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Aerobic Granulation Technology-Based Cresol Degradation: A Comparative Evaluation of Reactor Studies

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Abstract: Cresols (ortho, meta-, and para-isomers), potent xenobiotic compounds prevalent in industrial wastewaters, pose severe environmental and health threats and require robust bioremediation solutions. Aerobic granulation technology was assessed for its degradation efficiency towards the mixed cresol isomers system in batch and continuous reactors, addressing a key gap in existing research that has focused mainly on individual cresol isomers. The comparative reactor evaluation revealed that continuous operation achieved a 10.17% increase in cresol degradation efficiency compared to batch mode, highlighting its sustained performance. The continuous reactor demonstrated optimal cresol degradation at a flow rate of 120 mL h-1 (HRT 8.33 h), underpinned by elevated volumetric and specific degradation rates. The enzyme analysis confirmed elevated levels of catechol 1,2-dioxygenase and phenol hydroxylase, driving oxidative metabolism. The mechanism of biodegradation has been confirmed through enzyme activity assays and FT-IR spectral analysis, which demonstrated the absence of characteristic peaks associated with cresol functional groups and the emergence of oxygenated functional groups, thereby confirming the structural changes during aerobic granular degradation. The significant degradation efficiency and enzyme-assisted structural transformation of cresol validate aerobic granular sludge as a robust treatment system for cresol-contaminated wastewater.

1. INTRODUCTION

The global increase in water consumption has accelerated water contamination, driven by industrial growth, population expansion, urbanization, and intensified agricultural activities, resulting in environmental degradation and disrupting aquatic ecosystems, and posing serious health concerns to people. Almost 80% of wastewater is released untreated into the environment, particularly in low-and middle-income nations (UNESCO, 2024). There is a constant escalation in demand for industrial products due to a growing population, leading to the emergence of pollutants from both direct and indirect sources in the environment (Kanadasan et al., 2025). The levels of organic contaminants in wastewater, along with their growing complexity, have raised concerns about substantial threats to the ecosystem, their persistence, and limited biodegradability. Amongst these phenolic compounds, characterized by aromatic hydrocarbon derivatives, is a class of refractory organic pollutants that exhibit substantial toxicity and detrimental effects on aquatic biota, thereby contradicting the principles of green and sustainable water environment management (Chang et al., 2025; Chen et al., 2024). From being used in the chemical synthesis

of numerous compounds to serve as intermediates in the biosynthesis of secondary metabolites, and ultimately being found in the effluent of manufacturing industries, phenols and their derivatives are widely used organic compounds and a listed priority pollutant by the Indian Central Pollution Control Board (CPCB), and World Health Organization (WHO) (Cao et al., 2021; Kadia & Chhaya, 2025; Wu et al., 2022).

Cresol and its isomers—ortho, meta, and para cresols (CH3C6H5O)—are one such ubiquitous phenolic contaminants found in industrial effluents from various industries such as phenol manufacturing, petrochemical processing, coal gasification, coking and mining, paper production, printing and dyeing, plastics, and pesticide synthesis, with concentrations often ranging from 10 to 1000 ppm. Owing to their pronounced toxicity, these substances can cause severe skin and mucosal irritation and corrosion, disrupt the function of vital organs such as the pancreas, liver, and kidneys, and may have mutagenic, carcinogenic, and teratogenic effects even at low exposure levels. Furthermore, cresol disrupts biological denitrification, which undermines the efficiency of wastewater treatment (Chen et al., 2024; X. Wang et al., 2025; Zhang et al., 2025).

Phenolic wastewater treatment has involved both physical and chemical methods, such as membrane separation, advanced oxidation, ozonation, distillation, photocatalysis, and chemical or electrochemical oxidation (Bibi et al., 2023; Wu et al., 2022). While these techniques are commonly employed in traditional industrial wastewater treatment, they are limited by the production of toxic by-products, incomplete pollutant degradation, the need to dispose of chemically produced sludge, and high operational costs (Gholami-Bonabi et al., 2020; Tuan Tran et al., 2022).

Modern wastewater treatment plants (WWTPs) face increasing pressure to expand treatment capacity while complying with strict effluent discharge standards, reducing energy consumption, and minimizing their spatial footprint. This pressure is driven by rapid urbanization, which strains natural resources (Yu & Wang, 2024). Microbial bioremediation is gaining attention as an environmentally friendly and cost-effective method to support global initiatives, such as Sustainable Development Goal (SDG) 6.3, which aims to cut untreated wastewater in half and promote safe reuse and recycling through nature-based solutions (NbS) (Crowther et al., 2024). Activated sludge processes are common in biological wastewater treatment. However, their ability to biodegrade and remove emerging contaminants is limited, as many of these compounds pose toxicity risks to resident microbial communities. These issues have led to the search for alternative technologies, with aerobic granulation emerging as a promising replacement for traditional activated sludge systems (Kanadasan et al., 2025; Koumaki et al., 2021). Compared to activated sludge, Aerobic Granular Sludge (AGS) offers benefits in compactness, settling properties, biomass density, toxin resistance, and simultaneous nutrient removal. AGS shows higher efficiency, better operational stability, and the capacity to solve limitations of conventional wastewater treatment by effectively

removing emerging pollutants through biodegradation, adsorption by extracellular polymeric substances (EPSs), and entrapment within their complex matrix (Kanadasan et al., 2025).

Although aerobic granulation sludge technology has attracted attention for its potential to treat recalcitrant organic pollutants, few studies have examined its effectiveness in cresol degradation (Basheer & Farooqi, 2012b, 2012a). Mainly focusing on individual cresol isomers and neglecting the complexity of industrial wastewaters, where cresol isomers often coexist. This study addresses an important research gap by examining the degradation of a mixture of cresol (o, m, p isomer) system using aerobic granular sludge and assessing the degradation efficacy in both batch and continuous operational modes. Further, using enzyme assays and analytical technique, including FTIR a mechanistic insight into cresol degradation using granular biomass was highlighted.

2. MATERIALS AND METHODS

2.1 Synthetic Wastewater

The synthetic medium used in this study consisted of cresol (600 ppm) as the carbon source, along with a modified Bushnell-Hass medium (BHM) previously optimized for consortium AKUC-1 to enhance cresol degradation efficiency (Kadia & Chhaya, 2025). The optimized BHM included the following components (g L^{-1}): 0.2 $MgSO_4$•$7H_2O$; 0.0075 $CaCl_2$; 1.0 KH_2PO_4; 1.0 K_2HPO_4; 1.0 NH_4NO_3; 0.0075 $FeCl_3$, with sucrose (3.5 g L^{-1}) as an additional carbon source. Sucrose was added to maintain metabolic activity and improve biomass integrity during cresol breakdown (Kadia & Chhaya, 2025). The media was also supplemented with a micronutrient solution at a rate of 1 mL L^{-1}, containing (g L^{-1}): 0.05 $NiCl_2$; 0.05 $CoCl_2$ • $6H_2O$; 0.05 $(NH_4)6Mo7O_{24}$•$4H_2O$; 0.05 $ZnCl_2$; 0.05 H_3BO_3; 0.05 $AlCl_3$; 0.05 $MnSO_4$•H_2O; and 0.03 $CuCl_2$ (Bindhu & Madhu, 2014). This synthetic wastewater was used consistently in all experiments at pH 7.

2.2 Inoculum Source

Aerobic granular sludge enriched and cultivated with the cresol-adapted microbial consortium AKUC-1 was used as an inoculum in this study. The effect of inoculum size was evaluated with aerobic granules at inoculum sizes of 5%, 10%, 15%, and 20% (v/v) while monitoring cresol degradation until maximum degradation was achieved.

2.3 Evaluation of aerobic granules for cresol bioremediation

Cresol bioremediation was investigated in laboratory-scale glass column reactors, with a working volume of 2 liters (Figure 1a). The reactor was fed synthetic wastewater containing 600 ppm cresol, with influent and aeration introduced from the bottom using an aquarium air pump to ensure adequate mixing and oxygen transfer (Figure 1b). To evaluate the relative degrading efficiency of aerobic granular sludge for cresol degradation, separate batch and continuous reactor experiments were conducted. The effectiveness of aerobic granules in the reactor was assessed by collecting samples at 24-hour intervals, and the residual cresol concentration was determined by 4-amino antipyrine assay until maximum degradation was

reached. The reactor was operated at 28-35 °C with a pH of 7.0. To assess the impact of hydraulic retention time (HRT) in continuous reactor, it was operated at flow rates of 300, 240, 180, and 120 mL h^{-1}.

Unlike continuous operation, batch reactor operation involved filling the reactor with synthetic wastewater and conducting the process under closed conditions (without influent or effluent flow) while maintaining continuous aeration. Samples were collected at 24-hour intervals to monitor cresol degradation. Further the efficiency of cresol degradation by suspended consortium AKUC-1 and AKUC-1 derived aerobic granules was assessed in a continuous reactor operated at same physicochemical conditions in continuous reactor with flow rate of 120 mL h^{-1}. The reactor was inoculated with consortium AKUC-1 at an inoculum size of 10% (v/v) or with aerobic granules at 5% (v/v) in separate runs. The comparative evolution of both kinds of inoculum was done by monitoring residual cresol concentration in the effluent until peak degradation was achieved All experiments were conducted in duplicates and results are expressed as mean standard deviation.

The evaluation of reactor performance involved estimating the percent degradation of cresol, as outlined by Kadia & Chhaya (2025), alongside measurements of Chemical oxygen demand (COD), biochemical oxygen demand (BOD), all determined in accordance with Standard Methods (APHA, 2017).

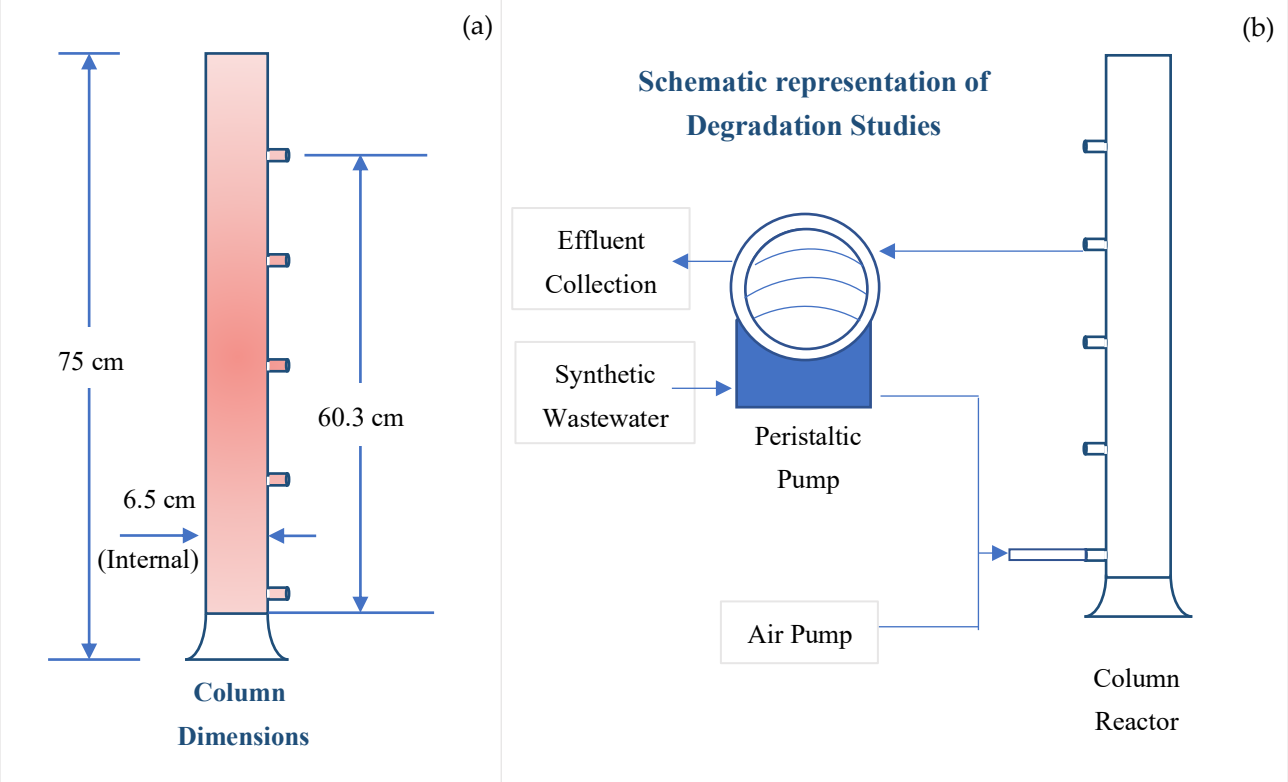

Figure 1: Design configuration of the laboratory-scale glass column showing column dimensions (a), and schematic layout of the experimental setup for aerobic cresol biodegradation (b).

Table 1: Performance evaluation of continuous reactor using mathematical expressions.

Equation No.	Parameters	Formulas
1	Flow Rate	$v = \frac{dV}{dt}$
2	Hydraulic Retention Time	$\tau = \frac{V\ (ml)}{v\ (ml/h)}$
3	Dilution Rate	$D = \frac{v\ (ml/h)}{Vr\ (ml)}$
4	Organic Loading Rate	$OLR = \frac{CODin \times v}{V}$
5	Overall Degradation Rate	$Vo = \frac{Co - Ct}{t}$
6	Volumetric Degradation Rate	$Vv = \frac{(Co - Ct) \times v}{V}$
7	Specific Substrate Utilization Rate	$Us = \frac{Vv}{Xo}$

where v is the flow rate, V is the bioreactor volume, Vr is the recirculation volume, Co is the cresol concentration in the inlet, Ct is the cresol concentration in the outlet, Xo is the biomass, and t is time.

2.4 Enzyme Assay

According to the method outlined by Silva et al. (2013), the cell-free extracts were prepared. The cells were centrifuged (10,000 rpm, 10 minutes) and harvested by resuspending in 50 mM phosphate buffer (pH 7). Cell lysis was achieved by sonication with 40-second pulses interspersed with 1-minute cooling periods on ice. Following centrifugation at 10,000 rpm for 15 minutes, cell debris was removed, and the clarified supernatant was used for enzyme analysis. The enzymatic activities of phenol hydroxylase, catechol 1,2-dioxygenase (C12O), and catechol 2,3-dioxygenase (C23O) were measured using spectro-

photometric methods at wavelengths of 340, 260, and 375, respectively. The activity of phenol hydroxylase was assessed by measuring the oxidation of NADPH (-ΔA340). The reaction mixture, with a final volume of 3.0 mL, included 2.56 mL of 0.05 M Tris-HCl buffer, 20 µL of NADPH at 10 mmol L^{-1}, 20 µL of phenol at 5 g L^{-1}, and 400 µL of crude enzyme extract. The molar extinction coefficient of 6,220 mM^{-1} cm^{-1} (Wang et al., 2019). The assay for catechol 1,2-dioxygenase involved measuring the increase in absorbance at 260 nm due to the formation of cis,cis-muconic acid over 3 min. (Nakazawa & Nakazawa, 1970). The activity of catechol 2,3-dioxygenase was measured through the formation of 2-hydromuconic semialdehyde (2-HMS) at 375 nm (Nozaki, 1970). The reaction system, with a final volume of 3.0 mL, comprised a potassium phosphate buffer at pH 7.5 (2.390 mL), catechol (600 µL, 1mmol L^{-1}), and crude enzyme (500 µL). The formation of enzymatic products was assessed by absorbance measurements, using molar extinction coefficients of 16,800 mM^{-1} cm^{-1} for muconic acid and 14,700 mM^{-1} cm^{-1} for 2-hydroxymuconic semialdehyde. The enzyme activity was calculated using the following equation

$$Enzyme\ Activity\ = \left\{\left(\varepsilon \times \frac{L}{V}\right)\left(\frac{\Delta\ OD}{min}\right)\right\}$$

Where, ΔOD represents the change in the absorbance, ε denotes the molar extinction coefficient, V indicates the reaction volume, and L refers to the cuvette path length.

Enzyme activities were evaluated in cell-free extracts derived from biomass collected after the active degradation of cresol, ensuring that the expression of cresol-degrading enzymes was induced by the substrate. Enzyme activities were measured in supernatants and reported as U/mL. Specific activity was not determined as the assay aimed mainly to identify the associated enzymes and clarify the primary pathway involved in cresol degradation.

2.5 Sample Preparation for FT-IR Analysis

Samples from the abiotic control and the treated effluent at maximum degradation were analyzed by FT-IR spectroscopy to assess structural changes resulting from cresol degradation. The bacterial cells were harvested by centrifugation (10,000 rpm, 10 minutes), and subsequently the supernatant was acidified to pH 2 using 0.5 M H_2SO_4, followed by ethyl acetate extraction (Panigrahy et al., 2020). The residues were dissolved in methanol for FT-IR analysis. The samples were scanned over 4000-400 cm^{-1}, and the resulting spectra were examined to identify modifications in the specific absorption bands of the parent compound (Ren et al., 2014).

3. RESULTS AND DISCUSSIONS

An integrated approach employing aerobic granular sludge as a biological treatment strategy for synthetic wastewater contaminated with cresol was investigated in both batch and continuous-flow lab-scale reactors. Aerobic granules, previously cultivated with the cresol-adapted consortium AKUC-1, were sourced from a sequencing batch reactor and utilized as inoculum in both reactors to evaluate cresol wastewater

remediation and elucidate reactor-specific performance dynamics. The microbial consortium AKUC-1, previously isolated and enriched in our lab, underwent partial taxonomic characterization via 16S rRNA gene analysis, which indicated a predominance of Firmicutes, especially Bacillus sp., suggesting their potential role in cresol degradation (Kadia & Chhaya, 2025). Prior investigations have documented the presence of Firmicutes in aerobic granular sludge communities involved in cresol degradation. Lee et al. (2011) reported the prevalence of Firmicutes in aerobic granules that can degrade cresol, whereas Chi et al. (2021) and Mahdavianpour et al. (2018), illustrated the ability of bacteria associated with this phylum to degrade phenol and p-cresol. The efficacy of aerobic granules in degrading cresol was assessed in both batch and continuous modes of operation at an influent concentration of 600 ppm

3.1 Effect of Inoculum Size

The impact of inoculum size on the degradation of cresol was evaluated, and cresol removal efficiencies of 91.11%, 95.22% 97.94% and 97.99% were successfully attained within a 72-hour period at inoculum sizes of 5, 10, 15, and 20% (v/v), respectively. The developed aerobic granules exhibited predominantly spherical to pseudo-spherical morphology, with particle size ranging from 0.51 to 7.7 mm. Aerobic granules operating at a smaller inoculum size of 5% (v/v) showed significant cresol removal while substantially lowering biomass input, although slightly greater degradation was observed at a larger inoculum size. Increased degradation observed with larger inoculum sizes indicates a rise in active biomass, leading to rapid metabolic activation and increased enzymatic capacity and enhancing substrate uptake kinetics.

The marginal enhancement beyond 5% (v/v) indicates a shift from biomass-controlled to substrate limited degradation. Higher inoculum showed similar performance, indicating that adequate active microbial consortia were present at 5% (v/v) for achieving near optimal cresol degradation and the addition to further biomass did not substantially enhance performance, indicating that the system is operating close to its maximal degradation capacity under the prevailing operation conditions.

The results of this study highlight the importance of inoculum optimization in biodegradation systems. Rafeeq et al. (2023) suggested that inadequate inoculum concentrations have prolonged lag phases, whereas excessive biomass may induce quorum-sensing-mediated metabolic inhibition. Furthermore, Krasňan et al. (2016) illustrated that the over accumulation of biomass increases mass transfer resistance, leading to the formation of diffusion-constrained or metabolically inactive zones that ultimately reduce reactor efficiency. Considering these, 5% (v/v) inoculum size was determined to be the most effective and sustainable operational concentration for further studies.

3.2 Reactor Studies

The continuous reactor was initially evaluated at different flow rates to optimize cresol degradation. When operated at lower flow rates (120-180 mL h^{-1}), longer hydraulic retention time supported effective

biodegradation, whereas at higher flow rates (240-300 mL h^{-1}), treatment degradation efficiency decreased (Table 2). The lower flow rates corresponded to an extended hydraulic retention time (HRT), leading to better substrate-biomass interaction and increased biodegradation efficiency. Conversely, at higher flow rates, a gradual decrease in treatment efficiency resulted, likely due to decreased contact time and partial biomass washout. In line with the current findings, Trivedi & Chhaya (2022) noted that lower flow rates in continuous systems significantly improved degradation efficiency, highlighting the critical role of hydraulic retention time in overall cresol degradation.

Table 2: Efficiency of aerobic granules in degrading cresol within a continuous flow reactor at various flow rates.

Cycle	C1	C2	C3	C4
Flow Rate (mL h^{-1})	120	180	240	300
HRT (h)	8.33	5.55	4.16	3.33
Degradation (%)	99.39	90.96	89.11	87.07

The batch and continuous reactors were operated independently, and both configurations demonstrated effective cresol degradation with notable differences in removal dynamics between the two modes. During the batch operation, removal efficiency for cresol was 90.42 ± 0.770 %, and a reduction of 84.36 % for COD, and 77.77 % for BOD was observed. In contrast, the continuous operation demonstrated comparable COD removal of 84.99 %, BOD removal of 79.23 %, and significantly enhanced cresol degradation of 99.65 ± 0.406 %. The cresol degradation profile showed a steady decrease in concentration with time in both batch and continuous modes (Figure 2).

The aerobic granular sludge exhibited improved cresol degradation in the continuous reactor, highlighting efficient substrate utilization during steady-state operation. The continuous operation proved more effective at degrading the target recalcitrant compound, emphasizing its suitability for consistent industrial wastewater treatment. The maximum cresol degradation in the continuous reactor occurred at a flow rate of 120 mL h^{-1}, corresponding to a hydraulic retention time (HRT) of 8.33 h and a dilution rate of 0.06 h^{-1}. Under these circumstances, the reactor's overall degradation rate is 70.56 mg h^{-1}, with an organic loading rate (OLR) of 31.61 kg COD m^{-3} d^{-1}. The system demonstrated the volumetric degradation rate of 35.28 mg cresol L^{-1} h^{-1}, and the specific substrate utilization rate of 0.706 mg g^{-1} h^{-1}, indicating notable biomass activity and successful substrate conversion leading to favorable microbial kinetics under the investigated operating conditions.

3.3 Enzyme Assay

The analysis of enzyme activity showed a significant increase in key enzymes involved in cresol degradation. Notably, phenol hydroxylase reached an activity level of 1134.3 U/mL, while catechol 1,2-dioxygenase had the highest activity of 1213.3 U/mL. Meanwhile, catechol 2,3-dioxygenase displayed lower activity of 91.66 U/mL. The heightened activity of phenol hydroxylase indicates an efficient initial hydroxylation of cresol to catechol, which is a critical step in cresol biodegradation (Wang et al., 2019). The dominance of catechol 1,2-dioxygenase compared to catechol 2,3-dioxygenase indicates that the ortho-cleavage pathway serves as the primary mechanism for aromatic ring fission in the degradation. The comparatively reduced activity of catechol 2,3-dioxygenase suggests that the meta-cleavage pathway plays a secondary role. According to Setlhare et al. (2018), catechol serves as a central intermediate in the aerobic degradation of phenolic contaminants, which further undergo intradiol (ortho) or extradiol (meta) ring cleavage catalysed by catechol 1,3-dioxygenase and catechol 2,3-dioxygenase, respectively.

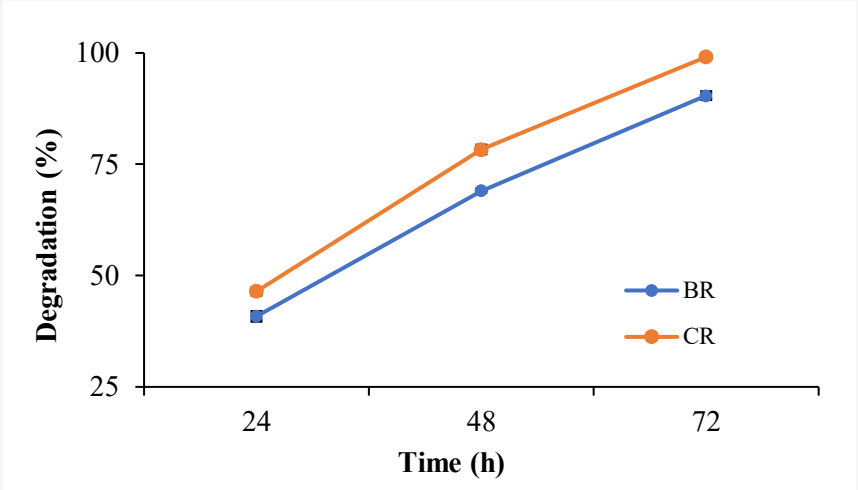

Figure 2: Comparison of cresol degradation by aerobic granules operated in batch reactor (BR) and tinuous-flow reactors (CR) over a 24 hour period

3.4 Cresol degradation analysis by FT-IR

Cresol degradation was assessed by the disappearance or attenuation of characteristic functional group peaks corresponding to cresol, as analysed by FT-IR spectroscopy. The sample collected from the abiotic control showed characteristic absorption bands at 2968.06, 1710.08, 1491.92, and 1464.66 cm^{-1}, corresponding to methyl, hydroxyl, and aromatic ring vibrations, respectively (Figure 3). The identified functional groups are characteristic of cresol structures, consistent with earlier studies (Panigrahy et al., 2020; Ren et al., 2014). The treated samples exhibited FT-IR peaks at 2966.63, 1370.65, and 1260.85 cm^{-1}, while the bands at 1710.08, 1491.92, and 1464.66 cm^{-1} disappeared, indicating disruption of the aromatic structure (Figure 4). According to Singh et al. (2017), the peak at 1260.85 cm^{-1} is attributed to the C-O group, whereas the band at 1370.65 cm^{-1} falls within the range associated with CH_3 bending or –COOH groups, as documented by Panigrahy et al. (2020) and Singh et al. (2017). The absence of peaks associated with aromatic and hydroxyl functional groups, along with the emergence of oxygenated functional groups,

suggests a biotransformation of cresol into oxygenated and aliphatic intermediates, consistent with enzyme-mediated degradation.

The enzyme assay indicated significant activity of phenol hydroxylase and catechol dioxygenase, implying the occurrence of cresol hydroxylation and subsequent ring-cleavage reactions. In line with this, FT-IR analysis of the treated samples revealed the absence of characteristic peaks associated with aromatic and phenolic functional groups, alongside the appearance of oxygenated functional groups, which indicates an enzyme-mediated structural transformation of cresol (Ali et al., 1998; Duffner & Müller, 1998; Kadia & Chhaya, 2025). The strong dominance of catechol 1, 2-dioxygenase activity over catechol 2, 3-dioxygenase indicates that cresol degradation mainly occurs through the ortho-cleavage pathway. Overall, these findings show that aerobic granules favour a metabolically efficient ortho-cleavage strategy, which explains the exceptional cresol removal seen in both batch and continuous reactor operations.

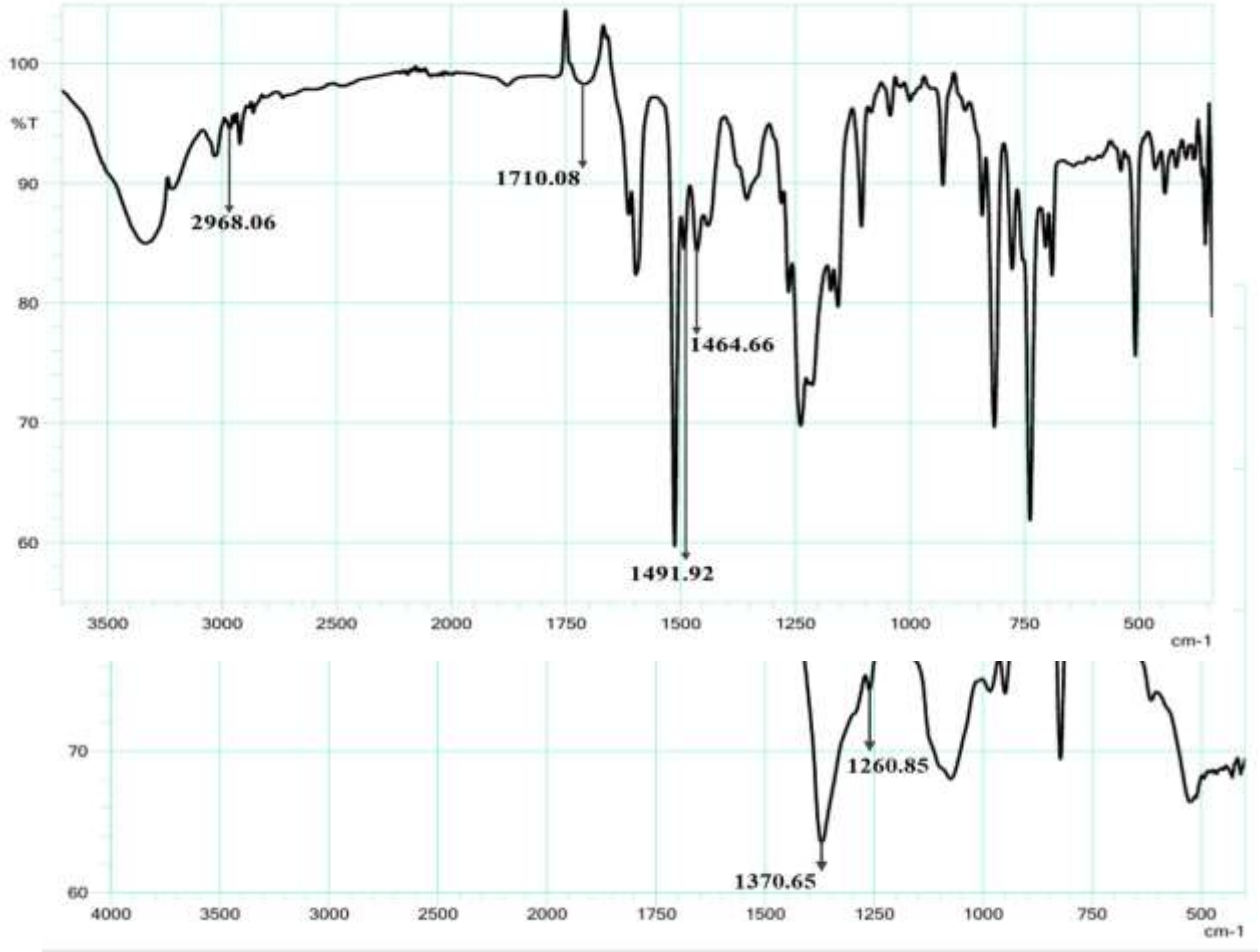

Figure 4*: FT-IR spectra of treated sample demonstrating the disappearance and emergence of functional group peaks during the cresol degradation by aerobic granules*

The correlation between FT-IR spectral shifts and enzyme activity offers a coherent mechanistic understanding: phenol hydroxylase probably facilitates the initial hydroxylation of cresol to catechol, subsequently proceeding with ring cleavage mainly via the ortho pathway, resulting in the generation of oxygenated intermediates that can be characterized using FT-IR. The combined insights from cresol removal efficiency, enzyme activity analyses, and FT-IR spectral alterations offer coherent and mechnaistically relevant understanding of cresol biodegradation within the studied paramters. Although chromatographic metabolite profiling could provide molecular level confirmation, the current comphrehensive evidence approch adequately substantiates the suggested ortho-cleavage dominated degrdataion pathway.

3.5 Comparative evaluation of consortium AKUC-1 and aerobic granules derived from AKUC-1 for cresol degradation

The suspended consortium AKUC-1 achieved 82.54 ± 2.927 % degradation after 96 hours. Despite using a larger inoculum, the aerobic granules cultivated with consortium AKUC-1 achieved 99.10 ± 0.715% cresol degradation within 72 hours. The superior performance of aerobic granules can be linked to better biomass retention and microbial accumulation, highlighting the significance of granular structure in continuous reactor systems. The 24-hour degradation profile clearly demonstrates that aerobic granules facilitate more rapid cresol removal than the suspended consortium AKUC-1, resulting in a significant decrease in residual cresol concentration during the initial operation phase (Figure 5).

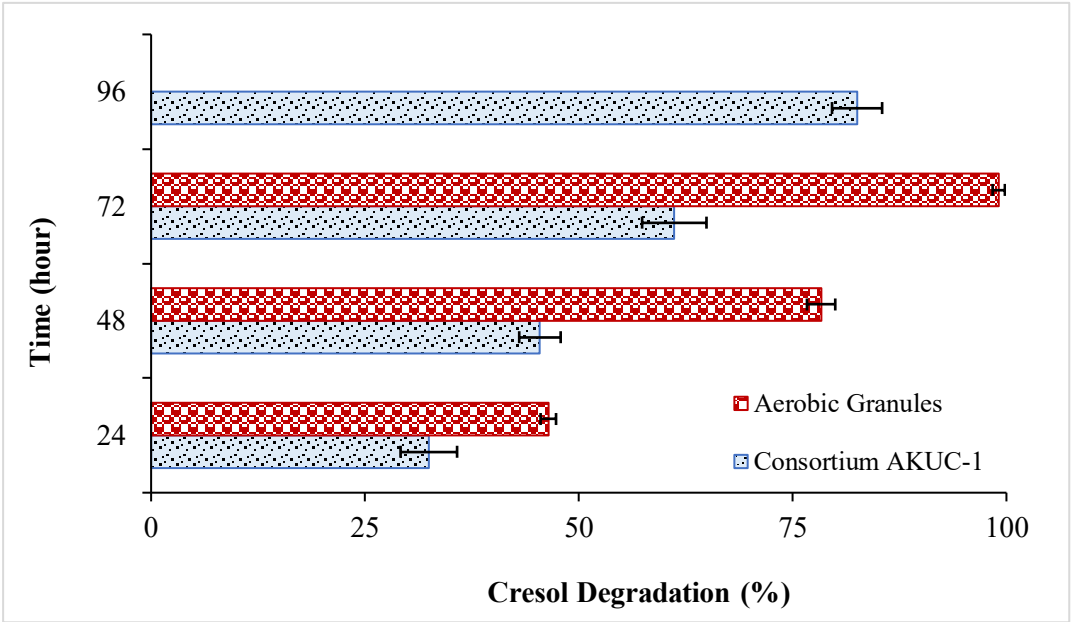

Figure 5: *Comparative cresol degradation profiles of aerobic granules and suspended consortium AKUC-1 over a 96-hour operational period in a continuous reactor*

4. CONCLUSIONS

This lab-scale study demonstrates the successful application of aerobic granules cultivated using consortium AKUC-1 for the biodegradation of a mixed cresol isomer system (o, m-, and p-cresol), filling an important

gap in the current literature, which predominantly focuses on individual isomers. The comparative reactor evaluation demonstrated enhanced removal efficiency during continuous operation compared to batch mode, with a noted increase of around 10% under the evaluated conditions, highlighting its suitability for consistent, prolonged treatment. Overall, the study's findings indicate that aerobic granular sludge facilitates effective, kinetically favourable cresol degradation under continuous reactor conditions. The elevated degradation effciiency observed in the granular system implies favourable reactor performance and highlights their potential to treat complex cresol-containing wastewaters and to be integrated into advanced wastewater treatment systems, thereby establishing an energy-efficient and sustainable approach. Future efforts must prioritize long-term stability, resilience to shock loads, and validation at scale under actual industrial effluent conditions to enable real-world use of aerobic granulation technology as a robust biotechnology strategy.

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Conflicts of Interest:

The authors declare no conflicts of interest.

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