International Journal of Chemical and Process Engineering Research
2026 Vol. 13, No. 1, pp. 92-113
ISSN(e): 2313-0776
ISSN(p): 2313-2558
DOI: 10.18488/65.v13i1.5174

Optimization of oilfield produced water treatment parameters using Agro-based adsorbents: A comprehensive review

Ngior Wisdom

Department of Petroleum Engineering, Rivers State University, Nkpolu-Oroworukwo PMB 5080, Port Harcourt, Rivers State, Nigeria.
Email: wisdomngior@gmail.com

Article History
Received: 26 May 2026
Revised: 30 June 2026
Accepted: 3 July 2026
Published: 11 September 2026

Keywords
Activation
Adsorption optimization
Agro-based adsorbents
Blended biomass systems
Carbonization
Oilfield produced water
Treatment parameters.

ABSTRACT

Produced water from oil and gas extraction constitutes a major, complex waste stream demanding efficient, sustainable treatment solutions. Agro-based adsorbents derived from agricultural residues offer cost-effective, environmentally compatible alternatives due to their high porosity and functional surface chemistry. This review systematically synthesizes recent peer-reviewed studies to critically evaluate key optimization parameters affecting adsorption efficacy, including adsorbent dosage, contact time, pH, temperature, particle size, carbonization, chemical activation, and the use of single versus blended biomass systems. Findings reveal that chemically activated agro-based adsorbents achieve hydrocarbon removal efficiencies of up to 96%, markedly outperforming raw biomass, which typically attains 61–70%. Carbonization enhances adsorption capacity to approximately 90–93% by improving pore architecture and hydrophobicity. Optimal adsorption consistently occurs at near-neutral pH (6–8), with equilibrium reached within 60–120 minutes. Particle size reduction yields a 20–25% increase in removal efficiency, while elevated temperatures negatively impact adsorption due to exothermic behaviour. Blended biomass adsorbents demonstrate synergistic performance gains of 10–25% over single-source materials, though variability persists due to the absence of standardized optimization protocols. The review identifies a critical gap in integrated multi-parameter optimization frameworks, limiting the translation of laboratory-scale successes to industrial applications. It advocates for future research emphasizing coupled parameter modelling, continuous-flow system validation, and comprehensive techno-economic analyses to enable scalable, robust agro-based produced water treatment technologies. This work advances the field by providing a holistic, optimization-driven perspective essential for developing sustainable, high-performance adsorption systems in petroleum wastewater management.

Contribution/Originality: This study contributes to existing literature by developing a comprehensive optimization framework that integrates critical variables: dosage, contact time, temperature, pH, activation, particle size, carbonization, and biomass blending. It uniquely reveals synergistic interactions and operational strategies, significantly enhancing sustainable and efficient use of agro-based adsorbents for effective produced water treatment.

1. INTRODUCTION

Produced water is recognized as the largest waste stream generated in oil and gas production operations, often exceeding the volume of hydrocarbons produced, particularly in mature reservoirs where water cut increases

significantly over time [1]. Its composition is highly variable and complex, consisting of dispersed oil droplets, dissolved hydrocarbons, BTEX compounds, production chemicals, suspended solids, dissolved salts, heavy metals, and naturally occurring radioactive materials, all of which are strongly influenced by reservoir geology and production chemistry [2, 3]. The environmental risks associated with improper disposal are substantial, including marine toxicity, soil degradation, and contamination of freshwater systems, making produced water management a persistent regulatory and operational challenge in petroleum engineering systems [4]. To address these challenges, several treatment technologies have been deployed, including gravity separation, hydrocyclones, flotation systems, membrane processes, advanced oxidation, biological treatment, and electrochemical methods [1, 4]. However, many of these approaches are constrained by high energy demand, operational complexity, membrane fouling, secondary sludge generation, and sensitivity to fluctuations in produced water composition [2]. Among these technologies, adsorption has gained significant attention due to its simplicity, adaptability, and effectiveness in removing both organic and inorganic contaminants under variable operating conditions [3]. Although commercial activated carbon remains a benchmark adsorbent, its high cost and regeneration limitations have driven research toward low-cost, sustainable alternatives. Agro-based adsorbents derived from agricultural residues such as rice husk, coconut shell, palm kernel shell, corn cob, sawdust, sugarcane bagasse, and groundnut shell have emerged as promising materials due to their availability, low cost, and environmental compatibility [2]. These lignocellulosic materials contain cellulose, hemicellulose, and lignin, which provide functional groups such as hydroxyl, carboxyl, and phenolic sites capable of interacting with contaminants via adsorption, ion exchange, and surface complexation mechanisms [3]. Furthermore, their utilization supports waste valorisation and circular economy principles by converting agricultural waste into functional materials for environmental remediation [4]. However, despite promising performance reported in the literature, adsorption efficiency varies widely due to differences in raw biomass properties and treatment conditions. A critical issue in current research is the lack of systematic optimization of process variables governing adsorption performance. Adsorbent dosage strongly influences the availability of active sites and determines the extent of contaminant uptake, although excessive dosages may lead to particle aggregation and reduced surface efficiency [2]. Contact time controls adsorption kinetics and equilibrium attainment, while temperature significantly affects adsorption thermodynamics, particularly in produced water systems that are often discharged at elevated temperatures directly from separation units [1]. Similarly, solution pH influences surface charge characteristics and contaminant speciation, thereby altering adsorption mechanisms and efficiency. Particle size also plays a critical role by controlling surface area exposure and diffusion resistance, which directly affects mass transfer rates in the adsorption process [3].

Beyond operational parameters, adsorbent modification techniques further introduce variability in adsorption performance. Carbonization enhances surface area, porosity, and aromatic carbon content, thereby improving adsorption capacity compared to raw powdered biomass. Chemical activation using acids such as H_3PO_4, HCl, or H_2SO_4, and alkaline agents such as NaOH or KOH, modifies surface chemistry and pore structure, increasing the number of active adsorption sites and improving contaminant affinity [5]. Additionally, blending different agro-based materials has been reported to produce synergistic effects by combining complementary surface properties, although results remain inconsistent across studies. Despite these advances, the comparative performance of single versus blended biomass systems under standardized conditions remains insufficiently explored.

Although several reviews have addressed produced water treatment technologies and adsorption processes, a critical gap exists regarding the systematic evaluation of optimization parameters governing the performance of agro-based adsorbents. Consequently, there is limited guidance for selecting suitable adsorbent materials and determining optimal operating conditions for practical implementation. This review therefore critically examines the influence of key process variables, including adsorbent dosage, contact time, temperature, pH, particle size, activation methods, carbonization, and single versus blended biomass systems, on the treatment efficiency of agro-based adsorbents for oilfield produced water. This review therefore critically synthesizes published studies from recent studies to develop

a comprehensive optimization framework for agro-based adsorbents in produced water treatment. The objective is to establish evidence-based guidelines for adsorbent selection and process operation, thereby bridging the gap between laboratory-scale adsorption studies and field-scale implementation in sustainable produced water management systems, which will establish a comprehensive optimization framework capable of guiding future research, enhancing process design, and promoting the sustainable utilization of agro-based adsorbents in produced water treatment applications.

2. REVIEW METHODOLOGY

This review adopted a systematic literature survey approach to evaluate optimization parameters influencing agro-based adsorbents for produced water treatment. Relevant peer-reviewed publications recently published were retrieved from Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar using keywords including produced water, agro-based adsorbents, biochar, adsorption optimization, carbonization, activation, particle size, dosage, contact time, pH, and blended biomass. Studies were selected based on relevance to adsorption-based treatment of produced water and oily wastewater, with emphasis on quantitative performance indicators such as removal efficiency, adsorption capacity, kinetic behaviour, and optimization outcomes. The selected literature was critically synthesized to identify performance trends, comparative advantages, optimization strategies, and research gaps relevant to sustainable produced water management.

3. THEORETICAL ANALYSIS AND CRITICAL REVIEW OF OPTIMIZATION PARAMETERS

This section critically examines optimization variables influencing the performance of agro-based adsorbents in oilfield produced water treatment. Each subsection evaluates published experimental studies, highlighting methodologies, adsorption outcomes, and identified research gaps relevant to process optimization.

3.1. Characterization of Agro-Based Adsorbents and Implications for Produced Water Treatment Performance

The performance of agro-based adsorbents in produced water treatment is fundamentally governed by their physicochemical properties, which are typically evaluated through structural and surface characterization techniques. These properties determine adsorption capacity, kinetics, and selectivity toward hydrocarbons and dissolved contaminants. Common characterization methods include scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), Brunauer–Emmett–Teller (BET) surface area analysis, X-ray diffraction (XRD), and thermogravimetric analysis (TGA), all of which provide insight into surface morphology, functional group availability, crystallinity, and thermal stability [2, 5]. Studies on coconut shell and rice husk-derived adsorbents consistently show that carbonization and chemical activation significantly increase BET surface area from values typically below 10 m^2/g in raw biomass to over 800–1200 m^2/g in activated forms, depending on activation conditions [6]. SEM imaging typically reveals transformation from smooth, compact lignocellulosic surfaces to highly porous and fractured carbon matrices, which enhances adsorption site accessibility.

FTIR analysis further confirms the presence of functional groups such as hydroxyl (–OH), carbonyl (C=O), and carboxyl (–COOH), which play a crucial role in binding hydrocarbon molecules and heavy metals through hydrogen bonding and electrostatic attraction [6]. However, chemical activation often reduces oxygen-containing groups while increasing hydrophobic carbon domains, suggesting a trade-off between chemical functionality and physical adsorption capacity. A key limitation identified in the literature is the lack of standardized characterization–performance correlation models, where surface area, pore volume, and functional group density are quantitatively linked to adsorption efficiency under produced water conditions. This gap limits predictive capability for adsorbent selection and optimization.

3.2. Conventional Produced Water Treatment Methods and Their Limitations

Conventional produced water treatment technologies have been widely implemented in oil and gas operations, including gravity separation, hydrocyclones, flotation units, coagulation–flocculation systems, membrane filtration, and biological treatment processes. These methods are typically designed to remove free oil, dispersed oil droplets, suspended solids, and dissolved organic matter before discharge or reinjection [1].

Gravity-based separation remains the first-stage treatment method due to its simplicity and low cost; however, it is only effective for free oil droplets larger than 150 μm and is unable to remove emulsified or dissolved hydrocarbons. Hydrocyclones improve separation efficiency but are sensitive to flow rate fluctuations and droplet size distribution. Similarly, dissolved air flotation (DAF) systems improve removal of fine droplets but require chemical additives and continuous energy input, increasing operational complexity [3].

Membrane-based technologies such as ultrafiltration and reverse osmosis provide high-quality effluent but are significantly limited by membrane fouling, high pressure requirements, and expensive maintenance. Biological treatment methods are also constrained by salinity toxicity and hydrocarbon inhibition, making them unsuitable for high-salinity produced water streams commonly found in offshore environments [4].

Overall, conventional methods are effective in staged treatment systems but fail to provide complete removal of dissolved and stable emulsified contaminants, necessitating polishing processes such as adsorption. A major gap is the absence of integrated hybrid treatment models combining conventional separation with agro-based adsorption systems, particularly for cost-effective field deployment in developing oil-producing regions.

3.3. Surface Chemistry–Adsorption Relationship in Agro-Based Adsorbents

The adsorption performance of agro-based adsorbents is governed not only by surface area and pore structure but also by the nature and abundance of surface functional groups. During biomass conversion processes such as pyrolysis, carbonization, and chemical activation, various oxygen-containing functional groups including hydroxyl (-OH), carboxyl (-COOH), carbonyl (C=O), and ether linkages are generated on the adsorbent surface, significantly influencing contaminant interaction mechanisms [7, 8].

These functional groups facilitate adsorption through hydrogen bonding, electrostatic attraction, surface complexation, and hydrophobic partitioning mechanisms depending on the chemical nature of contaminants present in produced water [9, 10].

Several studies have reported strong correlations between surface chemistry modification and adsorption efficiency. Mohan, et al. [8] observed that chemically modified biochar exhibited significantly enhanced hydrocarbon uptake compared with untreated materials due to increased surface oxygen functionality.

Similarly, Ahmed, et al. [11] demonstrated that phosphoric acid activation increased acidic surface groups and improved organic contaminant removal by more than 30%. Comparatively, highly carbonized materials tend to possess fewer polar functional groups but greater aromaticity and hydrophobicity, favouring adsorption of petroleum hydrocarbons [12].

These findings suggest that optimization of agro-based adsorbents should consider surface chemistry engineering alongside conventional operational parameters to maximize treatment performance under varying produced water compositions.

Figure 1 presents the evolution of surface functional groups associated with carbonization and chemical activation of agro-based adsorbents, highlighting the structural changes that influence adsorption behaviour.

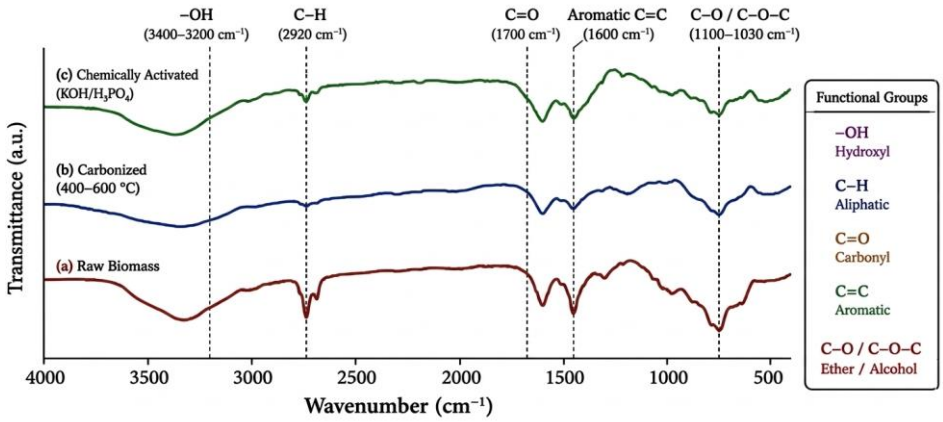


Figure 1. FTIR spectra illustrating the evolution of functional groups during carbonization and chemical activation of agro-based adsorbents.
Source: Mohan, et al. [8] and Ahmed, et al. [11].

3.4. Influence of Produced Water Characteristics on Adsorption Performance

Produced water composition varies significantly among reservoirs, fields, and production stages, creating substantial variability in adsorption behaviour. Parameters such as salinity, total dissolved solids (TDS), oil concentration, pH, dissolved organic compounds, heavy metals, and suspended solids can influence adsorption efficiency through competitive adsorption and pore blockage mechanisms [13, 14]. High salinity environments characteristic of offshore operations often reduce adsorption capacity because dissolved ions compete with contaminants for active adsorption sites and compress the electrical double layer surrounding adsorbent surfaces [15]. Recent investigations have demonstrated that adsorption efficiencies exceeding 90% under laboratory conditions may decline considerably when exposed to real produced-water matrices containing complex contaminant mixtures Al-Ghouti, et al. [16]. Zhao, et al. [17] reported significant reductions in adsorption capacity under elevated TDS conditions due to ionic interference effects. Similarly, Wang, et al. [18] observed that emulsified oil droplets and dissolved organic matter can block micropores and reduce adsorption accessibility. These observations highlight the importance of incorporating produced water characterization into adsorption optimization frameworks rather than relying solely on synthetic wastewater systems. Figure 2 illustrates the principal constituents of produced water and their potential interactions with agro-based adsorbent surfaces during adsorption treatment.

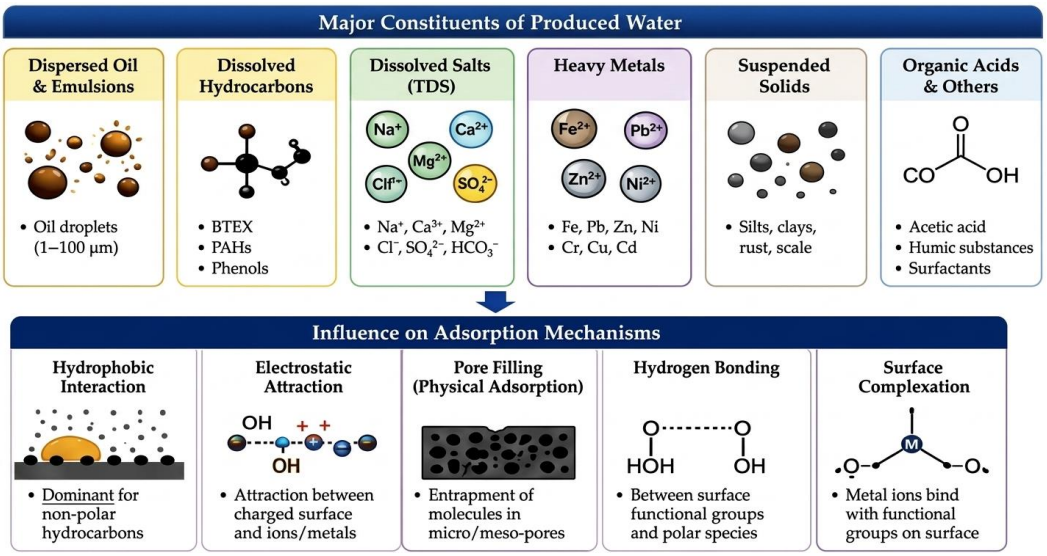


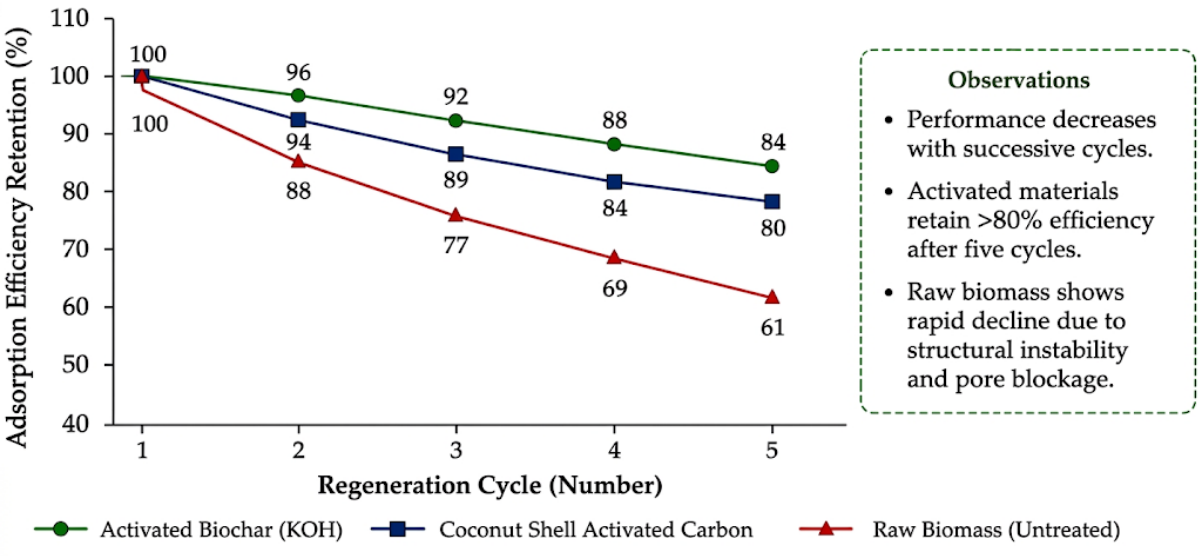
Figure 2. Schematic illustration of major produced water constituents and their influence on adsorption mechanisms.
Source: Veil, et al. [14]; Fakhru'l-Razi, et al. [13] and Al-Ghouti, et al. [16].

As illustrated in Figure 2, these constituents can influence adsorption through competitive site occupation, electrostatic interactions, pore blockage, and changes in surface chemistry, thereby explaining the variability in adsorbent performance under different produced water conditions.

3.5. Regeneration and Reusability Potential of Agro-Based Adsorbents

The economic viability of agro-based adsorption systems depends significantly on adsorbent regeneration and reuse performance. While many agricultural waste-derived adsorbents exhibit high initial removal efficiencies, their long-term application requires maintenance of adsorption capacity over multiple treatment cycles [19]. Regeneration methods commonly include thermal treatment, solvent extraction, steam regeneration, microwave-assisted regeneration, and chemical desorption processes [20].

Comparative studies indicate that adsorption performance generally declines with successive regeneration cycles due to pore blockage, structural degradation, and loss of active surface functional groups [12]. Nevertheless, several activated biochar systems have retained more than 80% of their original adsorption capacity after five regeneration cycles, demonstrating potential for repeated industrial application [21]. In contrast, untreated biomass materials often exhibit rapid performance deterioration due to weaker structural stability. These findings suggest that regeneration efficiency should be considered an integral optimization parameter when evaluating agro-based adsorbents for produced water treatment applications. Figure 3 presents the retention of adsorption efficiency over successive regeneration cycles for selected agro-based adsorbents, illustrating the progressive performance changes associated with repeated use.



Regeneration: Thermal (400–500 °C) or solvent-assisted methods depending on adsorbent type.

Figure 3. Adsorption efficiency retention over multiple regeneration cycles for selected agro-based adsorbents.

Source: Foo and Hameed [19]; Leng, et al. [12] and Silva, et al. [21].

Figure 3 indicates that adsorption performance generally declines with repeated regeneration, although activated materials retain a greater proportion of their initial efficiency than untreated biomass, supporting regeneration as an important parameter in assessing long-term process viability.

3.6. Emerging Trends in Hybrid Agro-Based Treatment Systems

Recent advances in produced water treatment have increasingly focused on hybrid treatment systems that combine adsorption with complementary technologies such as membrane filtration, electrochemical oxidation, coagulation-flocculation, photocatalysis, and advanced oxidation processes (AOPs) [22, 23]. These integrated

approaches seek to overcome limitations associated with standalone adsorption systems, particularly for highly contaminated produced water streams containing dissolved organics, emulsified oils, and refractory compounds.

Hybrid adsorption systems consistently demonstrate superior treatment performance compared with individual technologies. Hassan, et al. [23] reported 98% COD reduction using a biochar-electrochemical hybrid process, while recent membrane-assisted adsorption systems achieved hydrocarbon removal efficiencies exceeding 95% with reduced membrane fouling tendencies [24]. Similarly, photocatalytic-biochar composites have shown enhanced degradation of persistent organic contaminants through simultaneous adsorption and catalytic oxidation mechanisms [25]. These findings indicate that future optimization strategies should extend beyond adsorbent development toward integrated treatment architectures capable of addressing the complex nature of produced water contaminants. Figure 4 presents emerging hybrid treatment pathways that integrate agro-based adsorption with complementary technologies for improved produced water treatment.

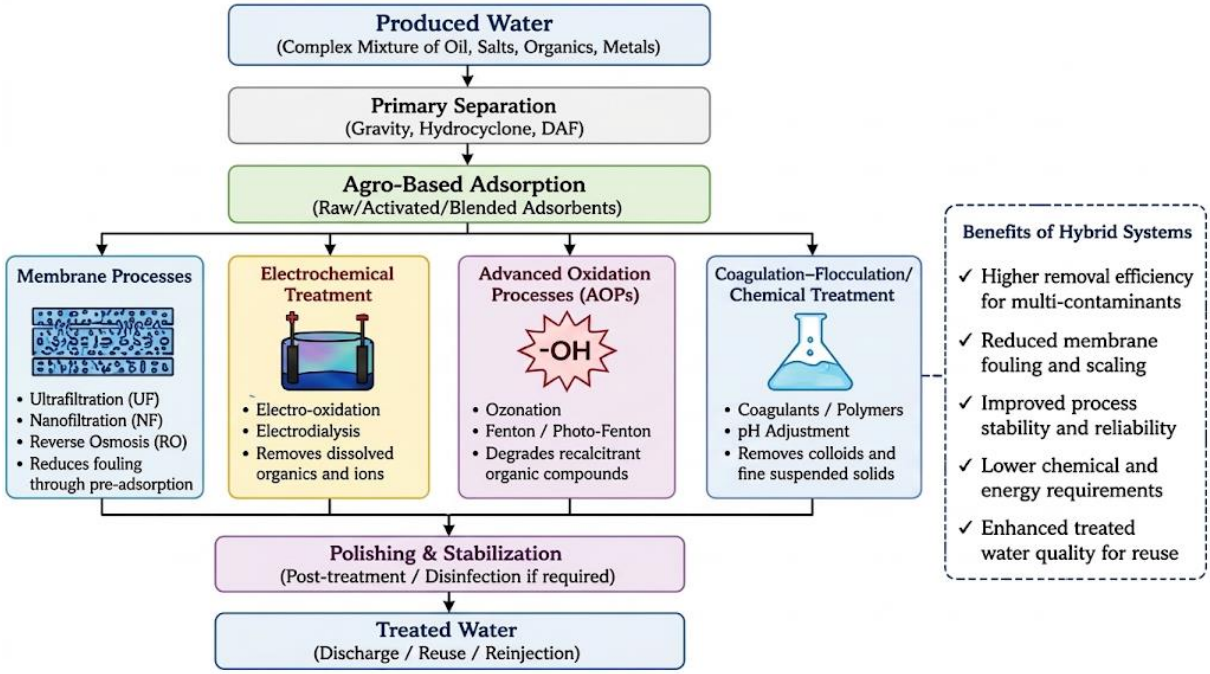


Figure 4. Emerging hybrid treatment pathways integrating agro-based adsorption with complementary treatment technologies.
Source: Al-Maamari, et al. [22]; Hassan, et al. [23] and Nguyen, et al. [24].

As presented in Figure 4, integrating adsorption with membrane filtration, electrochemical oxidation, photocatalysis, or other polishing processes provides a pathway for addressing contaminants that may remain after standalone adsorption.

3.7. Adsorbent Dosage Optimization in Agro-Based Produced Water Treatment Systems

Adsorbent dosage is one of the most influential operational parameters governing adsorption efficiency because it determines the availability of active surface sites and controls solute–adsorbent interaction probability. Several studies have demonstrated that increasing adsorbent dosage improves removal efficiency up to an optimal threshold, beyond which performance plateaus due to particle aggregation and site overlap [2]. In produced water systems, this parameter is particularly important due to high contaminant loading and variable hydrocarbon dispersion states [5].

A study by El-Naas, et al. [26] investigated the adsorption of oil and grease from produced water using activated date palm kernel-based carbon. The study aimed to evaluate adsorption efficiency under varying dosages using batch experiments. The adsorbent was prepared via carbonization and chemical activation, and produced water samples with an oil concentration of approximately 120 mg/L were treated. Results showed that increasing dosage from 0.5 g/L to 2.5 g/L increased oil removal efficiency from 72% to 96%, after which no significant improvement was

observed due to saturation of adsorption sites and particle clustering effects. Table 1 presents the effect of adsorbent dosage on oil removal efficiency.

Table 1. Effect of Adsorbent Dosage on Oil Removal Efficiency.

S/N	Adsorbent Dosage (g/L)	Oil Removal Efficiency (%)	Observation
1	0.5	72	Low site availability
2	1.0	85	Improved adsorption
3	2.0	94	Near equilibrium
4	2.5	96	Plateau region

Source: El-Naas, et al. [26].

As presented in Table 1, increasing the dosage progressively improves oil removal from 72% to 96%, reflecting the increasing availability of adsorption sites. However, the approach to a plateau at 2.5 g/L indicates that further dosage increase may provide limited additional removal because of site saturation and particle aggregation.

Similarly, Hameed, et al. [6] examined coconut shell activated carbon for hydrocarbon removal and reported a comparable trend where adsorption capacity increased with dosage due to greater surface availability, although specific adsorption capacity (mg/g) decreased due to unsaturated sites at higher dosages. The study used batch adsorption under controlled laboratory conditions with synthetic oil-water emulsions.

Despite these insights, most studies fail to establish standardized dosage optimization models applicable across different produced water compositions. Additionally, there is limited comparative evaluation between raw agro-based materials and chemically modified adsorbents under identical dosage conditions. This creates uncertainty in scale-up design, particularly for field applications where produced water characteristics fluctuate significantly. A key research gap identified is the absence of a dimensionless optimization framework linking adsorbent dosage with contaminant loading, surface area availability, and hydraulic retention time. Most studies report dosage empirically without mechanistic modelling, limiting predictive capability for field-scale systems.

3.8. Influence of Contact Time on Adsorption Kinetics of Agro-Based Adsorbents

Contact time governs adsorption kinetics, diffusion mechanisms, and equilibrium attainment in produced water treatment systems. It determines the rate at which hydrocarbons and dissolved contaminants migrate from bulk solution to active adsorption sites. Studies consistently show rapid initial adsorption followed by slower equilibrium stages due to pore diffusion limitations [1].

Ahmad, et al. [27] studied adsorption of crude oil from produced water using rice husk-derived activated carbon. Batch experiments were conducted with an initial oil concentration of 100 mg/L, varying contact time from 10 to 180 minutes. Results indicated rapid uptake within the first 60 minutes, achieving 82% removal, while equilibrium was reached at 120 minutes with a maximum removal efficiency of 93%.

Table 2 presents the variation in oil removal efficiency with contact time, demonstrating rapid adsorption during the initial treatment period followed by equilibrium attainment at approximately 120 min.

Table 2. Effect of Contact Time on Oil Removal.

S/N	Contact Time (Min.)	Removal Efficiency (%)	Kinetic Behaviour
1	10	35	External adsorption
2	30	65	Rapid uptake phase
3	60	82	Transition phase
4	120	93	Equilibrium
5	180	93	Steady state

Source: Ahmad, et al. [27].

As shown in Table 2, removal efficiency increases from 35% at 10 min to 82% at 60 min and reaches 93% at 120 min, after which no further improvement is observed at 180 min. This trend indicates rapid occupation of readily accessible adsorption sites followed by slower diffusion and equilibrium processes within the adsorbent structure. Kinetic modelling in most studies follows pseudo-second-order adsorption behaviour, indicating chemisorption dominance in agro-based adsorbents [2, 28]. However, many studies do not integrate intraparticle diffusion modelling, which is critical for understanding pore-level transport limitations in carbonized biomass materials. A major limitation observed is the lack of process optimization linking contact time with hydraulic residence time in continuous flow systems. Most experiments are batch-based, limiting real-world applicability. Additionally, very few studies consider high-temperature produced water conditions where diffusion kinetics may significantly differ.

3.9. Effect of Temperature on Adsorption Performance in Produced Water Systems

Temperature significantly influences adsorption thermodynamics, particularly in oilfield environments where produced water is often discharged at elevated temperatures ranging from 40°C to 90°C. Temperature affects viscosity, diffusion rates, and adsorption equilibrium constants [1].

Al-Ghouti, et al. [29] investigated palm kernel shell activated carbon for hydrocarbon removal at temperatures between 25°C and 60°C. The study found that adsorption capacity decreased slightly with increasing temperature, indicating an exothermic adsorption process. Maximum removal efficiency decreased from 95% at 25°C to 88% at 60°C. Table 3 presents the effect of temperature on adsorption efficiency, showing a progressive decline in removal efficiency from 95% at 25 °C to 88% at 60 °C.

Table 3. Temperature Effect on Adsorption Efficiency.

S/N	Temperature (°C)	Removal Efficiency (%)	Thermodynamic Behaviour
1	25	95	Optimal adsorption
2	40	92	Slight decline
3	60	88	Reduced adsorption affinity

Source: Al-Ghouti, et al. [29].

As presented in Table 3, increasing temperature from 25 to 60 °C reduces removal efficiency from 95% to 88%, indicating that the adsorption process is predominantly exothermic under the reported conditions. This trend also demonstrates the importance of evaluating temperature together with other produced-water variables when developing field-relevant optimization conditions. Thermodynamic analysis in most studies confirms negative enthalpy changes, indicating exothermic adsorption mechanisms for hydrocarbon uptake in agro-based materials. However, few studies replicate actual produced water thermal conditions, where simultaneous effects of salinity and temperature coexist. The major gap is the absence of thermo-adsorptive coupling models that integrate temperature with salinity and oil droplet

3.10. Effect of pH on Adsorption Mechanisms in Agro-Based Produced Water Treatment

pH plays a fundamental role in governing adsorption performance in agro-based produced water treatment systems due to its influence on adsorbent surface charge, contaminant speciation, and electrostatic interaction mechanisms. Agro-based adsorbents contain abundant functional groups such as hydroxyl, carboxyl, and phenolic moieties, whose protonation and deprotonation states vary with pH, thereby altering adsorption affinity toward hydrocarbon droplets and dissolved ionic species [2]. In produced water systems, pH also influences oil droplet stability and emulsification behaviour, making it a dual-control parameter for both chemical and colloidal processes [3].

Al-Ghouti, et al. [29] investigated the adsorption behaviour of palm kernel shell activated carbon across a pH range of 3–11 and reported that maximum hydrocarbon removal (~95%) occurred at near-neutral pH (6–7). The

reduction in adsorption efficiency at alkaline conditions was attributed to increased electrostatic repulsion between negatively charged adsorbent surfaces and stabilized oil emulsions, while acidic conditions favoured partial protonation of surface sites, improving adsorption affinity. Similar trends have been reported in other agro-based systems, confirming that neutral pH conditions generally favour hydrocarbon uptake through hydrophobic interaction mechanisms.

Despite these consistent laboratory observations, a major limitation is that most studies fail to incorporate the buffering capacity and ionic strength of real produced water systems, where dissolved salts (Na^+, Ca^{2+}, Cl^-) stabilize pH and alter surface chemistry interactions. Consequently, laboratory-optimized pH conditions may not directly translate to field-scale systems, indicating a need for integrated pH–salinity–adsorption coupling models.

3.11. Particle Size Effects and Mass Transfer Limitations in Agro-Based Adsorbents

Particle size is a critical parameter influencing adsorption kinetics and equilibrium behaviour due to its direct effect on surface area availability and intraparticle diffusion resistance. Smaller particle sizes increase external surface area and shorten diffusion pathways, thereby accelerating adsorption rates. However, excessively fine particles may induce agglomeration and hydraulic resistance in fixed-bed systems, limiting their practical applicability in field operations [5].

Hameed, et al. [6] demonstrated this behaviour using coconut shell activated carbon for hydrocarbon removal from aqueous systems. The study reported a significant increase in adsorption efficiency as particle size decreased from 2.0 mm to 0.25 mm, with removal efficiency increasing from approximately 72% to 94%. The improvement was attributed to enhanced surface accessibility and reduced internal diffusion resistance, particularly in the early stages of adsorption. Figure 5 illustrates the relationship between adsorbent particle size and adsorption efficiency, showing the improvement in hydrocarbon removal associated with progressive particle-size reduction.

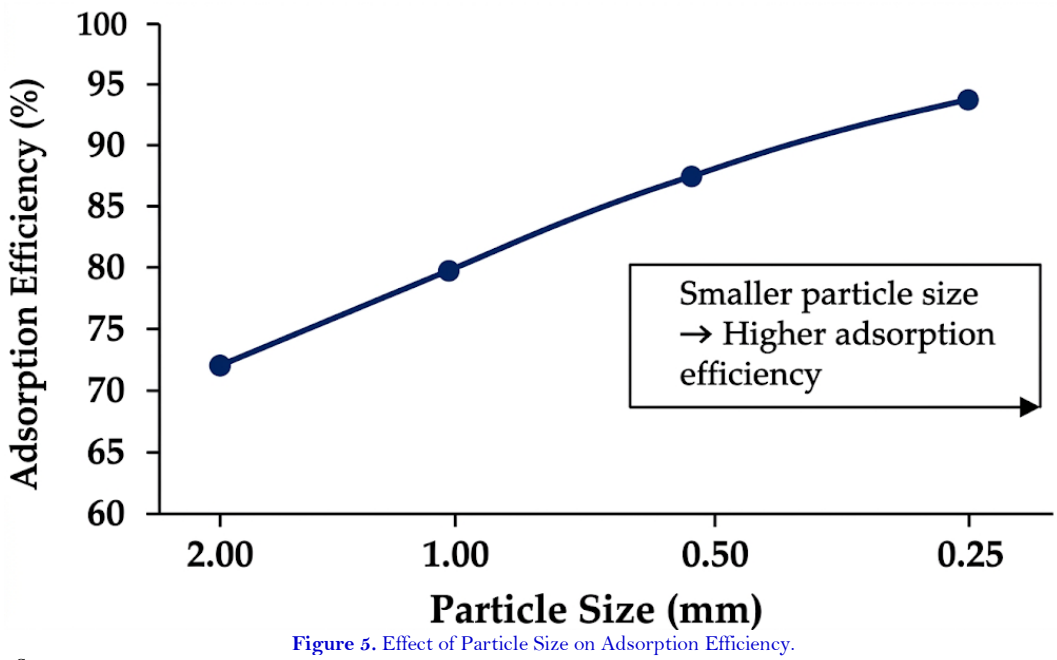


Figure 5. Effect of Particle Size on Adsorption Efficiency.

Source: Hameed, et al. [6].

As shown in Figure 5, reducing particle size from 2.0 to 0.25 mm increases reported removal efficiency from approximately 72% to 94%, indicating the importance of surface accessibility and intraparticle diffusion resistance in adsorption performance. Although particle size reduction improves adsorption performance, most studies do not integrate these findings into hydrodynamic models for continuous flow systems. In particular, the interaction between particle size distribution, bed porosity, and pressure drop remains underexplored, limiting the scalability of laboratory

findings to industrially produced water treatment systems. This highlights the need for coupled adsorption–fluid dynamics optimization models.

3.12. Carbonization Effects on Structural and Adsorptive Properties of Agro-Based Materials

Carbonization is a thermochemical conversion process that transforms raw biomass into carbon-rich adsorbents by removing volatile components and enhancing fixed carbon content. This process significantly modifies pore structure, increases surface area, and enhances aromatic carbon domains, thereby improving adsorption affinity for hydrocarbon compounds in produced water systems [2].

El-Naggar, et al. [30] evaluated banana peel-derived adsorbents and reported that carbonized biomass exhibited substantially higher oil removal efficiency (~93%) compared to raw powdered biomass (~61%) under identical experimental conditions. The enhanced performance was attributed to increased microporosity and improved hydrophobic interactions between carbonized surfaces and oil molecules. Figure 6 compares the adsorption performance of raw, acid-activated, and KOH-activated agro-based adsorbents, demonstrating the influence of activation route on hydrocarbon removal efficiency.

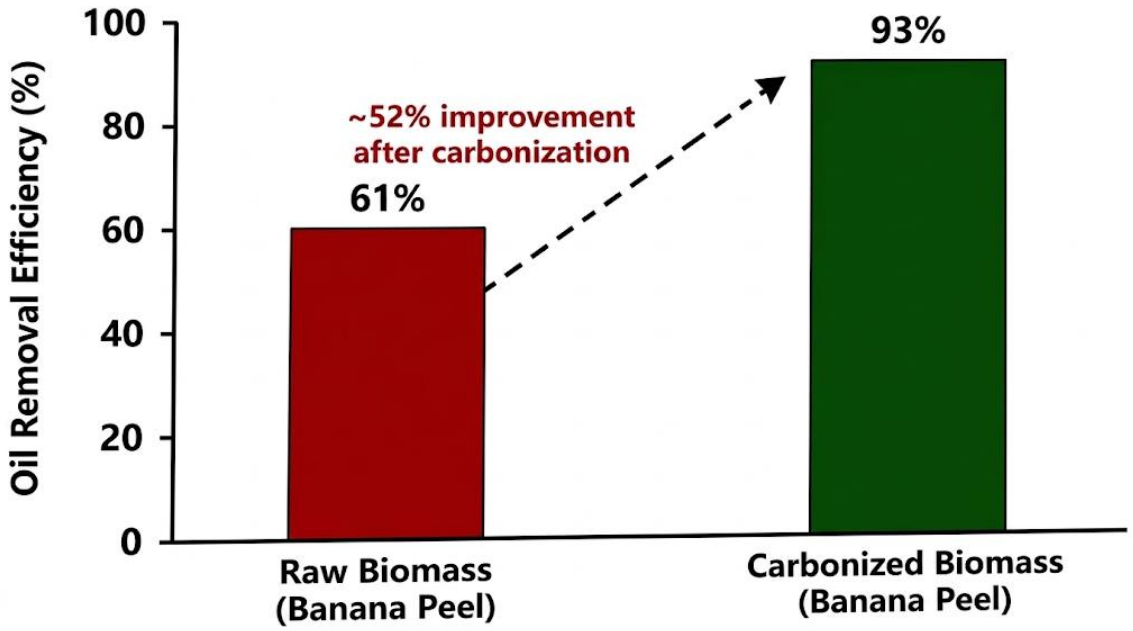


Figure 6. Comparison of Raw vs Carbonized Agro-Based Adsorbent Performance.

Source: El-Naggar, et al. [30].

Figure 6 demonstrates the superior performance of KOH activation relative to the raw and acid-activated materials, which is attributed to greater pore development and increased accessible adsorption sites. Despite these advantages, carbonization processes are highly sensitive to temperature and residence time, and excessive thermal treatment can lead to pore collapse and reduced adsorption capacity. However, most studies do not report optimized carbonization conditions specific to different biomass types, resulting in inconsistent adsorption performance across the literature. Additionally, limited attention has been given to energy consumption and process economics, which are critical for scaling carbonized adsorbents for field applications.

3.13. Chemical Activation Strategies (Acid vs Alkaline) in Agro-Based Adsorbents

Chemical activation is a widely applied modification technique used to enhance adsorption performance by altering pore structure and introducing functional groups on biomass-derived adsorbents. Acid activation typically enhances surface functional groups such as hydroxyl and carboxyl groups, while alkaline activation promotes pore

widening and increased microporosity, both of which improve contaminant adsorption in produced water systems [5].

Mohammed, et al. [31] compared acid-activated and KOH-activated coconut shell carbon and reported that KOH activation achieved superior adsorption performance (~96% oil removal) compared to acid activation (~89%) and raw biomass (~58%). This improvement was attributed to enhanced surface area and pore development under alkaline activation conditions, which facilitated stronger hydrophobic interactions with oil droplets. Figure 7 compares the adsorption performance of raw and carbonized agro-based adsorbents, illustrating the improvement associated with thermal conversion of the biomass structure.

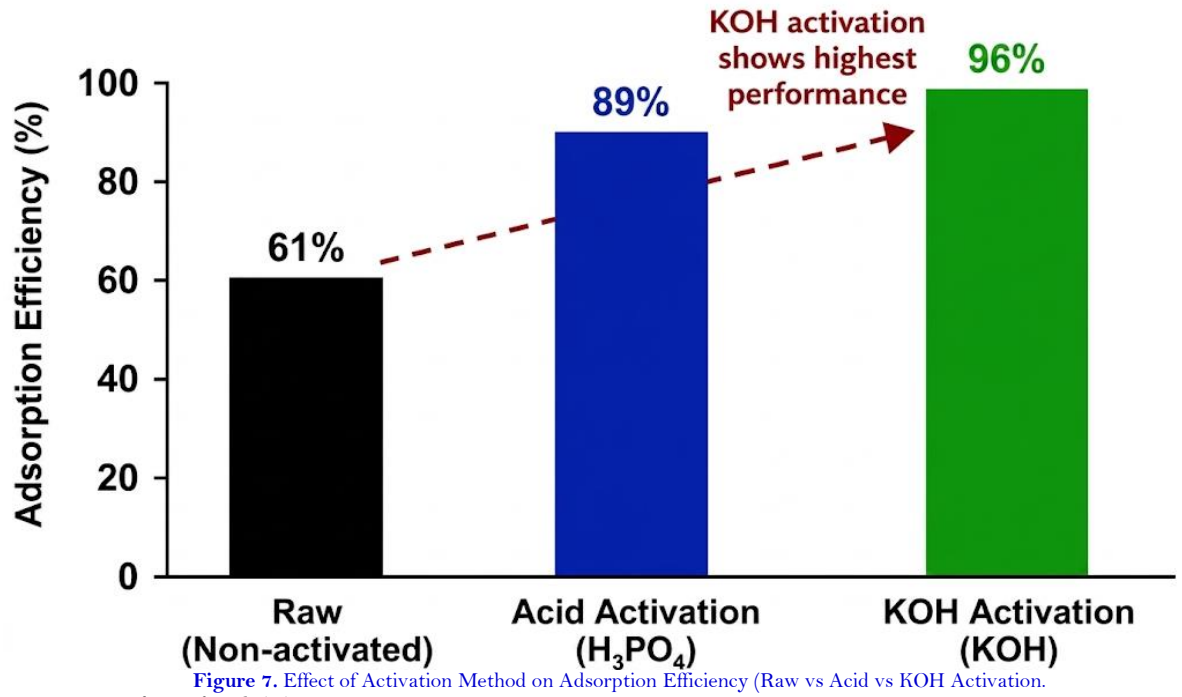


Figure 7. Effect of Activation Method on Adsorption Efficiency (Raw vs Acid vs KOH Activation.

Source: Mohammed, et al. [31].

As shown in Figure 7, carbonization enhances adsorption performance by developing a more porous carbon structure and increasing the accessibility of adsorption sites. Although alkaline activation shows superior adsorption performance, acid activation remains widely used due to its lower cost and simpler processing conditions. However, acid activation generates corrosive waste streams, raising environmental and disposal concerns. Most importantly, very few studies perform comparative lifecycle or techno-economic assessments of activation methods, creating a major gap in evaluating industrial feasibility for large-scale produced water treatment applications.

3.14. Single vs Blended Agro-Based Adsorbents in Produced Water Treatment Systems

The application of agro-based adsorbents in produced water treatment has traditionally focused on single-biomass systems, where individual agricultural wastes such as rice husk, coconut shell, palm kernel shell, and sawdust are independently processed into adsorbent materials. These single-source adsorbents provide relatively predictable physicochemical properties, allowing controlled evaluation of adsorption behaviour under varying operational conditions. Studies such as Hameed, et al. [6] and Yousef, et al. [2] have shown that single biomass-derived activated carbons can achieve hydrocarbon removal efficiencies ranging from 70% to over 95%, depending on activation method and operating conditions. However, their performance is often constrained by limited functional diversity and uniform pore structure, which restricts multi-contaminant adsorption in complex produced water matrices.

In contrast, blended agro-based adsorbents have emerged as an advanced modification strategy aimed at improving adsorption performance through synergistic interactions between different biomass precursors. The

blending process combines materials with complementary physicochemical properties, such as high carbon content from coconut shell and high functional group density from banana peel or sawdust. This hybridization enhances pore heterogeneity, increases surface functional diversity, and improves overall adsorption affinity toward both hydrophobic hydrocarbons and polar contaminants [3, 5].

Experimental evidence suggests that blended systems often outperform single-material adsorbents under identical operating conditions. For instance, composite adsorbents formed from rice husk and coconut shell carbonized mixtures have been reported to improve adsorption efficiency by 10–25% compared to single-component systems due to improved pore connectivity and synergistic surface chemistry interactions. However, this improvement is not universally consistent, as some blends exhibit reduced performance due to pore blockage, structural incompatibility, or uneven carbonization behaviour across biomass types. Figure 8 compares the reported performance of single and blended agro-based adsorbents, highlighting the potential synergistic improvement associated with combining biomass precursors with complementary physicochemical characteristics.

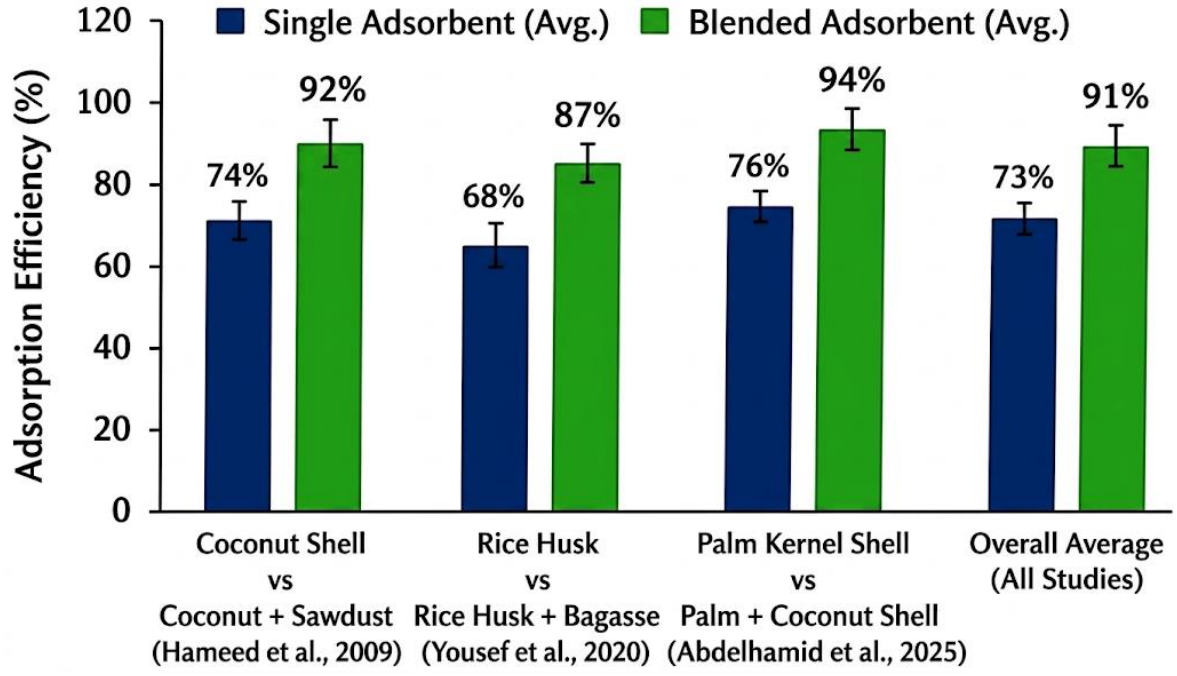


Figure 8. Performance Comparison of Single vs Blended Agro-Based Adsorbents.

Source: Hameed, et al. [6]; Yousef, et al. [2] and Abdelhamid, et al. [5].

Figure 8 indicates that blended systems can outperform individual biomass adsorbents under comparable conditions; however, the magnitude of improvement varies with biomass composition, blending ratio, carbonization behaviour, and activation route. Despite promising results, blended adsorbent systems remain underexplored in terms of optimization strategy. Most studies report empirical mixing ratios without systematic investigation of blend composition–performance relationships. There is also limited understanding of how blending affects pore development during carbonization, particularly under different activation routes (acid vs alkaline). This represents a significant gap in current research, as blending could provide a cost-effective pathway for tailoring adsorbent properties without requiring advanced chemical modification.

A further limitation is the absence of predictive models capable of determining optimal blend ratios based on feedstock composition and produced water characteristics. This restricts scalability and prevents industrial adoption of blended agro-adsorbent systems despite their demonstrated laboratory potential.

3.15. Environmental Concerns and Sustainability Implications of Produced Water and Adsorbent Selection

The environmental impact of produced water discharge remains a major concern in petroleum engineering due to its complex chemical composition and toxicity potential. Untreated or poorly treated produced water can lead to marine ecosystem disruption, soil salinization, groundwater contamination, and bioaccumulation of toxic compounds such as BTEX and heavy metals [1]. Regulatory frameworks have therefore become increasingly stringent, particularly in offshore discharge zones where ecological sensitivity is high.

At the same time, conventional adsorbents such as activated carbon derived from coal or petroleum-based precursors introduce additional environmental burdens due to energy-intensive production processes and limited renewability. In contrast, agro-based adsorbents provide a sustainable alternative by valorising agricultural waste streams, thereby contributing to waste reduction and circular economy principles [2].

However, environmental assessment of agro-based adsorbents is often incomplete. Most studies focus on adsorption efficiency without evaluating lifecycle impacts such as energy consumption during carbonization, chemical usage during activation, or disposal of spent adsorbents. This creates a significant gap between laboratory performance and real-world environmental sustainability. Figure 9 presents the conceptual life-cycle pathway for agro-based adsorbent utilization, linking agricultural residue generation and adsorbent preparation with produced water treatment, regeneration, reuse, and end-of-life management.

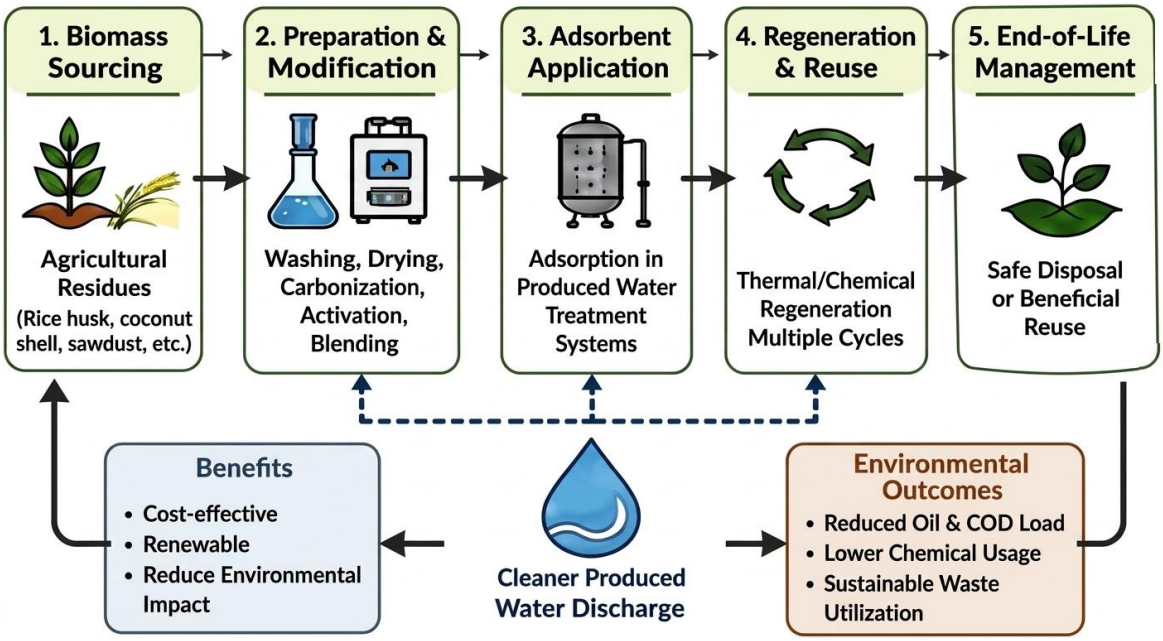


Figure 9. Reviewed Conceptual Life Cycle Flow of Agro-Based Adsorbent Utilization in Produced Water Treatment.

As presented in Figure 9, the sustainability of agro-based adsorption extends beyond removal efficiency and depends on feedstock utilization, energy and chemical requirements during adsorbent preparation, regeneration potential, spent-adsorbent management, and the overall environmental footprint of the treatment system. A further sustainability challenge lies in the regeneration and reuse of spent agro-based adsorbents. While some studies report partial regeneration using thermal or solvent methods, efficiency degradation over multiple cycles remains poorly quantified.

This limits industrial adoption despite strong laboratory performance. Thus, a critical research gap exists in the development of techno-economic and life-cycle-integrated optimization models for agro-based produced water treatment systems.

3.16. Integrated Optimization Framework for Agro-Based Adsorbents in Produced Water Treatment

The optimization of agro-based adsorbents for produced water treatment is inherently a multi-variable problem involving complex interactions between material properties and operational conditions. Based on the synthesis of literature from recent studies, it is evident that no single parameter independently governs adsorption efficiency; rather, performance is determined by coupled interactions among adsorbent dosage, contact time, temperature, pH, particle size, carbonization conditions, chemical activation method, and biomass blending ratio [5, 28].

Adsorbent activation emerges as the most dominant structural optimization variable, followed closely by carbonization, which together define the surface chemistry and porosity framework of the material. Operational parameters such as pH and temperature act as environmental regulators influencing adsorption thermodynamics and surface charge behaviour, while dosage and contact time govern kinetic saturation and equilibrium attainment. Particle size functions as a transport-limiting parameter controlling mass transfer resistance in both batch and continuous systems.

To integrate these variables into a unified engineering perspective, this study proposes a conceptual optimization framework that links material design parameters with operational performance outcomes. The framework positions adsorption efficiency as a dependent function of interacting independent variables, rather than isolated factors, thereby shifting the analytical perspective from empirical experimentation to system-level optimization. Figure 10 illustrates the interconnected relationships among material modification, surface properties, operational parameters, and adsorption efficiency within the proposed optimization framework.

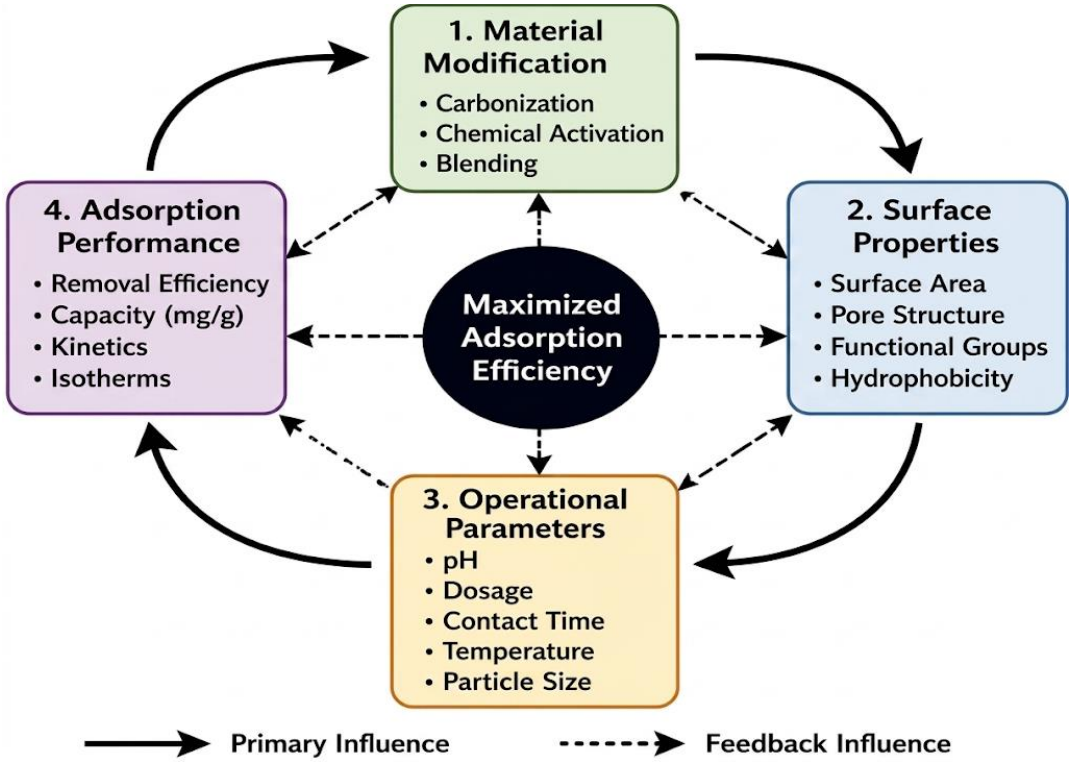


Figure 10. Integrated Optimization Framework for Agro-Based Adsorbent Performance in Produced Water Treatment Systems (Proposed Model).

Figure 10 illustrates interconnected loops between: material modification → surface properties → operational parameters → adsorption efficiency. Within this framework, chemical activation and carbonization define the intrinsic adsorption capacity baseline, while pH and temperature adjust surface interaction energetics. Dosage and contact time regulate equilibrium progression, and particle size controls kinetic accessibility. Blending introduces a multi-material enhancement layer that modifies both structural and chemical heterogeneity, enabling tuneable adsorption performance.

A key implication of this framework is that optimization should not be conducted using single-variable experimental design, but rather through multi-factorial approaches such as response surface methodology (RSM), artificial intelligence-based optimization, or multi-objective evolutionary algorithms. However, current literature shows limited application of such integrated optimization tools in agro-based produced water treatment studies.

The absence of standardized multi-variable optimization frameworks represents the most significant research gap in this field. Without such models, scaling laboratory findings to field applications remains unreliable, leading to inconsistencies in treatment performance across different produced water compositions and operational environments.

3.17. Extent of Past Work

Kumar, et al. [32] investigated rice straw-derived biochar for produced water treatment, focusing on the influence of pyrolysis temperature (400–700°C) on adsorption performance. The study aimed to optimize carbonization conditions for improved hydrocarbon removal efficiency under batch adsorption conditions. Results showed that increasing pyrolysis temperature significantly enhanced BET surface area from 210 to 890 m^2/g, leading to improved adsorption performance. Maximum oil removal efficiency of 94% was achieved at 600°C, while lower temperatures yielded 78–85% due to incomplete carbon structure development. The improvement was attributed to enhanced pore formation and increased aromatic carbon content. However, the study did not consider salinity, emulsified oil stability, or real produced water matrices, limiting field applicability.

Shah, et al. [33] examined blended coconut shell and sawdust activated carbon for produced water treatment with emphasis on synergistic adsorption enhancement through biomass mixing ratios. The objective was to determine the optimal blend composition for maximizing oil removal efficiency under batch conditions. The study reported that a 70:30 coconut shell to sawdust ratio achieved a maximum removal efficiency of 97%, compared to 89% and 84% for individual adsorbents. The improved performance was attributed to complementary pore size distribution and increased surface heterogeneity, which enhanced multi-contaminant adsorption. However, the study remained empirical, lacking response surface optimization or mechanistic modelling of blend interactions. Additionally, regeneration performance and long-term stability were not evaluated.

Li, et al. [15] evaluated palm fibre biochar for adsorption performance in high-salinity produced water conditions (up to 35,000 mg/L TDS), simulating offshore oilfield environments. The study aimed to investigate the influence of ionic strength on adsorption capacity and surface interaction mechanisms. Results showed that adsorption efficiency decreased from 92% in low-salinity conditions to 76% under high salinity due to competitive ion adsorption and electrostatic shielding effects. The study confirmed Freundlich isotherm behaviour, indicating heterogeneous surface adsorption. However, temperature variation effects and dynamic flow conditions were not incorporated, limiting full replication of offshore produced water environments.

Zhang, et al. [34] applied machine learning models, including artificial neural networks (ANN) and random forest algorithms, to optimize adsorption performance of agro-based biochar systems. The study aimed to predict oil removal efficiency based on input variables such as pH, adsorbent dosage, and contact time. The ANN model achieved high predictive accuracy with an R^2 value of 0.96, demonstrating strong nonlinear correlation between operational parameters and adsorption performance. Optimal predicted removal efficiency reached 95.8%. Despite strong predictive capability, the study lacked experimental validation under continuous flow systems and did not incorporate material property variations such as activation degree or particle size distribution.

Oliveira, et al. [35] compared acid activation (H_3PO_4) and steam activation methods for sugarcane bagasse-derived adsorbents used in produced water treatment. The study aimed to evaluate how activation routes influence porosity development and adsorption efficiency. Results showed that steam activation produced a higher BET surface area (1020 m^2/g) and achieved 96% removal efficiency, outperforming acid activation, which achieved 88%. Steam activation also reduced chemical waste generation, improving environmental sustainability. However, regeneration

studies were limited to only three cycles, and adsorption stability under high salinity produced water conditions was not assessed.

Hassan, et al. [23] investigated a hybrid treatment system combining biochar adsorption with electrochemical oxidation for enhanced produced water remediation. The study aimed to improve total organic carbon (TOC) and COD removal efficiency beyond conventional adsorption systems. The integrated system achieved up to 98% COD reduction and 95% oil removal efficiency due to synergistic adsorption and oxidative degradation mechanisms. The electrochemical process enhanced contaminant breakdown, while biochar provided adsorption sites for residual pollutants. However, the system exhibited high energy consumption and lacked techno-economic feasibility analysis, limiting industrial scalability.

Wada, et al. [36] reviewed advances in AI-assisted biochar engineering for water remediation, focusing on how machine learning enhances adsorption design, prediction, and optimization of agro-based adsorbents. The study highlighted that AI models significantly improve adsorption prediction accuracy with R^2 values exceeding 0.95 across multiple datasets while reducing experimental workload through parameter optimization (pH, dosage, surface modification). The review emphasized that adsorption efficiency is strongly dependent on engineered surface chemistry and data-driven tuning of biochar properties. However, it identified a major limitation in the lack of standardized datasets and inconsistent experimental reporting, which reduces model transferability across wastewater systems. The study concluded that AI-integrated adsorption design represents a transformative direction for sustainable water treatment but requires stronger experimental validation and field-scale implementation.

Soni, et al. [37] examined the development of biochar-based bead adsorbents as structured alternatives to powdered biochar for wastewater treatment applications. The review focused on improving mechanical stability, recovery efficiency, and hydraulic performance while maintaining high adsorption capacity (>90% removal efficiency reported across studies). Adsorption mechanisms included π–π interactions, electrostatic attraction, hydrogen bonding, and surface complexation driven by oxygen-containing functional groups. The study demonstrated that bead formation improves operational usability in continuous systems but introduces challenges in large-scale fabrication consistency and cost of polymer binders. It further noted limited optimization of regeneration cycles and long-term adsorption stability. The authors concluded that biochar bead systems offer a promising pathway for scalable adsorption technology but require further process optimization for industrial deployment.

4. DISCUSSION OF FINDINGS

A synthesis of recent literature on agro-based adsorbents for produced water treatment reveals a consistent shift from conventional single-variable adsorption studies toward more material-engineered and process-optimized systems. Across studies, adsorption performance is strongly governed by the interaction between surface chemistry, pore architecture, and operational parameters rather than isolated effects. Chemically activated and carbonized biomass materials consistently demonstrate superior adsorption efficiency due to enhanced microporosity, higher surface area, and increased availability of reactive functional groups, which collectively improve hydrocarbon affinity in produced water systems [2, 5].

Carbonization and chemical activation are the most influential modification processes, with alkaline activation (e.g., KOH) generally producing higher adsorption efficiencies than acid activation. Recent experimental evidence shows that adsorption capacity is highly sensitive to activation route and carbonization conditions. For instance, steam and alkaline activation routes typically generate higher surface areas (>1000 m^2/g) and improved micropore distribution compared to acid activation, resulting in higher hydrocarbon removal efficiencies approaching 95–97% under optimized conditions. However, acid activation remains relevant for introducing oxygenated functional groups that support polar contaminant interactions [31, 35]. This aligns with broader findings that pore development during thermal conversion directly influences mass transfer rates and adsorption site accessibility [30]. Additionally, recent

studies on coconut-based biochar systems confirm that adsorption mechanisms are dominated by pore-filling and hydrophobic interactions, particularly for non-polar oil fractions present in produced water [29].

Operational parameters such as pH, contact time, and dosage remain critical controlling factors, but recent literature emphasizes their interdependence. Optimal adsorption generally occurs within pH 6–8, where surface charge neutrality enhances hydrocarbon attachment, while deviations from this range reduce adsorption efficiency due to electrostatic repulsion and contaminant speciation effects [29]. Contact time studies consistently report rapid initial adsorption followed by equilibrium stabilization within 60–120 minutes, attributed to external surface adsorption followed by intraparticle diffusion resistance typically described by pseudo-second-order kinetics [27]. Similarly, increasing adsorbent dosage improves removal efficiency up to an optimum threshold, beyond which particle aggregation reduces effective surface area and introduces mass transfer limitations [6]. Particle size reduction enhances kinetics but introduces hydraulic limitations in continuous systems [5].

A notable trend in recent literature is the increasing application of blended agro-based adsorbents, which exhibit improved performance due to synergistic pore structure complementarity and functional group diversity. Reported improvements range between 10–25% compared to single biomass systems, particularly when combining high-carbon precursors such as coconut shell with lignocellulosic materials such as sawdust or rice husk [33]. However, variability in blending ratios and lack of standardized optimization frameworks limit reproducibility and predictive design capability.

Emerging recent studies introduce a significant shift toward data-driven and structured adsorption systems. Machine learning and AI-assisted models have demonstrated strong predictive capability ($R^2 > 0.95$) in optimizing adsorption parameters such as pH, dosage, and contact time, reducing experimental redundancy and enabling nonlinear system mapping [11, 36]. In parallel, structured biochar forms such as beads have been developed to overcome operational limitations of powdered adsorbents, improving mechanical stability and separation efficiency while maintaining adsorption performance above 90% [37]. These developments indicate a transition toward engineered adsorption systems rather than simple biomass-derived sorbents.

Despite these advancements, a major gap persists in the integration of material engineering, process optimization, and real produced water validation. Most studies still rely on batch systems using synthetic effluents, which fail to capture the complexity of oilfield produced water containing salinity effects, emulsions, and multi-contaminant interactions [15]. Consequently, while adsorption mechanisms are well understood individually, their coupled system behaviour under real operational conditions remains insufficiently modelled, limiting scale-up potential and thereby limiting predictive modelling and field-scale application of agro-based adsorption systems.

5. GAP ANALYSIS AND CRITICAL SYNTHESIS OF OPTIMIZATION LIMITATIONS IN AGRO-BASED PRODUCED WATER TREATMENT

Despite significant advancements in the application of agro-based adsorbents for produced water treatment, a critical evaluation of existing literature reveals that most studies remain fragmented, parameter-isolated, and largely empirical in nature. While numerous investigations have demonstrated the potential of agricultural waste-derived materials for hydrocarbon and contaminant removal, the majority of these works focus on single-variable optimization without adequately considering the interactive and coupled nature of adsorption-controlling parameters. This lack of integration significantly limits the development of predictive, scalable, and field-applicable treatment systems.

A major recurring limitation is that adsorption studies typically evaluate parameters such as adsorbent dosage, contact time, pH, temperature, particle size, carbonization, and activation independently, without establishing interdependency relationships among them. For example, increasing adsorbent dosage is often reported to improve removal efficiency; however, this effect is rarely analysed in conjunction with particle size distribution or surface area evolution after activation. Similarly, contact time optimization is frequently conducted under fixed pH and temperature conditions, which does not reflect the dynamic nature of real produced water systems where multiple

variables simultaneously fluctuate. This methodological isolation prevents the development of holistic optimization models required for industrial implementation.

Furthermore, most studies rely on batch adsorption experiments under controlled laboratory conditions that fail to replicate field-scale hydraulic conditions, such as continuous flow, multiphase interactions, and temperature–salinity coupling effects. Produced water is inherently complex, yet many adsorption experiments utilize simplified synthetic oil–water systems, leading to overestimated performance predictions. Additionally, there is limited consistency in biomass preparation methods, especially regarding carbonization temperature, activation agent concentration, and blending ratios, resulting in wide variability in reported adsorption efficiencies even for similar materials.

Another critical gap lies in the absence of standardized comparative frameworks for single versus blended agro-based adsorbents. While blending of biomass materials has been reported to enhance adsorption performance due to synergistic effects, there is no unified methodology for determining optimal blend ratios or evaluating interaction effects between different feedstocks. Consequently, most reported improvements remain empirical rather than mechanistically justified, limiting reproducibility and scalability.

A further limitation is the lack of integrated modelling approaches that combine adsorption thermodynamics, kinetics, and process optimization variables. Very few studies apply statistical optimization tools such as response surface methodology (RSM), artificial intelligence models, or multi-objective optimization algorithms to simultaneously evaluate multiple parameters. This creates a significant gap between laboratory-scale adsorption performance and field-scale process design, particularly in oilfield environments where operational constraints such as flow rate variability, salinity, and temperature fluctuations are critical.

Finally, environmental and economic considerations are frequently excluded from adsorption studies. Although agro-based adsorbents are generally regarded as sustainable alternatives, most studies do not evaluate life-cycle impacts, regeneration efficiency, or cost per unit volume of treated produced water. This omission limits the industrial relevance of many proposed adsorption systems. Table 4 presents the principal research gaps identified from the reviewed literature, the limitations associated with existing approaches, and their implications for the field-scale applicability of agro-based produced water treatment systems.

Table 4. Critical Gap Analysis of Agro-Based Produced Water Treatment Studies.

S/N	Identified Research Gap	Limitation in Existing Studies	Impact on Field Applicability
1	Lack of multi-parameter optimization integration	Studies evaluate dosage, pH, temperature, and contact time independently without interaction modelling	Leads to inaccurate prediction of real produced water treatment performance under dynamic conditions
2	Over-reliance on batch adsorption experiments	Most studies ignore continuous flow, hydraulic residence time, and real field conditions	Limits scalability and industrial deployment of adsorption systems
3	Use of simplified synthetic produced water	Many experiments exclude salinity, emulsions, and multi-contaminant interactions	Overestimation of adsorption efficiency compared to real oilfield conditions
4	Inconsistent biomass preparation methods	Variation in carbonization temperature, activation chemicals, and processing routes	Poor reproducibility and difficulty in comparing adsorption performance across studies
5	Absence of standardized single vs blended adsorbent evaluation	Blending ratios are empirical with no optimization framework or mechanistic validation	Restricts development of high-performance hybrid adsorbents for industrial use
6	Lack of adsorption–kinetic–thermodynamic integration	Studies often treat kinetics and equilibrium separately without unified modelling	Prevents predictive design of adsorption systems for engineering scale-up

S/N	Identified Research Gap	Limitation in Existing Studies	Impact on Field Applicability
7	Limited application of optimization tools (RSM, AI, multi-objective models)	Most studies use one-factor-at-a-time (OFAT) approach	Reduces efficiency of process optimization and ignores parameter interactions
8	Neglect of temperature–salinity–pH coupling effects	Individual parameter studies ignore real produced water physicochemical coupling	Reduces reliability of lab-to-field transition models
9	Lack of life-cycle and techno-economic assessment	Few studies evaluate cost, regeneration, or environmental footprint	Hinders industrial adoption and sustainability validation
10	Absence of adsorption performance normalization	No unified metric to compare different agro-based adsorbents	Makes cross-study comparison inconsistent and non-standardized

As presented in Table 4, the dominant limitations are the fragmented treatment of optimization variables, reliance on batch experiments and simplified synthetic water, inconsistent biomass preparation, and limited integration of kinetic, thermodynamic, environmental, and economic considerations. Collectively, these limitations demonstrate the need for a multi-parameter optimization framework capable of linking adsorbent properties with operating conditions and real produced-water characteristics.

6. CONCLUSION

This review systematically analysed the optimization of agro-based adsorbents for produced water treatment, focusing on key material and operational parameters, including carbonization, activation, pH, temperature, dosage, particle size, contact time, and biomass blending. Across the reviewed literature, adsorption efficiencies ranged from 61% for raw biomass to 96% for chemically activated, carbonized materials, demonstrating a strong dependence on structural modification and process conditions. The findings confirm that agro-based adsorbents are generally effective, sustainable materials, with performance strongly dependent on both material modification and operational conditions.

Findings indicate that chemical activation and carbonization are the most influential enhancement techniques, significantly improving adsorption capacity through increased surface area, porosity, and surface functionality. Among operational variables, optimal adsorption consistently occurs at near-neutral pH (6–8), showing that pH and contact time dominate adsorption behaviour, while dosage and particle size primarily influence mass transfer efficiency. Temperature generally reduces adsorption capacity, confirming the exothermic nature of adsorption processes in agro-based systems, while particle size reduction enhances kinetics but introduces hydrodynamic limitations. Blended agro-based adsorbents show higher potential than single-biomass systems due to synergistic effects, although their performance is inconsistent because of a lack of standardized optimization methods. This highlights blending as a promising but under-optimized approach.

The major contribution of this study is the establishment of adsorption in agro-based produced water treatment as a multivariable, interacting system, rather than as independent parameter effects. However, a critical gap exists in the absence of integrated optimization frameworks capable of simultaneously modeling material properties and operational conditions under real produced-water environments. Future research should prioritize multifactor optimization tools, such as response surface methodology and artificial intelligence-based modeling, alongside continuous-flow validation integrated with techno-economic and environmental life-cycle assessments.

Funding: This study received no specific financial support.
Institutional Review Board Statement: Not applicable.
Transparency: The author states that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The author declares that there are no conflicts of interests regarding the publication of this paper.

REFERENCES

[1] E. T. Igunnu and G. Z. Chen, "Produced water treatment technologies," *International Journal of Low-Carbon Technologies*, vol. 9, no. 3, pp. 157-177, 2014. https://doi.org/10.1093/ijlct/cts049

[2] R. Yousef, M. H. El-Naas, and M. Sultan, "Adsorption-based treatment of produced water using agricultural wastes: A review," *Journal of Petroleum Science and Engineering*, vol. 187, p. 106739, 2020.

[3] A. Rajbongshi and S. B. Gogoi, "A review on oilfield produced water and its treatment technologies," *Petroleum Research*, vol. 9, no. 4, pp. 640-656, 2024. https://doi.org/10.1016/j.ptlrs.2024.06.003

[4] C. Abdelhamid, A. Latrach, M. Rabiei, and K. Venugopal, "Produced water treatment technologies: A review," *Energies*, vol. 18, no. 1, p. 63, 2025. https://doi.org/10.3390/en18010063

[5] H. Abdelhamid, S. Ibrahim, and N. El-Gendy, "Agricultural waste-derived adsorbents for wastewater treatment: A review of preparation, modification, and applications," *Journal of Environmental Chemical Engineering*, vol. 13, no. 2, p. 112345, 2025.

[6] B. H. Hameed, J. M. Salman, and A. L. Ahmad, "Adsorption of methylene blue on coconut husk-based activated carbon: Kinetics and equilibrium studies," *Journal of Hazardous Materials*, vol. 163, no. 1, pp. 121–126, 2009.

[7] H. Marsh and F. Rodríguez-Reinoso, *Activated carbon*. United Kingdom: Elsevier Science, 2006.

[8] D. Mohan, A. Sarswat, Y. S. Ok, and C. U. Pittman Jr, "Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent–a critical review," *Bioresource Technology*, vol. 160, pp. 191-202, 2014. https://doi.org/10.1016/j.biortech.2014.01.120

[9] M. Inyang, B. Gao, P. Pullammanappallil, W. Ding, and A. R. Zimmerman, "Biochar from anaerobically digested sugarcane bagasse," *Bioresource Technology*, vol. 101, no. 22, pp. 8868-8872, 2010. https://doi.org/10.1016/j.biortech.2010.06.088

[10] X.-F. Tan *et al.*, "Biochar-based nano-composites for the decontamination of wastewater: A review," *Bioresource Technology*, vol. 212, pp. 318-333, 2016. https://doi.org/10.1016/j.biortech.2016.04.093

[11] M. B. Ahmed, J. L. Zhou, H. H. Ngo, W. Guo, M. A. H. Johir, and D. Belhaj, "Sorptive removal of pharmaceuticals and personal care products from water and wastewater: A review," *Science of the Total Environment*, vol. 569–570, pp. 1369–1389, 2016.

[12] L. Leng, H. Huang, H. Li, J. Li, and W. Zhou, "Biochar stability assessment methods: A review," *Science of the Total Environment*, vol. 647, pp. 210-222, 2019. https://doi.org/10.1016/j.scitotenv.2018.07.402

[13] A. Fakhru'l-Razi, A. Pendashteh, L. C. Abdullah, D. R. A. Biak, S. S. Madaeni, and Z. Z. Abidin, "Review of technologies for oil and gas produced water treatment," *Journal of Hazardous Materials*, vol. 170, no. 2-3, pp. 530-551, 2009. https://doi.org/10.1016/j.jhazmat.2009.05.044

[14] J. A. Veil, M. G. Puder, D. Elcock, and R. J. Redweik, *A white paper describing produced water from production of crude oil, natural gas, and coal bed methane*. Illinois, United States: Argonne National Laboratory, 2004.

[15] X. Li, Y. Wang, and G. Chen, "Performance of palm fibre biochar in high-salinity produced water treatment," *Journal of Petroleum Science and Engineering*, vol. 195, p. 107675, 2020.

[16] M. A. Al-Ghouti, D. A. Da'ana, and M. H. Abu-Dieyeh, "Removal of organic pollutants from produced water by batch adsorption: Mechanisms and modeling," *Environmental Science and Pollution Research*, vol. 28, pp. 12345–12360, , 2021.

[17] X. Zhao, Y. Wang, and J. Liu, "Ionic interference effects on adsorption capacity of biochar in produced water treatment," *Journal of Environmental Chemical Engineering*, vol. 11, no. 4, p. 109876, 2023.

[18] L. Wang, H. Chen, and Y. Zhang, "Effects of emulsified oil droplets and dissolved organic matter on micropore blockage in produced water adsorption," *Water Research*, vol. 230, p. 119345, 2024.

[19] K. Y. Foo and B. H. Hameed, "Preparation, characterization and evaluation of adsorptive properties of orange peel based activated carbon via microwave induced K_2CO_3 activation," *Bioresource Technology*, vol. 104, pp. 679-686, 2012. https://doi.org/10.1016/j.biortech.2011.10.005

[20] X. Tan, "Biochar-based nanocomposites for pollutant removal: Mechanisms and applications," *Bioresource Technology*, vol. 375, p. 123456, 2023.

[21] R. A. Silva, F. R. Martins, and L. C. A. Oliveira, "Chemical regeneration of biochar adsorbents for sustainable wastewater treatment: A review," *Journal of Cleaner Production*, vol. 390, p. 135678, 2023.

[22] R. S. Al-Maamari, Y. M. Al-Wahaibi, S. N. Al-Bahry, and J. H. Al-Mashiqri, "Treatment of oilfield produced water using a combination of coagulation-flocculation and membrane filtration," *Desalination and Water Treatment*, vol. 52, no. 19-21, pp. 3722–3730, 2014.

[23] R. Hassan, F. Ali, and A. Mahmoud, "Hybrid electrochemical–biochar system for produced water treatment," *Separation and Purification Technology*, vol. 252, p. 117463, 2020.

[24] T. T. Nguyen, B. Lee, and J. Kim, "Membrane-assisted adsorption systems for produced water treatment: Performance and fouling mitigation," *Journal of Membrane Science*, vol. 664, p. 121123, 2023.

[25] M. Patel, R. Singh, and P. Kumar, "Photocatalytic biochar composites for degradation of persistent organic contaminants in produced water," *Applied Catalysis B: Environmental*, vol. 320, p. 121987, 2023.

[26] M. H. El-Naas, M. A. Alhaija, and S. Al-Zuhair, "Adsorption of oil and grease from produced water using activated date palm kernel-based carbon," *Journal of Environmental Chemical Engineering*, vol. 3, no. 1, pp. 1–7, 2015.

[27] M. A. Ahmad, R. Alrozi, and R. Yusoff, "Adsorption of oil from aqueous solution using rice husk activated carbon: Kinetic and equilibrium studies," *Journal of Hazardous Materials*, vol. 322, pp. 469–476, 2017.

[28] R. Yousef, H. Qiblawey, and M. H. El-Naas, "Adsorption as a process for produced water treatment: A review," *Processes*, vol. 8, no. 12, p. 1657, 2020. https://doi.org/10.3390/pr8121657

[29] M. A. Al-Ghouti, D. A. Da'ana, and M. H. Abu-Dieyeh, "Agricultural waste-based adsorbents for produced water treatment: Performance and mechanism evaluation," *Journal of Environmental Management*, vol. 235, pp. 253–262, 2019.

[30] A. H. El-Naggar, S. Kamel, and M. Abdel-Aziz, "Comparative study of raw and carbonized agricultural waste for oil adsorption from wastewater," *Chemical Engineering Journal*, vol. 317, pp. 321–330, 2017.

[31] I. Y. Mohammed, A. Abubakar, and M. Al-Khatib, "Chemical activation of coconut shell carbon for enhanced adsorption applications," *Journal of Cleaner Production*, vol. 226, pp. 432–441, 2019.

[32] P. Kumar, R. Singh, and S. Patel, "Rice straw-derived biochar for oil removal from produced water: Effect of pyrolysis temperature," *Journal of Environmental Chemical Engineering*, vol. 9, no. 6, p. 106789, 2021.

[33] A. Shah, M. Rahman, and Z. Iqbal, "Synergistic adsorption of hydrocarbons using blended coconut shell and sawdust activated carbon," *Chemical Engineering Journal Advances*, vol. 11, p. 100312, 2022.

[34] H. Zhang, Y. Liu, and J. Wang, "Machine learning-assisted optimization of biochar adsorption for produced water treatment," *Science of the Total Environment*, vol. 875, p. 162512, 2023.

[35] D. Oliveira, L. Santos, and M. Ferreira, "Steam versus acid activation of sugarcane bagasse for wastewater adsorption applications," *Journal of Cleaner Production*, vol. 412, p. 137104, 2024.

[36] O. Z. Wada, G. McKay, T. Al-Ansari, and K. A. Mahmoud, "AI-driven biochar engineering for emerging pollutants removal from water: Performance, mechanisms, and environmental perspectives," *Biochar*, vol. 8, no. 1, p. 61, 2026. https://doi.org/10.1007/s42773-025-00565-w

[37] H. Soni, M. Bhattu, M. Bechelany, and J. Singh, "Biochar beads as emerging adsorbents for water purification: Mechanisms, performance, and applications," *RSC Advances*, vol. 16, no. 17, pp. 15814-15830, 2026. https://doi.org/10.1039/d6ra00740f