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A Case Study on the Treatment of Phenolic Wastewater from an Inland Natural Gas Field Using a Trickling Biofilter

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Abstract

Phenolic wastewater generated during natural gas recovery poses serious environmental challenges, requiring efficient and economical treatment solutions. This work documents a field case study on the performance of a lava rock-packed trickling biofilter for treating phenolic wastewater from a natural gas field. The system was seeded with municipal activated sludge and acclimated for one month before operation. Its performance was evaluated at varying empty bed residence times (EBRTs) and influent pH values, with a focus on chemical oxygen demand (COD) and phenol removal. Results showed that increasing EBRT improved treatment efficiency. For COD removal, efficiency reached up to 88% (554 to 65 mg/L) at 19 min EBRT. For phenol removal (tested in a separate run), removal exceeded 98% (9.5 to 0.146 mg/L) at the longest EBRT tested, 14.4 min. COD profiles along the filter depth indicated active biodegradation throughout the trickling biofilter, while performance remained stable across a broad pH range (2.5–9.1), with COD and phenol removal efficiencies of 72–88% and 84–92%, respectively. These findings highlight the robustness of trickling biofilters in handling variable wastewater conditions without the need for external nutrient supplementation. Overall, this study supports the view that trickling biofilters can be a cost-effective, low-maintenance, and sustainable option for treating phenolic wastewater from natural gas recovery operations.

1. Introduction

The process of natural gas recovery from inland gas fields generates a substantial volume of phenolic wastewater. The untreated discharge of this wastewater can lead to significant environmental pollution, including toxicity to aquatic life and contamination of soil and groundwater. Consequently, developing cost-effective and efficient treatment methods for phenolic wastewater has become an important focus of environmental research. Among various approaches, biological treatment methods have been shown to be particularly effective in degrading phenolic compounds and other hydrocarbons present in such wastewaters. These methods offer advantages such as lower operational costs and environmental sustainability compared to conventional physical or chemical treatments. Continued research is needed to optimize biological processes for large-scale applications and to improve their efficiency under varying wastewater compositions and environmental conditions (Pradeep *et al.*, 2015).

Treatment of phenolic wastewater has been extensively studied due to its environmental significance and the challenges involved. Jou and Huang (2003) employed a fixed film bioreactor for treating oil refinery wastewater using polyurethane cubes as the support medium. The system operated with a hydraulic retention time (HRT) of 8 hours, and the wastewater was supplemented with nitrogen, sulfur, and phosphorus to prevent nutrient limitation for microbial growth. Aeration maintained dissolved oxygen at approximately 2 mg/L. Influent chemical oxygen demand (COD) and phenol concentrations were about 500 mg/L and 30 mg/L, respectively. Under these conditions, the bioreactor achieved approximately 80% removal of influent COD and nearly complete removal of phenol, demonstrating the efficiency of fixed-film biological treatment for phenolic compounds.

Dargahi *et al.* (2017) investigated the removal of phenol from oil refinery wastewater using an anaerobic stabilization pond, and optimized the process through response surface methodology. Experiments based on a central composite design examined the effects of phenol concentration (200–400 mg/L), temperature (8–24°C), and hydraulic retention time (HRT, 2–5 days) on treatment efficiency. Results showed that optimal conditions—200 mg/L phenol, 24°C, and 2–5 days HRT—achieved maximum phenol removal efficiencies of 70.53%–81.63% and COD removal efficiency of around 69%.

Sequencing batch reactors have been widely applied for the treatment of phenolic wastewaters. Mousavi *et al.*

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(2010) investigated the performance of an aerobic granular sequencing batch reactor for treating saline wastewater containing high concentrations of phenol. The study evaluated the effects of influent phenol concentration (100–2000 mg/L), cycle time (14–24 h), and total dissolved solids (3–8%) on chemical oxygen demand and phenol removal efficiency. Results showed that the reactor could remove more than 99% of phenol at inlet concentrations up to 1,000 mg/L, with effective COD reduction and mineralization under optimal conditions. The granular biomass demonstrated strong resistance to phenol shock and excellent settling properties, indicating that the aerobic granular sequencing batch reactor system provides an efficient and flexible biological process for the treatment of phenol-laden saline wastewater.

Al Hashemi *et al.* (2014) conducted a study on the characterization and removal of phenolic compounds from condensate-oil refinery wastewater. Treatment of the wastewater using a sequencing batch reactor achieved an average phenol removal efficiency of approximately 98%. Frank *et al.* (2017) investigated the co-treatment of oil and gas produced water and municipal wastewater using a pilot-scale hybrid sequencing batch reactor-membrane bioreactor to explore a cost-effective alternative to disposal. At a 6% produced water fraction, the system effectively removed chemical oxygen demand, ammonia, trace organics, and inorganic contaminants.

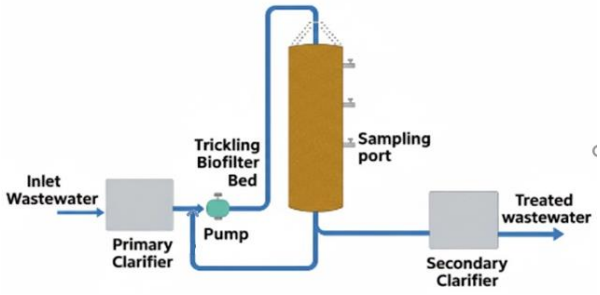
Various methods have been suggested for gas field wastewaters. Wang *et al. (2019)* investigated the treatment of mother liquor from gas field wastewater using the electro-Fenton process with added H_2O_2. Using Fe–Fe electrodes, the authors examined the influence of initial pH on COD removal efficiency, energy and electrode consumption, and the underlying removal mechanisms. Results showed optimal performance at pH 3, achieving a maximum COD removal of 71.9% within 3 h, with low energy (4.7 kWh/kg COD) and electrode (0.82 kg Fe/kg COD) consumption. Wei *et al.* (2020) investigated the treatment of high-concentration oil and gas field wastewater using a coupled sequencing batch reactor and ceramic membrane bioreactor. The system effectively reduced COD from 20,000–76,000 mg/L and oil concentrations from 600–2,200 mg/L to below 250 mg/L and 2 mg/L, respectively.

Wastewater generated during natural gas recovery typically contains a variety of organic pollutants, including phenolic compounds, as well as significant concentrations of dissolved salts. The focus of this research is the biological treatment of such phenolic wastewater. Although many studies have demonstrated the effectiveness of biological processes for treating phenolic wastewaters, these investigations have been largely limited to laboratory-scale experiments conducted under tightly controlled conditions with synthetic or idealized wastewaters (Jou & Huang, 2003; Mousavi *et al.*, 2010; Dargahi *et al.*, 2017). Furthermore, the limited field-scale studies that do exist have primarily focused on produced water from conventional oil extraction, rather than the specific wastewater generated during natural gas recovery operations, which presents distinct compositional characteristics—including varying salinity, hydrocarbon profiles, and seasonal fluctuations in flow and quality (Wei *et al.*, 2020). In contrast, there is a notable lack of published data on the performance of biofilm-based systems under actual field conditions for gas field phenolic wastewater, where variations in pH, organic loading, and hydraulic conditions pose additional challenges not replicable in laboratory settings. This gap is significant because laboratory findings often fail to translate directly to field applications due to differences in wastewater complexity, microbial community dynamics, and operational constraints. To address this gap, the present study provides a pilot-scale investigation of a trickling biofilter packed with lava rock media for the treatment of real phenolic wastewater from a natural gas field.

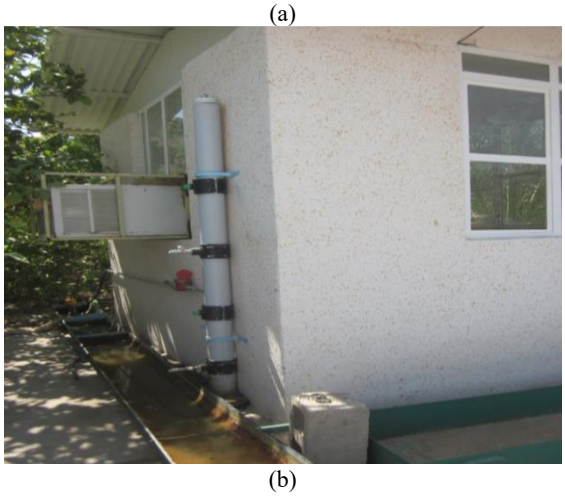
2. Materials and Methods

2.1. Experimental Setup

A PVC column with a height of 2 m and an internal diameter of 11 cm, packed with lava rock media, was used as the trickling biofilter. The average diameter of the lava rock particles was 2.5 cm. Four sampling ports were installed along the column height at 50 cm intervals. A trough with a length of 5.5 m and a diameter of 60 cm was employed as the primary clarifier to remove floating hydrocarbons from the wastewater before it entered the trickling biofilter. The effluent from the trickling biofilter was directed to a rectangular secondary clarifier (0.2 m × 0.5 m × 2 m) to separate suspended solids from the treated wastewater. The pretreated wastewater from the primary clarifier was pumped to the top of the trickling biofilter and distributed over the lava rock media using a distributor. Figure 1 shows a schematic and a photo of the system.



(a)



(b)

Figure 1. (a) Schematic of the System and (b) Photo of the Trickling Biofilter

2.2. Wastewater

During the course of this study, the primary clarifier was continuously fed with phenolic wastewater sourced from an inland natural gas field. The operating facility conducts routine analyses of the wastewater, which exhibits some variability in its characteristics. A representative analysis obtained from the industry is presented in Table 1. For this study, however, only COD and phenol concentrations were measured independently to assess the performance of the trickling biofilter.

2.3. Operational conditions

The trickling biofilter was operated under field conditions at the natural gas production site. Wastewater was distributed continuously over the top of the packing and allowed to percolate downward by gravity. A 25% recycle ratio of the effluent was maintained throughout the experiments, with the exception of the acclimation period, during which total recycling was applied.

The empty bed residence time (EBRT) was varied between 9.5 and 19 min by adjusting the influent flow rate using a clock valve. Based on the column dimensions (height 2 m, internal diameter 11 cm), the corresponding flow rates were approximately 1.0, 1.5, and 2.0 L min^{-1}. The hydraulic loading rate ranged from 6.3 to 12.6 $m^3 m^{-2} h^{-1}$. The organic loading rate (OLR) based on influent COD ranged from 35.6 to 92.1 kg COD m^{-3} day^{-1}, while the OLR based on phenol ranged from 0.72 to 1.15 kg phenol m^{-3} day^{-1}. Here, EBRT is defined as the empty bed volume of the trickling biofilter divided by the influent flow rate, representing the theoretical hydraulic retention time in the absence of packing. The hydraulic loading rate (HRT) is the volumetric flow rate per unit cross-sectional area of the reactor. The organic loading rate (OLR) is the mass of organic substrate (COD or phenol) applied per unit reactor volume per day, reflecting the organic load imposed on the microbial community. Temperature was not actively controlled, as the study aimed to evaluate system performance under realistic field conditions. The ambient temperature during the experimental period ranged from approximately 20 to 25°C. The influent wastewater had a dissolved oxygen concentration of approximately 8.5 mg L^{-1} (Table 1), and aeration was achieved passively through natural draft in the open-top column. No forced aeration was applied, consistent with the low-maintenance design of trickling biofilter systems.

2.4. Experiments

To develop the trickling biofilter, the column was initially filled with 10 L of activated sludge obtained from a municipal wastewater treatment plant and phenolic wastewater from a natural gas field. The mixture fully covered the lava rock packing and was left in the column for one month (acclimation phase) to allow for biofilm development.

Following this acclimation phase, the performance of the trickling biofilter was evaluated under various operating conditions. In the first series of experiments, the capacity of the trickling biofilter to reduce the chemical oxygen demand (COD) of the wastewater was assessed as a function of the empty bed residence time (EBRT). In the second series, phenol removal efficiency was examined under different EBRTs.

Additional experiments were conducted to monitor COD profiles along the height of the biofilter at three EBRT values. Finally, the effect of influent pH on the performance of the trickling biofilter was investigated. For all experiments, steady-state conditions were ensured by allowing sufficient time between operational adjustments and sample collection. Once steady state was achieved, six samples were collected from the sampling ports at one-hour intervals. Samples from each port were combined and analyzed in the laboratory for COD and phenol concentrations.

2.5. COD and Phenol Quantification

COD was quantified using the closed reflux method (APHA, 2012), and phenol was measured using the USEPA 4-aminoantipyrine method (USEPA, 1983). All analyses were performed by the laboratory staff at the gas field facility.

Table 1. A Representative Analysis of the Wastewater Treated in this Study.

Parameter	Unit	Value	Parameter	Unit	Value
pH	-	7.15	Nitrate (NO_3)	mg L^{-1}	23.8
EC	µs/cm	1166	Phosphate	mg L^{-1}	0.1
Turbidity	NTU	20	TPH	mg L^{-1}	21
TSS	mg L^{-1}	110	Cyanide	mg L^{-1}	ND
TDS	mg L^{-1}	757	Ammonium	mg L^{-1}	0.61
Settleable Solids	mg L^{-1}	0.09	Sodium (Na)	mg L^{-1}	80.5
Formaldehyde	µg L^{-1}	208	Potassium	mg L^{-1}	1.95
Fluoride	mg L^{-1}	1.87	Metals (Total)	mg L^{-1}	200
Nitrite (NO_2)	mg L^{-1}	0.36	Chloride (Cl)	mg L^{-1}	144
COD	mg L^{-1}	525	Sulfide (SH_2)	µg L^{-1}	ND
BOD	mg L^{-1}	292	Sulfate (SO_4)	mg L^{-1}	48
ABS	mg L^{-1}	0.246	Dissolved Oxygen (DO)	mg L^{-1}	8.5
Calcium (Ca)	mg L^{-1}	84	Phenol	mg L^{-1}	1.9
Iron (Fe)	mg L^{-1}	0.35	Oil	mg L^{-1}	1
Copper	mg L^{-1}	ND	Magnesium	mg L^{-1}	19
Cadmium	mg L^{-1}	ND	Mercury	mg L^{-1}	ND
Chromium	mg L^{-1}	0.14			
Lead (Pb)	mg L^{-1}	ND			

While independent replication of measurements was not performed due to field constraints, the laboratory's routine quality control procedures have verified that the coefficient of variation for both COD and phenol measurements is consistently <5%. This level of analytical precision supports the reliability of the reported data.

3. Results and Discussion

Figure 2 illustrates the relationship between empty bed residence time (EBRT) and COD removal in the trickling biofilter. As expected, increasing the EBRT led to a decrease in effluent COD concentration. At the longest EBRT tested (17.6 min), the effluent COD was reduced to 55 mg/L from an influent value of 470 mg/L, corresponding to a removal efficiency of approximately 88%. Even at a relatively short EBRT of 9.6 min, the system achieved substantial COD reduction, lowering the concentration from 441 mg/L to 194 mg/L.

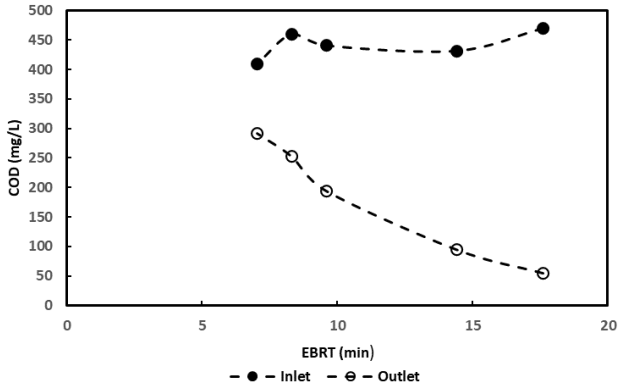


Figure 2. COD removal in the trickling biofilter as a function of EBRT

The improved performance at longer EBRTs can be attributed to extended contact time between the wastewater and the biofilm, enhancing substrate diffusion and microbial degradation processes (Davis, 2010). At high EBRTs, the applied COD loading rate remains below the bioreactor's maximum biodegradation capacity, allowing effective removal. At short EBRTs, the sharply increased loading rate overwhelms the finite intrinsic reaction rate of the biofilm. The system becomes reaction-rate-limited, meaning the biomass cannot degrade the substrate as fast as it is supplied, leading to the observed rise in effluent COD. This indicates that the overall performance is governed by the saturation of microbial kinetics under high hydraulic loading rather than by diffusional constraints.

Many hydrocarbons present in natural gas field wastewaters, particularly oxygenated compounds, are known to be readily biodegradable (Semple *et al.*, 2001; Rittmann & McCarty, 2001; Tuan *et al.*, 2011). The analysis of the raw wastewater (Table 1) confirms that the wastewater contains sufficient nutrients (e.g., N = NH_4^+ + NO_3^- + NO_2^- ≈ 24.8 mg/L as N, P = 0.1 mg/L as PO_4) to support microbial growth, justifying our decision not to add external nutrients This simplifies operation and reduces costs. The table also shows high BOD concentration, indicating that the wastewater is readily biodegradable. Similar findings have been reported in previous studies on the biological treatment of phenolic and hydrocarbon-laden wastewaters (Bai *et al.*, 2021). Camarillo and Stringfellow (2018) reviewed recent publications on biological treatment of oil and gas produced water, and highlighted that hydrocarbon-rich wastewaters can be efficiently treated in biofilm-based systems without external nutrient addition when nutrient levels are sufficient.

Figure 3 shows phenol removal from the wastewater in the trickling biofilter as a function of EBRT. The results indicate highly efficient phenol removal in the trickling biofilter. At the highest EBRT tested (14.4 min), with an influent phenol concentration of 9.5 mg/L, the biofilter achieved more than 98% removal, reducing the effluent concentration to 0.146 mg/L. Even at a shorter EBRT of 9.6 min, removal remained substantial, with phenol reduced from 7.6 mg/L to 0.836 mg/L. These results indicate that at longer EBRTs, the phenol loading rate remains well below the trickling biofilter's biodegradation capacity, allowing the biofilm to almost completely degrade the influent phenol. At shorter EBRTs, the loading rate increases but still falls within the maximum substrate utilization rate of the phenol-degrading microbial consortium. This suggests that the biofilm possesses a high specific affinity for phenol, and the trickling biofilter's kinetic capacity for phenol is not saturated within the tested EBRT range.

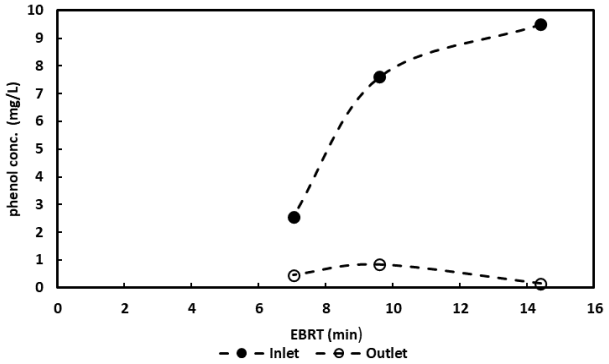


Figure 3. Phenol removal in the trickling biofilter as a function of EBRT

This high removal efficiency can be attributed to the initial seeding of the trickling biofilter with activated sludge, which provides a diverse microbial community capable of degrading a broad range of organic compounds. Furthermore, the one-month acclimation period allowed the microbial population to adapt to phenolic wastewater, enhancing their phenol-degrading activity. Acclimated biofilms in fixed-film systems can rapidly metabolize phenol, even at relatively high loading rates, due to the induction of specialized phenol-degrading enzymes. The acclimation of activated sludge to degrade phenolic compounds has been verified by Lim *et al.* (2013). Nakhli *et al.* (2014) reported that biofilm-based systems, particularly those acclimated to phenolic and aromatic compounds, maintain high degradation rates even under fluctuating influent concentrations. These studies highlight the importance of microbial acclimation and biofilm development in achieving efficient phenol removal

in trickling biofilter systems. Although biofilm establishment was not directly monitored through quantitative biomass measurements or microscopic analysis, successful biofilm development was inferred from the achievement of stable and reproducible COD and phenol removal performance following the one-month acclimation period. Figure 4 presents the COD profiles along the depth of the trickling biofilter at three different EBRTs (19 min, 12.7 min, and 9.5 min). In all cases, a gradual decrease in COD concentration was observed along the height of the column. At the longest EBRT (19 min), COD decreased from 554 mg/L at the inlet to 65 mg/L at the outlet, while at the shortest EBRT (9.5 min), the COD reduction was less pronounced, from 608 mg/L to 192 mg/L. The observed COD gradient along the biofilter depth indicates the presence of active biofilm throughout the column. As the wastewater percolates downward, the attached microbial communities progressively metabolize phenolic compounds and other biodegradable organics, resulting in gradual COD reduction along the filter depth. Large removal at higher EBRTs reflects the enhanced contact time, which facilitates substrate–biofilm interactions and allows for more effective degradation.

Figure 5 illustrates the influence of influent pH on the effluent COD and phenol concentrations of the trickling biofilter. Under highly acidic conditions (pH 2.5), COD decreased from 650 mg/L to 185 mg/L and phenol from 4.0 mg/L to 0.51 mg/L.

At near-neutral pH 7.5, the system achieved its best performance, reducing COD from 470 mg/L to 55 mg/L and phenol from 6.8 mg/L to 0.75 mg/L. Even at alkaline conditions (pH 9.1), COD was reduced from 643 mg/L to 148 mg/L and phenol from 4.7 mg/L to 0.61 mg/L. These results correspond to overall removal efficiencies of 72–88% for COD and 84–92% for phenol.

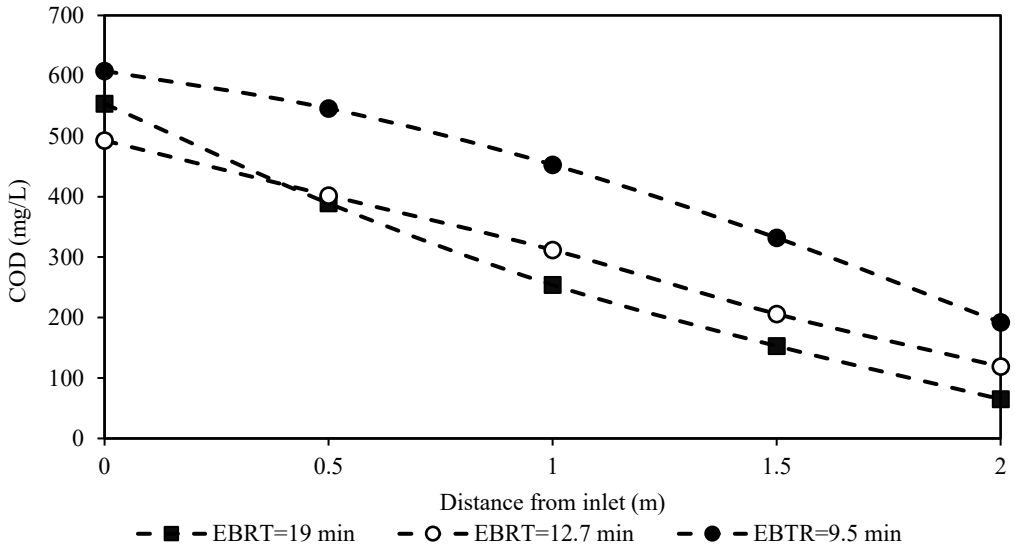


Figure 4. COD profile along the height of the trickling biofilter.

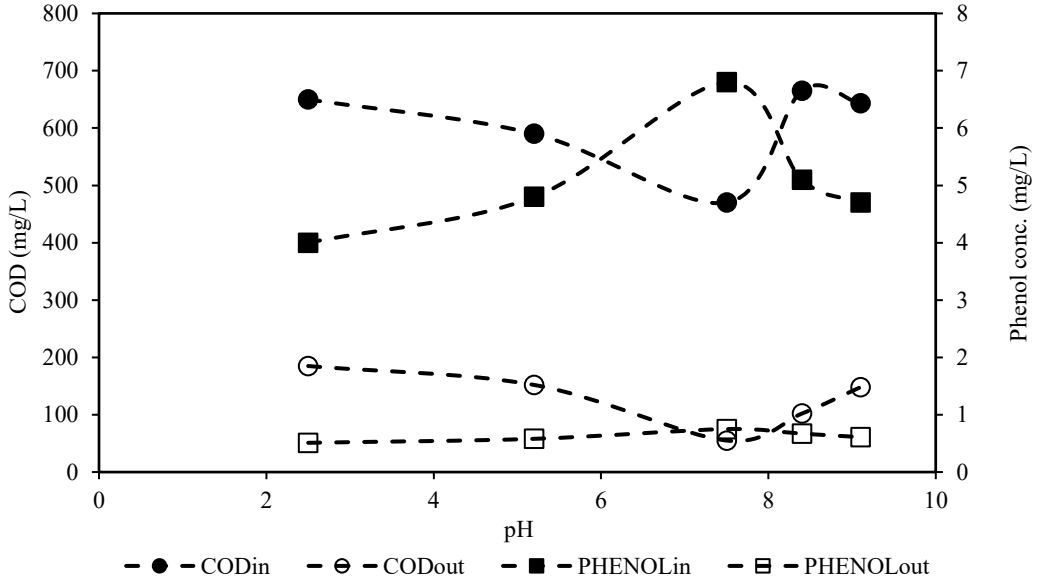


Figure 5. COD and phenol removal for the wastewater as a function of pH, EBRT=9.5 min.

The biofilter therefore maintained notable removal efficiency across a wide range of inlet pH values, with optimal performance near neutrality. Although substantial removal was observed even at extreme pH levels, such results likely reflect the ability of the biofilm to buffer its microenvironment rather than true microbial activity under bulk pH 2.5 or 9.1. Biofilms are known to create localized pH gradients through diffusion limitation and metabolic buffering (Tran *et al.*, 2024), which can protect embedded microorganisms from rapid or severe pH fluctuations. Similar observations have been reported in other biofilm-based systems that retain organic-matter removal under moderate pH shocks (Zhou, 2018). Further investigation of the biofilm's internal pH profile and microbial community structure would help clarify the mechanisms underlying the apparent robustness of this system. The ability of lava rock as a packing material to neutralize (to some extent) the influent acidic wastewater could explain the resilience of the trickling biofilter under severe acidic conditions. The performance of the lava rock-packed trickling biofilter in this field study compares favorably with general performance benchmarks reported for biological treatment systems. For COD removal, well-operated biofilm-based systems typically achieve efficiencies ranging from 60% to 88% (Tchobanoglous *et al.*, 2014), and the present system attained the upper end of this range (88%) at an EBRT of 19 minutes. For phenol removal, trickling biofilters and other biofilm reactors have been documented to achieve removal efficiencies exceeding 95% under optimized conditions (Zhou & Nemati, 2018; Banerjee & Ghoshal, 2010), with some systems reaching 97–99.9% in specialized packed-bed configurations. The high phenol removal (98%) achieved in this study at 14.4 minutes of EBRT is therefore consistent with the highest tier of reported performance. While many laboratory-scale systems require nutrient supplementation and extended hydraulic retention times to achieve such results, the present system operated at substantially shorter retention times and without external nutrient addition. This distinction is particularly significant given that field-scale wastewater treatment often faces constraints related to space, energy, and operational complexity. Overall, these comparisons confirm that the lava rock trickling biofilter performs at the highest tier of reported capabilities while offering the practical advantages of low maintenance, passive aeration, and nutrient self-sufficiency, making it a viable and sustainable option for treating phenolic wastewater from natural gas recovery operations.

While the results of this field study demonstrate the efficacy of the lava rock-packed trickling biofilter for phenolic wastewater treatment, several operational limitations merit consideration for full-scale implementation. Biofilm-based systems are inherently susceptible to biomass accumulation and clogging over extended operation, particularly when treating wastewater with high suspended solids content. Excessive biofilm growth can reduce void spaces, promote hydraulic channeling, and diminish treatment efficiency by creating preferential flow paths that bypass active biofilm zones. Although no clogging or channeling was observed during the relatively short experimental period of this study, long-term performance monitoring under continuous field operation would be necessary to evaluate biomass control strategies such as backwashing or periodic media flushing. Additionally, the lava rock media, while inexpensive and locally available, may experience gradual deterioration or surface fouling over years of service, potentially affecting biofilm attachment and hydraulic performance. The system's stability under transient loading conditions—including shock organic loads, intermittent operation, and seasonal temperature variations—also remains to be characterized. Future work should therefore focus on extended-term pilot trials to assess biomass management protocols, media longevity, and system resilience under realistic operational scenarios, thereby providing a comprehensive basis for scaling up this promising technology.

4. Conclusion

This case study demonstrated the effectiveness of a trickling biofilter packed with lava rock media for the treatment of phenolic wastewater generated from natural gas recovery operations under field conditions. The system achieved substantial reductions in both COD and phenol, with removal efficiencies reaching up to 88% for COD and over 98% for phenol at optimized empty bed residence times. Quantitatively, the optimal operating condition identified in this study was an EBRT of 19 min, which yielded the highest COD removal efficiency (88%, reducing influent COD from 554 to 65 mg/L) and corresponded to an organic loading rate of 35.6 kg COD m^{-3} day^{-1}. For phenol removal, the system achieved around 98% efficiency (from 9.5 to 0.146 mg/L) at an EBRT of 14.4 min, with a corresponding phenol loading rate of 0.95 kg phenol m^{-3} day^{-1}. The hydraulic loading rate during these optimal conditions ranged from 6.3 to 12.6 m^3 m^{-2} h^{-1}. These operating parameters provide practical design targets for similar applications. Notably, the system performed effectively without external nutrient supplementation and maintained stable performance across the tested EBRT range. The COD profile along the filter depth confirmed that active biodegradation occurred throughout the column. While the trickling biofilter demonstrated notable COD and phenol removal across a broad influent pH range (2.5–9.1), these results should be interpreted with caution. The experiments were conducted over a limited duration and did not include extended exposure to extreme pH conditions or repeated pH shock cycles. The observed performance at pH 2.5 and 9.1 may partly reflect the biofilm's capacity for local pH buffering and the neutralization potential of the lava rock media, rather than intrinsic microbial activity under such conditions (Tran *et al.*, 2024). Thus, while the system exhibits encouraging resilience to pH fluctuations, a more cautious interpretation is warranted. Long-term stability tests involving sustained operation at pH extremes and repeated shock loadings would be necessary to substantiate claims of full-scale robustness under variable field conditions. The results of this pilot-scale field study provide a foundation for scaling up the trickling biofilter technology for full-scale application. The lava rock media used in this study is widely available, inexpensive, and requires no manufacturing. The passive aeration design eliminates the need for blowers or diffusers, reducing both

capital and operational costs. However, scale-up considerations must address several factors. First, the hydraulic loading rates tested (6.3–12.6 $m^3\ m^{-2}\ h^{-1}$) are higher than those typical of conventional trickling filters (1–4 $m^3\ m^{-2}\ h^{-1}$) and may require careful distributor design to ensure uniform wetting of the media at full scale. Second, the 25% recycle ratio employed in this study helps buffer influent variability but may increase pumping energy requirements; optimization of this parameter at larger scales is warranted. Third, integration with existing primary and secondary clarifiers, as implemented in this study, represents a practical treatment train that could be adopted with minimal modification of existing gas field infrastructure.

The system's compatibility with variable pH and its nutrient self-sufficiency further reduces the need for chemical addition, simplifying operation. Future scale-up efforts should focus on pilot trials at larger diameters to validate hydraulic performance and biomass distribution, as wall effects and liquid maldistribution become more pronounced at smaller scales. Additionally, the long-term performance under seasonal temperature variations, which ranged from 20 to 25°C during this study, should be evaluated across annual cycles to confirm year-round reliability. Overall, the results underscore the potential of trickling biofilters as a promising low-cost, low-maintenance, and environmentally sustainable solution for the treatment of phenolic wastewaters from gas field operations. This study reports, to the best of our knowledge, one of the first pilot-scale evaluations of a trickling biofilter for gas field phenolic wastewater, providing performance data under actual operational conditions that are not captured in laboratory studies.

Conflict of interest

The authors declare no conflict of interest.

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Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

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Authors' Contributions

Mohammad Reza Keshtvarz conducted the experiments and collected the data. Mohammad Hassan Fazaelipoor conceived the research idea, supervised the study, and wrote the manuscript. All authors have read and approved the final version of the manuscript.

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