water was subsequently sent in the sewer system. Finally treated water enters DIS in which a 15 % solution of NaOCl was dosed at a rate of 1.17 L h^{-1}. The electrical consumption for the mixing of the reactor was assumed equals to 0.011 kWh m^{-3} (F14) (Bukhary et al., 2020a, 2020b). In Table S3 the inputs and outputs data used in the Life Cycle Inventory analysis with their description and database used are reported.

2.3. *Allocation unit*

Considering that the groundwater presents elevated arsenic and manganese contamination, in LCA-1 it is necessary to allocate the values referred to each treatment unit according to the effectiveness of each pollutant removal. The allocation has been made referring to the average removal rate of each treatment. The idea is that the greater the removal rate of arsenic compared to manganese, the greater the allocation unit for that treatment. The average concentration of manganese and arsenic before and after each treatment has been taken into consideration (Table S4) and used to calculate the allocation factors ($AF_{i,As}$) as reported in the Eq. (1).

$$AF_{i,\ As}(-) = \frac{\mu_{i,As}}{\mu_{i,As}+\mu_{i,Mn}} \tag{1}$$

where $\mu_{i,As}$ and $\mu_{i,Mn}$ are the removal rate of arsenic and manganese, respectively, in the i th treatment unit. The $AF_{i,As}$ in AER, BIO, COA, and FIL were 0.231, 0.074, 1 and 1 respectively. DIS did not intervene in arsenic removal (Table S4) and for this reason the allocation factor was null.

2.4. *Mitigation of the impacts: scenarios*

To answer the RQ2, in LCA-2 two different scenarios were compared with the current ones (S0):

Scenario 1 (S1). in order to mitigate the environmental impacts, renewable sources to produce electricity have been assumed in all stages. The mix involved energy from hydro (50 %) and wind power (50

%) sources. The details of the country mix and renewable energy are available in Table S5.

Scenario 2 (S2). in which all the energy required for the operation of the DWTP was sourced from 3 kWp multi-Si solar panel modules installed on a slanted roof (dataset from Ecoinvent database named "*Electricity, low voltage {GR}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Cut-off, U*" (Wernet et al., 2016)).

2.5. Environmental prices

To better compare the environmental impacts of the different treatments in the entire DWTPs, the environmental prices (EP) have been calculated according to the criteria proposed by de Bruyn et al. (2018) (Eq. (2)).

$$EP_{ij}(€\, m^{-3}) = EI_{ij} * SEP_{ij} \tag{2}$$

Where EI_{ij} is the environmental impact of the i-th category in the j-th treatment unit expressed per FU (1 m^3 of groundwater treated), while SEP is the specific environmental price according to de Bruyn et al. (2018) (Table S6). The evaluation did not take into account the following categories: ozone formation, mineral and fossil resource scarcity, and water consumption because the SEP was not found in the literature.

3. Results and discussion

3.1. Environmental impacts of arsenic removal

The results of the analysis of the environmental sustainability of treatments for arsenic removal are reported in Fig. 2. The most significant impact is produced by COA (0.694 mPt, 54 % of the total), followed by FIL (0.485 mPt, 38 % of the total), BIO (0.073 mPt, 6 % of the total) and AER (0.037 mPt, 3 % of the total) (Fig. 2a). Human health is the main endpoint for all treatment stages, while ecosystems and resources are less affected. The environmental impacts are mainly due to electrical consumption in all treatment stages: 85 %, 98 %, 77 %, and 100 % of COA, FIL, BIO, and AER, respectively. The other inputs, such as the use

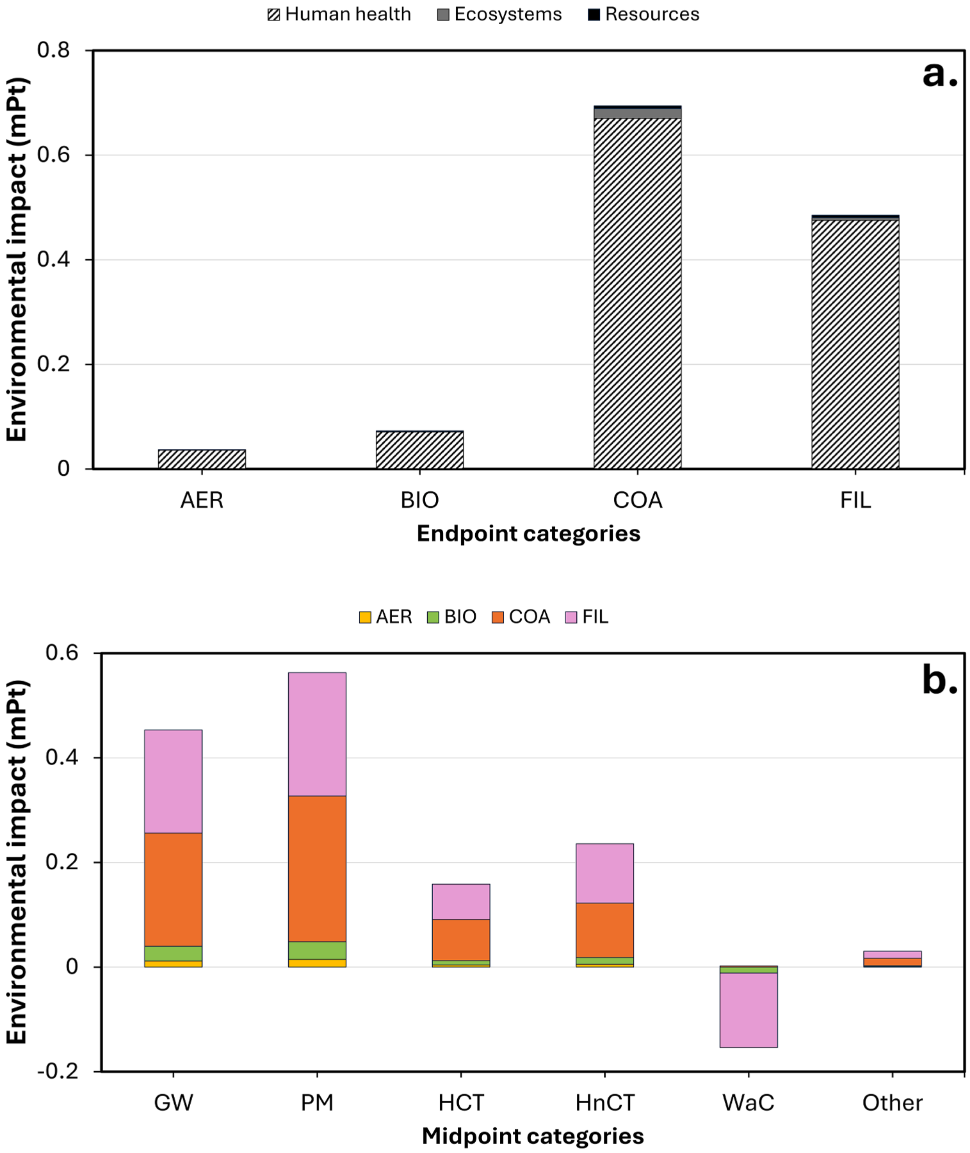

Fig. 2. Normalization of the environmental impact indicators by (a) processes contribution and (b) impact categories. FU: 1 mg arsenic removed. The category "Other" includes ozone depletion, ionizing radiation, ozone formation, terrestrial acidification, freshwater and marine eutrophication, terrestrial, freshwater, and marine ecotoxicity, land use, mineral and fossil resource scarcity.

of additives in COA and the material used for BIO and FIL, are the second cause of environmental impacts (14 %, 16 % and 1 %, respectively) but remains strongly lower than the electrical ones.

The high prevalence of impacts related to electricity consumption has also been highlighted for other processes such as electrocoagulation and activated carbon filtration followed by the materials used in the different technologies (Goyal et al. 2022, 2023) demonstrating that these are the two key factors to consider to promote the environmental sustainability of arsenic removal treatments. The high environmental impact of the entire sequence of conventional treatments for arsenic removal (1.289 mPt per mg of arsenic removed) showed the need to (i) intervene with management upgrades in order to increase the environmental sustainability of these treatments (reduce energy consumption, use of "green" sources for energy production, use of alternative less impactful chemical reagents) and (ii) develop the research for technologically more innovative solutions with high removal efficiency and low impact.

The environmental profile in terms of main midpoint impact categories is reported in Fig. 2b. The analysis suggests that four categories (i.e., global warming - GW, fine particulate matter formation - PM, human carcinogenic and non-toxicity – HCT and HnCT, respectively) have a significantly higher impact than the other ones. The most considerable contribution is given by PM formation with 0.563 mPt, followed by GW with 0.453 mPt, HnCT with 0.236 mPt, and HCT with 0.159 mPt.

All other impact categories are almost negligible counting for less than 0.01 mPt. Water consumption (WaC) presents negative impacts (−0.151 mPt) because the water used for backwashes in filtration and biological treatment is assumed to be subsequently treated with sewer system and returned to the environment, avoiding water depletion.

In terms of each indicator (Table 1), the removal of 1 mg of arsenic emits 0.0279 $kg_{CO2,eq}$, 0.05 $g_{PM2.5,eq,}$ 0.00286 $kg_{1,4\text{-}DCB}$ in case of HCT, 0.062 $kg_{1,4\text{-}DCB}$ for HnCT and −0.00363 m^3 of WaC. COA and FIL are the main origin of all impacts. COA prevails in GW (47.76 %), PM (49.50 %) and HCT (49.69 %) due to the use of energy and the consumption of chemical reagents, while FIL is the major contributor in HnCT (48.09 %) and WaC (95.27 %) due to the replacement of sand and the frequent backwashing of the filters, respectively.

In general, these results appear to be in line with the literature. The use of energy determines an environmental impact that depends on the energy mix used. In this case, having assumed a mix with a limited use of renewables consistent with the current scenario (Ioannidis et al., 2023), the impact is significant. The results showed that these two are therefore the most effective lines of intervention to increase the environmental sustainability of the present arsenic removal treatments. Instead, the impact generated using virgin filtering media (in BIO and FIL) is limited and therefore its potential replacement with recycled material cannot be considered an effective and decisive mitigation measure of the environmental impacts of these treatments.

Table 1
Contribution analysis of the main impact indicators per FU (1 mg of arsenic removed). Numbers in bold refer to the higher impacts related to each impact indicator. Numbers in square brackets refer to the percentage of the impact respect to the total of the same indicator.

Impact category	Unit of measure	Total	AER	BIO	COA	FIL
GW	kg CO_2 eq	2.79 E-02	7.26 E-04 [2.60]	1.73 E-03 [6.19]	**1.33 E-02 [47.76]**	1.21 E-02 [43.45]
PM	kg $PM_{2.5,}$ $_{eq}$	5.37 E-05	1.42 E-06 [2.64]	3.21 E-06 [5.97]	**2.66 E-05 [49.50]**	2.25 E-05 [41.90]
HCT	kg 1,4-DCB	2.86 E-03	7.54 E-05 [2.63]	1.47 E-04 [5.15]	**1.42 E-03 [49.69]**	1.22 E-03 [42.53]
HnCT	kg 1,4-DCB	6.20 E-02	1.45 E-03 [2.35]	3.35 E-03 [5.40]	2.74 E-02 [44.16]	**2.98 E-02 [48.09]**
WaC	m^3	−3.63 E-03	4.43 E-06 [−0.12]	−2.73 E-04 [7.53]	9.74 E-05 [−2.68]	**−3.46 E-03 [95.27]**

3.2. *Environmental impacts of DWTP and possible mitigation strategies*

Fig. 3 reports the outcomes of the environmental analysis based on the entire DWTP, assuming 1 m^3 of groundwater treated as FU. This evaluation has been made to estimate the global impact of groundwater treatment and not only of the arsenic removal (please, see Section 3.1).

In terms of endpoint categories, the results indicate that human health is the most affected endpoint category (13.6 mPt), followed by ecosystems (0.3 mPt) and resources (0.1 mPt). Furthermore, the evaluation of the environmental profile shows that DIS represented the treatment unit with the most significant impact counting for 5.3 mPt (35.3 %), followed by COA (4.1 mPt; 29.4 %) and FIL (3.4 mPt; 24.8 %) (Fig. 3a). Regarding DIS, the use of NaOCl, as chemical reagents was the major cause of impacts (98 %) while the use of $FeClSO_4$ counted for almost the 21 %. These results confirmed previous findings of Salazar et al. (2022) that highlighted the consumption of chemical reagents as the major contributors of the environmental impact of a DWTP. In the other processes (AER, BIO, and FIL), the environmental impacts produced were mainly due to electricity consumption ($>$ 67 %).

In terms of midpoint impact categories, the analysis suggested that the four categories (i.e., GW, PM, HCT and HnCT) have a significantly higher impact than the others (Fig. 3b). As for LCA-1, WaC presents negative impacts (-1.123 mPt) due to the assumption that water used for backwashes in FIL and BIO can be returned to the environment after proper treatment.

The higher contribution was given by PM formation counting for 6.190 mPt, followed by GW with 4.901 mPt, HnCT counting for 2.184 mPt, and HCT with 1.521 mPt. All other impact categories are almost negligible counting for less than 0.35 mPt.

In terms of each indicator (Table 2), the treatment of 1 m^3 of groundwater determines a total emission of 0.302 $kg_{CO2,eq}$, 0.591 $g_{PM2.5eq}$, 0.0275 $kg_{1,4\text{-}DCB}$, 0.574 $kg_{1,4\text{-}DCB}$, −0.0267 m^3 for GW, PM, HCT, HnCT and WaC, respectively. Similar results were obtained by Saad et al. (2019) that estimated 0.342 $kg_{CO2,eq}$ and 0.0165 $kg_{1,4\text{-}DCB}$ for GW and human toxicity (HCT + HnCT). The lower values could be attributed to the differences in the processes in water line (e.g., absence of coagulation, single stage filtration, absence of disinfection). The high variability of the processes in the different DWTPs, due to the different initial characteristics of the groundwater, makes difficult to compare the results of LCAs carried out on different plants (Section 3.3.).

DIS and FIL are the primary origin of all impacts. DIS prevails in GW (34.06 %) and PM (35.56 %), while the contribution of FIL is higher in HCT (31.30 %), HnCT (36.55 %) and WaC (90.75 %).

Considering that consumption from non-renewable sources represents one of the main issues in terms of environmental impacts, two alternative scenarios in which green sources have been used for electricity production were evaluated, namely S1 and S2. The use of hydro and wind power sources (S1) allowed the reduction of all the main impact indicators: in total impacts are reduced by almost 36 %, with the highest effect on HnCT (−34 %) (Fig. 4a). The best results in terms of environmental impact were obtained in the case of an energy mix that comes entirely from photovoltaics (S2). In this case, the impact of the environmental indicators is reduced by almost 53 %, with the highest effect being on HCT (54.6 %).

Regarding EP, current and alternative scenarios were compared (Fig. 4b). The EP aims to provide an economic indication of the environmental quality that varies depending on the environmental sectors affected (de Bruyn et al., 2018). In this sense, the results highlighted that a hypothetical variation of the energy mix with which the DWTP is powered by switching from the current scenario to a mix with hydro (50 %) and wind power (50 %) sources results in a lower EP compared to a

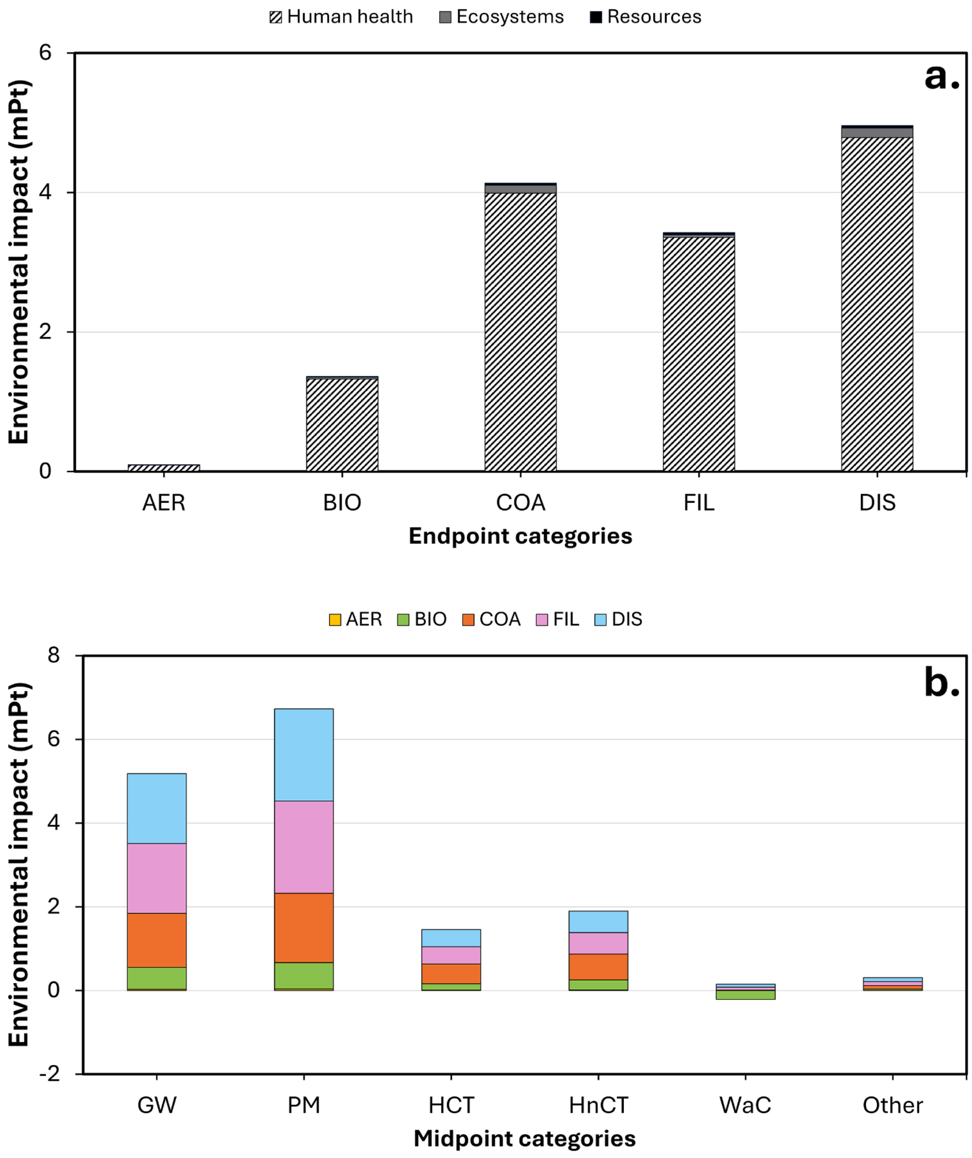

Fig. 3. Normalization of the environmental impact indicators by (a) processes contribution and (b) impact categories. FU: 1 m^3 of groundwater treated. The category "Other" includes ozone depletion, ionizing radiation, ozone formation, terrestrial acidification, freshwater and marine eutrophication, terrestrial, freshwater, and marine ecotoxicity, land use, mineral and fossil resource scarcity.

Table 2
Contribution analysis of the main impact indicators per FU (1 m^3 of groundwater treated). Numbers in bold refer to the higher impacts related to each impact indicator. Numbers in square brackets refer to the percentage of the impact respect to the total of the same indicator.

Impact category	Unit of measure	Total	AER	BIO	COA	FIL	DIS
GW	kg CO_2 eq	3.02 E-01	1.89 E-03 [0.63]	3.23 E-02 [10.70]	7.94 E-02 [26.30]	8.55 E-02 [28.32]	**1.03 E-01 [34.06]**
PM	kg $PM_{2.5,eq}$	5.91 E-04	3.68 E-06 [0.62]	6.00 E-05 [10.15]	1.58 E-04 [26.81]	1.59 E-04 [26.86]	**2.10 E-04 [35.56]**
HCT	kg 1,4-DCB	2.75 E-02	1.96 E-04 [0.71]	2.75 E-03 [10.03]	8.48 E-03 [30.86]	**8.60 E-03 [31.30]**	7.45 E-03 [27.11]
HnCT	kg 1,4-DCB	5.74 E-01	3.78 E-03 [0.66]	6.26 E-02 [10.90]	1.63 E-01 [28.38]	**2.10 E-01 [36.55]**	1.35 E-01 [23.51]
WaC	m^3	−2.67 E-02	1.15 E-05 [−0.04]	−5.13 E-03 [19.23]	5.82 E-04 [−2.18]	**−2.42 E-02 [90.75]**	2.07 E-03 [−7.76]

complete power supply via energy from photovoltaic. In fact, introducing a mix of energetic sources such as in S1 allowed the reduction of the EP by 10.7 % with respect to the current scenario while in S2 the EP increased by almost 22.6 %. This was mainly due to the enhancement of terrestrial ecotoxicity from 0.978 kg 1,4-DCB m^{-3} in case of current scenario (S0) to 1.212 kg 1,4-DCB m^{-3} of groundwater treated of S2. This determined to the huge increase in the EP from 8.69 € m^{-3} of groundwater treated to 10.77 € m^{-3} in S0 and S2, respectively.

At a first analysis, these results contrast with the evidence of the LCA which identified scenario S2 as the best one for reducing the impact of the DWP due to the use of energy. However, the two analyses give different information as: (i) LCA provides information linked to the impact of a process on the environment, while (ii) EP indicates the loss of well-being (defined with economic value) due to the emission in the environment of a unit of polluting substances (de Bruyn et al., 2018).

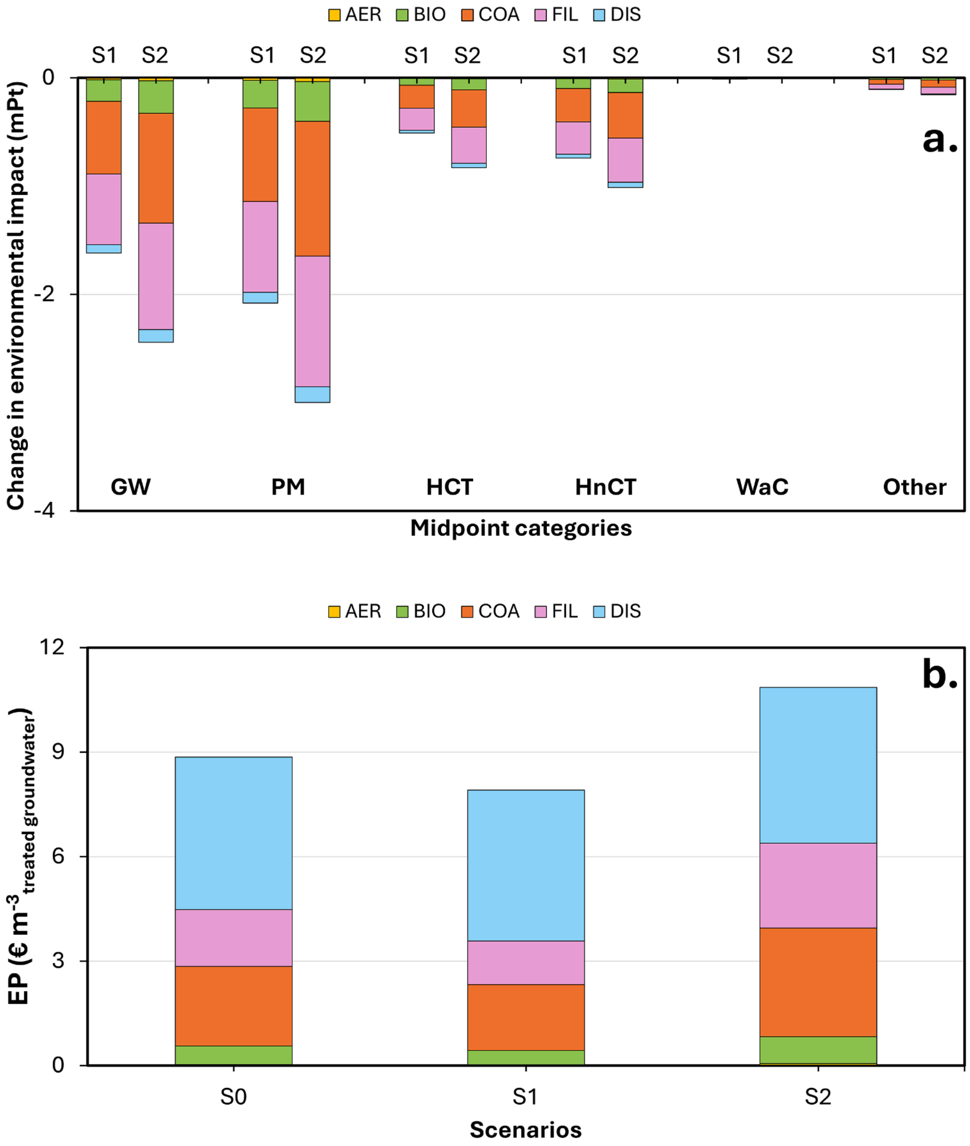

Fig. 4. (a) Change in the environmental impact by midpoint categories and different processes. (b) Environmental prices in different scenarios. FU: 1 m^3 of groundwater treated. S1: Scenario 1; S2: scenario 2. The category "Other" includes ozone depletion, ionizing radiation, ozone formation, terrestrial acidification, freshwater and marine eutrophication, terrestrial, freshwater, and marine ecotoxicity, lad use, mineral and fossil resource scarcity.

3.3. Possible limitations of the study

Due to the absence of information about electricity consumption and filters backwash water, literature was used to collect secondary data. Despite the efforts to refer to studies on similar DWTPs, this remains one of the main limitations of the study. In this sense, future research should consider to collect and use primary data. Another possible limitation is the specificity of each DWTP. In this study, the COA and DIS phases were modelled assuming the dosage of $FeClSO_4$ and the NaOCl, respectively, according to the information provided by the water utility. However, reagents used in other treatment facilities and the treatment line may differ, which can make comparison of results with previous studies difficult. Moreover, the specificity of each groundwater can lead to having, together with arsenic, the initial presence of different contaminants. This could determine different processes in the treatment chain and different allocation factors specific to each process, thus becoming another possible limit to the comparability of the results of the present work with those of other studies.

In scenario S2, the use of solar energy (produced through photovoltaic panels) as single source for the entire energy production has been assumed. However, although it may be a potentially acceptable assumption for an area such as Greece, where the DWTP under study is located, its potential applicability in other areas is strongly dependent on climatic factors.

Regarding the EPs, it should be highlighted that they were calculated according to the method proposed by de Bruyn et al. (2018), and two main limits currently remain. In fact, the SEPs are referred to 2015 and, to the best of our knowledge no more recent data are available. Moreover, these data are considered average prices for the Netherlands and therefore, variations cannot be excluded if the study refer to a different area. However, despite these limitations, these values represent the only example in the literature that provides an economic indication of the different midpoints of an LCA.

4. Conclusions

In this study, the LCA of a typical arsenic groundwater treatment plant located in Greece was carried out with two aims: (i) identify what is the most impactful process for arsenic removal and (ii) define possible solutions for mitigating the impact of the entire DWTP. Looking only treatments involved in removing arsenic, the results show that COA (0.694 mPt) and FIL (0.485 mPt) are the most impactful process (54 % and 38 % of the total, respectively), mainly due to the electricity consumption followed by chemicals. These results showed the need to upgrade the DWTP in order to reduce energy consumption, use of “green” sources for energy production, use of alternative less impactful chemical reagents. Instead, the replacement of virgin filtering media (in BIO and FIL) with recycled material cannot be considered an effective and decisive mitigation measure due to its limited impact.

Looking the entire DWTP, the use of reagents in the DIS was the reason why this had the most significant impact on the environment counting for the 35.3 %, followed by COA (29.4 %) and FIL (24.8 %). Two alternative scenarios in which green energy has been used were evaluated. Scenario S2 (only photovoltaic energy) represents the best scenarios with almost a 53 % reduction in the impact of the environmental indicators (vs. 36 % of Scenario S1).

The analysis of EPs showed that a mix of hydro (50 %) and wind power (50 %) sources was the best scenario while using only a photovoltaic source for energy production determines an increase of almost 22.6 % of EP with respect to the current situation, from 8.69 € m^{-3} of groundwater treated to 10.77 € m^{-3}. This is due to the increase in the impact indicator of the terrestrial ecotoxicity. The result of this analysis highlighted that the impact of the different treatments for the removal of arsenic in a groundwater can be considerable. A combined approach that considers the aspects resulting from the LCA analyses and the resulting environmental prices is suggested to implement more sustainable arsenic removal technologies. In future studies, this analysis can be supplemented by economic and social assessments, i.e. Life Cycle Costing and Social-LCA.

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CRediT authorship contribution statement

Alberto Pietro Damiano Baltrocchi: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Carnevale Miino:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ioannis A. Katsoyiannis:** Validation, Resources, Conceptualization. **Athanasia K. Tolkou:** Writing – review & editing, Validation. **Lucrezia Maggi:** Writing – original draft, Investigation. **Elena Cristina Rada:** Writing – review & editing, Validation. **Vincenzo Torretta:** Validation, Supervision, Project administration, Conceptualization.

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

All data generated or analysed during this study are included in this published article.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107878.

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