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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 effective bioremediation solutions. Aerobic granulation technology was assessed for its degradation efficiency toward a mixed cresol-isomer 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 10.21% increase in cresol degradation efficiency compared with 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), supported by elevated volumetric and specific degradation rates. Enzyme analysis confirmed elevated activities of catechol 1,2-dioxygenase and phenol hydroxylase, supporting oxidative metabolism. The biodegradation mechanism was supported by 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 structural changes during aerobic granular degradation. The significant degradation efficiency and enzyme-assisted structural transformation of cresol validate aerobic granular sludge as an effective 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, disruption of aquatic ecosystems, and serious human health concerns. Almost 80% of wastewater is released untreated into the environment, particularly in low- and middle-income nations (UNESCO 2024). The demand for industrial products continues to increase with population growth, 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 because of their substantial threats to ecosystems, persistence, and limited biodegradability. Among these contaminants, phenolic compounds, characterized as aromatic hydrocarbon derivatives, constitute a class of refractory organic pollutants that exhibit substantial toxicity and detrimental effects on aquatic biota, thereby conflicting with the principles of green and sustainable water-

environment management (Chang et al. 2025, Chen et al. 2024). Phenols and their derivatives are widely used organic compounds that serve in the chemical synthesis of numerous compounds and as intermediates in the biosynthesis of secondary metabolites and are ultimately found in effluents from manufacturing industries. They are listed as priority pollutants by the Indian Central Pollution Control Board (CPCB) and the World Health Organization (WHO) (Cao et al. 2021, Kadia & Chhaya 2025, Wu et al. 2022).

Cresol and its ortho-, meta-, and para-isomers ($CH_3C_6H_5O$) are ubiquitous phenolic contaminants found in industrial effluents from 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. Cresol also disrupts biological denitrification, thereby reducing wastewater-treatment efficiency (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). Although these techniques are commonly employed in conventional 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 halve the proportion of untreated wastewater 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 because 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 conventional activated sludge systems (Kanadasan et al. 2025, Koumaki et al. 2021). Compared with activated sludge, aerobic granular sludge (AGS) offers advantages in compactness, settling properties, biomass density, toxin resistance, and simultaneous nutrient removal. AGS shows higher efficiency, better operational stability, and the capacity to address limitations of conventional wastewater treatment by effectively removing emerging pollutants through biodegradation, adsorption by extracellular polymeric substances (EPSs), and entrapment within its complex matrix (Kanadasan et al. 2025).

Although aerobic granular sludge technology has attracted attention for its potential to treat recalcitrant organic pollutants, few studies have examined its effectiveness in cresol degradation (Basheer & Farooqi 2012a, 2012b). Previous studies have mainly focused on individual cresol isomers, neglecting the complexity of industrial wastewaters in which cresol isomers often coexist. This study addresses an important research gap by examining the degradation of a mixed cresol-isomer system (o-, m-, and p-cresol) using aerobic granular sludge and assessing degradation efficacy under both batch and continuous operating modes. Enzyme assays and analytical techniques, including FT-IR, were also used to provide mechanistic insight into cresol degradation by granular biomass.

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 $MgSO_4 \cdot 7H_2O$; 0.0075 $CaCl_2$; 1.0 KH_2PO_4; 1.0 K_2HPO_4; 1.0 NH_4NO_3; and 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 medium 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 $CoCl_2 \cdot 6H_2O$; 0.05 $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$; 0.05 $ZnCl_2$; 0.05 H_3BO_3; 0.05 $AlCl_3$; 0.05 $MnSO_4 \cdot H_2O$; 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

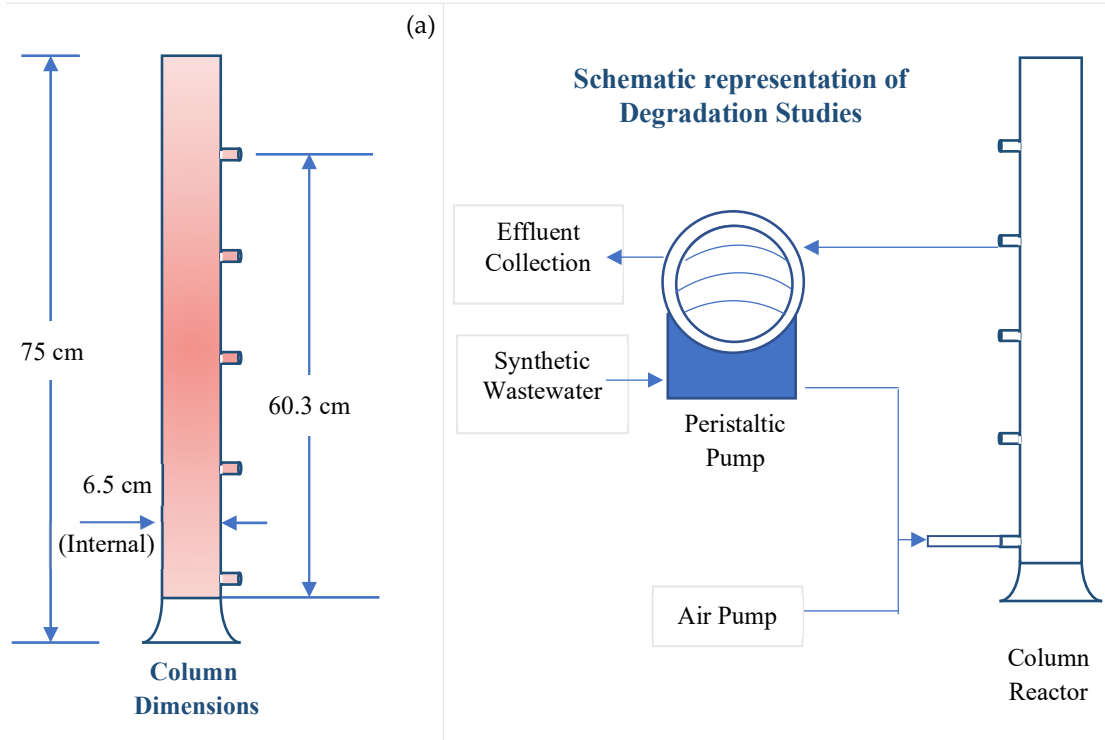


Fig. 1: Design configuration of the laboratory-scale glass column showing column dimensions (a) and the schematic layout of the experimental setup for aerobic cresol biodegradation (b).

Table 1: Performance evaluation of the 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	$Us = \frac{Vv}{Xo}$

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 L (Fig. 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 (Fig. 1b). To evaluate the relative degradation efficiency of aerobic granular sludge, separate batch and continuous reactor experiments were conducted. Reactor performance was assessed by collecting samples at 24 h intervals, and the residual cresol concentration was determined using the 4-aminoantipyrine assay until maximum degradation was reached. The reactor was operated at 28–35°C and pH 7.0. To assess the effect of hydraulic retention time (HRT) in the 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 h intervals to monitor cresol degradation. The efficiency of cresol degradation by suspended consortium AKUC-1 and AKUC-1-derived aerobic granules was further assessed in a continuous reactor operated under the same physicochemical conditions at a 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 evaluation of both inocula was performed by monitoring the residual cresol concentration in the effluent until peak degradation was achieved. All experiments were conducted in duplicate, and the results are expressed as mean ± standard deviation.

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

where v is the flow rate, V is the bioreactor volume, V_r is the recirculation volume, C_0 is the cresol concentration in the inlet, C_t is the cresol concentration in the outlet, X_0 is the biomass, and t is time.

2.4. Enzyme Assay

Cell-free extracts were prepared according to the method outlined by Silva et al. (2013). The cells were centrifuged (10,000 rpm, 10 min) and harvested by resuspension in 50 mM phosphate buffer (pH 7). Cell lysis was achieved by sonication with 40 s pulses interspersed with 1 min cooling periods on ice. Following centrifugation at 10,000 rpm for 15 min, cell debris was removed, and the clarified supernatant was used for enzyme analysis. The activities of phenol hydroxylase, catechol 1,2-dioxygenase (C12O), and catechol 2,3-dioxygenase (C23O) were measured spectrophotometrically at wavelengths of 340, 260, and 375 nm, respectively. Phenol hydroxylase activity was assessed by measuring the oxidation of NADPH ($-\Delta A_{340}$). 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. A molar extinction coefficient of 6,220 mM^{-1} cm^{-1} was used (Wang et al. 2019). The catechol 1,2-dioxygenase assay involved measuring the increase in absorbance at 260 nm due to the formation of cis,cis-muconic acid over 3 min (Nakazawa & Nakazawa 1970). Catechol 2,3-dioxygenase activity was measured through the formation of 2-hydroxymuconic semialdehyde (2-HMS) at 375 nm (Nozaki 1970). The reaction system, reported as having a final volume of 3.0 mL, comprised potassium phosphate buffer at pH 7.5 (2.890 mL), catechol (60 µL, 1 mmol L^{-1}), and crude enzyme extract (50 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. 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 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 min), after which 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 DISCUSSION

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 laboratory-scale reactors. Aerobic granules, previously cultivated with the cresol-adapted consortium AKUC-1, were sourced from a sequencing batch reactor and used 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 laboratory, 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). Previous 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 capable of degrading 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 operating modes at an influent concentration of 600 ppm.

3.1. Effect of Inoculum Size

The effect of inoculum size on cresol degradation was evaluated, and cresol removal efficiencies of 91.11%, 95.22%, 97.94%, and 97.99% were attained within 72 h at inoculum sizes of 5%, 10%, 15%, and 20% (v/v), respectively. The developed aerobic granules exhibited predominantly spherical to pseudospherical morphology, with particle sizes ranging from 0.51 to 7.7 mm. Aerobic granules operated at the smaller inoculum size of 5% (v/v) showed substantial cresol removal while reducing biomass input, although slightly greater degradation was observed at larger inoculum sizes. The increased degradation observed with larger inoculum sizes indicates an increase in active biomass, leading to rapid metabolic activation and greater enzymatic capacity, thereby enhancing substrate-uptake kinetics.

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

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

3.2. Reactor Studies

The continuous reactor was initially evaluated at different flow rates to optimize cresol degradation. At lower flow rates (120–180 mL h^{-1}), longer hydraulic retention times supported effective biodegradation, whereas at higher flow rates (240–300 mL h^{-1}), degradation efficiency decreased (Table 2). The lower flow rates corresponded to extended hydraulic retention times (HRTs), leading to better substrate-biomass interaction and increased biodegradation efficiency. Conversely, at higher flow rates, treatment efficiency gradually decreased, likely because of reduced contact time and partial biomass washout. Consistent 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.

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 batch operation, cresol removal efficiency was 90.42 ± 0.770%,

Table 2: Efficiency of aerobic granules in degrading cresol in 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

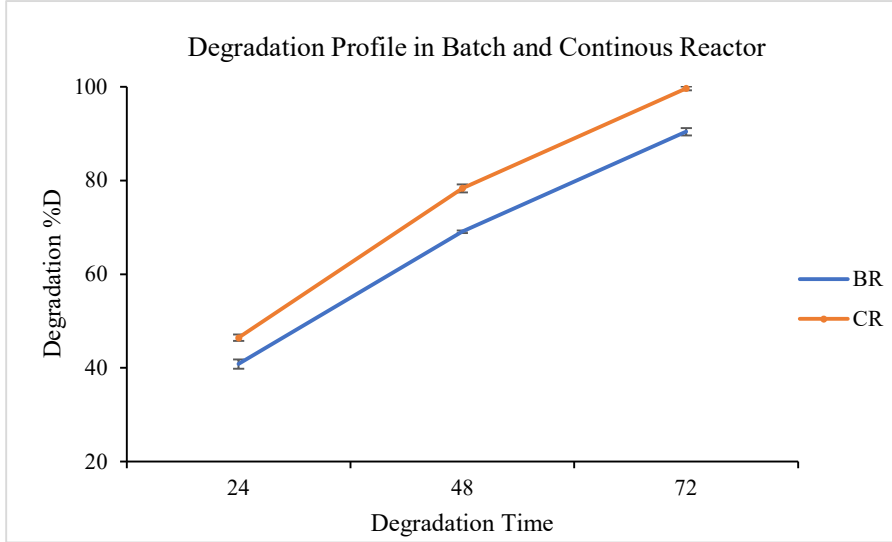


Fig. 2: Comparison of cresol degradation by aerobic granules operated in a batch reactor (BR) and a continuous-flow reactor (CR) over a 24 h time interval period.

while COD and BOD removals were 84.36% and 77.77%, respectively. In contrast, continuous operation demonstrated comparable COD removal of 84.99% and BOD removal of 79.23%, with enhanced cresol degradation of 99.65 ± 0.406%. The cresol degradation profile showed a steady decrease in concentration over time in both batch and continuous modes (Fig. 2).

The aerobic granular sludge exhibited improved cresol degradation in the continuous reactor, highlighting efficient substrate utilization during steady-state operation. Continuous operation was more effective at degrading the target recalcitrant compound, emphasizing its suitability for consistent industrial wastewater treatment. 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 conditions, the reactor's overall degradation rate was 70.56 mg h^{-1}, with an organic loading rate (OLR) of 31.61 kg COD m^{-3} d^{-1}. The system demonstrated a volumetric degradation rate of 35.28 mg cresol L^{-1} h^{-1} and a specific substrate utilization rate of 0.706 mg g^{-1} h^{-1}, indicating notable biomass activity and successful substrate conversion 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. 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. Catechol 2,3-dioxygenase displayed a lower activity of 91.66 U/mL. The heightened activity of phenol hydroxylase indicates 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 over catechol 2,3-dioxygenase indicates that the ortho-cleavage pathway serves as the primary mechanism for aromatic-ring fission during degradation. The comparatively lower 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 subsequently undergo intradiol (ortho) or extradiol (meta) ring cleavage catalyzed by catechol 1,2-dioxygenase and catechol 2,3-dioxygenase, respectively.

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 analyzed 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 (Fig. 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 (Fig. 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,

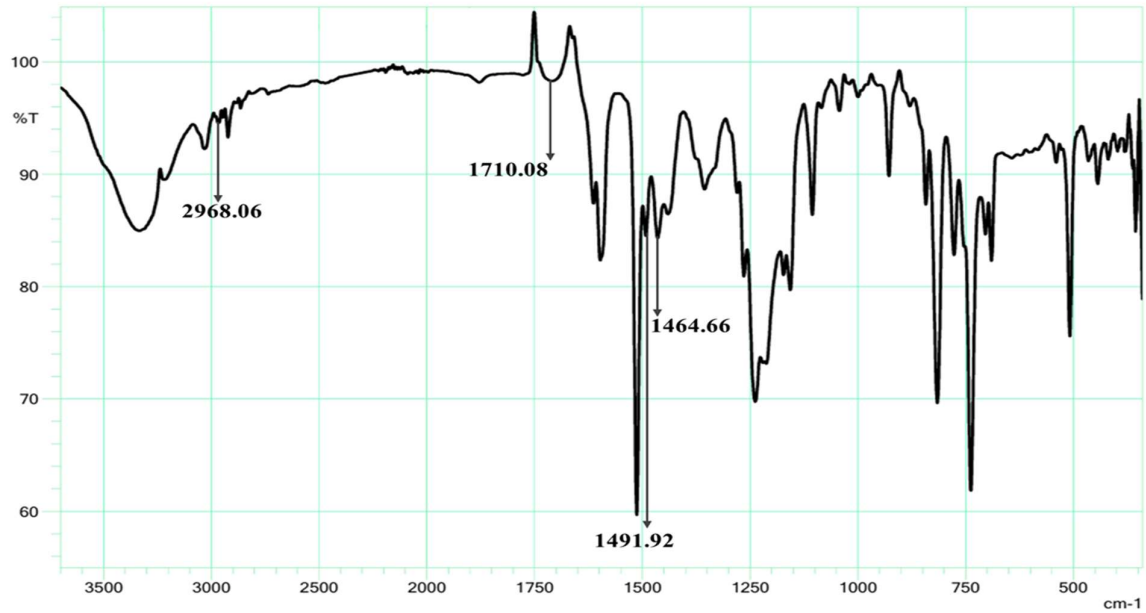


Fig. 3: FT-IR spectra demonstrating the appearance of characteristic functional-group peaks of the phenolic compound cresol in the abiotic control.

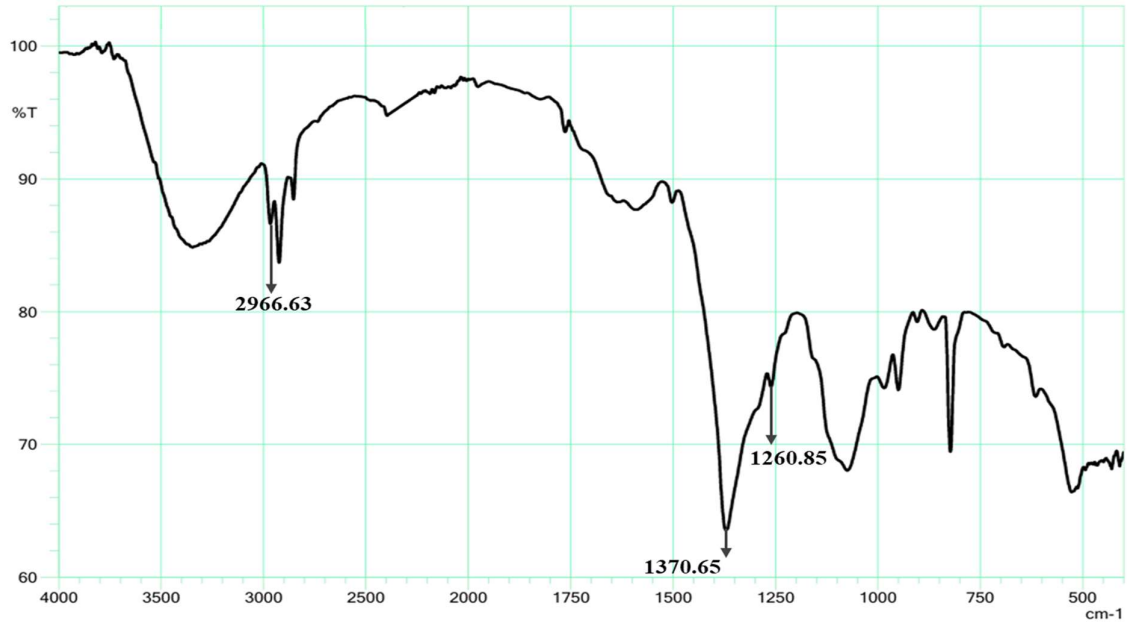


Fig. 4: FT-IR spectra of the treated sample demonstrating the disappearance and emergence of func-tional-group peaks during cresol degradation by aerobic granules.

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

The enzyme assay indicated significant activity of phenol hydroxylase and catechol dioxygenases, implying the occurrence of cresol hydroxylation and subsequent ring-cleavage reactions. Consistent with this finding, FT-IR analysis of the treated samples revealed the absence of characteristic peaks associated with aromatic and phenolic functional groups,

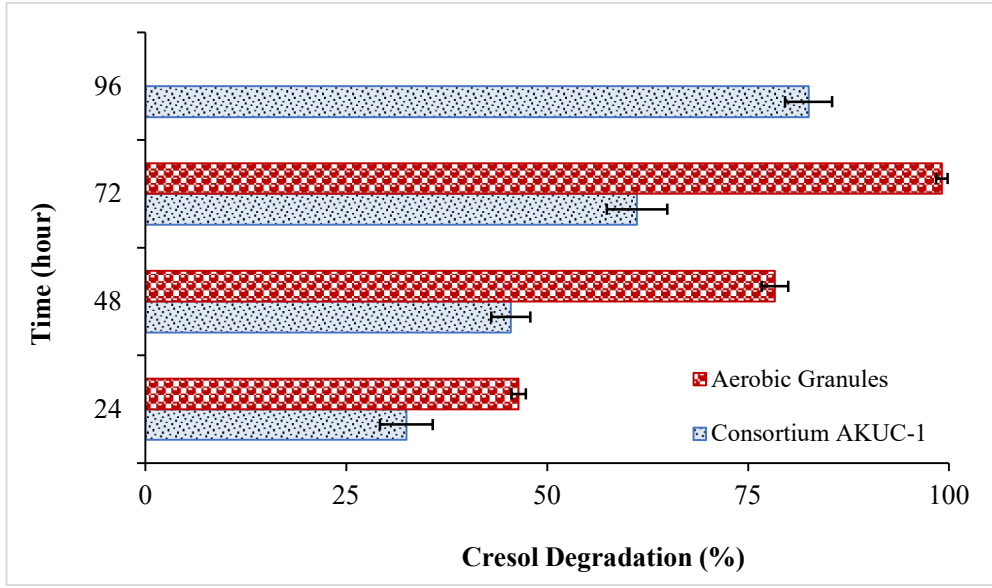


Fig. 5: Comparative cresol degradation profiles of aerobic granules and suspended consortium AKUC-1 over a 96 h operating period in a continuous reactor.

along with the appearance of oxygenated functional groups, indicating 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 favor a metabolically efficient ortho-cleavage strategy, which explains the high cresol removal observed in both batch and continuous reactor operations.

The correlation between FT-IR spectral shifts and enzyme activity offers a coherent mechanistic interpretation: phenol hydroxylase probably facilitates the initial hydroxylation of cresol to catechol, followed by 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 provide a coherent and mechanistically relevant understanding of cresol biodegradation under the studied parameters. Although chromatographic metabolite profiling could provide molecular-level confirmation, the current comprehensive evidence adequately substantiates the suggested ortho-cleavage-dominated degradation 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 h. Despite the larger inoculum used for the suspended consortium, the aerobic granules cultivated with consortium AKUC-1 achieved 99.10 ± 0.715% cresol degradation within 72 h. 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 degradation profile demonstrates that aerobic granules facilitated more rapid cresol removal than the suspended consortium AKUC-1, resulting in a substantial decrease in residual cresol concentration during the initial operating phase (Fig. 5).

4. CONCLUSIONS

This laboratory-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), addressing 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 with batch mode, with an increase of approximately 10% under the evaluated conditions, highlighting its suitability for consistent, prolonged treatment. Overall, the findings indicate that aerobic granular sludge facilitates effective, kinetically favorable cresol degradation under continuous reactor conditions. The elevated degradation

efficiency observed in the granular system indicates favorable reactor performance and highlights the potential

of aerobic granules to treat complex cresol-containing wastewaters and be integrated into advanced wastewater treatment systems, thereby establishing an energy-efficient and sustainable approach. Future efforts should 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 biotechnology strategy.

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