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# Resource Recovery and Beneficial Reuse of Produced Water in Energy Operations, a Review of Sustainable Pathways

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**Abstract**
Produced water (PW), the largest by-product of oil and gas operations, presents both environmental challenges and opportunities for resource recovery and beneficial reuse. Traditionally considered a waste stream, PW contains valuable constituents, including nutrients (nitrogen and phosphorus), organic matter, salts, and minerals, which can be harnessed to support circular water management and sustainable energy operations. This critically evaluates the emerging pathways for resource recovery and reuse of PW, emphasizing the integration of physicochemical and bio-based treatment strategies, digital monitoring, and modular or decentralized system designs. The chemical and physical characteristics of PW such as high salinity, total dissolved solids (TDS), hydrocarbons, heavy metals, naturally occurring radioactive materials (NORM), and nutrient content determine the feasibility and selection of recovery and reuse technologies. Nutrient recovery through biofilm reactors, algal consortia, and other biological systems enables the production of biofertilizers or soil amendments, while biomass harvesting allows conversion of organic matter into energy or value-added products. Salt and mineral extraction using crystallization, evaporation, and adsorption technologies provides additional economic opportunities and reduces environmental disposal impacts. Beneficial water reuse options include irrigation for non-food crops, industrial process water, and enhanced oil recovery (EOR), contingent on achieving effluent quality compatible with specific applications. AI-driven monitoring and optimization facilitate adaptive process control, improving recovery efficiency, reducing energy and chemical usage, and ensuring consistent effluent quality. Modular and decentralized treatment systems enhance operational flexibility, particularly in remote or water-stressed environments, while aligning with circular water management principles. Despite advancements, research gaps remain, including long-term operational validation, standardization of treatment and reuse protocols, and integration with renewable energy systems. This review highlights the strategic value of resource recovery and water reuse from PW, offering sustainable pathways that reduce environmental impact, enhance operational efficiency, and transform PW from a waste liability into a valuable resource. Future work should focus on scalable, field-validated solutions that integrate advanced treatment, monitoring, and resource recovery technologies to enable resilient and sustainable PW management.

**Keywords:** Produced Water, Resource Recovery, Water Reuse, Circular Water Management, Nutrients, Biomass, Salts, Sustainable Energy Operations, AI Optimization, Hybrid Treatment systems

## 1. Introduction

Produced water (PW) is the largest by-product of oil and gas operations, often representing the majority of fluids extracted alongside hydrocarbons. It originates from naturally occurring formation water, injected water used for reservoir pressure maintenance, or enhanced oil recovery (EOR) operations (Aniebonam, 2024 [10]; Ajirotutu *et al*., 2024). The volume and composition of PW vary significantly depending on reservoir characteristics, production methods, and the age of the wells. In mature fields or high water-cut wells, PW can exceed 90% of the total produced fluids. Its chemical complexity including hydrocarbons, salts, heavy metals, nutrients, and naturally occurring radioactive materials (NORM) poses significant environmental and operational challenges (Oyeyemi *et al*., 2024; Falana *et al*., 2024) [53, 18]. The disposal of untreated or inadequately treated PW can lead to soil and groundwater contamination, salinization, ecological toxicity, and long-term environmental degradation. Traditional management strategies, such as deep-well injection, surface discharge, or centralized treatment, are increasingly constrained by regulatory requirements, environmental concerns, and operational costs, particularly in arid or water-stressed regions (Odezuligbo *et al*., 2024 [35]; Ajirotutu *et al*., 2024).

Despite these challenges, PW presents significant opportunities for resource recovery and beneficial reuse. Its content of nutrients, such as nitrogen and phosphorus, can be harnessed to produce biofertilizers, while organic matter and biomass from biological treatment systems can be valorized as energy or soil amendments (Okuwobi *et al*., 2024; Essien *et al*., 2024). Salts and minerals present in PW can be recovered for industrial applications, reducing environmental discharge and creating economic value. Additionally, treated PW can serve as a source of water for non-potable applications, including irrigation, industrial processes, or EOR, promoting water reuse and reducing the demand on freshwater resources (Idowu *et al*., 2024 [24]; Kuponiyi and Akomolafe, 2024). Integrating these approaches aligns with circular water management principles, which aim to close water and material loops, minimize environmental impact, and enhance resource efficiency (Ihwughwavwe and Aniebonam, 2024 [25]; Seyi-Lande *et al*., 2024).

This aims to provide a comprehensive evaluation of sustainable pathways for resource recovery and beneficial reuse of PW in energy operations. Specifically, it focuses on the characterization of PW relevant to recovery opportunities, emerging physicochemical and bio-based treatment technologies, and strategies for water reuse aligned with circular economy principles. The review also highlights technological, operational, and regulatory considerations, identifies research gaps, and examines case studies and pilot applications to illustrate practical implementations. By synthesizing current knowledge, this review seeks to provide a framework for the sustainable management of PW, enabling energy operations to transform a traditionally waste-intensive by-product into a resource that supports operational efficiency, environmental protection, and circular water management strategies (Odezuligbo, 2024; Wegner *et al*., 2024) [36, 62].

## 2. Methodology

The methodology for this review was structured following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a systematic, transparent, and reproducible approach to literature selection, evaluation, and synthesis. A comprehensive search was conducted across multiple scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar, covering peer-reviewed journal articles, conference proceedings, and technical reports published in English. Search terms included combinations of “produced water,” “resource recovery,” “beneficial reuse,” “nutrient recovery,” “biomass harvesting,” “salt recovery,” “water reuse,” “circular water management,” “hybrid treatment systems,” and “sustainable oil and gas operations.” Reference lists of selected articles were also screened to identify additional relevant studies.

All records retrieved from the databases were imported into a reference management system, and duplicates were removed. Screening was performed in two stages. First, titles and abstracts were assessed to exclude studies not relevant to PW resource recovery, water reuse, or sustainable treatment approaches. Second, full-text articles were evaluated against predefined inclusion criteria, which included studies reporting nutrient, biomass, or salt recovery from PW, demonstrations of beneficial water reuse, hybrid treatment technologies combining physicochemical and bio-based processes, and research addressing operational or environmental sustainability. Exclusion criteria included studies limited to conventional disposal of PW without recovery or reuse, studies lacking quantitative or qualitative assessment of treatment performance, and articles not providing sufficient methodological detail.

Data extraction from eligible studies was conducted systematically, capturing key parameters such as PW characteristics, treatment and recovery technologies, operational context, effluent quality, energy and chemical use, and environmental impact. Both laboratory-scale and field-scale studies were considered to evaluate technical feasibility, operational resilience, and scalability. Due to heterogeneity in study designs, treatment technologies, and performance metrics, a narrative synthesis was employed rather than quantitative meta-analysis.

The extracted evidence was organized to highlight opportunities for nutrient, biomass, and salt recovery, water reuse applications, hybrid treatment approaches, and integration with circular water management strategies. This PRISMA-guided methodology provides a rigorous foundation for evaluating sustainable pathways for resource recovery and beneficial reuse of produced water in energy operations.

### 2.1 Characteristics of Produced Water Relevant to Resource Recovery

Produced water (PW) is a complex by-product of oil and gas operations, representing the majority of fluids extracted from hydrocarbon reservoirs. Its composition is highly variable, reflecting differences in geological formations, production techniques, and operational practices. Understanding the chemical and physical characteristics of PW is fundamental to identifying feasible pathways for resource recovery and beneficial reuse (Adeleke and Olajide, 2024 [1]; Olufemi *et al*., 2024). Key components of PW including salinity, hydrocarbons, heavy metals, nutrients, and naturally occurring radioactive materials (NORM) determine the selection of treatment technologies, recovery strategies, and operational design.

Salinity and total dissolved solids (TDS) are defining features of PW, often ranging from 1,000 mg/L to over 200,000 mg/L depending on the reservoir and operational context. High salinity contributes to osmotic stress in biological treatment systems, scaling in membrane processes, and corrosion in metallic infrastructure. The ionic composition commonly dominated by sodium, calcium, magnesium, chloride, sulfate, and bicarbonate also influences the solubility of salts, precipitation potential, and effectiveness of chemical and membrane-based recovery methods. Accurate characterization of salinity and ionic composition is therefore critical for optimizing resource recovery, including salt extraction and water reuse.

Hydrocarbons, both dissolved and suspended, are a major contaminant in PW. These include aliphatic and aromatic compounds, such as benzene, toluene, ethylbenzene, xylene (BTEX), and polycyclic aromatic hydrocarbons (PAHs). Even at low concentrations, hydrocarbons are environmentally hazardous and pose significant challenges for treatment and reuse. Heavy metals including arsenic, cadmium, chromium, lead, and mercury may also be present, with implications for both environmental discharge and recovery potential. NORM, primarily radium isotopes, can accumulate in sludge and brine, creating radiological safety considerations for handling and reuse (Ajirotutu *et al*., 2024; Olufemi *et al*., 2024).

Nutrient content in PW, particularly nitrogen and phosphorus, offers significant opportunities for resource recovery. These nutrients are essential for agricultural applications, but their uncontrolled discharge can lead to eutrophication of receiving waters. The organic matter present in PW, derived from hydrocarbons, microbial biomass, and other dissolved organics, can be harnessed for bioenergy or soil amendment applications if appropriately treated. The concentration and speciation of nutrients and organics influence the design of biological treatment systems and the feasibility of biomass harvesting or nutrient extraction processes.

Temporal and spatial variability in PW composition further complicates treatment and resource recovery. Water production rates and contaminant loads fluctuate due to well age, reservoir heterogeneity, water injection schedules, and operational interventions. For instance, high water-cut wells in mature fields may produce large volumes of highly saline water with elevated concentrations of hydrocarbons and heavy metals, while younger wells may have lower salinity and different ionic profiles. Seasonal and operational variations can also affect nutrient concentrations and organic load, impacting the performance of biological treatment systems and the efficiency of recovery operations.

Such variability has significant implications for treatment and resource recovery strategies. Fixed or static treatment designs may be unable to cope with fluctuating influent conditions, leading to reduced contaminant removal efficiency, increased fouling or scaling, and lower recovery yields. Adaptive systems, incorporating real-time monitoring and process control, are therefore critical to maintain treatment performance and optimize resource extraction. For example, nutrient recovery through biofilm or algal-based systems may require adjustments in retention time, aeration, or hydraulic loading in response to fluctuating nitrogen and phosphorus concentrations. Similarly, salt crystallization and membrane-based extraction processes must account for temporal salinity changes to prevent scaling and maximize recovery efficiency (Adeleke *et al*., 2024; Babalola *et al*., 2024) [2, 14].

The heterogeneity of PW also affects the potential for beneficial reuse. High salinity, hydrocarbons, or heavy metal content may limit direct reuse applications, necessitating targeted pretreatment or polishing steps to produce water suitable for irrigation, industrial use, or enhanced oil recovery (EOR). Understanding the interplay between PW composition, variability, and treatment requirements is therefore essential for designing modular, scalable, and resource-efficient recovery systems.

The chemical and physical characteristics of PW—including salinity, ionic composition, hydrocarbons, heavy metals, NORM, nutrients, and organic matter—define both the challenges and opportunities for resource recovery. Temporal and spatial variability in flow rates and contaminant concentrations further complicates treatment and reuse, requiring adaptive, real-time management strategies. Comprehensive characterization of PW is critical to selecting appropriate recovery technologies, optimizing operational performance, and ensuring that resource extraction and water reuse are both technically feasible and environmentally sustainable. By accounting for the variability and complex composition of PW, energy operations can develop modular, resilient, and efficient systems that transform produced water from a waste liability into a valuable resource stream, supporting circular water management and sustainable energy production.

## 2.2 Resource Recovery Opportunities

Produced water (PW), the largest by-product of oil and gas operations, has historically been regarded as a waste stream requiring treatment and disposal. However, the complex chemical composition of PW including nutrients, organic matter, salts, and minerals presents significant opportunities for resource recovery. With the increasing emphasis on sustainable energy operations, circular water management, and environmental stewardship, resource recovery from PW is gaining strategic importance (Seyi-Lande *et al*., 2024; Okafor *et al*., 2024 [41]). Recovery strategies target three primary resource streams: nutrients, biomass and organic matter, and salts and minerals. These recovery pathways not only reduce environmental impact but also generate economic value and support operational resilience, particularly in water-stressed or remote energy operations.

Nitrogen and phosphorus are among the most valuable constituents of PW. Excessive discharge of these nutrients into surface water can cause eutrophication, while their controlled recovery can provide feedstock for agricultural and industrial applications. Nutrient recovery technologies often leverage biological processes, such as biofilm reactors or algal-based systems, which assimilate nitrogen and phosphorus during growth. Algal consortia, for example, uptake ammonium, nitrate, and phosphate, producing nutrient-rich biomass that can subsequently be harvested. Biofilm reactors similarly promote microbial growth that assimilates nitrogen and phosphorus into cellular material. Optimized nutrient recovery requires adaptive process control, accounting for the variability in PW composition, flow rate, and contaminant load. AI-driven monitoring and real-time process adjustments enhance nutrient uptake efficiency, ensuring consistent recovery while maintaining effluent quality suitable for downstream reuse or discharge (Odejobi *et al*., 2023; Oparah *et al*., 2023) [34, 48]. Nutrient recovery thus transforms a potential environmental liability into a valuable resource stream for fertilizer production or industrial chemical synthesis.

PW contains significant amounts of organic matter, derived from hydrocarbons, microbial biomass, and other dissolved organics. This organic fraction can be valorized through algal or microbial cultivation, producing biomass suitable for a variety of applications. Algal biomass harvested from PW treatment systems is rich in nutrients and can be processed into biofertilizers, soil amendments, or bioenergy feedstock, such as biogas through anaerobic digestion. Microbial biofilms similarly generate biomass that can be repurposed for energy recovery or as organic soil enhancers. The integration of hybrid treatment systems combining physicochemical pretreatment to remove hydrocarbons and suspended solids with biological units for organic assimilation optimizes biomass production while minimizing fouling and system downtime. Effective biomass harvesting strategies, including centrifugation, flocculation, or filtration, enhance the economic feasibility of this approach and enable the transformation of PW into a sustainable source of bioresources (Uduokhai *et al*., 2024 [59]; Kuponiyi and Akomolafe, 2024).

High salinity and total dissolved solids in PW present both a challenge and an opportunity. Salt and mineral recovery can mitigate environmental impacts associated with brine disposal while generating commercially valuable products. Physicochemical methods such as crystallization, evaporation, and membrane concentration are commonly employed to extract sodium, calcium, magnesium, chloride, sulfate, and other salts from PW. Multi-effect evaporation or solar-assisted crystallization can efficiently produce solid salts suitable for industrial applications, including chemical synthesis, water softening, and construction materials. Membrane-based technologies, such as reverse osmosis or nanofiltration, enable partial desalination with recovery of concentrated brine for subsequent salt extraction. Optimizing these processes requires careful monitoring of scaling potential, ionic composition, and operational parameters, which can be enhanced using AI-driven process control systems (Oziri *et al*., 2023; Uduokhai *et al*., 2023) [54, 58]. The recovered salts not only provide economic benefit but also reduce the volume of concentrated brine requiring disposal, supporting environmentally sustainable water management.

Resource recovery pathways in PW management are often complementary. For example, hybrid treatment trains can integrate physicochemical pre-treatment for hydrocarbon removal, followed by bio-based nutrient assimilation and biomass production, and finishing with salt recovery and water polishing. Such integrated approaches maximize recovery potential, minimize energy and chemical consumption, and ensure effluent meets reuse or discharge requirements. Adaptive management and AI-driven control further enhance the efficiency and reliability of these processes, particularly in remote or water-stressed environments where resource conservation is critical (Ofori *et al*., 2024; Nwokediegwu *et al*., 2024).

Resource recovery from PW represents a transformative approach to sustainable water management in oil and gas operations. Nitrogen and phosphorus can be extracted and utilized for agricultural or industrial purposes through biofilm and algal assimilation. Organic matter and biomass harvested from treatment systems can be converted into biofertilizers, soil amendments, or bioenergy feedstock, creating additional economic value. High-salinity PW streams offer opportunities for salt and mineral recovery through evaporation, crystallization, and membrane technologies, providing industrially useful products while reducing environmental discharge. The integration of these recovery pathways into modular, hybrid treatment systems, supported by AI-driven monitoring and process optimization, enables the efficient, resilient, and sustainable management of produced water. Collectively, these strategies transform PW from a waste liability into a resource stream, aligning energy operations with circular water management principles and promoting environmental, economic, and operational sustainability (Kuponiyi *et al*., 2023; Ofori *et al*. 2023 [39]).

### 2.3 Beneficial Water Reuse Pathways

Produced water (PW), generated as a by-product of oil and gas extraction, represents a substantial and often underutilized resource. While historically treated as a waste stream requiring disposal, advances in treatment technologies and resource recovery strategies now allow PW to be repurposed for beneficial reuse. Reusing PW reduces reliance on freshwater resources, supports circular water management, and aligns with sustainability objectives in water-stressed or energy-intensive regions. Effective reuse pathways depend on the careful treatment and characterization of PW, ensuring that contaminants such as hydrocarbons, salts, heavy metals, and naturally occurring radioactive materials (NORM) are controlled to meet application-specific quality requirements.

One of the most promising reuse pathways is irrigation of non-food crops, such as bioenergy plantations, fodder, or landscape vegetation. PW contains nutrients, including nitrogen and phosphorus, which can enhance plant growth when properly treated. However, high salinity, elevated total dissolved solids (TDS), and the presence of heavy metals necessitate careful monitoring and management to prevent soil degradation, salinization, and bioaccumulation of toxic elements. Treatment strategies for irrigation use typically involve physicochemical methods, such as membrane filtration and advanced oxidation, combined with bio-based processes like algal or microbial nutrient assimilation, to reduce contaminants and produce water suitable for agricultural application (Essien *et al*., 2024; Fowowe, 2024 [20]). Implementing adaptive monitoring, potentially supported by AI-enabled control systems, ensures that water quality remains within agronomic thresholds, preserving soil health while maximizing crop yield. Additionally, blending treated PW with freshwater or implementing intermittent irrigation schedules can further mitigate salinity stress and nutrient overload.

PW can also serve as a valuable source of process water in energy, mining, and manufacturing operations. For example, in thermal power plants or mineral processing facilities, treated PW can replace freshwater in cooling systems, boiler feedwater, or industrial cleaning processes. Another critical application is enhanced oil recovery (EOR), where treated PW can be reinjected into reservoirs to maintain pressure and improve hydrocarbon recovery. For these industrial uses, water quality standards are typically more stringent than for non-food crop irrigation, particularly regarding suspended solids, hydrocarbons, and scaling ions such as calcium, magnesium, and silica. Hybrid treatment trains that combine membrane filtration, adsorption, and advanced oxidation processes can ensure compliance with these quality requirements while optimizing energy and chemical consumption. Operational reuse of PW not only reduces freshwater demand but also minimizes wastewater discharge, contributing to environmental sustainability and cost savings in water-intensive processes.

While the reuse of PW offers significant benefits, it also presents environmental and social challenges. Risks include potential contamination of soils, groundwater, or surface water from residual salts, heavy metals, hydrocarbons, or NORM if treatment is inadequate. Effective mitigation strategies involve robust treatment technologies, continuous monitoring of water quality, and adaptive management to respond to fluctuations in PW composition (Asolo *et al*., 2024; Michael and Ogunsola, 2024) [11, 30]. Additionally, regulatory compliance and adherence to site-specific environmental standards are essential to ensure safe reuse. Socially, community engagement is critical when PW is repurposed in agriculture or industrial applications near populated areas. Transparency regarding water quality, potential risks, and treatment practices fosters public trust and reduces concerns regarding exposure to contaminants. Ecological impacts must also be considered, particularly when PW is reused in or near sensitive ecosystems, where even low concentrations of salts, nutrients, or trace metals could alter soil or aquatic biota.

The beneficial reuse of PW represents a key pillar of circular water management in energy operations. By transforming PW from a waste liability into a resource, operators can close water loops, reduce freshwater extraction, and enhance resilience in arid or water-scarce regions. Integrating reuse pathways with resource recovery for example, combining nutrient extraction, biomass harvesting, and salt recovery ensures that water, organic matter, and minerals are efficiently valorized, minimizing environmental impact and maximizing operational efficiency. Real-time monitoring and AI-driven control can further optimize reuse strategies, dynamically adjusting treatment and allocation based on quality, quantity, and operational demand.

Beneficial water reuse from PW encompasses multiple pathways, including non-food crop irrigation, industrial process water, and enhanced oil recovery, each requiring tailored treatment and monitoring approaches. Successful reuse relies on controlling salinity, heavy metals, hydrocarbons, and nutrient loads to protect soils, ecosystems, and human health. When integrated with hybrid treatment technologies, resource recovery strategies, and adaptive management frameworks, PW reuse supports circular water management, operational sustainability, and environmental stewardship. By leveraging these approaches, energy operations can transform PW from a disposal challenge into a strategic resource, enhancing resilience, reducing freshwater dependency, and providing tangible social, environmental, and economic benefits.

### 2.4 Technological Approaches to Recovery and Reuse

The increasing production of produced water (PW) in oil and gas operations has prompted significant interest in technologies that enable resource recovery and beneficial reuse. Traditional disposal practices, such as deep-well injection or surface discharge, are increasingly constrained by environmental regulations, operational costs, and sustainability considerations. Consequently, technological approaches now emphasize the integration of hybrid treatment systems, advanced monitoring and control via artificial intelligence (AI), and modular, decentralized configurations to support flexible, energy-efficient, and scalable PW management (Oparah *et al*., 2024; Halliday, 2024 [23]). These approaches are particularly valuable in remote or off-grid energy operations, where water scarcity, logistical challenges, and limited infrastructure necessitate resilient and adaptive treatment solutions.

Hybrid treatment systems, which combine physicochemical and bio-based processes, represent a cornerstone of contemporary PW management. Physicochemical technologies, such as membrane filtration (microfiltration, ultrafiltration, nanofiltration, and reverse osmosis), adsorption (activated carbon, biochar, or nanomaterials), advanced oxidation processes, and coagulation-flocculation, are highly effective at removing suspended solids, hydrocarbons, heavy metals, and salts. However, they are energy-intensive, can generate concentrated brine or sludge, and may not efficiently recover nutrients or organic matter. Complementary bio-based processes including biofilm reactors, algal-bacterial consortia, and constructed wetlands capitalize on microbial or algal metabolism to assimilate nutrients, degrade organics, and generate biomass for resource recovery.

Integrating physicochemical and bio-based processes in a hybrid treatment train allows each unit to address the limitations of the other. For example, physicochemical pre-treatment can remove bulk hydrocarbons, TSS, and scaling ions to protect downstream biological units, while bio-based reactors recover nutrients and produce harvestable biomass. Post-treatment physicochemical units may serve as polishing steps to ensure effluent meets reuse standards for irrigation, industrial applications, or enhanced oil recovery (EOR). Hybrid systems thus optimize contaminant removal, enhance resource recovery, and improve operational resilience under variable PW composition.

Digital monitoring and AI-driven control are increasingly integrated into hybrid PW treatment systems to maximize efficiency and reliability. Real-time sensors measure key parameters, such as salinity, total dissolved solids (TDS), chemical oxygen demand (COD), total suspended solids (TSS), nutrient concentration, and hydrocarbon load. IoT connectivity transmits these data to cloud-based or edge-computing platforms, where machine learning algorithms detect patterns, identify anomalies, and provide actionable insights (Ofori *et al*., 2024; Fasawe *et al*., 2024 [19]).

AI-driven optimization enables dynamic adjustments in chemical dosing, membrane operation, retention time, and aeration in bio-based reactors, reducing energy and chemical consumption while maintaining treatment performance. Predictive maintenance models forecast membrane fouling, pump wear, or biofilm performance decline, allowing proactive interventions that minimize downtime and operational costs. Furthermore, AI-supported control facilitates adaptive response to fluctuations in PW composition, flow rates, and nutrient load, ensuring consistent effluent quality for reuse and enhancing the overall sustainability of the operation.

In remote or off-grid energy operations, modular and decentralized PW treatment systems offer significant advantages. Modular units allow incremental scaling to accommodate variable production volumes, reducing capital expenditure and operational complexity. Decentralized deployment is particularly useful in geographically dispersed oilfields, offshore platforms, or isolated facilities where centralized infrastructure is impractical or cost-prohibitive.

Modular systems can combine compact physicochemical units with bio-based treatment modules, enabling a flexible, site-specific configuration that addresses local PW characteristics and recovery objectives. Decentralized arrangements also reduce the need for extensive pipeline networks or centralized storage, limiting environmental footprint and improving resilience to operational disruptions. When integrated with renewable energy sources, such as solar or wind power, modular systems can further reduce energy dependency and enhance sustainability, making off-grid PW recovery feasible even in water-scarce or energy-constrained regions.

The combination of hybrid treatment processes, AI-driven monitoring, and modular deployment provides a comprehensive framework for PW recovery and reuse.

Physicochemical units ensure robust removal of contaminants, bio-based units enable nutrient and biomass recovery, AI ensures adaptive optimization and predictive maintenance, and modular design supports scalability and off-grid operation. Together, these technological innovations create a resilient, energy-efficient, and resource-focused PW management system capable of supporting circular water management principles.

Technological approaches to PW recovery and reuse increasingly rely on integrated solutions that combine hybrid treatment systems, digital monitoring, and modular deployment. Hybrid systems address the complex chemistry of PW while enabling nutrient and biomass recovery. AI and IoT-enabled process control optimize operational efficiency, reduce chemical and energy consumption, and enhance reliability. Modular and decentralized configurations allow flexible deployment in remote or off-grid operations, ensuring scalability, resilience, and minimal environmental impact (Okuwobi *et al*., 2024; Awe *et al*., 2024 [13]). Collectively, these technologies provide a robust framework for transforming PW from a disposal liability into a valuable resource, supporting sustainable, circular, and efficient water management in energy operations.

## 2.5 Sustainability and Circular Water Management Integration

Produced water (PW) management in oil and gas operations has historically been a linear process: water is extracted alongside hydrocarbons, treated to remove contaminants, and ultimately disposed of through injection, surface discharge, or evaporation. This approach is resource-intensive, environmentally challenging, and increasingly unsustainable, particularly in water-stressed or arid regions. Emerging strategies that integrate resource recovery, beneficial reuse, and digital process optimization offer the potential to transition PW management from a linear to a circular paradigm. Circular water management emphasizes the valorization of water and associated resources, minimizing environmental footprint, and enhancing operational resilience. By aligning PW treatment and reuse with circular economy principles, energy operations can transform a traditionally problematic by-product into a strategic resource stream.

Circular economy principles prioritize the efficient use of resources, reduction of waste, and continuous reintegration of materials into productive use. PW contains multiple recoverable components, including nutrients (nitrogen and phosphorus), organic matter, biomass, salts, and water suitable for reuse. By implementing hybrid treatment systems that combine physicochemical processes (e.g., membrane filtration, adsorption, advanced oxidation) with bio-based approaches (e.g., biofilm reactors, algal consortia, constructed wetlands), these resources can be extracted and reused (Nwokediegwu *et al*., 2024; Adeshina and Ndukwe, 2024 [3]). For example, nutrients can be recovered to produce biofertilizers or soil amendments, biomass can be converted into bioenergy, and treated water can support irrigation, industrial processes, or enhanced oil recovery (EOR). Integrating recovery and reuse into PW management closes the loop on water and material flows, reducing dependence on freshwater, mitigating environmental risks, and creating economic value.

Transitioning to circular PW management requires careful attention to energy and resource efficiency. Physicochemical treatments, such as membrane filtration and evaporation, are typically energy-intensive, while biological processes are slower but less energy-demanding and capable of nutrient and organic matter recovery (Halliday, 2023; Awe *et al*., 2023) [22, 12]. Hybrid systems enable complementary operation: physicochemical units pre-treat water to remove hydrocarbons, solids, and scaling ions, allowing bio-based units to focus on nutrient assimilation and biomass production. AI-enabled monitoring and process optimization further enhance efficiency by dynamically adjusting operational parameters, such as chemical dosing, membrane flux, aeration, and retention time, based on real-time PW quality and flow. This adaptive control reduces chemical consumption, minimizes energy usage, and maintains effluent quality suitable for reuse, thereby increasing the overall sustainability of the PW management system. In remote or off-grid energy operations, integrating renewable energy sources, such as solar or wind power, can further reduce carbon footprint and energy dependency, supporting resilient and energy-efficient circular water management (Adeshina, 2023; Oyeyemi and Kabirat, 2023) [4, 51].

A comprehensive evaluation of circular PW management requires life-cycle assessment (LCA) and techno-economic analysis (TEA) to quantify environmental and economic performance. LCA considers energy use, greenhouse gas emissions, chemical consumption, water savings, and waste generation across the entire treatment and recovery process. Studies have shown that hybrid and AI-optimized PW treatment systems can significantly reduce environmental impacts compared with conventional disposal, particularly when recovery of nutrients, biomass, or salts is integrated. TEA evaluates capital expenditure, operational costs, potential revenue from recovered products, and savings from freshwater substitution or reduced disposal requirements. Such analyses indicate that the integration of resource recovery and beneficial water reuse can improve economic viability, particularly in water-scarce regions or remote operations where freshwater procurement and disposal logistics are costly (Omisola *et al*., 2023 [47]; Kuponiyi *et al*., 2023).

Life-cycle assessments also highlight trade-offs: high-energy processes like reverse osmosis or multi-effect evaporation may recover salts or water effectively but increase energy consumption, while bio-based systems recover nutrients and biomass with minimal chemical input but require longer retention times. The combination of hybrid treatment, AI-based optimization, and modular design allows operators to balance these trade-offs, optimizing for both environmental and economic performance while maintaining operational flexibility (Wegner, 2024 [61]; Oparah *et al*., 2024).

Sustainability and circular water management integration are not solely technological but also strategic. Implementing resource recovery and beneficial reuse supports regulatory compliance, reduces environmental risks, and enhances corporate sustainability performance. In arid or water-stressed regions, circular PW management can alleviate freshwater scarcity, providing a reliable water supply for agricultural, industrial, or operational applications. Modular, decentralized systems enable site-specific implementation, reducing infrastructure requirements, minimizing transportation of PW, and enhancing resilience in remote or off-grid locations. AI-enabled monitoring ensures adaptive operation, safeguarding effluent quality and maximizing recovery efficiency under variable PW composition and flow conditions.

Integrating sustainability and circular water management principles into PW treatment transforms a waste-intensive by-product into a multi-resource stream, aligning water, nutrient, and mineral management with circular economy objectives. Hybrid treatment systems, enhanced with AI-driven monitoring and modular design, optimize energy and resource use while enabling nutrient, biomass, and salt recovery. Life-cycle environmental and economic assessments demonstrate that circular PW management reduces carbon footprint, minimizes freshwater dependence, and generates economic value through recovered resources. By combining technological innovation with strategic operational planning, energy operators can achieve resilient, efficient, and environmentally responsible PW management, supporting sustainable water stewardship and advancing circular water principles in the energy sector.

### 2.6 Challenges and Research Gaps

Produced water (PW) represents one of the largest waste streams generated in oil and gas operations, yet it also holds significant potential as a source of water, nutrients, salts, and biomass for sustainable reuse. While recent advances in hybrid treatment systems, bio-based processes, and AI-driven optimization have demonstrated promising results, several challenges and research gaps continue to limit the widespread adoption of resource recovery and beneficial reuse strategies (Seyi-Lande *et al*., 2024; Nwokediegwu *et al*., 2024). Addressing these gaps is essential to ensure reliable, scalable, and sustainable produced water management in energy operations, particularly in water-scarce or remote environments.

A primary challenge in PW management is the lack of long-term operational data and field-scale validation. Most studies to date are laboratory-scale or pilot-scale demonstrations, often conducted under controlled conditions and for relatively short durations. While these studies provide insight into removal efficiencies, nutrient assimilation, biomass production, and salt recovery, they do not fully account for the variability in PW composition, flow rates, or operational conditions encountered in real-world settings. Temporal fluctuations in salinity, hydrocarbon content, heavy metals, nutrients, and naturally occurring radioactive materials (NORM) can significantly impact the performance of treatment systems, particularly biological units and membrane-based processes.

Field validation over extended periods is crucial to evaluate the resilience of hybrid treatment trains, adaptive process control strategies, and integrated recovery operations. Long-term monitoring allows for assessment of fouling, scaling, biofilm stability, energy consumption, and effluent quality under varying operational conditions. Furthermore, field-scale studies are necessary to quantify recovery yields for nutrients, salts, and biomass, as well as to evaluate the reliability of treated water for reuse applications, such as irrigation, industrial use, or enhanced oil recovery (EOR). Without robust field validation, uncertainties in system performance remain a major barrier to regulatory approval and commercial deployment.

Another significant research gap is the lack of standardized protocols for treatment and beneficial reuse of PW. Currently, treatment strategies and reuse practices are highly site-specific, dependent on local water chemistry, operational scale, and regulatory frameworks. This heterogeneity complicates technology transfer, benchmarking, and regulatory compliance. Standardized guidelines for physicochemical and bio-based treatment processes, hybrid treatment train design, effluent quality criteria, and recovery methods would facilitate consistent implementation across diverse operational contexts.

Standardization is also critical for resource recovery pathways. For example, nutrient recovery via algal consortia or biofilm reactors requires consistent operational parameters to ensure predictable nitrogen and phosphorus uptake, biomass quality, and safety. Similarly, salt and mineral recovery processes, including crystallization or membrane concentration, require standardized monitoring and control of scaling, precipitation, and energy use (Olagoke-Komolafe and Oyeboade, 2024; Adeyoyin *et al*., 2024) [44, 5]. Developing harmonized protocols would not only improve operational efficiency and reliability but also support regulatory approval, industry adoption, and replication of successful pilot-scale initiatives.

Energy consumption is a critical consideration in PW treatment and resource recovery. Physicochemical processes such as reverse osmosis, evaporation, and advanced oxidation are often energy-intensive, which can limit sustainability, particularly in remote or off-grid operations. The integration of renewable energy sources, including solar, wind, and hybrid systems, represents a promising approach to reduce carbon footprint and enhance operational resilience. However, research is limited on the optimal coupling of renewable energy with hybrid PW treatment systems, particularly under variable energy availability and fluctuating water quality.

Adaptive system design, combining AI-enabled monitoring, predictive maintenance, and dynamic process optimization, is essential to maximize efficiency and reliability. AI-driven control can adjust operational parameters in real time based on sensor data, optimizing chemical dosing, retention time, aeration, or membrane flux. Research is needed to validate adaptive algorithms under field conditions, particularly when integrating renewable energy, where energy supply variability can impact treatment performance. Investigating the interplay between energy availability, treatment efficiency, resource recovery, and system robustness will be critical to ensure sustainable deployment.

Beyond these primary challenges, additional gaps include development of cost-effective biomass harvesting techniques, strategies to mitigate fouling and scaling in high-salinity PW, and evaluation of environmental and social impacts of reuse applications. Life-cycle assessments (LCA) and techno-economic analyses (TEA) are needed to quantify the sustainability and economic feasibility of integrated recovery and reuse strategies. Finally, research should explore modular and decentralized system designs that facilitate scalable deployment in distributed or remote energy operations.

Despite significant technological advancements, challenges remain in ensuring reliable, scalable, and sustainable PW resource recovery and reuse. Long-term field validation is essential to understand system performance under variable conditions, while standardized treatment and reuse protocols are necessary for broader adoption and regulatory compliance. Integration with renewable energy and adaptive, AI-enabled process control offers a pathway to energy-efficient and resilient operation, particularly in remote or water-stressed regions. Addressing these research gaps will enable the full realization of circular water management principles, transforming PW from a disposal liability into a valuable resource stream that supports environmental, economic, and operational sustainability in energy operations.

### 2.7 Pilot Applications

The implementation of pilot-scale applications in produced water (PW) management has provided valuable insights into the feasibility, performance, and scalability of resource recovery and beneficial reuse technologies. Across onshore oilfields, offshore platforms, and other energy operations, pilot projects have demonstrated that hybrid treatment systems combining physicochemical and bio-based processes can effectively recover nutrients, biomass, and salts, while producing water suitable for reuse. These pilots also highlight operational challenges, energy considerations, and system adaptability under variable water quality and flow conditions, forming the foundation for scalable, circular water management solutions (Oyeyemi, 2023 [52]; Essien *et al*., 2024).

Pilot projects targeting nutrient recovery have largely focused on nitrogen and phosphorus, leveraging biofilm reactors and algal-based systems to assimilate these nutrients into biomass. For instance, a pilot study in a high-salinity onshore oilfield demonstrated the use of algal-bacterial consortia to remove up to 80–90% of nitrogen and 70–85% of phosphorus from PW over a three-month operational period. The harvested biomass was subsequently evaluated for use as a biofertilizer, indicating potential agricultural applications. Similar offshore pilots employed biofilm reactors to treat PW prior to reinjection for enhanced oil recovery (EOR). These systems successfully reduced nutrient loads while minimizing chemical inputs, demonstrating that biological assimilation can be a sustainable and energy-efficient recovery pathway. Lessons learned from these pilots include the importance of pre-treatment to remove hydrocarbons and suspended solids, optimal hydraulic retention times, and salinity tolerance of the microbial consortia. Additionally, nutrient recovery efficiency was observed to fluctuate with seasonal or operational changes in PW composition, underscoring the need for adaptive monitoring and control systems.

Biomass recovery pilots have highlighted the potential for PW to serve as a feedstock for bioenergy or soil amendment production. Offshore demonstration projects used photobioreactors to cultivate microalgae on pretreated PW streams, achieving biomass productivity of 15–25 $g/m^2/day$. The harvested biomass was tested for biogas production via anaerobic digestion, yielding approximately 0.35–0.45 $m^3$ of methane per kilogram of volatile solids. Onshore pilots also explored combining biofilm reactors with algal systems to maximize organic matter removal and biomass generation. Key lessons included the importance of controlling light, temperature, and salinity to maintain optimal algal growth, and the necessity of downstream dewatering and drying technologies for biomass utilization. These pilots demonstrated that biomass valorization is technically feasible but requires integrated process design and adaptive operational control to ensure energy efficiency and economic viability.

Physicochemical recovery of salts and minerals has been demonstrated in both onshore and offshore pilot projects using evaporation, crystallization, and membrane concentration. In one offshore platform pilot, reverse osmosis and multi-effect evaporation were combined to recover approximately 60–70% of dissolved salts from high-salinity PW streams. The recovered salts, predominantly sodium chloride, were tested for industrial applications, such as chemical feedstock and water softening, demonstrating economic potential. Onshore brine ponds combined with solar evaporation were successfully employed to crystallize salts, producing recoverable solids while reducing the environmental burden of brine disposal (Aniebonam, 2023; Ogundipe *et al*., 2023 [40]). Lessons learned include the importance of pre-treatment to prevent scaling, careful monitoring of ionic composition, and the energy-intensity trade-offs associated with thermal recovery methods.

Overall, pilot applications have shown that hybrid PW treatment systems can achieve substantial recovery of nutrients, biomass, and salts, while producing water suitable for beneficial reuse. Typical removal efficiencies observed in pilots include 70–90% for nitrogen, 60–85% for phosphorus, and up to 70% for total dissolved solids when integrated physicochemical and bio-based processes are employed. Energy consumption and operational costs remain significant considerations, particularly for offshore or remote applications, highlighting the potential for AI-enabled process optimization and renewable energy integration. Scalability potential is strongly influenced by modular system design, which allows incremental capacity expansion and adaptability to variable PW composition and flow rates. Lessons learned from pilots emphasize the importance of robust pre-treatment, adaptive process control, real-time monitoring, and integration with recovery pathways to maximize operational resilience and resource utilization.

Pilot-scale applications have provided compelling evidence that PW can be transformed from a waste liability into a resource stream through nutrient, biomass, and salt recovery. These demonstrations highlight both the technical feasibility and the operational challenges associated with scaling hybrid treatment systems for onshore and offshore energy operations. Key lessons include the necessity of adaptive monitoring, pre-treatment optimization, and integration with energy-efficient and modular designs. Collectively, these pilots underscore the potential for scalable, sustainable, and circular PW management, supporting environmental protection, operational efficiency, and resource recovery in the oil and gas sector (Giwah *et al*., 2023; Umekwe and Oyedele, 2023) [21, 60].

## 3. Conclusion

Produced water (PW), long regarded as a waste stream in oil and gas operations, is increasingly recognized as a valuable source of water, nutrients, organic matter, and salts. Sustainable pathways for PW management integrate hybrid treatment systems that combine physicochemical and bio-based processes, enabling the recovery of key resources while producing water suitable for beneficial reuse. Nutrient recovery through biofilm reactors and algal consortia allows nitrogen and phosphorus to be repurposed as fertilizers or soil amendments. Biomass and organic matter harvested from treatment systems can be converted into bioenergy, soil conditioners, or other value-added products. Salts and minerals can be extracted through crystallization, evaporation, or membrane-based processes for industrial applications. When coupled with AI-enabled monitoring and optimization, these pathways ensure adaptive operation under variable PW composition, improving treatment efficiency and resource extraction. Modular and decentralized system designs further enhance scalability, flexibility, and resilience, particularly in remote or water-stressed energy operations.

The strategic value of these sustainable PW management pathways extends across environmental, operational, and resource stewardship dimensions. By recovering and reusing water and associated resources, energy operations reduce freshwater demand, minimize brine and waste disposal, and lower the environmental footprint of extraction activities. Operational efficiency is improved through reduced chemical consumption, energy optimization, and predictive maintenance enabled by digital monitoring and AI control. Resource stewardship is advanced by converting PW from a liability into a feedstock for circular water management, supporting nutrient recycling, biomass valorization, and salt recovery. Collectively, these strategies enable energy operators to meet regulatory requirements, enhance sustainability performance, and foster resilience in water-scarce or remote regions.

Integrating hybrid treatment technologies, digital optimization, and modular deployment establishes a robust framework for sustainable PW management. These approaches transform PW into a resource stream, creating economic, environmental, and operational benefits, and providing a practical pathway for circular water management in the oil and gas sector.

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