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Water Pinch Analysis in Petroleum Refineries: A Review of Methods, Case Studies, and Future Trends

Teba K. Husen[1], Mohammad A. Taher[2], Mohammad N. Faris[3]
[1,3]Department of Chemical Engineering, Faculty of Engineering, Basra University, Iraq
[2]Department of Chemical and Petroleum Refining Engineering, Basrah University for Oil and Gas, Iraq
E-mail: [1]teba.kadhim@uobasra.edu.iq, [2]moh.may@buog.edu.iq, [3]mahmod.faris@uobasrah.edu.iq

Abstract
One of the major industrial consumers of water is petroleum refineries, which depend extensively on fresh water for purposes such as cooling, steam generation, desalting, and product separation. This substantial demand creates significant environmental and economic problems, for instance, in areas with water shortage, like the Middle East, and therefore it becomes crucial to implement systematic measures of water conservation. Water Pinch Analysis (WPA) is an efficient technique employed to achieve such goals through process integration and reuse optimization. This paper reviews the use of WPA in petroleum refineries with the focus on methodologies, industrial case studies, and future trends. The main idea behind these studies is that WPA can drastically cut the fresh water supply (even up to 56%) which is accompanied by lowering wastewater generation and their costs. Apart from the graphical and tabular methods (composite curves, water cascade analysis) presented in the review paper, this is also the interaction of decision frameworks (Life Cycle Assessment, Heat Pinch, AI/ML) and recent progress in digitalization and zero liquid discharge. By comparing data from several refineries (Kaduna, Tehran, Kermanshah, etc.), the paper looks at the accomplishments, barriers, and possibilities for research. Water Pinch Analysis (WPA) is a strategic tool that can help the refining industry reach its sustainability goals.

Keywords: Water Pinch Analysis (WPA), Petroleum Refineries, Water Conservation, Process Integration, Sustainability

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1. Introduction

Petroleum refineries, which are criticized for the massive water consumption of the different processes such as cooling, washing, and steam production, are still releasing large volumes of heavily polluted wastewater loaded with oils, COD, heavy metals, and other hazardous organic

compounds [1]. Such changes necessitate adherence to tough environmental laws and control of the operational budget. In addition, water management has become a very sensitive issue as the industry is an extremely heavy consumer, the refining sector being the one that accounts for about 16% of the world's water with estimations going to double this consumption by 2035 [2]. The amount of wastewater generated based on production is equal to 3.5–5 m^3 for every ton of processed oil, thus the demand for efficient treatment technologies [3]. Given that water resources are finite and that environmental issues are worsening, it has become indispensable to resort to low-cost and efficient treatment and segregation methods, mainly because of the tightening of regulations worldwide and the increase in freshwater prices [3].

2. Challenges in water usage and wastewater treatment.

Water management in petroleum refineries is a complicated technical challenge. The problem begins with the diversity of waste streams that include desalter water, spent caustic, and oily wastewater, which need to be treated separately. The refineries also have to face the presence of pollutants such as organic chemicals, ammonia, phenols, aromatic hydrocarbons, and heavy metals [4]. These contaminants are difficult to handle due to their complexity. They are not easily decomposable and often go through treatment methods that are already in place. That is why there is a need for advanced and flexible technologies [3]. Besides, conventional treatment systems are costly to run due to the low pollutant degradability and because of the risk of the creation of secondary pollution. These factors put a considerable financial challenge on refineries and show the necessity of more cost-effective solutions without delay [4]. Besides the treatment expenses, the operators have some practical problems of scaling and corrosion in cooling and heat-exchange equipment, as well as microbial growth (for instance, Legionella in cooling towers) that can deteriorate performance and cause a risk to long-term operational sustainability [5].

3. Motivation for using Water Pinch Analysis.

Water Pinch Analysis (WPA) is a structured and dependable method for creating water-treatment networks that deliver significant savings in fresh water by integration and reuse of process streams with a minimum of fresh water and other types of interventions [6,7]. The approach uses graphical instruments such as the source–sink composite curves and water cascade analysis to fix limiting consumption targets and to give directions for the design of effective reuse networks [7]. Practical effectiveness of these instruments has been verified, e.g., in an Iranian refinery the WPA single parameter-based (COD or TDS) freshwater demand was lowered by 45% and jointly (COD and TDS) even by 56%, wastewater discharge at the same time was reduced by 31–52 m^3/h [2]. Furthermore, a Decision Support System (DSS) equipped with MINLP and MILP models has recently been developed for the local Refineries implementation of WPA evidenced by 17.6% freshwater saving and up to 90% water reutilization in a Model Petroleum Refinery [8]. These studies lead to the conclusion that WPA is a practical method for consumption reduction and water saving promotion in the oil industry and not only a theoretical approach.

4. Overview of Water Pinch Analysis

Water Pinch Analysis (WPA) is a method derived from pinch analysis which was initially developed for energy systems. It's a method aimed at reducing the use of fresh water and the production of wastewater by process integration and the efficient use of available water sources [9]. The 'pinch' in the approach signifies the lowest amount of water that is able to meet all the demands of the processes. By comparing the composite curves of water-producing streams (sources) with those of water-consuming streams (sinks), WPA finds the possibilities of reuse and thus assures that the use of fresh water is at the lowest level.

Table 1. The main concepts in Water Pinch Analysis (WPA).

concept	explanation
Sources:	Streams within the system that can be reused, such as condensate or process-generated water.
Sinks:	Units that require water input, including cooling and washing operations.
Water Quality Constraints:	Maximum allowable concentrations of specific pollutants (e.g., COD or TDS).
Reuse:	Direct transfer of water from a source to a sink without further modification.
Recycle:	Returning water to the same unit after minor treatment.
Regeneration:	Treating water that does not meet quality limits to upgrade it for reuse

This framework allows engineers to identify multiple conservation strategies, such as repeated use and quality improvement, rather than relying solely on fresh water [9].

5. Source–Sink Composite Curves

They use this graphical method to find energy-efficient water consumption goals in an operating system. In this technique, water feed streams (sources) and water demand streams (sinks) are displayed on one graph of volume versus contaminant concentration [10,11]. The method combines two kinds of streams into a single representation, thus the process does not require multiple diagrams or iterations and it is a simple visualization of the essential "pinch" point. This point determines the least amount of fresh water that can be used while still keeping the network balanced in terms of sources and sinks.

Figure 1 shows the source–sink composite curves, highlighting the pinch point where the minimum freshwater and wastewater targets are set.

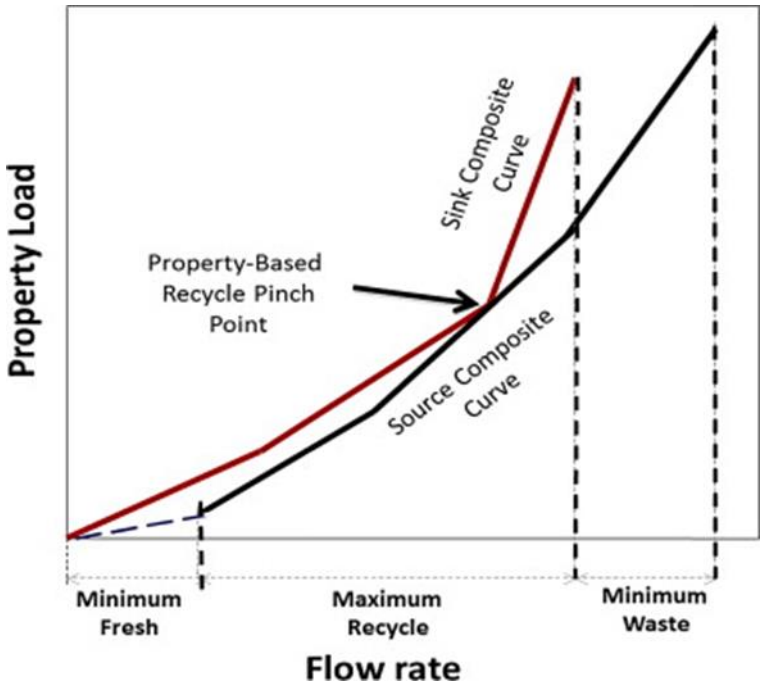

Figure 1. Source–Sink Composite Curve for Water Pinch Analysis.

6. Water Cascade Analysis (WCA)

This approach is a quantitative one and relies on iterative spreadsheet calculations to clarify the differences in water distribution at different purity levels, thus it is different from the traditional graphical methods (Manan et al)[12]. By using WCA, precise targets for water usage and wastewater flow rates are yielded, the pinch point is identified, and the sketch of an optimal network can be made just, without the complex iterative steps of the Water Surplus Diagram. Water Cascade Analysis (WCA) is a tabular substitute for graphical targeting. The work process is presented in Figure 2.

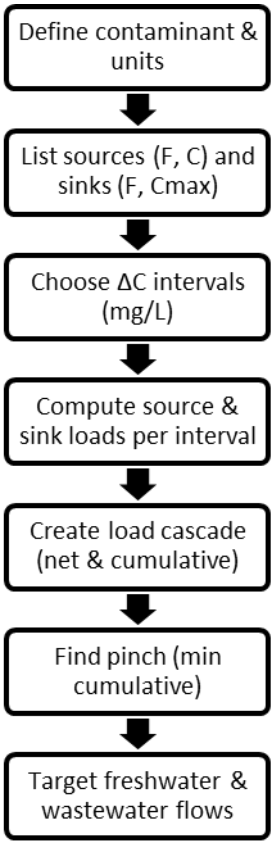

Figure 2. Water Cascade Analysis (WCA) Workflow.

The graphical method provides clear visual representation and is a powerful targeting tool, while the tabular approach (WCA) offers flexibility, high accuracy, and ease of computational iteration, making it more suitable for practical applications and engineering design with large datasets [13].

7. Water Management in Petroleum Refineries.

Petroleum refineries require massive quantities of water for multiple interconnected processes. This includes crude oil desalting, where water is used to wash crude oil and remove dissolved salts and impurities to protect equipment from corrosion and damage [14].

Next is steam generation, which powers engines and heat exchangers, making it the second-largest water consumer after cooling (Water and Wastewater Management...). Water is also used in cooling systems, whether through once-through, semi-closed, or closed-loop systems, to cool equipment and thermal processes (Water Use and Reuse in Petroleum Refining).

Additionally, water is used for equipment and facility washing, firefighting, and sanitary and utility services within the refinery [15].

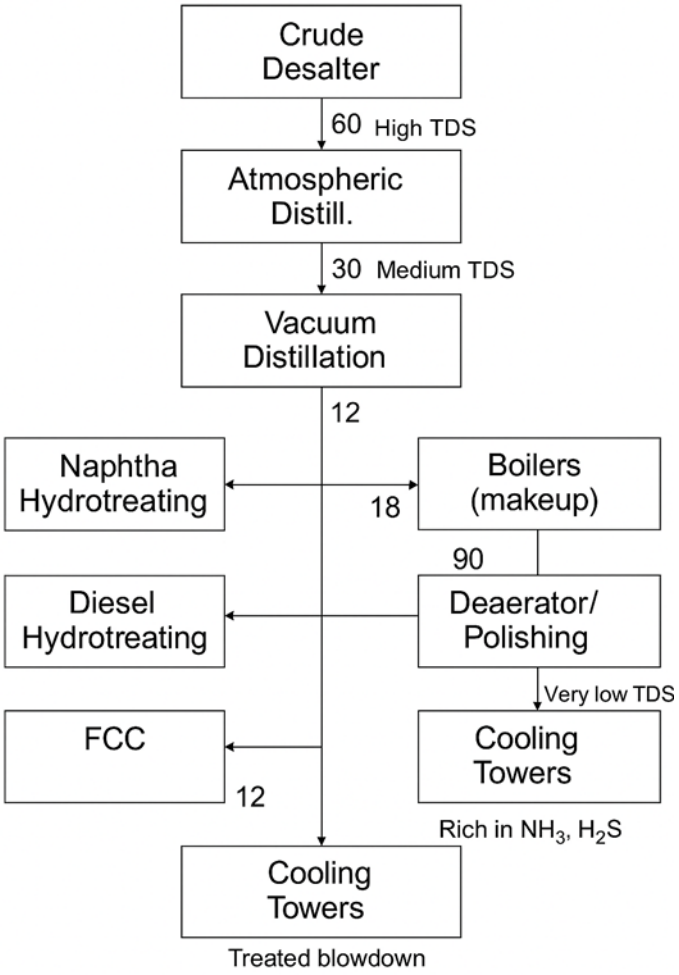

Figure 3. Schematic of Water-Intensive Processes in a Petroleum Refinery.

8. Typical Water Consumption and Wastewater Generation Patterns

As per research, 80-90% of water that is brought in is released as wastewater in petroleum refineries since the water is not utilized in the production of the final product [16]. The average wastewater generation capacity is between 0.4 and 1.6 times the volume of the processed crude [17].

Refineries produce from 3.5 to 5 m^3 of wastewater per ton of processed crude when recirculating cooling is used [18]. Various data sources reveal that the most of the consumed water is evaporated or reused, while 26% to 46% of the total water intake is turned into wastewater, which includes operational discharge, rainwater runoff, and tank containment (Water & Wastewater Management).

9. Environmental Regulations and Discharge Limits

Environmental regulations impose strict standards on refinery wastewater discharge, setting permissible pollutant limits, which sets pollutant limits and mandates refineries to implement best management practices [19].

10. Case Studies of WPA Implementation in Refineries

Water Pinch Analysis has been practically and successfully applied in oil refineries, as evidenced by various field studies. By way of illustration, the refinery-wide implementation of WPA technology in Kermanshah Province, Iran, was featured effective in reducing the fresh water

consumption from 45% (79 m³/h) for a single pollutant to 56% (99 m³/h) for a two-contaminant (COD and TDS) joint analysis [20].

At the same time, a research at the refinery in Tehran incorporated three contaminants (suspended solids, hardness, and COD) and raked in freshwater consumption reduction figures of 37-40% in the dual-contaminants analyses. It was eventually verified that the tri-contaminants analysis led to a 17.35% consumption reduction [21].

In the Nigerian study at the refinery in Kaduna, the authors applied WPA following a single-contaminant approach and a methodology that involved the identification of water sources and sinks, determination of the "pinch" point, and optimal design of a water network, supplemented by a detailed economic evaluation [22].

Figure 4 is a comparative representation of water-saving measures in various oil refinery case studies (Kaduna, Tehran, Kermanshah), expressed as percentages of their freshwater consumption.

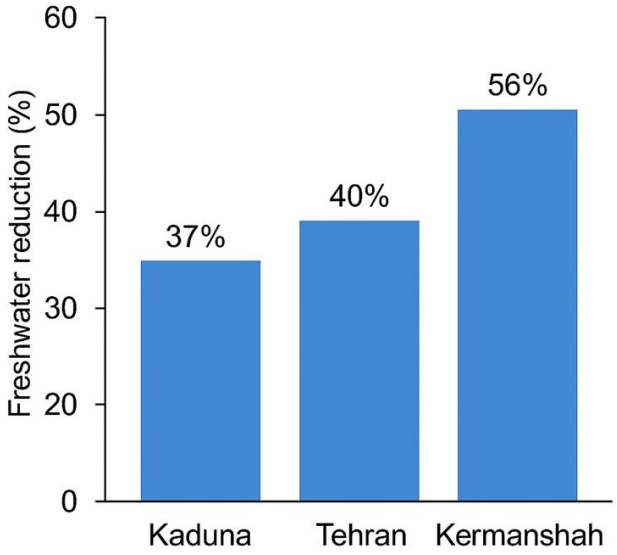

Figure 4. Freshwater Consumption Reduction in Refineries (WPA Case Studies).

11. Tools and Software Used in WPA.

Specialized software and tools are essential for the practical application of WPA. Among these, GAMS is a leader, as it solves various models, including LP, MILP, and MINDP, thus allowing the design of industrial water networks with a high level of accuracy [23].

Innovative instruments enable also visual network analysis through diagrams like Source-Sink Composite Curves or Water Cascade Analysis. Besides, there are state-of-the-art computational means for developing flexible and convertible network designs as noted in the specialized literature on industrial integration [24].

The application of WPA has resulted in an actual fresh water saving—up to 56% in the case of Iran [25]—and thus a reduction of wastewater discharge by up to 52% in the case of dual-contaminant scenarios.

From a money-saving point of view, water recycling and reuse lower the operation costs and improve the environmental management systems in refineries. Research works also point out that WPA is a potential source of environmental safety by means of giving less contaminated wastewater [25].

Besides, the best water network design of WPA releases less energy to be consumed for that part of the water treatment, which necessitates related heating/cooling. This causes the overall

system to have better operational performance and to meet stringent environmental standards [26]. Integration with Other Techniques WPA is a solid-stage unit that is represented in and merges automatically with larger system-solving paradigms like LCA, Heat Pinch, and AI/ML optimization, as is depicted in Figure 5.

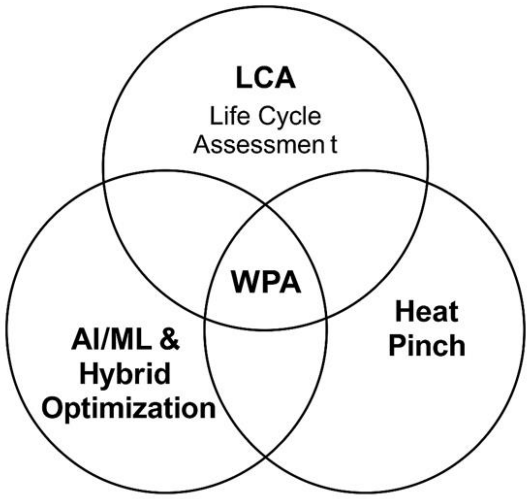

Figure 5. Integration of WPA with Other Techniques.

12. Integration with Life Cycle Assessment (LCA)

The combined approach hides the best features of Water Pinch Analysis (WPA) and Life Cycle Assessment (LCA) to evaluate the overall environmental performance of water consumption in refineries-from resource extraction to disposal (evaluation "cradle-to-grave"). In line with ISO 14040 standards, LCA determines the inputs and outputs of production systems to calculate the overall environmental footprint, while Water Footprint quantifies water consumption at each stage of the lifecycle.

This is also in line with the WPA goal to cut down on consumption and improve water integration. These hybrid methods, Water Footprint Pinch Analysis [27] or Water Scarcity Pinch Analysis [28], give a detailed quantitative and qualitative description of water consumption, the optimized water networks according to environmental impact evaluation (PMC).

13. Integration with Process Integration and Heat Pinch Analysis

Process Integration is a major engineering technique that concentrates on the minimization of mass and energy flows. For instance, Heat Pinch Analysis is a method that saves energy by taking the heat off the hot streams and giving it to the cold streams at the "pinch point" [29]

Firstly, the joint use of WPA and Heat Pinch techniques allows the saving of water and energy at the same time, thus lessening the pressure on resources and enhancing economic and environmental performances as well. In fact, the combination of Heat Pinch and Exergy Analysis can be a source of the places from where energy can be resupplied to cogeneration systems (PMC).

14. Mathematical Optimization Models

To put WPA into practice in a cost-effective manner, mathematic programming techniques—Linear Programming (LP), Mixed Integer Linear Programming (MILP), and Mixed Integer Nonlinear Programming (MINLP)—are used by researchers to find optimal water reuse and recycling networks. It has been shown by the research that the combination of Pinch Analysis with mathematical models has changed since 2003, however, it is still less far-reaching than the other process integration methods (e.g. CO_2 capture systems) [30]. Besides, superstructure-based

optimization models serve as a tool to locate the best network configurations for water, energy, and waste treatment in the interfaced systems (PMC).

15. Artificial Intelligence / Machine Learning (AI/ML) Techniques

AI and ML are increasingly being applied to enhance engineering systems like WPA through:

Data-driven optimization, which uses deep learning for dynamic response to operational fluctuations.

Physics-Informed Neural Networks (PINNs) use machine learning combined with physical laws to provide accurate predictions of water systems—even when the data is sparse or incomplete [31].

Artificial intelligence-driven mathematical programming substantially enhances the ability to manage uncertainties and speeds up the optimization cycles, thereby making the WPA more adaptive and efficient [31].

16. Challenges and Limitations

1) Data Availability and Quality

Poor data quality and lack of good data are the major barriers of implementing Water Pinch Analysis (WPA) in petroleum refineries. Often off-gas data is recorded for the control and monitoring of the process, but not for advanced analysis, thus there are restrictions in the accuracy, timeliness, and coverage of the crucial variables [32].

Industrial data is usually huge and comes from different sources, which makes it difficult to standardize and clean ("garbage in, garbage out"). Most of the time, errors originate from measurement devices or from the time when the data was recorded (aleatoric and epistemic uncertainties).

Data validation and reconciliation methods play a key role in ensuring that data is trustworthy. These methods not only eliminate random and systematic deviations but also result in consistent datasets that truly reflect the process conditions. Nevertheless, institutional cultures that facilitate data sharing between operational and analytical teams are still at a low level, thus there is limited access to reliable, integrated data (Innovations in Data Quality…).

2) Complexity in Real-World Industrial Systems

Refinery operations involve a lot of complexity in terms of processes, streams, and are spread across various units, hence it is difficult to model and simplify them for practical WPA applications.

The accuracy of models in refineries can be influenced by the following: Sediment buildup, Technological load changes, and Slow changes in temperature and pressure. Such factors cause systems to move away from the steady-state models that are necessary for WPA, thus making it difficult to pinpoint the exact "pinch point" location and the best reuse network for carrying out the operation without using advanced analytical tools and iterative refinements.

3) Economic Barriers and Practical Implementation

While water efficiency technologies can yield significant financial returns—with the World Water Council estimating $4 in savings for every $1 invested—high upfront costs remain a major adoption barrier [33,34,35,36].

17. Future Trends and Research Opportunities

Figure 6 highlights emerging trends that transform WPA from a static analysis into a dynamic, real-time optimization practice.

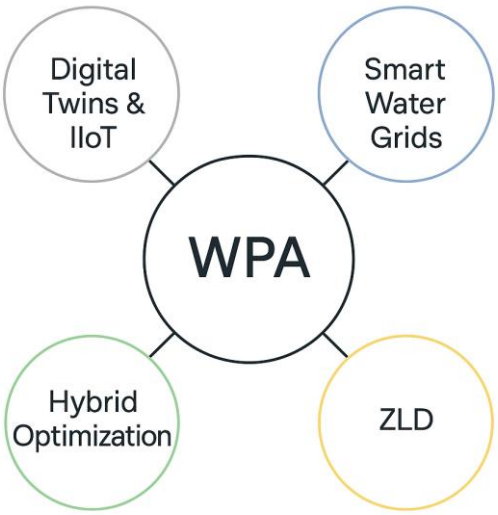

Figure 6. Future Trends in WPA for Refineries.

1) Digitalization and Real-Time WPA

The digitization of refinery environments (Digitalization) represents a significant qualitative leap leading the way to the implementation of cascade, real-time Water Pinch Analysis (WPA). Thanks to the Digital Twin technologies and the Industrial Internet of Things (IIoT) adoption, operational data can be obtained in real time. In this way, the direct evaluation and optimization of water reuse and treatment networks based on the current plant state turn out to be a natural consequence [37].

In a similar vein, Al-Maliki and Al-Saad in their paper, signify that the use of analytical techniques to monitor and evaluate water quality parameters in oil facilities not only facilitates a more efficient treatment process, but also enables real-time operational decision-taking [38].

Such an approach empowers refineries with the capability to envision the most efficient water use scenarios, gradually diminish the consumption of freshwater and at the same time, avoid the occurrence of "pinch point" violations.

2) Smart Water Grids in Refineries

Smart water grids transition to interconnected systems that are constantly monitored by sensors and AI-driven analytics are used to optimize water distribution across refinery processes. These systems provide Leak detection and rapid response, Internal water recycling with adaptive control and Energy and resource efficiency (like smart power grids) capabilities.

Through the use of IIoT and machine learning, smart water grids become a win-win situation for the environment and the operation of the plant while at the same time the resource strain is being reduced (Smart Grid Theory, IIoT Applications).

18. Advanced Hybrid Optimization Methods

The future of optimal water network design lies in hybrid mathematical modeling, combining Real-time data integration with LCA (Life Cycle Assessment), Energy-water nexus analysis and AI-enhanced LP/MILP/MINLP optimization. These methods enable semi-automated, adaptive decision-making, improving prediction accuracy and network adjustments in changing operational environments.

3) Circular Economy and Zero Liquid Discharge (ZLD)

Zero Liquid Discharge (ZLD) is on its way to becoming one of the major moves of industrial water technology that complies with the principles of a circular economy. In general, ZLD

configurations recycle more than 95% of industrial wastewater, produce value-adding byproducts (salts, minerals), reduce their environmental impact, and comply with the regulations [39].

Firstly, it is figured out that for refineries located in water-scarce areas, ZLD is the main instrument to assure water security, environmental sustainability, and waste-to-value conversion (e.g., salt recovery for industrial use). What's more, ZLD makes it possible to have closed-loop water recycling and meet national sustainability goals, thus reducing environmental risks in the long term [40,41,42,43,44]. Abdullah and Abdulrazzaq studied treatment of oil-field produced water with natural coagulants, which led to very high reductions of turbidity and suspended solids, thus enhancing water quality and making water reuse for industrial applications easier while discharge to the environment is reduced [45]. This is an indication of the adoption of ZLD systems in oil plants not only as a concept but also as practically significant, particularly when they are combined with sustainable treatment technologies that facilitate circular water utilization and environmental protection.

19. Conclusion

This review has been very positive with the WPA acting as a very effective water management tool in a refinery when implemented in a structurally organized manner. Case studies have been reporting consistent figures of water savings of 37–56% in addition to the lowering of wastewater discharge and the improvement of operational efficiency. The importance of WPA lies in its ability to lead water reuse and recycling networks and to plan water flows according to the location of the most critical pinch points, thus resulting in strategically and technically accurate improvements not only in the quantity but also in the quality of water consumption.

In fact, WPA is a systematic tool that supports the realization of sustainable water management goals in refineries, such as reducing the use of freshwater, cutting operational costs related to water treatment, and decreasing environmental risks caused by the discharge of toxic wastewater.

WPA when coupled with life cycle assessment, heat pinch, and AI/ML extends its domain beyond water savings to water-energy-cost co-benefits. Challenges in data quality, system complexity, and economic barriers still exist. Future research should be oriented to real-time WPA facilitated by digital twins, hybrid optimization models, and zero liquid discharge systems to enable the refinery operations to be in line with circular economy goals.

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