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History of Water Integration in the Oil Refining Industry – A Systematic Review

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The process of water use in the oil refinery industry remains a hot topic due to its toxic effect on environment and huge water consumption. The implementation of the techniques for decreasing environmental pressure by minimizing freshwater abstraction, reducing wastewater generation, and decreasing associated costs is still an actual and emerging topic for application. This paper presents a systematic review dedicated to the application of water integration in oil refineries. In total, 31 relevant papers were identified and investigated. The evolution of the processing and water-associated units, variations in the contaminants, the history of techniques development, and the selection of objective functions were investigated. The majority of the related research has been dedicated to testing new water pinch models aiming for freshwater minimization. The technological advances and development of mathematical programming techniques moved focus towards building superstructures and responding to challenges related to water scarcity and cost optimization. The application of water integration in refineries towards minimizing water footprint indicates a crucial topic that needs more investigation. Incorporating water integration within the framework of the circular economy and exploring the water-energy nexus hold significant promise yet remain under-investigated research directions.

1. Introduction

Since the middle of the 19th century, the oil refining sector has grown to be a fundamental part of the modern world. The historical development of the sector has empowered refineries to achieve greater processing depth, enabling the production of substantial volumes of gasoline and a diverse range of petrochemical feedstocks critical for the subsequent transformation into everyday products (Griffiths et al., 2022). The increase in refinery capacity worldwide has shown permanent growth from 13,355 to 16,204 thousand m^3 daily between 2002 and 2021 (BP, 2022).

The process of water use in the oil refinery industry still attracts attention of the researchers due to its toxic effect on environment and huge water consumption (Mohamed et al., 2023). Being intensive water consumers, they are potentially vulnerable to supply disruptions due to climate change (Jamaludin et al., 2023). Refineries are different from each other, in terms of water flow rates involved and the level of contamination present in their wastewater. Water network design depends on several factors, including the water and wastewater management system inside each particular refinery, the level of implementation of best available techniques (BAT), and consideration of the circular economy principles (Radelyuk et al., 2021). The last factor defines the concept of “reduce, reuse, and recycle”, when effluent water from one technological unit is allowed to be used in another process at the same site. Water reuse achieves a triple aim: decreasing pressure on freshwater sources by minimizing freshwater consumption, improving water quality by reducing wastewater generation, and decreasing charges for smaller volume of water used. These aims are achieved by solving the problem of optimal water allocation using water integration, via either water pinch analysis, or equivalent mathematical programming models based on superstructures.

The implementation of water integration in the oil refinery sector has evolved together with the development of water integration area. The research by Radelyuk et al. (2021) has shown that there is still space to implement relevant water integration techniques in both developed and developing countries to achieve sustainable water use in the oil refinery sector.

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As the oil refinery sector still plays an important role in the world's economy, it can be beneficial to overview pathways of water use with a particular focus on water integration in the sector. This review aims to investigate the evolution and practical meaning of water integration research in the oil refinery industry. The outcomes of this study can be used by a variety of researchers and practitioners as a guide for understanding the key aspects of water integration in oil refineries worldwide.

2. Methodology

The objective of the review was to evaluate the following parameters related to water integration in the oil refinery sector. Firstly, characteristics of the water use processes were identified to describe general patterns, including industrial units and the list of contaminants used in water allocation problems. Secondly, the evolution of techniques and tools for water integration coupled to an overview of optimization results were discussed. Finally, to provide recommendations for future works in the studied area.

The criteria for considering the publications eligible for inclusion in the review were twofold: they might cover (i) the use of water integration in (ii) the oil refinery sector. The Scopus database was used for the search of relevant publications, among them 31 were selected, as relevant (Figure 1). Among them, more than half were dedicated to developing and / or improving the water integration methods, where data from oil refineries were used primarily to test new techniques. 9 papers were focused on solving real-world optimization problems with already known water integration tools. 4 review publications focused on the different aspects of the progress of implementation of water integration in the oil refinery sector. A majority of the reviewed studies (27) employed a reduction in freshwater abstraction as their primary objective function. Comparatively, less than half of the studies prioritized the minimization of wastewater generation and its associated costs (14 for both). The geographic distribution of the reviewed studies reveals the following patterns Nearly half of the publications originated from Iran and Brazil, countries with substantial oil refining capacities within the Middle East and South America, respectively (BP, 2022). While the United States and China collectively represent the largest share of global refining capacity, their contributions to the analyzed literature were comparatively limited (6 publications). Noteworthy are publications from the United Kingdom and Malaysia associated with established research groups in the field of process integration.

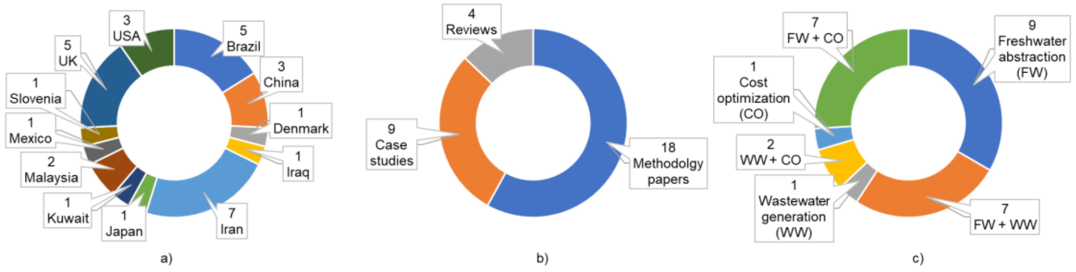

Figure 1: The distribution of the reviewed publications according to a) origin of the studied refineries or leading authors; b) scope of the paper; c) objective functions

A review of titles and abstracts suggests a primary focus on the terminology associated with water integration applications ("contaminant," "reuse," "problem," "cost," "use," and "freshwater") rather than on the specific characteristics of the petrochemical industry (Figure 2).

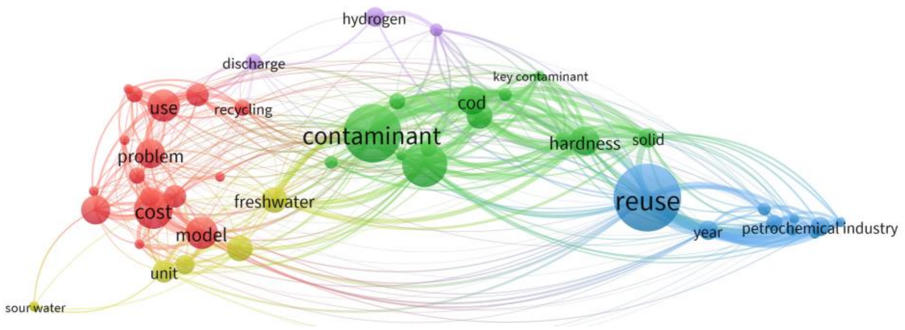

Figure 2: The interconnections between terms extracted from titles and abstracts from the reviewed publications

3. Characteristics of refineries in water integration: units of interest and selected contaminants

The number of units considered for water integration depends on the number of data points available and the volume of water sufficient for designing optimal "sources-sinks" allocation. Steam strippers (distillation), hydrodesulphurization units (HDS), and desalters were targeted water-consuming units for testing developing methodologies in a pioneering work by Takama et al. (1980). Koppol et al. (2004) expanded this basic configuration by incorporating caustic treating and amine sweetening units, increasing the number of available water sources and sinks. Al-Redhwan et al. (2005) were the first to utilize a large number of units within a superstructure model, an approach subsequently adopted by several researchers (e.g., Deng et al., 2018). Hwang and Moore (2011) provided the most comprehensive description of overall water balance across all available units, potentially offering the most optimal water distribution within a refinery considering 26 potential sources and 30 sinks.

Modern water integration practices encompass a wider range of water- and steam-using units within refineries. These may include an atmospheric crude distillation unit, a vacuum distillation/rerun unit, a tail gas treatment unit, a hydrocracking unit, a gas oil desulfurization unit, an atmospheric residue desulfurization unit, a kerosene desulfurization unit, a fluid catalytic cracking unit, a desalting unit, a delayed coking unit, and additional sources of supplied water. Desalting units are typically some of the largest water consumers in a refinery due to their low water quality requirements. The resulting wastewater stream often contains high levels of contaminants, rendering it unsuitable for direct reuse. Cooling tower systems also represent significant water consumers, with a portion of the water lost to evaporation and another portion discharged via blowdown streams containing high level of total dissolved solids (TDS). Regenerated water utilities often serve as the primary water sinks within refineries, relying on the implementation of Best Available Techniques (BAT) to achieve the required water quality. Bagajewicz and Faria (2009) emphasized the importance of incorporating wastewater treatment systems into water allocation models. While final treated refinery effluent may be reused within the refinery for applications similar to non-contaminated rainwater, it typically necessitates advanced treatment technologies beyond BAT (Radelyuk et al., 2021).

Within petroleum refining processes, water serves a dual purpose: facilitating the removal of contaminants from hydrocarbons and transporting process reagents. A review of the selected literature identified the following key contaminants in refinery effluents: hydrocarbons (HC), suspended solids (SS), salts, hydrogen sulfide, ammonia, BOD / COD, and hardness. These contaminants can be further categorized based on their fate within refineries. Environmental impact is primarily assessed using hydrocarbons as a key indicator of contamination. Conversely, potential threats to refinery infrastructure are evaluated through the lens of hardness or salts as targeted contaminants. HC, H_2S, and SS remain consistently identified as critical contaminants in both processed water streams and wastewater throughout the history of water integration in this sector. The selection of contaminations sets reflects two approaches to water integration: focusing on a single critical parameter (single-contaminant approach) or incorporating a broader range of target chemicals to represent real-world scenarios.

Starting with the single contaminant approach, Takama et al. (1980) selected H_2S, oil, and suspended solids as indicators to test the applicability of water pinch analysis in refineries. The seminal work by Wang and Smith (1994) was the first where multiple contaminants were considered for water network synthesis. Their work included hydrocarbons, H_2S, and salts as reference contaminants, which were subsequently adopted by numerous researchers. Kuo and Smith (1998) presented a variation where salts were replaced by suspended solids. Nabi Bidhendi et al. (2010) initiated a different approach by selecting COD and hardness as targeted contaminants. Mughees and Al-Ahmad (2015) utilized this data to test their methodology based on single- and double-contaminant approaches for determining freshwater demand in industrial processes. These parameters remain relevant even nowadays (Hashemi et al., 2024). Efforts to expand the approach to four or more contaminants began with Koppol et al. (2004), who employed salts, organics, H_2S, and ammonia for water integration. This approach facilitated a focus on both environmental harm and equipment damage caused by these pollutants.

4. Characteristics of water integration in refineries: techniques used and problems solved

Several factors, including geographical location, water availability, socio-economic conditions, environmental awareness levels, and research focus, can influence the objectives for water integration in oil refineries. These objectives were the primary determinant in selecting the most appropriate methodological approach. A review of the included publications identified three main methodological approaches (Figure 3): (i) modelling, referring to programming techniques; (ii) graphical methods, such as those utilizing limiting curves or source/sink composite curves; and (iii) numerical approaches, exemplified by water cascade analysis (Klemeš et al., 2018).

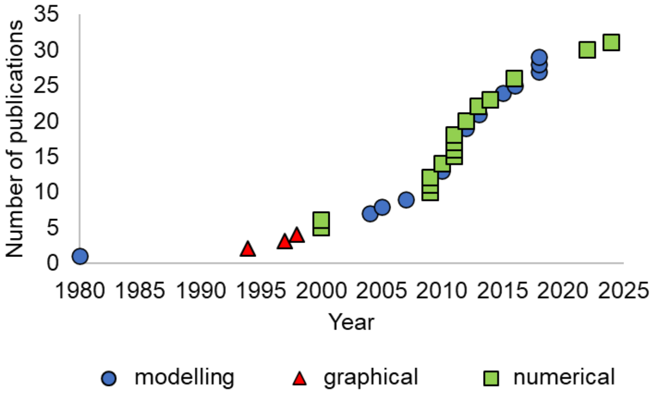

Figure 3: Methodological approaches used in reviewed publications

Takama et al. (1980) pioneered the modeling of water-using and wastewater-treating subsystems within refineries, considering both water allocation and total annualized costs. Wang and Smith (1994) introduced the concept of a graphical Water Limit Profile of Limiting Composite Curves as an alternative to mathematical programming for single- and multi-contaminant problems. The authors highlighted two key aspects: the advantages of implementing regeneration units and the recognition that optimization projects may not always be driven by cost considerations. Water scarcity might become a compelling objective for water reuse schemes, aligning with the future concept of water footprint. Quaglia et al. (2014) presented the only known research to utilize water footprint as the objective function, demonstrating a reduction of 21.8 % in total annualized cost and 45.3 % in water footprint. Bagajewicz (2000) conducted a milestone review, summarizing the state-of-the-art in water allocation and water treatment process solutions specifically within the context of oil refineries. This review emphasized the efficiency of mathematical programming in generating both globally optimal and sub-optimal solutions, providing detailed explanations of linear and non-linear programming for single- and multi-contaminant problems.

The next period in water integration for the oil refining sector was characterized by intensive development of existing models through the incorporation of novel parameters and techniques. Al-Redhwan et al. (2005) pioneered the application of GAMS software, which further gained widespread adoption. The authors adapted a stochastic approach to investigate the impact of fixed freshwater resources on wastewater minimization opportunities. The results indicated a potential 58 % reduction in freshwater abstraction achievable through the combined implementation of reuse and regeneration-reuse options. Superstructure models were formulated as programming problems, with each water user and treatment unit represented by an inlet mixer and an outlet splitter, respectively, to account for various refinery configurations. This comprehensive approach enabled the exploration of solutions maximizing water recovery, minimizing freshwater costs, investment costs, wastewater treatment costs, material recovery, piping costs, optimizing the water consumption index, and adhering to environmental discharge constraints.

The development of novel tools and software indicated another trajectory within the evolution of water integration for petroleum refining. Ulson de Souza et al. (2009) developed and explored the Water Source Diagram method for testing regenerative unit scenarios. This work was followed by an investigation into the feasibility of retrofitting a sour water network within a petroleum refinery (Sujo-Nava et al., 2009). Zhang et al. (2016) further contributed by developing a visual solution tool specifically designed for targeting and designing water networks involving single contaminants while promoting calculations based on regeneration reuse.

Real-world case studies have highlighted the conditional nature of water integration in refineries, often revealing the complexity of contrasting optimization targets designed to achieve practical implementation. Koppol et al. (2004) pioneered a case study focused on implementing a regeneration unit and achieving zero wastewater discharge through linear programming for multiple contaminants. This approach resulted in a wastewater discharge reduction ranging from 114.8 to 33.6 t/h, with a corresponding annual operating cost savings of $ 0.895 million. Multiple studies have investigated Iranian refineries. For instance, Mohammadnejad et al. (2012) explored various contaminant combinations, including double- and triple-contaminant approaches. They constructed water network diagrams and composite curves specific to Iranian refineries, demonstrating a potential freshwater abstraction reduction of 42-63 % depending on the selected indicators and approach (single or double contaminant). However, when considering all three contaminants simultaneously, the freshwater reduction decreased to approximately 17 %. Hansen et al. (2016) investigated water reuse opportunities within cooling towers in the petrochemical industry. Subsequently, the authors (Hansen et al., 2018) evaluated water reuse alternatives by minimizing clarified water consumption as an objective function. This approach offered the potential to save 385,440 m^3/year of water, which is sufficient to supply a population of 6,350 for one year. Additionally, it could eliminate the generation of 201,480 m^3/year of wastewater. Khor et al. (2011) employed a superstructure optimization approach for membrane separation-based water regeneration network synthesis. This work aimed to demonstrate the efficacy of reverse osmosis as a regeneration tool. Their findings revealed potential annual savings of $ 4,267,000 and a 58 % reduction in both freshwater use and wastewater generation, with a payback period of 2.1 years. Deng et al. (2018) introduced a similar approach applicable to large-scale refineries. Their model incorporated various types of water sources for water-using processes. This approach achieved reductions of 21.6 % and 19.8 % in freshwater consumption and total annualized costs, respectively.

The most recent advancements in water integration research for oil refineries center around the emerging concept of the circular economy. Sarrafzadeh (2022) introduced the “water closed-loop system (WCLS)” framework, which is based on 5Rs (refuse, reduce, reuse, recycle, and reform) to achieve minimal water demand. This methodology aims to identify the optimal implementation strategy for the 5Rs within an oil refinery to achieve the lowest water consumption. The study demonstrated reductions in water consumption of 28.66 % and 46.33 % under reuse and recycle scenarios, respectively.

5. Summary and further research

This review provides a comprehensive analysis of the current state-of-the-art for water integration within the oil refining industry. It examines the techniques employed for water allocation, targeted contaminants, addressed challenges, and the driving forces behind the adoption of water integration. The ongoing evolution of water integration methodologies, coupled with advancements in industrial processes and sophisticated treatment technologies, has resulted in a substantial reduction in water consumption by oil refineries globally. Since the mid-1990s, the development of Best Available Techniques (BAT) for regeneration units has significantly enhanced the efficacy of water integration. Consideration of a large number of contaminants and units makes the built superstructure more realistic with more reliable generated results. At the same time, this approach can also lead to increased model complexity, potentially hindering analysis and reducing efficiency. This potential drawback can be mitigated through the judicious selection of performance indicators and process units tailored to individual cases, with due consideration for local circumstances.

Several critical knowledge gaps necessitate further research that has received limited attention in existing works. A historical shift has been observed, transitioning from a focus on simple cost optimization to the acceptance of impending water scarcity risks, particularly as a crucial measure for climate change adaptation. This concept represents an emerging area of research. While the majority of reviewed studies prioritize the reduction of freshwater abstraction, only one has considered water footprint aspects. This approach offers a more holistic perspective by comprising the effect of minimizing emissions into natural water sources and reducing freshwater abstraction. No studies were identified that employed the water footprint as an objective function incorporating both quantitative and qualitative water factors for optimization. No research was found that integrates an energy parameter into the model, aiming to reduce energy losses within the water-using superstructure. These under-investigated areas hold the potential to unlock novel water integration applications in the oil refinery sector. The implementation of this approach across refineries globally remains an untapped opportunity, particularly within the framework of the emerging circular economy concept. This concept fosters sustainable development and aims to mitigate the significant threats posed by irrational and unsustainable water use.

This review serves a dual purpose: as a guiding tool for engineers working in the oil refining sector and as a starting point for researchers in process integration to investigate under-explored conceptual and practical challenges. The following limitations should be acknowledged by readers. Due to inherent time lags and potential delays in the Scopus database indexing, the most recent advancements in process integration may not be comprehensively covered. Additionally, the review’s focus on water integration within the oil refining industry might exclude potentially efficient applications in other sectors.

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