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Conceptual Framework for Sustainable Produced Water Treatment Using Agricultural Waste–Derived Adsorbents

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Abstract- The management of produced water generated from oil and gas operations remains a critical environmental and sustainability challenge, particularly in regions facing water scarcity and weak wastewater infrastructure. Produced water is characterized by complex mixtures of dissolved salts, hydrocarbons, heavy metals, and chemical additives, necessitating treatment technologies that are both effective and economically viable. This presents a conceptual framework for sustainable produced water treatment using agricultural waste derived adsorbents, integrating principles of circular economy, green chemistry, and low-cost environmental remediation. The framework outlines the systematic conversion of abundant agricultural residues such as rice husks, coconut shells, maize cobs, sugarcane bagasse, and groundnut shells into functional adsorbent materials through physical, chemical, or thermochemical activation processes. These bio-based adsorbents exhibit high surface area, tunable porosity, and surface functional groups capable of removing key produced water contaminants, including heavy metals, oil residues, and organic compounds. The proposed framework encompasses four interlinked stages: (i) feedstock selection and pretreatment based on regional agricultural waste availability, (ii) adsorbent synthesis and modification to enhance adsorption performance, (iii) integration into modular produced water treatment systems, and (iv) post-treatment management, including adsorbent regeneration, reuse, or environmentally safe disposal. Emphasis is placed on scalability, lifecycle sustainability, and adaptability to onshore and offshore oil and gas operations. The framework also highlights socio-economic co-benefits, such as waste valorization, reduced reliance on imported treatment media, and opportunities for local enterprise development. By aligning produced water treatment with sustainable resource utilization, this conceptual framework provides a strategic pathway for reducing environmental risks, lowering operational costs, and supporting regulatory compliance. It offers a foundation for future experimental validation, techno-economic assessment, and policy-oriented research aimed at advancing sustainable water management practices in energy-producing regions, particularly in developing economies.

Keywords: Produced Water Treatment; Agricultural Waste; Bio-Based Adsorbents; Sustainability; Circular Economy; Oil And Gas Wastewater; Environmental Remediation

I. INTRODUCTION

Produced water is the largest volume by-product generated during oil and gas exploration, production, and processing activities. It originates from formation water naturally present in hydrocarbon-bearing reservoirs and from injected water used for enhanced oil recovery operations (Awe, 2017; Akpan *et al*., 2017). As oil and gas fields mature, the water-to-oil ratio typically increases, resulting in progressively larger volumes of produced water over the lifecycle of a field. This wastewater stream is characterized by complex and highly variable physicochemical properties, including high salinity, dispersed and dissolved hydrocarbons, heavy metals, naturally occurring radioactive materials (NORMs), and residual production chemicals such as corrosion inhibitors and demulsifiers (Adebiyi *et al*., 2017; Awe *et al*., 2017). The sheer volume and contaminant complexity of produced water make its management a critical operational, environmental, and regulatory concern for the global energy industry (Akinrinoye *et al*., 2015; Osabuohien, 2017).

The disposal of produced water poses significant environmental and regulatory challenges. Improper handling or discharge can lead to soil degradation, surface and groundwater contamination, and adverse ecological impacts on aquatic ecosystems (Awe and Akpan, 2017; Efobi *et al*., 2017). High salinity and toxic constituents can impair plant growth, disrupt microbial communities, and reduce water quality for downstream users. Consequently, regulatory frameworks in many jurisdictions impose stringent limits on oil and grease content, total dissolved solids, heavy metals, and organic pollutants prior to discharge or reuse (Adebiyi *et al*., 2014). Compliance with these regulations often requires multi-stage treatment processes and continuous monitoring, which can be particularly challenging in remote or resource-constrained oil-producing regions. In offshore operations, space limitations and zero-discharge policies further complicate produced water management, while onshore operations must address risks related to reinjection-induced seismicity and long-term subsurface impacts (Drioli *et al*., 2016; Ayele *et al*., 2016).

Conventional produced water treatment technologies include physical, chemical, and biological processes such as gravity separation, hydrocyclones, flotation units, membrane filtration, chemical coagulation, and advanced oxidation. While these technologies are effective for specific contaminants, they are often capital-intensive, energy-demanding, and operationally complex. Membrane-based systems, for example, suffer from fouling and high replacement costs, while chemical treatments generate secondary waste streams that require additional handling and disposal (Gude, 2015; Assayie *et al*., 2017). Biological processes are frequently limited by high salinity and the presence of toxic compounds, reducing their robustness and reliability. As a result, conventional treatment systems may be economically prohibitive for small-scale operators and difficult to sustain in developing economies (Ball and Weeda, 2015; Feron, 2016).

These limitations underscore the need for sustainable and low-cost alternatives for produced water treatment. In recent years, increasing emphasis has been placed on resource-efficient and environmentally benign technologies that align with circular economy principles. Agricultural waste–derived adsorbents have emerged as promising candidates due to their low cost, local availability, and favorable adsorption properties (Tripathi and Ranjan, 2015; Sulyman *et al*., 2017). Materials such as rice husks, coconut shells, sugarcane bagasse, and maize cobs can be converted into effective adsorbents capable of removing heavy metals, hydrocarbons, and organic pollutants from produced water. The utilization of such waste materials not only reduces treatment costs but also addresses agricultural residue disposal challenges, creating synergistic environmental and socio-economic benefits (Creutzig *et al*., 2015; Chaukura *et al*., 2016). Therefore, developing sustainable produced water treatment frameworks based on agricultural waste–derived adsorbents represents a strategic pathway toward environmentally responsible and economically viable water management in oil and gas operations.

II. METHODOLOGY

This study adopts the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology to systematically identify, screen, and synthesize existing scientific evidence relevant to the development of a conceptual framework for sustainable produced water treatment using agricultural waste–derived adsorbents. The methodology was designed to ensure transparency, reproducibility, and rigor in the selection and analysis of peer-reviewed literature addressing produced water characteristics, adsorption-based treatment technologies, and the valorization of agricultural waste materials.

A comprehensive literature search was conducted across major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar. The search strategy employed a combination of keywords and Boolean operators such as "produced water treatment," "oil and gas wastewater," "agricultural waste," "bio-based adsorbents," "activated carbon from biomass," and "sustainable adsorption." The search was limited to articles published in English between 2000 and 2024 to capture both foundational studies and recent technological advancements. Additional relevant studies were identified through backward and forward citation tracking to minimize the risk of omitting influential publications.

Following the initial search, all retrieved records were exported to reference management software, and duplicate entries were removed. Titles and abstracts were then screened to assess relevance to the study objectives. Articles focusing exclusively on non-adsorptive treatment technologies, non-agricultural adsorbent materials, or wastewater streams unrelated to oil and gas operations were excluded. The remaining full-text articles were assessed against predefined eligibility criteria, including relevance to produced water treatment, use of agricultural or biomass-derived adsorbents, and availability of sufficient methodological or performance data.

Data extraction was performed using a standardized template to capture key information, including agricultural feedstock type, adsorbent preparation method, target contaminants, adsorption mechanisms, treatment performance, regeneration potential, and reported sustainability or cost considerations. Qualitative synthesis was applied to identify recurring themes, technological trends, and performance benchmarks, while quantitative findings were comparatively analyzed where data consistency permitted.

The synthesized evidence informed the development of the proposed conceptual framework by linking agricultural waste availability, adsorbent production pathways, and produced water treatment requirements. Emphasis was placed on sustainability, scalability, and applicability in resource-constrained contexts. Through the structured PRISMA approach, this methodology ensures that the conceptual framework is grounded in robust scientific evidence and provides a reliable foundation for future experimental validation, techno-economic analysis, and policy-oriented research.

2.1 Produced Water Characteristics and Treatment Requirements

Produced water is a complex wastewater stream generated during oil and gas exploration and production, representing the largest volume of effluent associated with hydrocarbon extraction (Nasiri *et al*., 2017; Gazali *et al*., 2017). Its characteristics are influenced by geological formation, reservoir age, production techniques, and operational practices. Understanding the chemical composition and variability of produced water is essential for designing effective treatment strategies that meet regulatory, environmental, and operational requirements for reuse, discharge, or reinjection.

The chemical composition of produced water is highly heterogeneous and often dominated by elevated salinity levels. Total dissolved solids (TDS) concentrations can range from a few thousand milligrams per liter to values exceeding those of seawater, depending on the reservoir formation and degree of water rock interaction. High concentrations of sodium, chloride, calcium, magnesium, and bicarbonate ions are common, contributing to scaling, corrosion, and osmotic stress in treatment systems. Salinity is one of the primary constraints limiting the applicability of biological treatment processes and poses significant challenges for water reuse, particularly in agricultural or industrial applications requiring low TDS.

In addition to dissolved salts, produced water contains hydrocarbons in both dispersed and dissolved forms. These include free oil droplets, emulsified oil, and low-molecular-weight aromatic compounds such as benzene, toluene, ethylbenzene, and xylene (BTEX). Polycyclic aromatic hydrocarbons (PAHs) may also be present at lower concentrations but pose heightened environmental and toxicological risks due to their persistence and bioaccumulative potential. Even at trace levels, hydrocarbons can impair aquatic ecosystems, necessitating stringent removal prior to discharge or reuse.

Heavy metals constitute another critical component of produced water. Elements such as lead, cadmium, chromium, nickel, zinc, barium, and iron are commonly detected, originating from reservoir minerals, corrosion of production equipment, and chemical additives. Some of these metals, including barium and strontium, contribute to scale formation, while others pose direct toxicity risks to humans and ecosystems. The presence of naturally occurring radioactive materials, often associated with barium and radium, further complicates treatment and disposal strategies, particularly with respect to sludge management and regulatory compliance (Nelson *et al*., 2015; Aziz *et al*., 2017).

Produced water also contains a wide range of chemical additives introduced during drilling, completion, and production operations. These include corrosion inhibitors, scale inhibitors, biocides, demulsifiers, surfactants, and polymers. While essential for maintaining operational efficiency, these chemicals increase the organic load and chemical oxygen demand of produced water and may exhibit toxicity or resistance to degradation. Their complex interactions with naturally occurring constituents can reduce the effectiveness of conventional treatment processes and contribute to fouling or secondary pollution.

The composition of produced water varies significantly across onshore and offshore operations. Onshore produced water often exhibits higher variability in salinity and contaminant concentration due to differences in reservoir geology and enhanced recovery techniques such as water flooding or chemical injection. Management options onshore may include surface discharge, reuse for industrial purposes, or reinjection, each requiring tailored treatment approaches. Offshore produced water, by contrast, is typically discharged directly into the marine environment after treatment, subject to strict oil-in-water and toxicity limits. Space constraints, weight limitations, and the need for continuous operation offshore favor compact and robust treatment systems, often prioritizing physical and chemical processes over biological ones (Katsanevakis *et al*., 2016; Su *et al*., 2017).

Treatment objectives for produced water are defined by the intended end use or disposal pathway. For discharge into surface water bodies or marine environments, treatment focuses on reducing oil and grease, suspended solids, toxic metals, and dissolved organic compounds to meet regulatory thresholds. In cases where produced water is intended for beneficial reuse, such as irrigation, industrial processes, or dust suppression, more stringent treatment may be required to control salinity, specific ions, and residual organic contaminants. Reinjection, commonly used for pressure maintenance or disposal, requires treatment to prevent formation damage, scaling, corrosion, and microbial growth that could compromise reservoir integrity and well performance.

The diverse and variable characteristics of produced water necessitate flexible and adaptive treatment strategies. Single-technology solutions are rarely sufficient, and integrated treatment trains are often required to address multiple contaminant classes simultaneously. These complexities highlight the importance of developing sustainable, cost-effective, and adaptable treatment approaches that can be customized to specific operational contexts. In this regard, adsorption-based systems, particularly those utilizing agricultural waste–derived materials, offer promising potential to address key produced water treatment requirements while enhancing environmental sustainability and economic feasibility (Sengupta et a., 2015; Yentekakis and Goula, 2017).

2.2 Agricultural Waste as a Sustainable Resource

Agricultural activities generate vast quantities of residual biomass each year in the form of husks, shells, stalks, cobs, and bagasse. These agricultural waste streams are often treated as low-value by-products, despite their significant potential as renewable resources for environmental and industrial applications. In many developing and agrarian economies, agricultural residues are produced in close proximity to oil and gas operations and other industrial activities, creating opportunities for localized, low-cost resource utilization. Recognizing agricultural waste as a sustainable resource is therefore central to advancing environmentally responsible technologies, including adsorption-based water treatment systems.

Among the most abundant agricultural waste streams are rice husks, coconut shells, maize cobs, sugarcane bagasse, and groundnut shells. Rice husks constitute approximately 20% of rice grain weight and are generated in large volumes across Asia and Africa. They are rich in silica and carbon, making them suitable for conversion into adsorbents and biochar materials. Coconut shells, widely available in tropical regions, possess high lignin content and mechanical strength, which contribute to the production of activated carbons with high surface area and durability. Maize cobs are another widely distributed residue, composed primarily of cellulose, hemicellulose, and lignin, providing a porous structure favorable for adsorption after appropriate treatment. Sugarcane bagasse, a fibrous by-product of sugar production, is generated in millions of tons annually and contains high carbon content, while groundnut shells offer similar compositional advantages along with widespread availability in agricultural regions (Arshadi *et al*., 2016; Sarker *et al*., 2017).

The disposal of agricultural waste poses both environmental and economic challenges. Open burning of residues, a common practice in many rural areas, releases particulate matter, greenhouse gases, and toxic compounds, contributing to air pollution and climate change. Uncontrolled dumping can lead to land degradation, pest proliferation, and methane emissions during anaerobic decomposition. From an economic perspective, improper disposal represents a loss of potentially valuable materials that could be transformed into marketable products. The costs associated with waste management, including collection, transportation, and disposal, further strain limited municipal and rural infrastructure, particularly in low- and middle-income countries.

Conversely, the valorization of agricultural waste offers significant environmental and economic benefits. Converting residues into functional materials such as adsorbents reduces the volume of waste requiring disposal while simultaneously providing low-cost alternatives to conventional, often imported, treatment media. The use of locally sourced agricultural waste can lower production and transportation costs, enhance supply chain resilience, and reduce dependence on non-renewable raw materials. Moreover, waste-derived products can create additional income streams for farmers and rural communities, fostering local enterprise development and employment opportunities.

The utilization of agricultural waste as a resource is closely aligned with circular economy principles, which emphasize resource efficiency, waste minimization, and the continuous use of materials within closed-loop systems. Rather than following a linear "take–make–dispose" model, agricultural residues are reintegrated into the value chain as raw materials for environmental remediation technologies (Wu *et al*., 2015; Burckart and Butterworth, 2017). This approach supports sustainable production and consumption patterns by extending the lifecycle of biomass resources and reducing the environmental footprint associated with material extraction and waste disposal.

Waste-to-resource strategies also align with broader sustainability and climate objectives. The conversion of agricultural waste into bio-based adsorbents can result in lower embodied energy and carbon emissions compared to the production of conventional activated carbon from fossil-based sources. Additionally, biochar and similar materials may offer carbon sequestration benefits, further contributing to climate change mitigation. When applied to wastewater treatment, these materials enable synergistic solutions that address both waste management and water pollution challenges.

In the context of produced water treatment, agricultural waste–derived materials represent a strategically valuable resource. Their abundance, renewability, and favorable physicochemical properties make them well-suited for adsorption-based removal of contaminants such as heavy metals and hydrocarbons. By integrating agricultural waste valorization into water treatment frameworks, it is possible to achieve cost-effective, environmentally sustainable solutions that support circular economy objectives while addressing critical water management challenges in resource-constrained settings.

2.3 Agricultural Waste–Derived Adsorbents

Agricultural waste–derived adsorbents have gained increasing attention as sustainable alternatives to conventional adsorbent materials for wastewater treatment applications (Khatoon and Rai, 2016; Sulyman *et al*., 2017). Their attractiveness lies in their low cost, renewability, local availability, and favorable physicochemical characteristics, which can be tailored to remove a wide range of contaminants. The effectiveness of these adsorbents depends largely on appropriate feedstock selection, preparation methods, and surface modification strategies that enhance adsorption performance and stability.

Feedstock selection is a critical initial step in the development of agricultural waste–derived adsorbents. Availability is a primary criterion, as large and consistent supply ensures scalability and economic feasibility. Residues such as rice husks, coconut shells, maize cobs, sugarcane bagasse, and groundnut shells are particularly suitable due to their widespread production and minimal competing uses. Cost considerations further favor agricultural waste materials, as they are often obtained at little or no cost aside from collection and transportation. Carbon content is another key factor, since high lignocellulosic composition, rich in cellulose, hemicellulose, and lignin, contributes to the formation of porous carbon structures upon activation. Physicochemical properties such as ash content, moisture level, density, and inherent mineral composition also influence adsorbent yield, surface area, and adsorption behavior. For instance, low ash content is desirable to prevent pore blockage, while appropriate mineral content can enhance specific adsorption mechanisms.

The transformation of agricultural waste into effective adsorbents typically involves activation processes designed to increase surface area, porosity, and the availability of active sites. Physical activation is one of the most commonly employed methods and involves carbonization of the biomass at elevated temperatures in an inert atmosphere, followed by activation using oxidizing gases such as steam or carbon dioxide. This process creates a network of micro- and mesopores by selectively removing carbon atoms, thereby enhancing adsorption capacity. Physical activation is environmentally favorable due to the absence of chemical reagents; however, it often requires high temperatures and longer processing times, which may increase energy consumption.

Chemical activation offers an alternative approach that generally operates at lower temperatures and yields higher surface areas. In this method, agricultural waste is impregnated with chemical activating agents such as phosphoric acid, potassium hydroxide, zinc chloride, or sodium carbonate prior to thermal treatment. These chemicals promote dehydration, cross-linking, and pore development during carbonization, resulting in well-developed porous structures. Chemical activation is particularly effective for producing adsorbents with high microporosity and tailored surface chemistry. Nonetheless, concerns related to chemical recovery, secondary pollution, and overall environmental impact necessitate careful process optimization and waste management.

Thermochemical and biochar-based processes represent another important class of adsorbent preparation techniques. Biochar is produced through pyrolysis of biomass under limited or no oxygen conditions, typically at moderate temperatures. The resulting material retains a significant portion of the original biomass structure while exhibiting enhanced stability and porosity. Biochar-based adsorbents can be further activated physically or chemically to improve adsorption performance (Tan *et al*., 2016; Cao *et al*., 2017). These processes are attractive due to their relatively low energy requirements and potential for carbon sequestration, aligning well with sustainability and climate mitigation goals.

Beyond activation, surface modification and functionalization strategies play a crucial role in enhancing the adsorption efficiency and selectivity of agricultural waste–derived adsorbents. Surface oxidation using acids, bases, or oxidizing agents can introduce functional groups such as hydroxyl, carboxyl, and carbonyl groups, improving affinity for metal ions and polar organic compounds. Impregnation with metal oxides, polymers, or surfactants can further tailor surface properties to target specific contaminants. For example, iron-modified biochars have demonstrated enhanced removal of heavy metals, while surfactant-treated adsorbents improve hydrocarbon adsorption. These functionalization techniques enable customization of adsorbents for specific produced water contaminants, enhancing their applicability across diverse treatment scenarios.

Agricultural waste–derived adsorbents represent a versatile and sustainable class of materials whose performance can be optimized through careful feedstock selection, appropriate activation methods, and targeted surface modification. Their adaptability and environmental advantages make them promising candidates for integration into cost-effective and sustainable water treatment frameworks.

2.4 Adsorption Mechanisms and Performance

Adsorption is a key physicochemical process governing the removal of diverse contaminants from produced water using agricultural waste–derived adsorbents. The effectiveness of adsorption-based treatment systems depends on the interaction between contaminant species and the surface characteristics of the adsorbent, including surface area, pore structure, and functional groups. Understanding the mechanisms involved in the removal of heavy metals, oil and grease, and organic pollutants, as well as the factors influencing adsorption efficiency, is essential for optimizing performance and ensuring reliable produced water treatment.

Heavy metal adsorption is primarily driven by surface complexation, ion exchange, electrostatic attraction, and precipitation mechanisms. Agricultural waste–derived adsorbents typically possess oxygen-containing functional groups such as carboxyl, hydroxyl, and carbonyl moieties, which serve as active binding sites for metal ions. These functional groups can form coordination bonds with metals such as lead, cadmium, chromium, and nickel, effectively immobilizing them on the adsorbent surface. Ion exchange processes occur when metal ions in solution replace naturally occurring cations, such as calcium or magnesium, present on the adsorbent matrix. Electrostatic attraction further enhances adsorption when the surface charge of the adsorbent is opposite to that of the metal species, a condition strongly influenced by solution pH (Eldridge *et al*., 2015; Yan *et al*., 2016). In some cases, localized precipitation of metal hydroxides or carbonates on the adsorbent surface contributes to overall removal efficiency, particularly at higher pH levels.

Oil and grease removal from produced water involves a combination of physical adsorption, hydrophobic interactions, and pore-filling mechanisms. Agricultural waste–derived adsorbents, especially those converted into activated carbon or biochar, exhibit hydrophobic surfaces that preferentially attract non-polar hydrocarbon molecules. The porous structure of these materials enables the entrapment of oil droplets and emulsified hydrocarbons within micro- and mesopores. Van der Waals forces and capillary action further facilitate the retention of oil and grease on the adsorbent surface. Surface modifications, such as surfactant treatment or increased aromaticity during carbonization, can enhance hydrophobicity and improve affinity for hydrocarbon contaminants, making adsorption an effective polishing step following primary oil–water separation.

Organic pollutant uptake encompasses the removal of dissolved organic compounds, including aromatic hydrocarbons, phenols, and residual production chemicals. Multiple mechanisms contribute to this process, including π–π interactions between aromatic structures of organic pollutants and the carbonaceous surface of the adsorbent, hydrogen bonding with surface functional groups, and pore diffusion. The high surface area and tunable pore size distribution of agricultural waste–derived adsorbents allow for effective interaction with both low- and high-molecular-weight organic compounds. In addition, chemical functionalization can enhance selectivity toward specific organic contaminants, improving overall treatment performance in complex produced water matrices.

The efficiency of adsorption processes is strongly influenced by operational and environmental factors, notably pH, temperature, contact time, and adsorbent dosage. pH plays a critical role by affecting both the speciation of contaminants and the surface charge of the adsorbent. For heavy metals, lower pH values may reduce adsorption due to competition with hydrogen ions, whereas higher pH levels often enhance metal uptake by increasing negative surface charge and promoting precipitation mechanisms. For organic pollutants and hydrocarbons, pH influences solubility and ionization state, thereby affecting adsorption affinity.

Temperature impacts adsorption kinetics and equilibrium behavior. In many cases, adsorption of heavy metals and organic compounds is endothermic, with higher temperatures increasing adsorption capacity by enhancing molecular mobility and diffusion into pores. However, excessively high temperatures may reduce adsorption due to desorption or structural changes in the adsorbent. Therefore, temperature optimization is necessary to balance performance and energy efficiency (Li *et al*., 2015; Henninger *et al*., 2017).

Contact time determines the extent to which adsorption equilibrium is achieved. Rapid initial adsorption is commonly observed due to the availability of abundant active sites, followed by a slower phase as these sites become occupied. Adequate contact time is essential to maximize removal efficiency, particularly in continuous-flow systems where hydraulic retention time is limited. Adsorbent dosage directly affects the number of available adsorption sites; increasing dosage generally improves contaminant removal but may reduce adsorption capacity per unit mass due to site aggregation or reduced driving force.

Adsorption mechanisms and performance are governed by complex interactions between adsorbent properties, contaminant characteristics, and operational conditions. A thorough understanding of these factors is essential for designing efficient adsorption-based systems for produced water treatment using agricultural waste–derived adsorbents.

2.5 Conceptual Framework for Sustainable Produced Water Treatment

The growing volume and complexity of produced water generated by oil and gas operations necessitate treatment approaches that are not only technically effective but also environmentally and economically sustainable. A conceptual framework for sustainable produced water treatment using agricultural waste–derived adsorbents provides a structured pathway that integrates resource recovery, low-cost material development, and adaptable treatment configurations. This framework is designed to align with circular economy principles while addressing the operational realities of both onshore and offshore oil and gas facilities.

The framework architecture defines the system boundaries from agricultural waste generation to treated produced water discharge, reuse, or reinjection. Upstream boundaries include the sourcing of agricultural residues and their conversion into functional adsorbents, while downstream boundaries encompass treatment performance, waste minimization, and end-of-life management of spent materials. Within these boundaries, the framework emphasizes material flow efficiency, minimal energy consumption, and reduced environmental footprint. External factors such as regulatory requirements, local resource availability, and site-specific produced water characteristics are considered as contextual inputs that influence system design and operational decisions (Duru *et al*., 2015; Dale *et al*., 2016).

Stage 1 of the framework focuses on agricultural waste sourcing and pretreatment. This stage involves the identification and selection of suitable agricultural residues based on availability, consistency of supply, cost, and physicochemical properties. Common feedstocks include rice husks, coconut shells, maize cobs, sugarcane bagasse, and groundnut shells, which are widely generated in agrarian regions. Pretreatment processes such as washing, drying, size reduction, and removal of impurities are applied to enhance feedstock uniformity and improve subsequent adsorbent yield and performance. Efficient logistics and localized sourcing are emphasized to reduce transportation costs and associated emissions, thereby strengthening the sustainability of the overall system.

Stage 2 encompasses adsorbent synthesis and optimization. In this stage, pretreated agricultural waste is converted into adsorbent materials through physical activation, chemical activation, or thermochemical processes such as pyrolysis. Process parameters including temperature, activation time, and activating agents are optimized to achieve desired surface area, pore structure, and functional group distribution. Performance optimization is guided by target contaminant profiles in produced water, such as heavy metals, hydrocarbons, and dissolved organic compounds. Laboratory-scale characterization and adsorption studies inform material selection and processing conditions, ensuring that the synthesized adsorbents meet both performance and cost-effectiveness criteria.

Stage 3 involves the integration of agricultural waste–derived adsorbents into produced water treatment systems. This stage addresses system configuration and operational compatibility with existing oil and gas infrastructure. Batch treatment systems are suitable for small-scale operations or intermittent produced water flows, offering simplicity and ease of control. Continuous-flow configurations, such as fixed-bed or fluidized-bed columns, are more appropriate for large-scale and steady-state operations, providing consistent treatment performance and scalability. The framework also supports hybrid systems that combine adsorption with conventional treatment technologies, including gravity separation, flotation, membrane filtration, or advanced oxidation. In such systems, adsorption functions as a polishing or complementary step, enhancing overall contaminant removal while reducing the load on energy-intensive or chemically demanding processes.

Stage 4 addresses adsorbent regeneration, reuse, and end-of-life management, which are critical for long-term sustainability. Regeneration techniques such as thermal treatment, solvent washing, or chemical desorption are evaluated based on effectiveness, cost, and environmental impact. Reusable adsorbents reduce material consumption and operational costs, improving the economic viability of the treatment system. When regeneration is no longer feasible, environmentally responsible end-of-life options are considered, including incorporation into construction materials, controlled disposal, or energy recovery through combustion (Paterson *et al*., 2017; Yang *et al*., 2016). Special attention is given to the management of adsorbents containing concentrated contaminants to prevent secondary pollution.

This conceptual framework provides a holistic and adaptable approach to sustainable produced water treatment. By integrating agricultural waste valorization, optimized adsorbent development, flexible system design, and responsible end-of-life management, the framework offers a viable pathway for reducing environmental risks, lowering treatment costs, and supporting sustainable water management in oil and gas operations, particularly in resource-constrained and developing regions.

2.6 Sustainability and Lifecycle Considerations

Sustainability and lifecycle considerations are central to evaluating the long-term viability of produced water treatment systems based on agricultural waste–derived adsorbents. Beyond treatment efficiency, these systems must demonstrate reduced environmental impacts, efficient use of energy and materials, and measurable advantages over conventional adsorbents. A lifecycle-oriented perspective enables a comprehensive assessment of environmental performance from raw material sourcing through adsorbent production, use, regeneration, and end-of-life management.

Environmental impact assessment (EIA) provides a systematic approach for evaluating the potential ecological effects associated with agricultural waste–derived adsorbents. At the raw material stage, the use of agricultural residues as feedstock significantly lowers environmental burdens compared to virgin materials, as it avoids land-use change, mining, or deforestation. The diversion of residues from open burning or uncontrolled disposal reduces emissions of particulate matter, methane, and other pollutants. During adsorbent production, environmental impacts are primarily associated with energy consumption and, where applicable, chemical activation processes. These impacts can be mitigated through the use of low-temperature pyrolysis, renewable energy inputs, and recovery or reuse of activating agents. At the operational stage, adsorption-based treatment generates minimal secondary waste compared to chemical precipitation or membrane processes, further reducing environmental risk.

Energy and material efficiency are critical determinants of sustainability in produced water treatment systems. Agricultural waste–derived adsorbents typically require lower embodied energy than conventional activated carbons produced from coal or petroleum-based precursors. The utilization of locally available biomass reduces transportation energy and associated emissions, while decentralized production models enable flexible scaling. Material efficiency is enhanced through high adsorption capacity, which allows smaller quantities of adsorbent to achieve desired treatment outcomes. Additionally, the potential for adsorbent regeneration and reuse improves resource efficiency by extending material lifespan and reducing the demand for continuous production of new adsorbents (Ummartyotin and Pechyen, 2016; Zodrow *et al*., 2017).

Carbon footprint reduction represents a key advantage of agricultural waste–derived adsorbents. Lifecycle greenhouse gas emissions are generally lower due to the renewable nature of biomass feedstocks and the avoidance of energy-intensive extraction and processing associated with fossil-based adsorbents. In some cases, biochar-based adsorbents contribute to net carbon sequestration by stabilizing carbon that would otherwise decompose and release carbon dioxide or methane. Waste reduction benefits are also significant, as the conversion of agricultural residues into adsorbents transforms a disposal liability into a value-added product. This dual benefit addresses both waste management challenges and water pollution control, aligning with broader sustainability and climate mitigation goals.

When compared with conventional adsorbents, such as commercial activated carbon and synthetic resins, agricultural waste–derived adsorbents demonstrate several sustainability advantages. Conventional activated carbon production involves high-temperature activation of coal or petroleum coke, resulting in substantial energy consumption and carbon emissions. Synthetic adsorbents often rely on non-renewable feedstocks and complex manufacturing processes that generate chemical waste. In contrast, agricultural waste–derived materials utilize renewable feedstocks, simpler processing routes, and offer opportunities for localized production. Although conventional adsorbents may exhibit higher or more consistent adsorption capacities in some applications, the performance gap has narrowed considerably due to advances in biomass activation and surface functionalization techniques.

From a lifecycle cost perspective, agricultural waste–derived adsorbents are generally more economical, particularly in regions with abundant biomass resources. Lower raw material costs, reduced transportation requirements, and the potential for regeneration contribute to favorable cost profiles. Furthermore, the social and environmental co-benefits associated with agricultural waste valorization, such as rural employment and reduced environmental pollution, are not typically captured in conventional cost analyses but represent important sustainability considerations.

Sustainability and lifecycle assessments highlight the strong environmental and resource-efficiency advantages of agricultural waste–derived adsorbents for produced water treatment. Reduced environmental impacts, lower energy and material requirements, decreased carbon footprint, and effective waste reduction position these materials as compelling alternatives to conventional adsorbents (Schanes *et al*., 2016; Malakahmad *et al*., 2017). Incorporating lifecycle considerations into system design and decision-making strengthens the case for adopting sustainable adsorption-based technologies in produced water management, particularly in resource-constrained and environmentally sensitive contexts.

2.7 Techno-Economic and Scalability Assessment

The implementation of agricultural waste–derived adsorbents for produced water treatment must be evaluated not only in terms of technical performance but also through a techno-economic and scalability lens. Understanding cost implications, operational feasibility, and adaptability to varying production contexts is essential for translating laboratory-scale innovations into practical field-level and industrial solutions. A rigorous assessment ensures that sustainable water treatment technologies are both economically viable and operationally scalable, particularly in resource-constrained and developing regions.

Cost implications are a primary determinant of the feasibility of bio-based adsorbents. Agricultural residues, such as rice husks, coconut shells, maize cobs, sugarcane bagasse, and groundnut shells, are generally low-cost or freely available, representing a major advantage over conventional adsorbents like commercial activated carbon or synthetic resins. Costs associated with feedstock collection, preprocessing (e.g., drying, washing, size reduction), and transportation are minimal compared to energy-intensive conventional materials. However, the total cost of bio-based adsorbents also includes expenses related to activation, surface functionalization, and quality control. Physical activation processes may require high-temperature furnaces or pyrolysis units, which contribute to capital and operational expenditures, whereas chemical activation introduces the additional cost of reagents and neutralization or waste handling. Despite these costs, bio-based adsorbents often remain more economical due to the low raw material cost, potential for regeneration, and reduced energy and chemical demands relative to conventional options. Lifecycle cost analysis further demonstrates that the ability to regenerate and reuse adsorbents reduces the frequency of replacement, thereby improving cost-effectiveness over long-term operations.

Scalability is another critical consideration, encompassing the transition from laboratory experiments to field-level and industrial applications. Agricultural waste–derived adsorbents exhibit intrinsic scalability advantages because feedstocks are widely produced and often concentrated in specific agricultural regions. Modular production units can be deployed locally to convert residues into adsorbents on-site, minimizing logistics and enabling rapid response to production demands. For small- to medium-scale oil and gas operations, batch adsorption systems can be effectively implemented, offering flexibility and operational simplicity. Larger-scale and continuous-flow systems, such as fixed-bed columns or fluidized-bed reactors, are suitable for industrial applications where consistent treatment volumes are required. The modular nature of these configurations allows capacity expansion by adding additional units or beds, facilitating incremental scaling without major infrastructure overhaul. Hybrid system integration with conventional treatment technologies, such as hydrocyclones, flotation, or membrane filtration, further enhances scalability by enabling staged contaminant removal while optimizing overall system performance (Pontié and Charcosset, 2016; Konvensional, 2017).

The applicability of agricultural waste–derived adsorbents in resource-constrained and developing regions is particularly compelling. Many developing countries face challenges such as limited capital investment, unreliable energy supply, and inadequate wastewater management infrastructure. In these contexts, bio-based adsorbents offer a low-cost and locally sourced alternative that can be implemented with minimal energy input and limited technical expertise. Decentralized production and deployment reduce dependency on imported treatment media and enable local communities to participate in value-added agricultural waste utilization. This approach not only addresses water treatment challenges but also generates socio-economic benefits, including rural employment and the creation of small-scale enterprises focused on adsorbent production, regeneration, and maintenance. Furthermore, the low environmental footprint and alignment with circular economy principles make these systems attractive for regions seeking to comply with regulatory standards while minimizing ecological impact.

Techno-economic assessment must also consider operational parameters, including adsorption capacity, regeneration frequency, and maintenance requirements. Optimizing these factors enhances the cost-performance ratio and ensures that the treatment system remains viable under variable production conditions. For example, adsorbents with high adsorption efficiency reduce the quantity required per unit of produced water, decreasing both material and handling costs. Effective regeneration strategies further extend adsorbent life, reducing total operational expenditure. Sensitivity analyses in pilot studies can provide insight into the effects of feedstock price fluctuations, energy costs, and process modifications, enabling informed decision-making for scalable implementation.

Agricultural waste–derived adsorbents present a promising techno-economic solution for produced water treatment that balances low cost, performance, and scalability. Their ability to leverage abundant local feedstocks, integrate into modular and hybrid treatment systems, and provide value in resource-constrained settings positions them as practical and sustainable alternatives to conventional adsorbents. Comprehensive techno-economic and scalability assessments ensure that these systems are not only environmentally sustainable but also financially feasible and operationally adaptable, facilitating wider adoption across diverse industrial and field-level contexts (Thomassen *et al*., 2016; Mentis *et al*., 2016).

2.8 Socio-Economic and Policy Implications

The adoption of agricultural waste–derived adsorbents for produced water treatment extends beyond environmental and technical considerations, encompassing significant socio-economic and policy dimensions. By transforming agricultural residues into value-added products, this approach offers opportunities for local economic development, job creation, and alignment with regulatory frameworks and sustainability objectives. Understanding these implications is essential to facilitate broad adoption and long-term viability, particularly in developing and resource-constrained regions.

Local value creation is a primary socio-economic benefit of utilizing agricultural waste for adsorbent production. Agricultural residues, such as rice husks, coconut shells, maize cobs, sugarcane bagasse, and groundnut shells, are often underutilized or disposed of through open burning, landfilling, or uncontrolled decomposition. Converting these residues into functional adsorbents creates a tangible economic output from otherwise low-value biomass. Local farmers and cooperatives can supply feedstock, providing an additional income stream that complements traditional agricultural activities. The establishment of small-scale processing units for feedstock pretreatment, activation, and packaging further generates local business opportunities. By integrating agricultural waste into a circular economy framework, regions can retain economic value within the community while reducing environmental burdens associated with residue disposal (Sauvé *et al*., 2016; Iacovidou *et al*., 2017). Such value creation supports economic resilience and diversifies income sources for rural populations.

Employment opportunities associated with agricultural waste valorization extend across multiple stages of the production and treatment chain. Collection, transportation, and sorting of agricultural residues require labor, often creating seasonal or permanent jobs in rural areas. Production facilities for adsorbent synthesis, whether through pyrolysis, chemical activation, or physical activation, necessitate skilled and semi-skilled labor for operational management, quality control, and safety compliance. The deployment of adsorption-based produced water treatment systems in industrial or field-level contexts further generates employment in system installation, monitoring, maintenance, and regeneration of adsorbents. Community-based production models, where cooperatives or local enterprises manage feedstock supply and initial processing, empower local populations, stimulate economic activity, and promote knowledge transfer. This distributed model of production fosters local ownership and strengthens social acceptance of sustainable water treatment technologies.

Policy alignment is a critical factor for the successful adoption of agricultural waste–derived adsorbents. Regulatory frameworks for produced water management often specify limits on oil and grease content, total dissolved solids, heavy metals, and other contaminants prior to discharge or reuse. Incorporating bio-based adsorbents into treatment processes enables operators to achieve compliance with these standards while reducing reliance on chemical-intensive or energy-intensive conventional technologies. Additionally, national and international sustainability goals, including circular economy initiatives, waste minimization strategies, and climate change mitigation policies, support the integration of agricultural waste valorization into industrial processes. Policies promoting renewable resources, local manufacturing, and rural economic development can further incentivize adoption. For example, tax credits, grants, or low-interest loans for small-scale bio-based production units can accelerate technology deployment and strengthen economic and environmental outcomes.

Beyond compliance and incentives, policy considerations must also address the standardization and quality assurance of bio-based adsorbents. Regulatory agencies may require certification of adsorbent performance, particularly regarding adsorption capacity, contaminant removal efficiency, and environmental safety of spent materials. Establishing clear guidelines and performance benchmarks ensures that agricultural waste–derived adsorbents are both reliable and safe for produced water treatment applications. Policies that support research, innovation, and pilot-scale testing can facilitate the translation of laboratory-scale findings into practical field implementations, enhancing confidence among stakeholders, including oil and gas operators, regulators, and local communities.

Socio-economic benefits are further amplified when the approach aligns with broader sustainability objectives. The integration of agricultural waste valorization with produced water treatment addresses multiple challenges simultaneously: reducing environmental pollution, enhancing water quality, generating local employment, and promoting sustainable resource management. This multi-benefit approach resonates with national development priorities in many developing regions, where water scarcity, agricultural waste management, and rural poverty coexist as pressing issues. By framing agricultural waste–derived adsorbents as part of a systemic solution to environmental and socio-economic challenges, stakeholders can justify investment and policy support (Amrose *et al*., 2015; Suykens and van Rijswick, 2016).

The socio-economic and policy implications of adopting agricultural waste–derived adsorbents for produced water treatment are substantial. Local value creation, employment generation, and community-based production models provide tangible economic and social benefits, while alignment with regulatory and sustainability goals ensures environmental compliance and long-term viability. The integration of technical, economic, and policy dimensions reinforces the potential of this approach as a sustainable and scalable solution for produced water management. When supported by enabling policies and community engagement, agricultural waste–derived adsorbents can contribute meaningfully to both environmental stewardship and socio-economic development.

2.9 Research Gaps and Future Directions

While agricultural waste–derived adsorbents show significant promise for sustainable produced water treatment, several critical research gaps remain that must be addressed to enable their widespread adoption and long-term operational viability. Current studies are largely laboratory-based, focusing on fundamental adsorption performance under controlled conditions. To advance these materials from conceptual frameworks to practical field applications, pilot-scale testing, long-term performance evaluation, and integration with digital monitoring and optimization tools are essential. Addressing these research gaps will ensure that agricultural waste–derived adsorbents are not only effective but also economically and operationally sustainable across diverse oil and gas production contexts.

One of the most pressing research gaps is the need for pilot-scale and field validation. Laboratory studies often employ small volumes of produced water with simplified contaminant compositions, which may not accurately reflect the variability and complexity encountered in operational oil and gas sites. Produced water characteristics vary by reservoir geology, production method, chemical additives, and seasonal factors, potentially affecting adsorption efficiency. Pilot-scale studies that process larger volumes under realistic flow conditions, temperature fluctuations, and contaminant loads are essential to validate laboratory findings. Such studies can also identify practical challenges related to hydraulic management, pressure drop, fouling, and scaling within adsorbent columns or hybrid treatment systems. Field validation provides critical data on operational feasibility, durability of adsorbents under fluctuating water compositions, and integration challenges with existing treatment infrastructure, serving as a bridge between research and industrial deployment (Assouline *et al*., 2015; Mehta *et al*., 2015).

Long-term performance and regeneration studies represent another significant research gap. Most current investigations focus on single-use adsorption experiments, with limited assessment of adsorbent stability, capacity retention, and performance over multiple treatment cycles. Understanding the kinetics of adsorption–desorption processes over extended periods is crucial for estimating operational lifespans, maintenance schedules, and overall lifecycle costs. Regeneration strategies—including thermal treatment, solvent washing, or chemical desorption—require systematic evaluation to determine their efficiency, potential secondary environmental impacts, and influence on adsorbent structural integrity. Studies on the effects of repeated cycles of adsorption and regeneration on surface area, pore structure, and functional groups are particularly important to ensure consistent contaminant removal over time. Additionally, understanding the fate of adsorbed contaminants, particularly heavy metals and hydrocarbons, during regeneration is critical for safe end-of-life management and environmental compliance.

Integration with digital monitoring and optimization tools represents a forward-looking research direction that could enhance the performance, scalability, and adaptability of agricultural waste–derived adsorbent systems. Real-time monitoring of produced water parameters such as pH, turbidity, hydrocarbon concentration, and metal ion levels using sensors and Internet of Things (IoT) devices can provide continuous feedback on treatment efficiency. Coupling this data with predictive analytics and machine learning models enables dynamic optimization of operational parameters, including flow rate, contact time, and regeneration frequency. Digital tools can also facilitate predictive maintenance by detecting early signs of adsorbent saturation, fouling, or structural degradation, minimizing downtime and reducing operational costs. In addition, integrating digital decision-support systems can improve resource allocation, energy use, and process efficiency, particularly in remote or offshore oil and gas installations where manual monitoring is challenging.

Beyond these specific areas, broader research is needed to evaluate the techno-economic and socio-environmental impacts of large-scale deployment. Cost-benefit analyses comparing agricultural waste derived adsorbents to conventional treatment technologies under realistic field conditions are limited. Likewise, assessments of community engagement, local supply chain development, and environmental co-benefits including waste reduction, carbon footprint mitigation, and circular economy integration require further investigation. Comparative studies across different feedstocks, activation methods, and hybrid system configurations can identify optimal approaches tailored to specific geographic, economic, and regulatory contexts (Puigjaner *et al*., 2015; Milani *et al*., 2017).

Advancing agricultural waste–derived adsorbents from laboratory research to practical implementation requires addressing key knowledge gaps in pilot-scale validation, long-term performance, and digital integration. Field-scale testing will establish operational feasibility and robustness, while extended adsorption–regeneration studies will clarify lifecycle performance and cost-effectiveness. The incorporation of digital monitoring, predictive analytics, and optimization tools can further enhance system reliability, efficiency, and scalability. Together, these research directions provide a roadmap for transforming sustainable, bio-based adsorption technologies into reliable, economically viable, and environmentally responsible solutions for produced water management in the oil and gas industry (Isikgor and Becer, 2015; Bennich and Belyazid, 2017).

CONCLUSION

The conceptual framework for sustainable produced water treatment using agricultural waste–derived adsorbents provides a comprehensive and systematic approach for addressing one of the most pressing environmental challenges in oil and gas operations. By integrating principles of circular economy, resource valorization, and low-cost environmental remediation, the framework demonstrates how agricultural residues such as rice husks, coconut shells, maize cobs, sugarcane bagasse, and groundnut shells can be transformed into functional adsorbents. These materials are capable of removing a wide range of produced water contaminants, including heavy metals, hydrocarbons, and dissolved organic compounds, through mechanisms such as surface complexation, hydrophobic interactions, and pore entrapment. The framework's multi-stage architecture from feedstock sourcing and pretreatment, through adsorbent synthesis and optimization, to integration into batch or continuous-flow treatment systems and end-of-life management offers a structured roadmap for translating laboratory findings into operational systems.

Beyond technical contributions, the framework emphasizes sustainability and socio-economic value creation. By utilizing locally available biomass, it reduces environmental burdens associated with agricultural waste disposal, lowers the carbon footprint compared to conventional adsorbents, and promotes energy and material efficiency. The potential for adsorbent regeneration and reuse enhances economic feasibility, while localized production and treatment implementation create employment opportunities and stimulate rural enterprise development. Policy alignment with environmental regulations and circular economy objectives further strengthens the framework's applicability across diverse oil and gas production contexts.

Strategically, this conceptual framework provides a pathway for sustainable produced water management that balances environmental, economic, and operational considerations. It enables oil and gas operators, regulators, and local communities to implement low-cost, scalable, and environmentally responsible treatment solutions. Moreover, the framework supports future innovation through pilot-scale validation, long-term performance studies, and integration with digital monitoring and optimization tools, ensuring adaptability to evolving water treatment challenges. In essence, the framework represents a viable, circular, and sustainable strategy for mitigating the environmental impacts of produced water while delivering tangible socio-economic benefits.

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