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Current Approaches to Petroleum Wastewater Treatment for Reuse: A Systematic Review

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Abstract: The petroleum industry is a significant consumer of water, leading to the generation of substantial volumes of wastewater. This water contains high levels of organic and mineral components which can severely pollute coastal waters, rivers, estuaries, shorelines, soil, and groundwater. Once treated, the purified water can be reused for various purposes, particularly in regions experiencing water stress. This work presents a systematic review of research on the treatment methods for reusing petroleum wastewater globally, conducted from the 2000s to May 21, 2024. The study protocol was drafted following the updated reporting guidelines for systematic reviews as outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020. Data were collected from Google Scholar, OpenAlex, and Crossref. A total 13 articles were included. Combined processes (69%) and unit operations (31%) emerged. The review suggests that, in addition to conventional treatment methods, other techniques are necessary to valorise petroleum wastewater. To reuse refinery wastewater, treatment technologies include conventional treatment techniques, membrane processes, advanced oxidation processes, lime softening, reverse osmosis, reverse electrodialysis, or combinations thereof. Some unit operations, such as the Jar-test procedure using drinking water sludge, mechanical vapor compression, flocculation-coagulation using ascorbic and citric acids, a new solar-driven homogeneous sodium hypochlorite/iron process, and membrane distillation, have shown promising results for potential reuse.

1. Introduction

Industrial development is a crucial driver of economic growth, fostering job creation and enhancing productivity through the introduction of new equipment and technologies (Agrar and Derraz, 2023). However, certain industries, particularly those involved in hydrocarbon production, generate substantial volumes of wastewater daily. For instance, the production of hydrocarbons results in wastewater volumes ranging from 0.4 to 1.6 times the volume of the processed oil (Coelho *et al.*, 2006; Jafarinejad and Jiang, 2019), with this ratio potentially reaching as high as 7.2 in certain regions (Mansour *et al.*, 2024). Consequently, water, rather than hydrocarbons, is the most produced fluid by the oil industry in terms of volume.

Studies have demonstrated that water produced by petroleum industries contains a variety of organic and inorganic pollutants. Notably, petroleum wastewater is often contaminated with ammonia and sulfides (Aljuboury *et al.*, 2017; Elmobarak *et al.*, 2021), as well as oils and fats, phenols, and volatile compounds (Faris and Abdel-Magid, 2003; Dimoglo *et al.*, 2004). Andrade *et al.* (2011) identified the presence of hazardous compounds such as benzene, toluene, xylene, and ethylbenzene in oil wastewater. These substances can have detrimental environmental impacts (Bruce *et al.*, 1987; Jaishankar *et al.*, 2014; Rabani *et al.*, 2020). When released directly into the environment, petroleum wastewater becomes a significant source of surface and groundwater contamination (Mokif *et al.*, 2022).

This produced water must be treated to eliminate its pollutant load to comply with increasingly stringent discharge standards. Techniques exist for sustainable water management and pollution control (Nguyen and Le Tran, 2024; Thamarai *et al.*, 2024). Several techniques exist for treating petroleum wastewater (Razzouki *et al.*, 2015; Aljuboury *et al.*, 2017; Akartasse *et al.*, 2022) for discharge without reuse objectives. However, if the treatment is effective, the treated water could be repurposed for various applications, particularly in regions where water resources are scarce and water supply systems are fragile (Maddikeari *et al.*, 2024; Ochoa Garza *et al.*, 2024). More advanced treatment systems are required in such cases, as the water must meet higher quality standards for reuse (Pombo *et al.*, 2011). For example, the reuse of refinery wastewater in the refining process demands a Chemical Oxygen Demand (COD) value of less than 150 mg/L (Aljuboury *et al.*, 2015), while Total Organic Carbon (TOC) and COD values must be reduced to below 20 and 30 mg/L, respectively, for the reuse of wastewater in firefighting (Pombo *et al.*, 2013). After employing conventional techniques, additional technologies may be necessary depending on the intended reuse.

This review systematically presents the research conducted on the treatment of petroleum wastewater for reuse, aiming to identify the most effective processes for recycling and repurposing wastewater generated by oil refineries.

2. Methodology

This systematic review was conducted to identify and synthesize information from the literature regarding the treatment of petroleum wastewater, with a particular focus on methods that facilitate the reuse of this water. The objective of this work was to highlight the most effective techniques for the recycling and repurposing of petroleum wastewater. The study protocol was developed following the updated reporting guidelines provided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 (Page *et al.*, 2021).

2.1. Literature search

The documentary research was conducted systematically using the “Publis or Peris” software in conjunction with online databases such as “Google Scholar,” “OpenAlex,” and “Crossref” as search engines. The focus was on research related to the treatment for reuse of petroleum wastewater. Search keywords included “petroleum wastewater,” “treatment,” and “reuse,” with a maximum of 1,000 results per search engine. This review encompasses research conducted from the 2000s up to May 21, 2024. A combination of terms, including ("petroleum wastewater" OR "petroleum effluents" OR "petroleum refinery wastewater" OR "water from petroleum refineries" OR "wastewater in oil and gas industries") AND ("treatment" OR "remediation" OR "reclamation" OR "bioremediation" OR "pollutants removal") was used for literature searches. Only studies presenting data on petroleum wastewater treatment, published or presented in English, were considered for inclusion.

2.2. Search strategy

After gathering the works from the various search engines, a Zotero collection was created to organize and process all obtained documents. Duplicates were removed. Next, the titles of the articles were reviewed, and those meeting the entry criteria were selected, while others were excluded. The abstracts of the selected articles were then examined, and only those pertinent to the treatment for the reuse of petroleum wastewater were retained. The final inclusion criteria for studies were: the article must be available electronically through our institution as a full text. This process is illustrated in **Figure 1**. Two authors made an independent selection according to the criteria provided above.

2.3. Screening

The process was conducted in two rounds, by each author to minimize the risk of excluding relevant studies, carefully considering the inclusion/exclusion criteria at each stage. Data extraction was performed independently after a thorough double reading of the articles. Additionally, supplementary research was conducted on Google Scholar to clarify certain aspects of the various articles.

2.4. Data extraction

The data extracted from each included study included the following details: the country of origin, the objective of the study, the technology used, the targeted parameters, and the reference of publication.

3. Results

Through the described research technique, a total of 2,485 studies were collected from the three cited databases. Subsequently, 183 studies were removed due to duplication, leaving 2,302 studies. Further analysis led to the exclusion of 1,722 studies based on their titles, with 554 of these lacking a combination of treatment, petroleum wastewater, and reuse. Additionally, 6 studies were excluded because full texts were inaccessible. The full texts of the remaining 20 studies were evaluated, resulting in the inclusion of 13 articles (see **Figure 1**).

3.1.Geographical distribution of studies

As illustrated in **Figure 2**, the studies can be categorized by their country of publication. The majority were conducted in Brazil (Andrade *et al.*, 2011; De Abreu Domingos and Da Fonseca, 2018; Dias *et al.*, 2012; Pombo *et al.*, 2011; Souza *et al.*, 2011), Mexico (Nacheva *et al.*, 2008; Pugh *et al.*, 2009), and Iran (Jalayer *et al.*, 2019; Pourehie and Saien, 2021). Other countries, including India (Singh and Shikha, 2018), Egypt (Mansour *et al.*, 2024), Algeria (Sellami *et al.*, 2016), and the United States (Wong, 2011), also contributed to the subject.

3.2. Petroleum wastewater treatment processes

The technologies used for treating petroleum wastewater can be categorized into combined processes and unit operations. Combined Processes involve integrating multiple techniques or adding treatments to conventional methods. Conventional wastewater treatment methods at oil refineries include gravity separation, dissolved air flotation, demulsification, coagulation, flocculation, and biological treatments (such as aerated lagoons, activated sludge systems, and biodiscs).

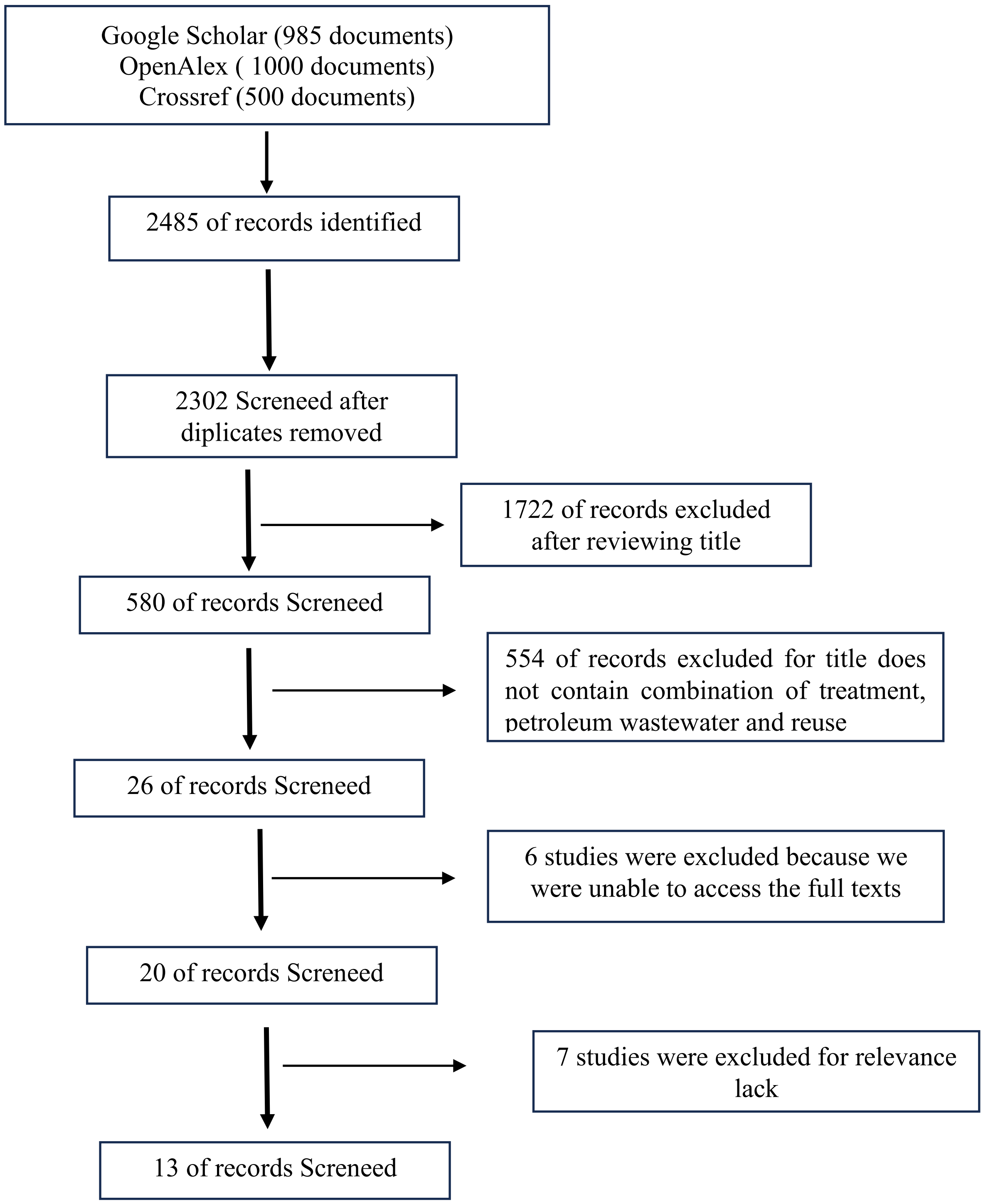
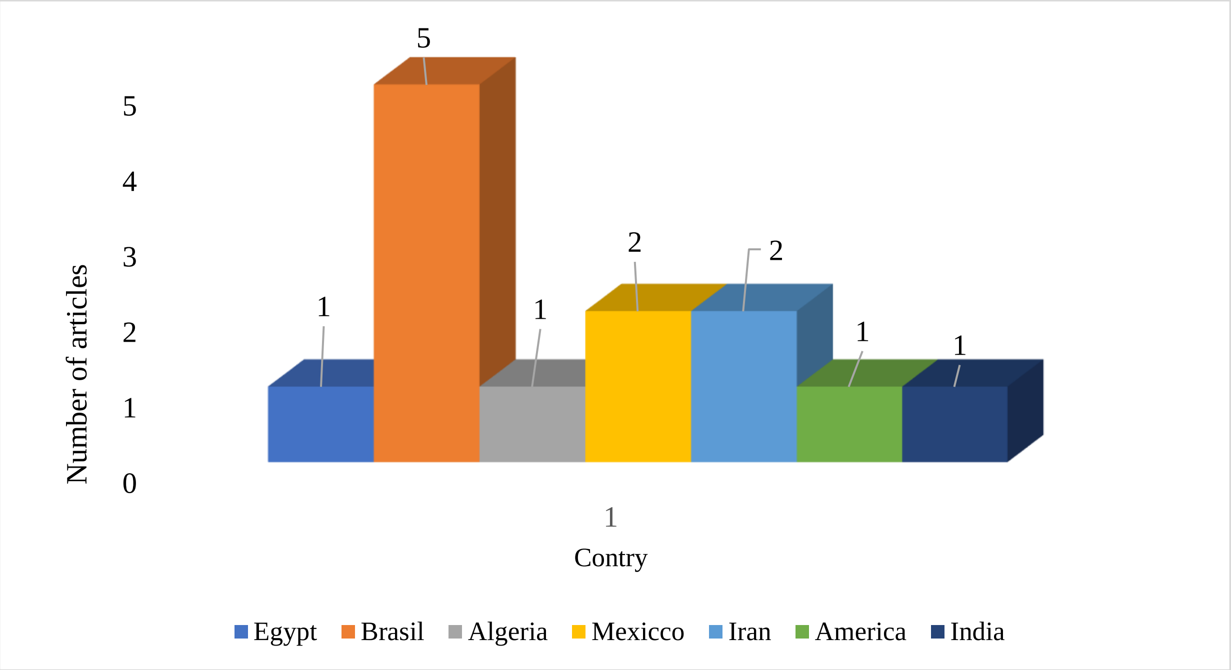


Figure 1: Protocol employed standard for a literature review

Unit Operations that have shown promise for reuse include:

- Jar-test procedures using drinking water sludge (Mansour *et al.*, 2020),
- Mechanical vapor compression (MVC) processes (Andrade *et al.*, 2011),
- Flocculation-coagulation using ascorbic and citric acids (Sellami *et al.*, 2016),
- Solar-driven homogeneous sodium hypochlorite/iron processes (Pourehie and Saien, 2021),
- Membrane distillation processes (Jalayer *et al.*, 2019).



- **Figure 2**: Articles included per country

In addition to these methods, advanced techniques are often required after conventional treatment to ensure that petroleum wastewater meets reuse standards. These include:

- Membrane technologies (Pugh *et al.*, 2009; Pombo *et al.*, 2011; Wong, 2011; Azzaoui *et al.*, 2014; Nacer *et al.*, 2015; Singh and Shikha, 2018),
- Advanced oxidation processes (Souza *et al.*, 2011; Nacheva *et al.*, 2008; Jaafar *et al.*, 2016),
- Lime softening (Nacheva *et al.*, 2008; Pugh *et al.*, 2009),
- Reverse osmosis (Pombo *et al.*, 2011; Pugh *et al.*, 2009; Singh and Shikha 2018).

These advanced methods or combinations are essential for achieving the quality to reuse petroleum wastewater. This graph shows that in addition to conventional treatment, other techniques are necessary for the valorization of petroleum wastewater. **Table 1** details the recovery objectives, the processes used, and the pollution parameters targeted. Most studies concentrate on on-site reuse within petroleum processes. Only two studies (Andrade *et al.,* 2011; Sellami *et al.,* 2016) explore off-site valorization, specifically for irrigation purposes.

Table 1: Report of work done to reuse the petroleum wastewater depending on the type of reuse

Country	Objectif	The method applied	Removed parameters	Reference
Egypt	treatment of oil-free petroleum-produced water to be reused in the oil field	Jar-test procedure experiment using drinking water sludge	Turbidity, dissolved cations, and anions.	(Mansour *et al.*, 2020)
Brazil	investigate the utilization of a combined process to treat refinery wastewater to produce water with the quality required for use in boilers.	Combined process: moving-bed biofilm reactor and slow-rate sand filtration, reverse osmosis	COD, DCO, Phenol, ammoniac, dissolved salts.	(Dias *et al.*, 2012)
	study the best available techniques for the treatment of oil refinery wastewater for purposes of reuse after conventional wastewater treatment	Combined processes including membrane processes, reverse osmosis, or reverse electrodialysis	Ions (dissolved salts)	(Pombo *et al.*, 2011)
	Removal of organic matter from refinery wastewater by adsorbent and ion exchange resins process after conventional treatment	Adsorbent and ion exchange resins the laboratory scale	Organic matter.	(De Abreu Domingos and Da Fonseca, 2018)
	Distillation of oil field produced water for reuse on irrigation water	mechanical vapor compression (MVC) process	Salts, metals, and dissolved hydrocarbons	(Andrade *et al.*, 2011)
	Oil-Refinery Wastewater Treatment Aiming Reuse	Combined process: Advanced Oxidation Processes with Biological Activated Carbon	Organic matter	(Souza *et al.*, 2011)
Algeria	Treatment of petroleum wastewater for reuse in industrial fields or irrigation	Flocculation-coagulation using: Ascorbic and Citric acid	suspended matter, turbidity, Hydrocarbons, COD, and BOD_5	(Sellami *et al.*, 2016)
Mexico	review the wastewater reuse experience at several Pemex refineries in Mexico for the production of boiler feed water after conventional oil removal processes,	Combined process: lime softening followed by reverse osmosis, or membrane-only TDS removal.	water hardness, silica, barium, and dissolved inorganic solids.	(Pugh *et al.*, 2009)
	select the best treatment system for the oil production wastewater for reuse in the secondary oil recovery	Combined process: softening, chemical oxidation, isdecarbonisation and filtration	Hardness, Sr, S^{2-}, TSS, TOC, Ba, Si, and Fe.	(Mijaylova Nacheva *et al.*, 2008)

Iran	Solar-driven homogeneous sodium hypochlorite/iron process in the treatment of petroleum refinery wastewater for reusing	New -solar-driven homogeneous sodium hypochlorite/iron process	COD, TOC.	(Pourehie and Saien, 2021)
	Feasibility study of petroleum wastewater treatment by membrane distillation process after conventional treatment	Membrane distillation process	Electrical conductivity	(Jalayer *et al.*, 2018)
America	Application of membrane processes as a tertiary wastewater treatment for reuse in the petro industries	Combined process : microfiltration, ultrafiltration, nanofiltration and reverse osmosis	Suspended solids and Ions (dissolved salts)	(Wong, 2011)
India	Presenting techniques developed to deal with oily wastewater for reuse or recycling	Combined process	multiple pollutants	(Singh and Shikha, 2018)

COD chemical oxygen demand, *DCO* dissolved organic carbon, BOD_5 biochemical oxygen demand in 5 days, *Sr* strontium, S^{2-} inorganic anion of sulfur, *TSS* total suspended solids, *TOC* total organic carbon, *Ba* Barium, *Si* silicon, *Fe* iron

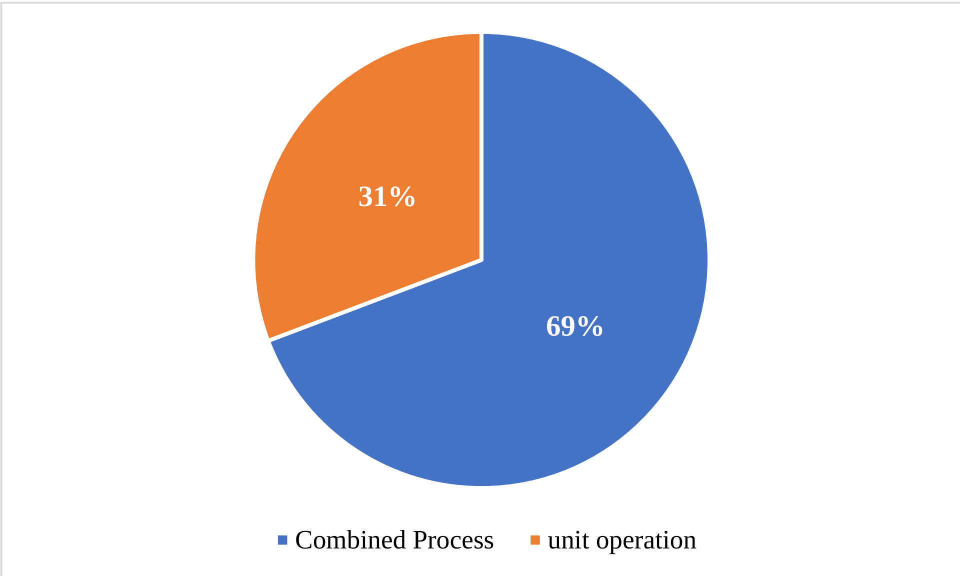


Figure 3: Distribution of processes such as combined and unit operations.

4. Discussion

This systematic review examines recent studies on the treatment of petroleum wastewater for reuse, covering research from the 2000s through May 21, 2024, with 13 articles included. Brazil is the one most interested in this area, followed by Mexico and Iran (**Figure 2**). The study highlights that after conventional treatments, commonly used methods for petroleum wastewater reuse include membrane processes, advanced oxidation processes, lime softening, reverse osmosis and reverse electrodialysis, alone or in combination. Indeed, combined processes are the most frequently studied for the treatment of petroleum wastewater (**Figure 3**). These combined methods are particularly effective due to their ability to treat various recalcitrant compounds (Aljuboury *et al.*, 2017; Elmobarak *et al.,* 2021). In fact, petroleum wastewater contains a variety of components, a unitary operation may not be effective for the reuse of this water. But the combination of several unit operations has been successful in many cases. A unit operation is often used depending on the target pollutant or a group of pollutants. For example, in a study reported by Mansour *et al.* (2020) whose target pollutants were actions and anions, the jar-test procedure using water treatment sludge (WTS) gave a rate of significant elimination. When the target pollutants are other than ions, the technique changes: Rodrigo de Abreu Domingos *et al*. (2018) used adsorbent and ion exchange resins for the removal of organic matter from oil refinery wastewater and the results were as significant as those reported in the literature for activated carbon. But, by application of a compound softening system, followed by oxidation, decarbonation and filtration, Mijaylova Nacheva *et al.* (2008) obtained a highly significant elimination of organic and inorganic compounds. Similar results were obtained by Dias *et al.* (2012) by application of a process combining a moving bed biofilm reactor, slow sand filtration and reverse osmosis. These exploits could be explained by the combination of softening targeting ionic pollution, oxidation targeting organic compounds and filtration for suspended solids.

Other unitary techniques have been tested for the valorization of olive oil wastewater. Among them, only mechanical vapor compression (MVC) was able to significantly reduce salts, metals and dissolved hydrocarbons (Andrade *et al.,* 2011). The others were only effective for a group of compounds: distillation for the compounds responsible for electrical conductivity and a new sodium/iron hypochlorite process powered by solar energy for the compounds to name just a few. A similar study on car wash wastewater found that combined methods also hold the most promise for effective sanitation (Sarmadi *et al.,* 2020).

Conclusion

This work systematically studied the technologies used for the reuse of petroleum wastewater. It emerges from this study that different hybrid processes and unit operations exist for the valorization of this water. Some technologies like membrane processes, advanced oxidation processes, lime softening, reverse osmosis, reverse electrodialysis, or their combination combined with conventionnel treatment are the most commonly used processes. Combined processes are the most frequently studied for the treatment of petroleum wastewater Some unit operations unitary techniques have been tested for the valorization, but only mechanical vapor compression (MVC) was able to significantly reduce salts, metals and dissolved hydrocarbons can give satisfactory results for possible reuse. For an industrial application, other parameters must be taken into account. The energy and economic aspects should be seriously investigated when choosing the process. It is up to each operator to choose the process that suits them according to their reality.

STATEMENTS & DECLARATIONS

Ethical Approval: Not applicable

Consent to Participate: Not applicable

Consent to Publish: Not applicable.

Author Contributions

All authors contributed to the study conception and design. Data collection and analysis were performed by Ismael OUSSEINI NAFIOU supervised by Mahamadou Mounir ZAKARI and Rabé

KANE. The first draft of the manuscript was written by OUSSEINI NAFIOU Ismael and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Conflict of interest: There are no conflicts to declare

Data Availability Statement

The datasets analyzed during this study are available in a folder in the Zotero interface, available from the corresponding author: nafiouismaelousseini@gmail.com

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