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The Role of Technological Innovations in Improving Oil Extraction Efficiency in South Sudan

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ABSTRACT

Purpose: The purpose of this study was to explore the role of technological innovations in improving oil extraction efficiency in South Sudan, with a specific focus on recovery rates, operational costs, reservoir management, and real-time data accuracy.

Methodology: In the research, a descriptive methodology was used to find out the effect of the contributing factors on the oil production results.

Findings: Results show that EOR methods, such as reactive injection of water (CW), clearly increase the recovery yield, and reactive injection of gas (GE) technologies obviously enhance the recovery efficiency and the energy security. Further, real-time information systems and modern reservoir management techniques facilitate better decision-making, more efficient production activities and are also scarcity-reducing. Nonetheless, development of South Sudan's oil sector is constrained by the presence of outdated infrastructure, lack of technical ability and insufficient funding for technology.

Unique Contribution to Theory, Practice and Policy: The conclusion reached from the study is that these innovations are necessary to help with maximizing resource use, to help with cost reduction and to enable sustainable development in the country's oil industry. Target areas of advice include giving importance to EOR methods, incorporating real-time data technology, and developing technical capacity to modernise the South Sudan oil industry.

Keywords: *Technological Innovations, Oil Extraction Efficiency*

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INTRODUCTION

BACKGROUND TO THE STUDY

For more than one century the oil extraction industry has been the major pillar of global energy supply and the main driver of contemporary economic development and industrial development, and dramatically influencing the direction of the social lives all over the world (Ezechi & Muda, 2019). Since its inception, oil has been a critical driver of the industrial revolution, fuelling innovations in transportation, manufacturing, and agriculture, and providing the energy necessary to power factories, machinery, and vehicles that have become integral to modern life (Xu et al., 2018). Its impact extends far beyond energy production; oil has facilitated the globalization of trade by powering ships, trains, and airplanes that transport goods and people across continents, creating interconnected economies and cultural exchanges (Masitah et al., 2022). In addition, oil served as the cornerstone for the creation of petrochemicals, the building blocks for a wide range of industries producing plastics, drugs, animal feed, and synthetic materials that form the basis of consumer goods. With the industrialization and urbanization of nations, oil dependence has increased and has, therefore, become an importance and backbone of economic stability and prosperity (Abdul-Hamid et al., 2022). Li and Alharthi (2023) asserted that the vast revenues generated from oil production and exportation have fuelled the development of infrastructure, healthcare, and education in many oil-rich nations, positioning oil as a transformative economic force. Furthermore, the strategic importance of oil has profoundly influenced geopolitical landscapes, driving alliances, conflicts, and policies aimed at securing access to this vital resource (Solano-Rodríguez et al., 2021). Since the birth of OPEC to regulate production and subsequent pricing, to the geopolitical competition among countries for energy security, oil has determined the pattern of global power and political relations (Olopade et al., 2019). In parallel, the growth of the industry has been far from unproblematic, as criticism regarding environmental damage and its role in climate change has been levied against it, leading to calls for innovation and sustainability within the industry. Although these are challenges that there is, the oil extraction industry continues to be a crucial part of the global energy landscape, its importance still evident by its contribution to powering industrial societies and providing comforts of modern life. The profound impact of oil over the last 100 years of energy production underlines the key role of oil beyond its energy contribution, as an enmeshed part of energy production for economic, social, and political realms of global society, a main pillar of progress, yet it is also a topic of ongoing innovation (Ikhsan Cholil, 2022).

The oil extraction industry has been one of the main engines for economy-scale industrialization and societal change supporting technologies in various industries and defining modern civilization (Domingues et al., 2020). Domingues et al. (2022) pointed out that oil has driven the growth of heavy industries (steel, automotive, aircraft), all of which underpin the manufacture of vital goods and services, and hence global trade and commerce. Its energy has driven factories and mass production, and set the stage for international web of supply chains, which increase trade and promote economic interdependency (Sun et al., 2018). In addition to being a fuel, oil and its derivatives have been found to be irreplaceable for the numerous applications, which has led to transformations in the industry of healthcare, agriculture and consumer goods. Plastics, derived from petroleum, are omnipresent in daily life, forming the basis of products ranging from packaging to medical devices like syringes and diagnostic tools, which are vital for modern healthcare systems (Eliche-Quesada et al., 2015). In turn, oil-based fertilizers have contributed to the transformation of agriculture, leading to increased crop yields and to provide food for the increasing population in this manner, offsetting mitigating significant challenges to food security (Ouadrhiri et al., 2023). In the consumer goods sector, chemical compounds derived from oil have spurred the development of diverse products such as detergents, cosmetics, clothing, and electronics, significantly improving the quality of life (Geow et al., 2021). In transportation and aviation, oil has made it possible to connect distant regions, facilitating the movement of people and goods, promoting cultural exchanges, and strengthening global economic ties. Its function in assisting military operations and humanitarian aid also highlights its strategic significance, as it offers the fuel to enable rapid response to crises and emergencies. Afzainizam et al. (2016) claimed this amazing universality points to the transformative role of oil in various dimensions of the human experience, which prepares it to be much more than just a power source, becoming a fundamental driver for innovation, development, and hence global advancement. Its profound influence on industries, economies, and societies underscores its indispensability while simultaneously posing challenges that demand thoughtful strategies for sustainable use in the future (Perone et al., 2022).

The historical and current importance of the oil extraction industry goes far beyond that of an energy supplier. It has been a major catalyst for the development of global infrastructure, enabling the construction of roads, pipelines, ports, and refineries that serve as the foundation of modern economies (Paul & Radhakrishnan, 2020). The strong supply chains in this sector have connected oil-producing areas with the whole world, promoting economic integration, and enabling the flow of goods and services across the globe (Witter et al., 2014). Silvamany et al. (2021) further noted that this interconnectedness enabled urbanization and expansion of metropolitan areas, and cities in oil-rich countries often becoming the economic powerhouses. In addition, oil revenues have supported major national development projects, setting up industrialised infrastructure, energy grids, and transport systems essential in delivering sustainable development (Manasseh et al., 2023). This way, the oil industry has served in a crucial way not only in the industrialisation but also in the capacity of government to promote the development and the uplifting of their populations' lives.

Furthermore, the oil sector has played a seminal role in driving the tech advances that shape everyday life (Cascio & Narayan, 2020). Advanced drilling methods (hydraulic fracturing and horizontal drilling) now allow the ability to access hydrocarbons in difficult environments, shale formations (Plata et al., 2019) and deep-sea reservoirs. These developments have provided the platform for the continuing supply of oil, and for the energy industry to comply with ever-increasing demands on the global energy supply. In addition, the oil waste has transformed several sectors into new materials, such as synthetic fibers, lubricants, and medicaments that are at the core of everyday life (Smeu et al., 2022). The energy and technology improvements that brought about aviation, space travel, and rapid transport are deeply indebted to the oil sector. Through relentless advances of science and engineering, the oil extraction industry has not only retained its importance, but also provided the context for the wider technological progress with lasting impact on the current global landscape (O'Callaghan-Gordo et al., 2016).

From an economic viewpoint, the oil industry has been one of the major wealth generators and economic unifiers, especially in oil-exporting countries. The funds generated by the sale of oil captured by the country have allowed governments to commit to the development of infrastructure and healthcare services, educational programs and other essential areas, thus enhancing the quality of life of millions of people (Kaikade Sabnis, 2022). Regions rich in oil resources have become global economic hubs, attracting foreign investments and fostering international partnerships (Kangasluoma, 2021). This economic activity has not only created jobs directly within the industry but also stimulated growth in related sectors such as construction, logistics, and financial services.

Moreover, Hassani et al. (2017) has argued that the oil and gas extraction sector has been the driving force of geopolitics, driving international relations and trade practices. The significance of oil in the strategic sense has resulted in the formation of trade agreements, alliances and partnerships which have consolidated the global economy (Bricout et al., 2022). Van De Graaf et al. (2020) stressed that nations with abundant oil reserves have wielded considerable influence on the global stage, leveraging their resources to negotiate favourable terms in economic and political affairs.

TECHNOLOGICAL INNOVATIONS IN THE OIL AND GAS INDUSTRY

Throughout decades, technological advancements have been a disruptive power in oil production industry, responding to the challenges brought by dwindling conventional oil reserves and increasing need of energy (Rong & Qamruzzaman, 2022). These developments have made it possible not only to maintain, but to considerably improve the scale of production (Jiao et al., 2021). Perhaps the most revolutionary achievement has been in the field of Enhanced Oil Recovery (EOR) technologies, the way in which oil is extracted from reservoirs changed drastically (Sircar et al., 2021). Using thermal recovery, chemical injection, and gas injection, EOR has made it possible for producers to access unrecoverable oil, increasing an before-EOR recovery rate from low as 20-40% to high as 60% of the total oil content in the reservoir (Gbadamosi et al., 2022). This dramatic enhancement has given a new life cycle to oil production's economics, making even marginal or declining oil fields able to be valuable assets.

Wang et al. (2022) claimed that thermal recovery, one of the key EOR techniques, involves the use of heat to reduce the viscosity of heavy oils, making them easier to extract. Steam injection, one of the most employed methods of thermal recovery, is especially successful in extracting the heavy oil resources and tar sand resources (Dong et al., 2020). In contrast, chemical injection uses surfactants, polymers or alkalis to modify the chemical nature of the oil and to

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enhance its flow performance in the reservoir (Nowrouzi et al., 2021). This technique has also been shown to be very beneficial in improving the sweep efficiency of water flooding applications. Gas injection, which involves the use of gases like CO_2 or nitrogen, not only boosts reservoir pressure but also improves oil displacement by reducing interfacial tension (Du & Nojabaei, 2019). Taken together, these approaches form a paradigm change in the oil recovery field and it is now possible to recover oil from increasingly challenging geological structures.

In addition to EOR, the emergence of horizontal drilling has pushed the oil industry to the next level of efficiency and productivity (Ziaie et al., 2023). Su et al. (2023) claimed that in contrast to what one would normally do with conventional vertical drilling, by using horizontal drilling producers are able to tap into a greater amount of the reservoir by drilling horizontally across the oil-saturated formations. This technique maximizes the contact area between the wellbore and the reservoir, significantly increasing the volume of oil that can be recovered. Horizontal drilling is game changer for accessing unconventional resources (e.g., shale oil and tight oil reservoir) that were thought to be nonviable with their poor permeability (Khan et al., 2021). When producers can effectively use such resources, horizontal drilling has made it possible to access enormous new reserves and extend the use of known oil fields.

Similarly, hydraulic fracturing, commonly referred to as fracking, has revolutionized the way oil and gas are extracted from tight geological formations (Li et al., 2015). This method uses the high-pressure injection of fluid into the intact rock to induce fractures that form conduits in the rock for oil and gas to flow to the wellbore (Chen et al., 2021). Hydraulic fracturing, when used in conjunction with horizontal drilling has been an effective key for unlocking large reserves of shale oil and gas, especially on areas like the US (Guo et al., 2022). The integration of these technologies has reversed the U.S. from oil importer country to oil producing country, illustrating the overwhelming effect that innovation brings to nation energy independence and global market.

These technological advances have, in turn, enabled the industry to look at and produce oil from challenging conditions. Deep-sea reserves, which were once inaccessible due to technological limitations, are now being tapped using advanced drilling techniques and robust offshore platforms (Baco et al., 2016). Oil removal extraction from these reservoirs, often 1-2,000 m deep beneath the ocean surface, has been made possible by technology advancement in offshore subsea equipment, robots, and real-time monitoring systems (Thilakarathna et al., 2022). Such advancements have expanded the industry's reach into previously untapped territories, significantly boosting global oil reserves.

Finally, these innovations reflect the industry's broader commitment to adapting to a rapidly changing energy landscape. By continually investing in research and development, oil companies have demonstrated their ability to overcome technical and economic challenges while meeting the world's growing energy demands. The confluence of EOR, horizontal drilling, and hydraulic fracturing is a foundation for modern oil production and allows for this essential resource to be sustained and optimized in terms of efficiency and sustainability. While these technologies are maturing, their contribution to the future of the oil extraction industry is ultimate.

In summary, the oil extraction industry has been a fundamental pillar of global economic and industrial growth, with its impacts reverberating across numerous sectors and regions. Its roles in energy supply, wealth creation, technological innovation, and international specialization have secured for it a central role in current development, implying that it possesses no equal claim in the moulding of the world order.

PROBLEM STATEMENT

Although South Sudan is endowed with considerable oil reserves, it still suffers from significant challenges in fully exploiting the performance potential of its oil extraction systems (International Monetary Fund, 2020). The country's oil sector has long been based on conventional extraction techniques, which are inefficient and do not recover much of the remaining reserves (International Monetary Fund, 2020). These legacy approaches, combined with aging infrastructure, a lack of technical capability, and geopolitical turmoil, have led to poor oil recovery rates, which prevent the industry from fulfilling its potential to provide economic growth and development. Furthermore, environmental issues in relation to wasteful extraction processes, including oil spills and greenhouse gas emissions, have added to the difficulty, jeopardizing regional ecosystems and human health.

Technological advances can be beneficial for maximizing the efficiency of oil production worldwide by enabling the access to technical and marginal oil fields with a minimal amount of waste and operational costs (Zulqarnain et al., 2021). Nevertheless, in South Sudan, the translation of and adaptation to advanced methods within the field of petroleum such as Enhanced Oil Recovery (EOR) technologies, horizontal drilling, hydraulic fracturing, and digital monitoring systems has been minimal because of a shortage of investment, a lack of supporting infrastructure, and a lack of access to the very latest developments in technologies (Ali, 2022). These constraints do not allow the country to grasp the full potential of its natural resources to attain sustainable economic development.

The issue is further exacerbated by fluctuating global oil prices, which place additional pressure on South Sudan's economy to optimize its oil production processes (Chanie, 2021). If extraction efficiency is not dramatically improved, the country is in danger of losing its place in the global oil market. In addition, because the world is moving towards cleaner energy, it becomes imperative for South Sudan to modernise its oil sector, so production processes not only are outstandingly efficient, but are also, if possible, environmentally sustainable. Failure to deal with these problems could bring about economic decline, higher dependence on external aid, and aggravate environmental harm.

Whilst many studies document world-wide gains in oil extraction, a local context analysis of the economic, infrastructural, and socio-political circumstances that influence South Sudan ability to deploy these technologies efficiently is largely missing. This absence of empirical literature not only prevents the development of evidence-based policies, but also leaves unresolved important questions about the practical feasibility, scalability, and sustainability of applying high levels of oil extraction technologies to the South Sudanese environment. The situation is further aggravated by the variable world oil prices that at the same time put a heavier burden on the South Sudanese economy for making its oil production efficient. Without a major improvement in the efficiency of the extraction process, the country could lose its competitive advantage in the global oil market. Additionally, with the world moving toward cleaner energy, there is a pressing need for South Sudan to enter the 21st century for the oil industry by making sure the production processes are not only productive but also environmentally clean. Failure to deal with these challenges has the potential to lead to economic inefficiency, growing reliance on external aid and worsening environmental conditions. This paper aims to fill this important knowledge void by investigating the impact of technological advancements in enhancing oil production effectiveness in South Sudan. Through the identification of the obstacles to technological adoption and the evaluation of the potential consequences of noble extraction technologies, this thesis intends to provide useful information on how South Sudan can improve the efficiency, competition, and sustainability of its oil industry under changing economic and environmental pressures.

GENERAL RESEARCH OBJECTIVE

The general objective of this study is to investigate the role of technological innovations in oil extraction in South Sudan.

SPECIFIC RESEARCH OBJECTIVES

This study's specific research objectives are:

1. To establish the effect of recovery rates in oil extraction in South Sudan.
2. To identify the effect of operational costs in oil extraction in South Sudan.
3. To determine the effect of reservoir management in oil extraction in South Sudan.
4. To examine the effect of real-time data accuracy in oil extraction in South Sudan.

RESEARCH QUESTIONS

1. What is the effect of recovery rates on oil extraction efficiency in South Sudan?
2. How do operational costs influence oil extraction efficiency in South Sudan?
3. What is the impact of reservoir management practices on oil extraction efficiency in South Sudan?
4. How does real-time data accuracy affect oil extraction efficiency in South Sudan?

SCOPE OF THE STUDY

The current study is cantered on the study of technological innovations of oil extraction efficiency in South Sudan. Among others, the paper explores the effects of some of the most important factors including recovery rates, operational costs, reservoir management regimes, and the quality of real-time data in determining the performance and sustainability of oil recovery processes. The work is restricted to extraction industry of oil in South Sudan, based on its specific difficulties such as outmoded infrastructure and low use of cutting-edge technologies, as well as environmental.

The research takes into account both qualitative and quantitative data sources, both drawing from qualitative and quantitative information from industry experts, policy papers, and published work as part of modelling the barriers to and the potential for technological adoption within the country. Temporal aspect includes the latest and recent developments of oil extraction technologies and a special attention is given to their relevance to socio-economic and infrastructural context of South Sudan.

Geographically, this study is restricted to oil producing areas of South Sudan, so that the results are applicable in a direct way to the South Sudanese oil industry. Yet, (2) the paper also draws upon global best practice in order to propose practical recommendations for how to increase the efficiency of oil extraction. The results are expected to be of utility to policymakers, industry stakeholders, and academics as evidence-informed approaches to optimize the performance of the oil sector while addressing economic, environmental and technical concerns.

LITERATURE REVIEW

THEORETICAL FRAMEWORK

RESOURCE OPTIMIZATION THEORY

Resource Optimization Theory argues that achieving optimal use of existing resources is essential for achieving optimal productivity, sustainability, and profitability in all fields (Dai & Xiao, 2018). Underlying this model is the premise that resources, physical, financial, and human, are scarce and need to be carefully managed to use them as effectively as possible. The theory in the field of industrial production regards this as a key notion, namely, the vital role is to use those sophisticated tools, techniques, and technologies to reduce the waste, improve the efficiency, and produce as much output possible. Organizations can overcome underperformance and changes in operational needs by adopting innovations, which in turn allow the improvement of current and future resource streams. The theory further points out the need of a structured design scheme for allocation of resources, focusing on processes and technologies that can deliver the best return of investments meanwhile enjoying a light environmental footprint (Li & Zhao, 2022). This systemic view prompts industries to not just aim for short-term gains, but also for long-term sustainability and resilience, to tie resource management to the larger economic and environmental purposes.

Additionally, Resource Optimization Theory highlights the important role of technological invention in the transformation of unexploited inaccessible resources (Ravishankar et al., 2021). For example, in extractive industries such as oil production, the theory posits that innovative technologies like Enhanced Oil Recovery (EOR) methods, horizontal drilling, and real-time data analytics are key to increasing resource efficiency. These technologies enable operators to tap into previously considered economically prohibitive reserves, help to recover greater fractions of currently existing reservoirs, and minimize operational inefficiencies.

Furthermore, the model emphasizes the interaction between resource efficiency and cost control, proposing the implementation of the systems which minimize production costs while maximizing the recovery rate and quality control (Bui & Thel al., 2023). It offers a priori basis for industries claim that investment in innovation should be justified as a solution to challenges associated with the scarcity of resources, the increasing operational costs, and strict environmental laws.

Resource Optimization Theory is of enormous interest to this work in that it offers a holistic context within which to consider the consequences of technological innovation in boosting oil extraction efficiency in South Sudan. By focusing on strategic management of resources, the theory integrates with the problems that South Sudan's oil sector has to deal with, like low recovery rates, wet technology, and high operating costs. Applying this theory helps to conceptualize how advanced technologies can unlock the country's untapped oil reserves, enhance the efficiency of extraction processes, and reduce wastage. To exemplify, EOR methods and digital monitoring systems can be framed by the paradigm of resource efficiency, the objectives of the methods are to obtain the best possible yield from current oil reservoirs with minimum environmental costs and operational expenses.

The theory further highlights the need to find a right balance between economic and environmental ones, a point that matters to South Sudan, as it requires at the same time both to achieve economic growth and to reduce the ecological hazards resulting from oil exploitation. Using the parameters of Resource Optimization Theory, this work aims to pinpoint those technologies and practices which will be most effective in enabling South Sudan to reach those targets. In addition, the theory offers a systematic way to analyze the way in which technological innovations could change the oil sector and suggests entry points in terms of the ranking and introduction of resource optimisation strategies suitable to the socio-economic and infrastructural peculiarities of the country. In the end, such a theory application allows a better explanation of the way in which oil reserves of South Sudan can be used in a sustainable and efficient way to fuel long-term development.

TECHNOLOGY ACCEPTANCE MODEL

The Technology Acceptance Model (TAM) posits that the successful adoption and utilization of new technologies are primarily influenced by two key factors: perceived usefulness and perceived ease of use (Aburbeian et al., 2022). Perceived usefulness refers to the degree to which a user believes that a specific technology will enhance their performance or efficiency, while perceived ease of use relates to the effort required to adopt and use the technology effectively. TAM asserts that these perceptions directly influence users' attitudes toward a technology, shaping their intention to adopt and actual usage behaviour (Park & Park, 2020). The model emphasizes that the perceived benefits of a technology must outweigh the challenges associated with its implementation for users to accept it fully. Furthermore, TAM suggests that external variables such as organizational culture, user training, and support systems play a critical role in shaping these perceptions, highlighting the importance of contextual and environmental factors in technology adoption (Berakon et al., 2021).

In addition to these foundational assertions, TAM expands on the interplay between individual and organizational factors in technology acceptance. It argues that the alignment between technological capabilities and organizational needs significantly impacts the likelihood of successful implementation (Zaineldeen et al., 2020). The model also introduces behavioural intentions as an intermediary between users' attitudes and actual technology use, recognizing that intention serves as a strong predictor of adoption. TAM further asserts that ongoing user experiences can reshape initial perceptions, underscoring the importance of iterative feedback and adaptation in fostering long-term acceptance (Ilyas et al., 2023). In industries such as oil extraction, TAM highlights the need for integrating user-centric approaches in technology deployment, ensuring that tools are not only effective but also accessible and user-friendly for operators and decision-makers (Alnemer, 2022).

The Technology Acceptance Model is directly applicable to this study as it provides a theoretical lens to examine the factors influencing the adoption of technological innovations in South Sudan's oil industry. Given the challenges faced by the sector, including limited technical expertise and resistance to change, TAM helps to identify the underlying reasons why certain technologies are embraced or rejected by stakeholders. By analyzing perceptions of usefulness and ease of use, this study can explore how advanced technologies, such as Enhanced Oil Recovery (EOR) methods, real-time data analytics, and automated drilling systems, are viewed by operators and decision-makers in the South Sudanese context. The model also facilitates an understanding of the barriers to technology adoption, such as inadequate training, lack of awareness, or concerns over cost and implementation complexity.

TAM's emphasis on external variables, such as organizational support and infrastructure, is particularly relevant to South Sudan, where the oil industry faces systemic challenges like outdated facilities and limited investment in capacity building. By applying TAM, this study can assess how these external factors shape perceptions and influence the decision-making process regarding the adoption of innovative technologies. Furthermore, TAM provides insights into how behavioral intentions can be cultivated through targeted interventions, such as education, training programs, and demonstration projects, to promote acceptance and effective utilization of new technologies. Ultimately, the application of TAM in this study enables a nuanced analysis of the human and organizational dimensions of technology adoption, offering strategies to align technological innovations with the needs and capacities of South Sudan's oil sector for improved efficiency and sustainability.

EMPIRICAL LITERATURE

RECOVERY RATES AND OIL EXTRACTION

Technological innovations have played a key role in improving recovery rates in oil recovery, as supported by a number of studies detailing their transformative effect on the industry. Massarweh and Abushaikha (2020) examined how some EOR technologies can help improve production rate recovery rates, pointing out that thermal, chemical flooding and gas injection technologies have made it possible to deliver an extra up to 60% of oil reserves recovered (as opposed to 20-30% that remained recoverable using primary and secondary recovery strategies). They also discussed the effectiveness of these methods in the context of mature oil fields, where conventional methods are inadequate to extract further resources. Similarly, Schneider et al. (2023) addressed the chemical EOR and showed enhancing the oil´s mobility both in the chemical EOR solution and in the recovered oil in the reservoir, as well as how the increasing displacement efficiency in chemical EOR solution could lead to better recovery in conventional and unconventional reservoirs. Sheng's work also highlighted with the flexibility of chemical EOR in different geological formations, it has become the basis of contemporary recovery methods. In a related study, Pothula et al. (2023) examined the cost-effectiveness of thermal recovery methods, particularly steam injection, in heavy oil fields. Pothula et al. found that while initial investments in thermal recovery are high, the long-term benefits in terms of increased recovery rates and extended field lifespan justify the expenditure, positioning it as a viable solution for resource optimization.

Beyond EOR, drilling technology innovation has also been contributory to an increase in rates of recovery. Negin et al. (2016) also presented a thorough description of the methods used in horizontal drilling, illustrating how this method increases the contact surface of the wellbore in contact with the reservoir, thus promoting better rates of oil flow and recovery. Negin et al's evidence showed that horizontal drilling is most effective in very low permeability, tight reservoirs and when they are not suitable to traditional vertical drilling strategies. Mohan and Kumar (2019) studied the combination of hydraulic fracture and horizontal drilling and showed that the combination can allow the extraction of oil from shale reservoirs and other unconventional resources. Their study showed the complementarity between these technologies for increasing recovery rates at a lower number of wells. In addition, Udoh (2021) studied the application of CO_2 injection in EOR as an approach to increase the oil recovery and carbon emission reduction at one and the same time. Their study showed that CO_2 injection improves recovery rates by reducing oil viscosity and increasing reservoir pressure, making it a dual-purpose solution with environmental and economic benefits.

The studies demonstrated why technological innovations play a key role in improving recovery rates in oil extraction, and demonstrate their applicability in a variety of reservoir types and geological problems. The integration of advanced techniques such as EOR, horizontal drilling, and hydraulic fracturing has not only improved resource efficiency but also extended the productive life of oil fields, ensuring a steady supply of oil in the face of declining conventional reserves. By drawing on global best practices and technological advancements, these insights provide a foundation for exploring how such innovations can be effectively implemented in contexts like South Sudan, where the potential for resource optimization remains largely untapped.

OPERATIONAL COSTS AND OIL EXTRACTION

Operational cost is an important factor affecting the efficiency and profitability of oil extraction process. High operating costs, a result of the combination of out-of-date equipment, labour bottlenecks, and energy-consuming procedures, can be a major constraint of production efficiency and the overall economic soundness of oil fields. Technological advancements have demonstrated some potential to reduce these costs. According to Cheng et al. (2021), advancements in automation, digital monitoring technologies and optimized drilling methods have played a central role in improving operational workflows, minimizing downtime, and minimizing energy use. These developments simplify processes, which allow companies not only to produce more oil at less cost, which is especially important in price-sensitive market segments. Furthermore, Gao et al. (2023) placed a strong emphasis on how predictive maintenance technologies can be used to reduce the failure of equipment and unplanned\ stoppages to reduce costs. The adoption of cost-savings technologies aims at increasing oil producer's both efficiency and profitability, despite depressed oil market price levels for specific situations.

RESERVOIR MANAGEMENT AND OIL EXTRACTION

Efficient reservoir management is one of the big pillars for maximum recovery of oil and continuous exploitation of resources. Reservoir management is a process of continually monitoring the performance of the reservoir, planning the extraction process, and controlling the reservoir pressure to maximise oil production. Modern technology, based on real-time reservoir simulation, geophysical imaging, and integrated reservoir management systems, has changed irreversibly the way reservoirs are studied and used. As described by Mwaurah et al. (2019) these technologies provide a more precise insight into reservoir dynamics and allow operators to create focused extraction strategies to optimize production rates. Moreover, Modupalli et al. (2022) also noted that digital twin technology—that is, an on-line model of the reservoir—facilitates decision making by modelling the extraction event in near real-time. Good reservoir management is not just to increase the recovery rates but also how long the oil field can be productive, which is one of the key points of efficient oil extraction.

REAL-TIME DATA ACCURACY AND OIL EXTRACTION

Real-time data accuracy plays a crucial role in the optimization of oil extraction processes, as an effective interaction enables the optimization of decision making, operational efficiency and resources to be applied. Real-time data technologies and devices (e.g., high-performance sensors, IoT devices, and data analytics platforms) enable operators to accurately monitor reservoir conditions, equipment performance and environmental conditions. According to Garofalo et al. (2020) By the amendment of accurate real-time data, operational agility is improved over time, with a consecutive result namely the capacity to rapidly react to unanticipated variation in the behaviour of a reservoir or the behaviour of its equipment). This leads to waste reduction, reduced downtime and optimized extraction rates. In addition, Rani et al. (2021) proved that real-time data analytics enhance the reliability of predictive models, which in turn enable more accurate prediction and planning in oilfield operations. Using high fidelity real-time data, oil companies are able to derive intelligent decisions that lead to increased recovery efficiency, cost reductions, and reduced environmental risk and therefore represents an important part of contemporary oil extraction schemes.

CONCEPTUAL FRAMEWORK

The proposed conceptual framework describes the association among independent variables recovery rates, operational costs, reservoir management, and real-time accuracy of data with the dependent variable-oil production. This framework offers a systematic method for the study of the interplay of such dominant factors in oil extraction process efficiency and effectiveness. By examining each variable and its associated indicators, the framework highlights the multidimensional nature of oil extraction, offering a comprehensive lens to understand and improve the industry's performance.

The oil recovery ratio, residual oil saturation, and recovery efficiency. These indicators are based on the capacity of an extraction process to optimize available resources and to minimize losses, and can be used to understand how technologies, e.g., enhanced oil recovery (EOR) methods, can be utilised to enhance performance. High recovery rates are essential for ensuring the economic viability of oil fields and extending their productive lifespan.

Operational costs are also a significant independent variable comprising the cost per barrel produced, maintenance costs, and energy costs, etc. These indices characterize the financial efficiency of oil extraction operations, and their implications on the overall level of profitability. The framework highlights the need to implement low-cost technologies and operational strategies to minimize costs but to preserve or improve extraction efficiency. Efficient cost management is of paramount importance in settings such as South Sudan, where economic and infrastructural limitations make the oil sector difficult.

Reservoir management is emphasized as one key strategy with potential to maximize oil production. Performance metrics including reservoir pressure and water-to-oil ratio, and reservoir performance monitoring capture the success of strategies applied in reservoir management and maximization of recovery. The framework indicates that sophisticated instruments and methods such as digital supervision and reservoir simulation are crucial for improving the performance of the reservoir and thus guaranteeing sustainable use of the resource.

In the end, the essentiality of real-time data quality is revealed as one of the crucial enablers of effectively oil production. Indicators such as sensor precision, data latency, and forecasting accuracy illustrate the role of accurate, timely data in informing operational decisions. Having exploited real-time data technology operators are able to increase responsiveness, decrease inefficiencies and manage recovery in the best possible way. The inclusion of real-time data accuracy in the framework highlights the importance of integrating digital solutions into traditional oil extraction practices.

In general, the framework connects these predictor variables to the dependent variable, oil extraction, in terms of daily production level, well productivity and production decline rate as shown in figure 1. This interaction highlights why enhanced recovery, operational, reservoir, and real-time data accuracy all contribute to the effectiveness, sustainability, and profitability of oil production systems as a group. The framework offers strong base for analysis and

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solution of issues in the oil industry, in resource rich but underdeveloped regions such as South Sudan.

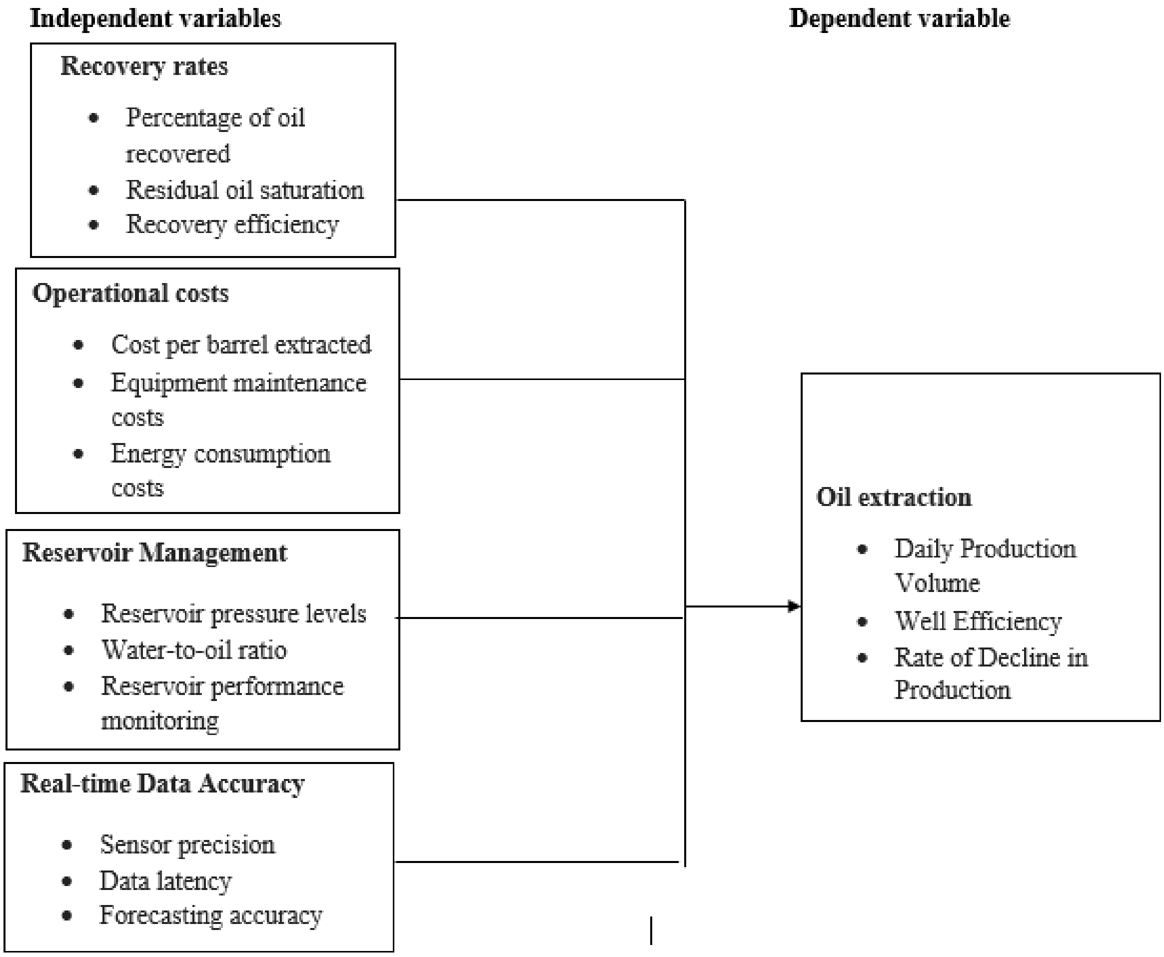

Figure 1: ***Conceptual Framework***

Source: Researcher's Conceptualization (2025)

RESEARCH METHODOLOGY

RESEARCH DESIGN

The study adopted a descriptive research design to systematically analyse the role of technological innovations in oil extraction efficiency. This design, using a secondary data approach, facilitated the synthesis and evaluation of existing quantitative and qualitative data from various credible sources. The descriptive design was chosen to allow for an in-depth examination of the relationships between technological innovations and key indicators such as recovery rates, operational costs, reservoir management, and real-time data accuracy.

By employing a descriptive research design and relying on secondary data sources, this study provided a robust framework for analysing the role of technological innovations in improving oil extraction efficiency in South Sudan. The methodology ensured the reliability and validity of the findings while drawing on a broad range of existing knowledge.

DATA COLLECTION METHODS

The study relied exclusively on secondary data collection methods. Data was gathered from a variety of credible sources, including academic journals, government documents, oil industry reports, and relevant case studies. This approach focused on materials with specific relevance to the study objectives, including studies addressing recovery rates, operational costs, reservoir management practices, and real-time data technologies. These materials were accessed through online academic databases, institutional repositories, and official websites. These sources were selected to provide comprehensive insights into the practical challenges, opportunities, and impacts of technological innovations in the oil sector. Secondary data collection allowed the study to draw on a broad base of pre-existing knowledge and insights, ensuring comprehensive coverage of the research topic. Priority was given to peer-reviewed articles, official reports, and credible industry publications to ensure data reliability.

DATA ANALYSIS

The collected secondary data was analysed using content analysis and descriptive statistics. Content analysis was applied to identify patterns, themes, and relationships in the data related to recovery rates, operational costs, reservoir management, and real-time data accuracy. Descriptive statistical tools were used to synthesize numerical data from the secondary sources, facilitating a quantitative understanding of the impact of technological innovations on oil extraction efficiency. This approach allowed for the systematic integration of qualitative and quantitative findings to meet the study objectives.

ETHICAL CONSIDERATIONS

Ethical principles were upheld throughout the study. All secondary data sources were properly cited to acknowledge the original authors and ensure intellectual property rights were respected. The study adhered to academic integrity standards by using data from credible and authorized sources, avoiding any form of plagiarism or misuse of information.

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RESULTS AND DISCUSSION

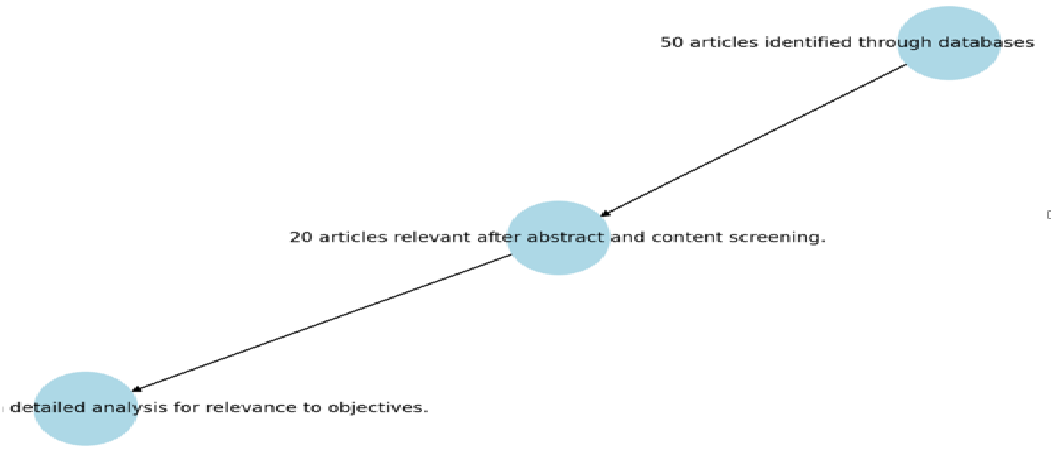

Figure 2: ***ARTICLE SELECTION PROCESSES***

Source: Researcher (2025)

Figure 2 above illustrates the article selection process for this study:

1. Initial Search: 50 articles were identified through databases and industry reports.
2. Relevance Screening: 20 articles were deemed relevant after abstract and content screening.
3. Final Selection: 3 articles were selected after a detailed analysis for alignment with the study objectives.

This stepwise approach ensured that only the most relevant and high-quality articles were included in the final analysis.

RESULTS

STUDY 1: ABDALRAHEEM ET AL. (2022)

The present study examined the impact of Enhanced Oil Recovery (EOR) methods, covering steam flood, CO2-promoted steam flood, and cyclic steam stimulation, in Sudan's FUL Oilfield. The results show that continuous steam flooding provides the highest oil saturations among tested approaches. While CO_2-assisted steam flooding showed a reduction in water cut, its impact on the oil recovery factor was minimal, contributing only a small incremental improvement in recovery. This highlights the superior efficiency of continuous steam flooding as a standalone method for heavy oil extraction in similar reservoirs.

STUDY 2: KOTENEV ET AL. (2018)

This study explored the use of gas injection as an energy-efficient technology for improving oil recovery. Oil recovery by 8–10% was achieved by gas injection, representing a major (further) advancement in resource recovery. Besides, the combination of underground gas storage gas not only improved the oil recovery rates, but also improved energy security, as it is an essential reserve of energy for future energy demand. These findings underscore the dual benefits of gas injection, addressing both recovery efficiency and broader energy management challenges.

STUDY 3: ASSAVANIVES ET AL. (2023)

This study introduced an innovative approach to improving oil production and operational efficiency through the use of real-time flowline simulations in S1 flowline networks. Results indicate that the employment of real-time data driven optimized production could lead to a possible 10 % decrease in production pressure, subsequently enabling a production increase of 3 840 barrel/d. This shows the utility of real-time data technology for the optimization of production processes and the overall performance of oil production processes.

DISCUSSION

Results from these studies, working together, highlight the revolutionary role that technological advancements have brought about in the efficiency of oil extraction. Abdalraheem et al. (2022) stress the need of selecting the optimal EOR practices for particular geological and reservoir characteristics. Due to the superior performance of continuous steam flooding, thermal recovery is likely one of the most efficient mechanisms for heavy oil reservoirs, particularly for high viscosity oil reservoirs. Nevertheless, such a small effect of CO2- promoted steam flooding indicates that technology integration should take into account reservoir properties, so as to avoid a waste of benefits. In the case of South Sudan, where similar heavy oil reservoirs exist, this data suggests using continuous steam flooding could be a realistic and effective competitive recovery solution.

Kotenev et al. (2018) explain the great promise of gas injection with respect to increasing oil recovery yields while responding to energy security issues. The 8%–10% increase in recovery rates obtained by using gas injection highlights its usefulness as a complementary gas injection, in particular, when conventional primary and secondary recovery methods have been exhausted. Moreover, the added benefit of underground gas storage suggests that this approach could contribute to strategic energy management in South Sudan, where energy infrastructure is underdeveloped. These results suggest in favour of a consideration, of gas injection, in a coupled oil production and energy management approach of the type.

Finally, Assavanives et al. (2023) show the important contribution of real-time data-driven technologies in oil production optimization. Through the deployment of a 10% pressure drop that enabled a 3,840 barrels/day increase in production, the paper shows the role that real-time flowline simulations can play in maintaining high operational efficiency and minimizing losses. In the context of South Sudan, where technical and operational difficulties are everyday occurrences, the implementation of similar technologies may well result in a substantial increase in production rate and cost efficiency. This is consistent with the overall aim of the study of using state-of-the-art applications to solve problems for oil producers in resource limited settings.

In conclusion, the findings from these studies reinforce the importance of technological innovation in improving oil extraction efficiency. By way of the acceptance of sophisticated EOR techniques, gas injection technologies, or real-time data analytics, these innovations have the capacity to change oil production activities in South Sudan. Through combining these methods, the country can overcome the inefficiencies, fully utilize the resources and promote the development of oil industry's sustainability in the country.

CONCLUSION AND RECOMMENDATIONS

CONCLUSION

The current research investigated the significance of technological advancements to increase oil recovery efficiency in the Republic of South Sudan, focusing on recovery rates, operational costs, reservoir management, and the validity of real-time data. Results highlight that IT applications are crucial in solving the performance bottlenecks that currently constrain the performance of South Sudan's oil sector. Enhanced Oil Recovery (EOR) via steam flooding, for example, has been shown to be a successful means of boosting the recovery factor, thus, representing a practical option for South Sudan heavy oil reservoirs. Also, gas injection technologies have been used to enhance oil recovery and ensure operational efficiency. Overall, the combination of real-time data-enabled systems and novel reservoir management techniques has been found to increase decision-making, increase production accuracy, and decrease losses. The paper shows that implementation of these innovations has the capability of drastically changing South Sudan's oil extraction industry by improving resource use, reducing operational costs and by bringing sustainability practice. Yet, the country is confronted with a broad range of challenges, such as the obsolete infrastructure, the lack of technical knowledge, and the insufficient financial support to technology development, making it critical to overcome these challenges in order to realize the full potential of technological innovations. In summary, this work lays the groundwork to understand the key factors that determine oil extraction efficiency, and offers some clarity to how the economy of South Sudan can be restructured to foster long-term sustainability and competitiveness in the oil industry.

RECCOMENDATIONS

To enhance recovery rates through EOR techniques, South Sudan should give special attention to introduction of enhanced oil recovery (EOR) techniques, including continuous steam flooding, to improve the oil recovery rate in heavy oil reservoirs. Feasibility studies should be performed to evaluate the applicability of other state-of-the-art techniques, e.g., CO_2-enhanced EOR, in those cases where water cut and reservoir conditions are extremely difficult to handle. However, to reduce operational costs through technological integration, cost reducing technology investments, including automated monitoring and economizing hardware, are a critical step in reducing cost per barrel extracted. Government and oil companies must work together to bring predictive maintenance technologies to the marketplace to reduce equipment failures and unanticipated downtime. In addition, in order to improve reservoir management practices, it is better to manage the performance of the reservoir, state-of-the-art reservoir management methods, including digital twin technology and real-time reservoir modelling should be implemented. Such practices have a potential for enhancing reservoir pressure control, water-to-oil ratio control, and the recovery efficiency. Training programmes are highly recommended to make operators capable of using these technologies in an optimal way. Likewise in leveraging real-time data for accurate decision-making, the implementation of real-time data technologies, such as flowline simulations and IoT-enabled devices, should be given priority to improve the fidelity and alacrity of oil extraction processes. Such systems can have a positive impact on accuracy modeling, minimization of operational, and planning of production strategies, consequently, it can lead to higher efficiency and resource optimization. Nevertheless, building technical capacity and infrastructure such as capacity development must be pursued to overcome the existing technical skill deficiency in the oil sector. Relationships with international organizations, research institutes, and technology vendors need to be established to educate and introduce new practices. Further, it will be important to have infrastructure improvements, digital systems, and pipeline networks to underpin technological advances. Promoting policy and investment frameworks is key. The authorities should make favorable policies to encourage foreign and domestic investment in oil extraction technologies. Incentives such as tax breaks and public-private partnerships can promote innovation while creating conditions favourable to the incorporation of technologies. Last but not least, fostering environmental sustainability is core. In order to comply with international environmental regulations, carbon capture and storage (CCS) should be introduced in oil extraction operations in South Sudan adopting environmentally sustainable technologies. These measures will help reduce emissions and environmental degradation while promoting sustainable development in the oil sector. Through the adoption of these recommendations, South Sudan will be able to increase the productivity of its oil extraction, improve economic performance, and guarantee the viability of its oil industry. With these steps it will be possible to achieve the best possible use of this country's natural resources and make it a commercially competitive actor in the global energy market, as well as to take environmental issues into account.

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