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# EVALUATION OF THE FACTORS AFFECTING HYDRODYNAMIC CHARACTERISTICS OF A HYBRID ANAEROBIC BAFFLED REACTOR

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## Abstract

The residence time distribution is used to study the hydrodynamic behaviour through the pulse input tracer technique. The effect of presence of media, compartment wise variation in the mixing patterns and the influence of hydraulic retention time in the hydrodynamic characteristics of the reactor is studied. The influence of the number of compartments is more predominant than the hydraulic retention time and presence of media. The flow regime in the first, second, and third compartments is in intermediate state, and plug-flow in the rear compartment. The interactive effects of the present work are evaluated using response surface methodology.

**Keywords** Anaerobic baffled reactor (ABR); Residence time distribution (RTD); Dead space; Hydraulic efficiency; Response surface methodology (RSM)

## 1. Introduction

The major problems faced like the water crisis, deterioration of surface water and the depletion of underground water resources leads to reuse and recycling of wastewater. Thus the need for the technical and economically viable technology for the wastewater treatment to satisfy the water needs and meet the stringent regulations for the wastewater discharge arises. Anaerobic treatment, combined with other treatment methods, emerged as the advanced technology for environmental and resource protection, especially in developing countries. The development of an innovative reactor design to implement anaerobic technology is the anaerobic baffled reactor (ABR). The ABR has several compartments that force the wastewater to flow under and over the vertical baffles arranged from inlet to outlet (1). This makes a large amount of active biomass come into intimate contact with the wastewater to increase the efficiency of reactor (2). The advantage of the ABR are a) construction aspects like simple design, reduced clogging, low capital and operating cost, no moving parts, no mechanical mixing, and b) biomass aspects like low sludge production, high solids retention time, retention of biomass without fixed media c) operation aspect like low hydraulic retention time, stable to organic shock. One of the disadvantages of conventional ABR is poor effluent quality. Usually, post-treatment aerobic systems are used in combination with the ABR to meet the discharge limits (3). In recent decades, the ABR has attained many modifications and combinations with other aerobic processes to increase domestic, industrial, and refractory wastewater treatment efficiency. The hydrodynamics and degree of mixing strongly influence the contact between the biomass and the substrate. Thus the efficiency of the reactor is strongly influenced by hydrodynamic behaviour in the reactor (4). The completely mixed condition lowers the treatment efficiency in the reactor due to high mixing (5). In contrast, the unstirred plug-flow condition lowers the treatment performance by the accumulation of organic acids by lowering its pH value (1). Thus, the intermediate state condition between the plug flow and the completely mixed condition provides the highest treatment efficiency. This intermediate state can be achieved by many factors such as recycling, variation in hydraulic retention time, fluid channelling by the creation of dead zones, geometrical changes in the reactor, or the combination of all these factors. In this paper, the flow regime is varied by changing the hydraulic retention time, increasing the number of compartments, and some geometrical changes in the reactor to achieve the maximum treatment efficiency by studying its hydrodynamic behaviour. The present work was evaluated using response surface methodology (RSM) with respect to the simultaneous effect of two independent variables (HRT, Number of compartments) to study the interactive effect of four interrelated parameters as responses.

## 2. Materials and Methods

### 2.1. Experimental Setup of HABR

The hybrid anaerobic baffled reactor (HABR) used in this study was acrylic material comprising four compartments with length, breadth, height of 500 mm, 400 mm, and 500 mm respectively, with a working volume of 100 L. The volume of first three compartments was 20 L (Length 100mm, Breadth 400mm, and height of 500mm) and the fourth compartment was 40 L (Length 200mm, Breadth 400mm, and height 500mm). The hanging baffles were used in the individual compartment to divide into up-flow and down-flow chambers in a ratio of 1:4. Each chamber had a sampling port located 15 cm from the chamber's top. The first chamber acted as a normal settling chamber, whereas the second, third and fourth compartment up-flow chambers were filled with different media. The second and fourth compartment up-flow chambers were fully packed with media for the height of 30cm, and in the third compartment up-flow chamber, 40% of the volume was filled with media. The characteristics of media are given in Table 1. The hanging baffle in the first compartment was provided in a zigzag manner. The schematic diagram of the HABR is presented in Fig.1.

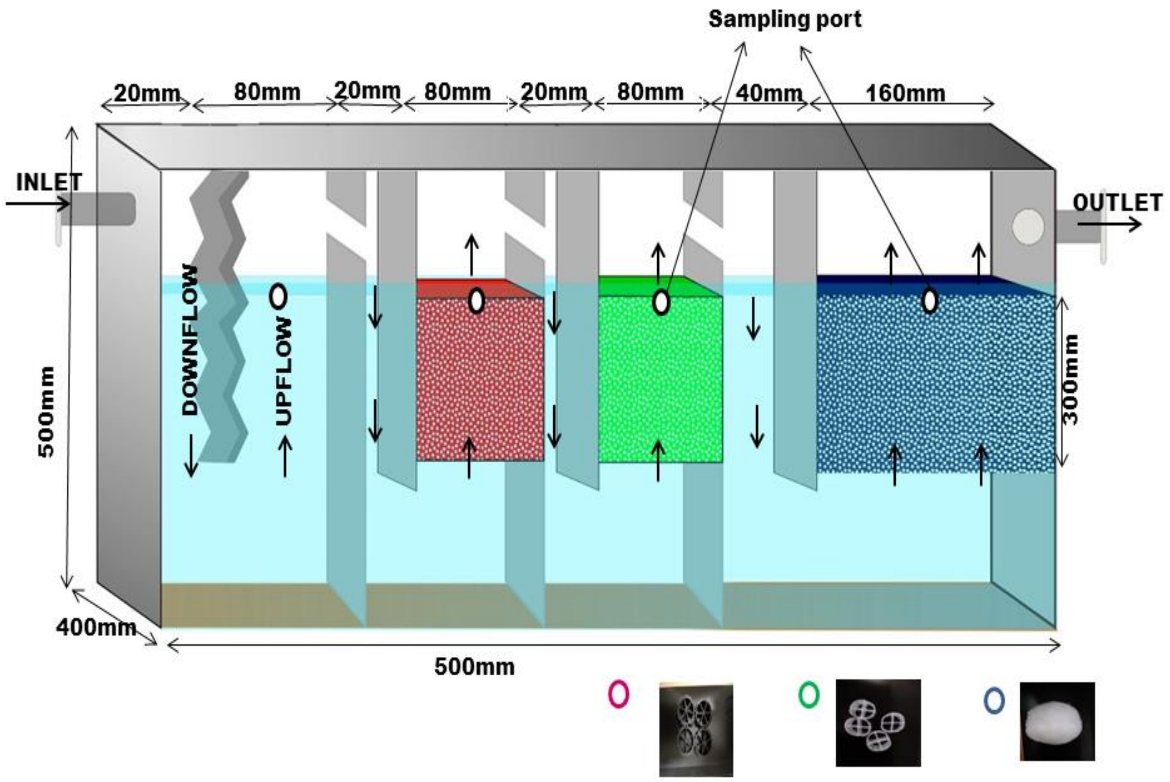


**Fig. 1. Schematic diagram of HABR**

**Table 1 Media characteristics**

| **Material** | **Polypropylene** | **Polypropylene** | **Polyethylene** |
|---|---|---|---|
| **Outer diameter** | **20mm** | **10mm** | **60mm** |
| **Inner diameter** | **18mm** | **8mm** | **-** |
| **Height** | **14.5mm** | **7mm** | **-** |
| **Density ($g/cm^3$)** | **0.97** | **0.98** | **0.96** |
| **Specific surface area** | **500 $m^2/m^3$** | **680 $m^2/m^3$** | **1000 $m^2/m^3$** |
| **Colour** | **black** | **White** | **White** |

| **Image** |  |  |  |
|---|---|---|---|

## 2.2. Experimental procedure

In the first stage, the residence time distribution studies by tracer stimulus-response technology were used to study the hydraulic characteristics of the reactor. The Ponceau 4R was used as the tracer throughout the study because the tracer will not be absorbed or will not react with the substances inside the reactor (6). The maximum absorbance of the Ponceau 4R was at 508 nm (7). The tracer was injected as pulse input within 10 seconds into the inlet. Then the samples were collected at constant intervals for two times the HRT. The samples were collected in all four compartments. The samples were absorbed using a UV-visible spectrophotometer at 508 nm, and the RTD curves were drawn for all four compartments. The above procedure was carried out in the HABR with and without media by varying the HRT to 4h, 8h, and 12h. The hydrodynamic indices were calculated using the axial dispersion model and tank in series model with reference to Table 2.

**Table 2 the hydrodynamic indices**

| S.No | Parameters | Equation | Reference |
|---|---|---|---|
| 1 | Mean cell residence time ($\tau$) | $\tau = \int_0^\infty tC(t)dt$ | (1,8-11) |
| 2 | Variance ($\sigma_m^2$) | $\sigma_m^2 = \int_0^\infty t^2C(t)dt - \tau^2$ | (1,8-11) |

| | | | |
|---|---|---|---|
| 3 | Dispersion number (d) | d=$(D\|uL)$ | (3,9,12) |
| 4 | Number of the continuous stirred tank in series (N) | N = $1/\sigma_{\theta}^{2}$ | (12) |
| 5 | Hydraulic efficiency (λ) | λ= e ( $1-(1/N)$ ) | (12 - 15) |

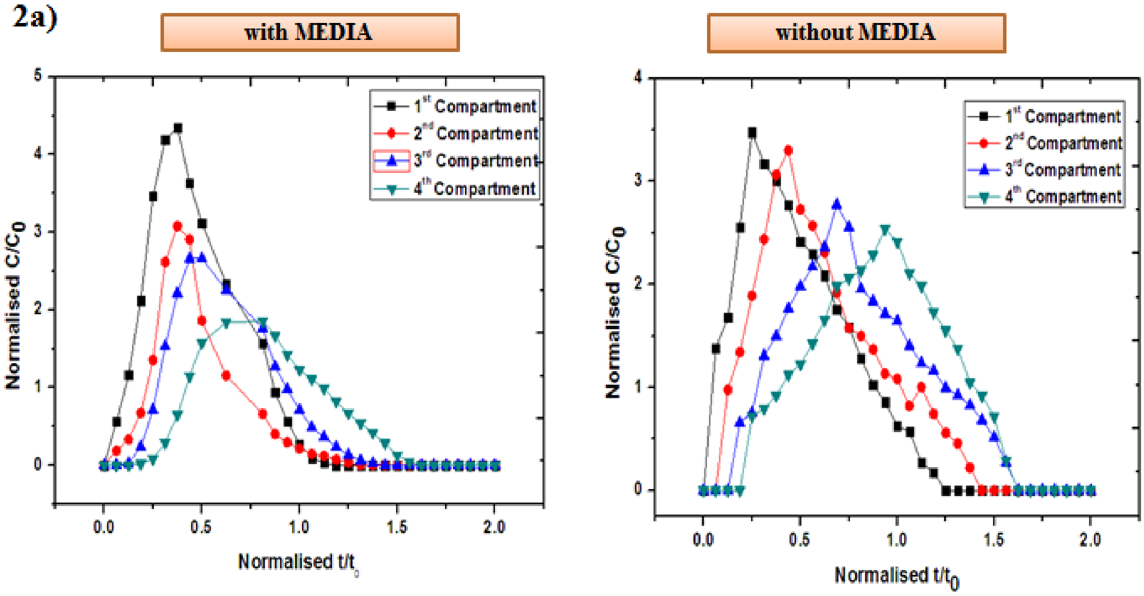
In the second stage, the experimental values obtained from all runs were evaluated using the Response Surface Methodology by central composite design. In the present study, CCD was used to study two parameters (HRT and Number of compartments) to evaluate four different responses.

## 3. Results and discussion

### 3.1. RTD study

The residence time distribution was used to study the hydraulic characteristics in the reactor. The RTD curves plot the normalised concentration against the normalised time. Fig. 2a-2c shows the RTD curves of HABR with and without media at different HRTs in all compartments. The normalised concentration drastically increases with respect to normalised time after reaching maximum value, the curve starts decreasing.

2a)


with MEDIA
without MEDIA
Normalised C/C0
Normalised t/t0
1st Compartment
2nd Compartment
3rd Compartment
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0
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5
0.0
0.5
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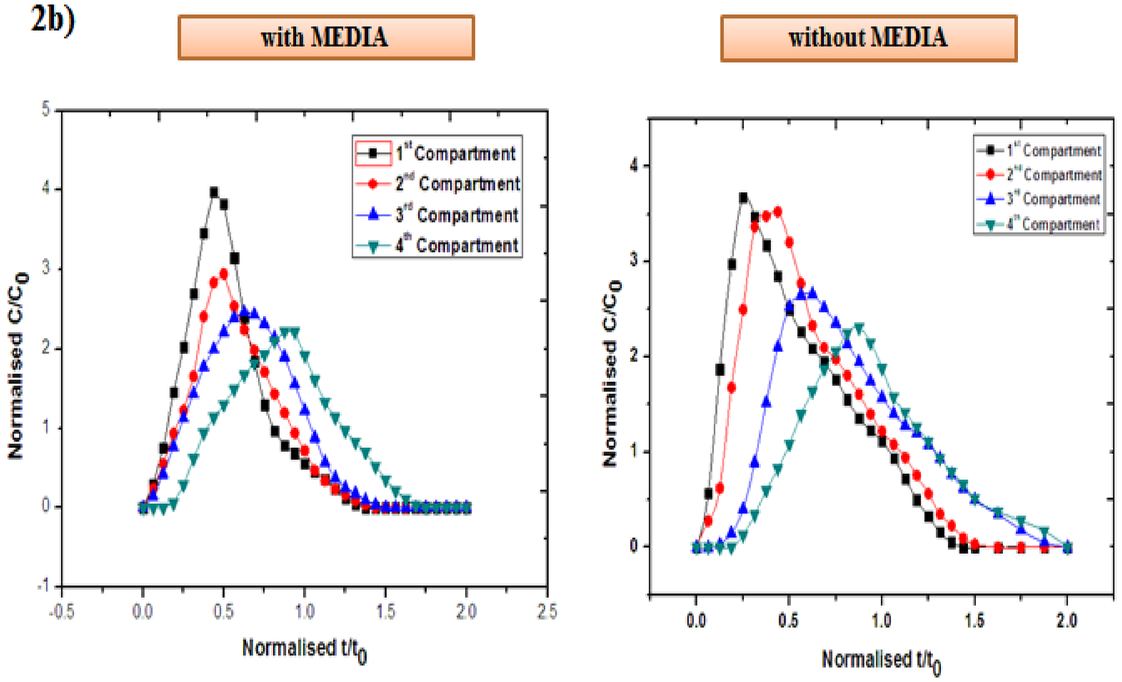
1.5
2.0

2b)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2c)

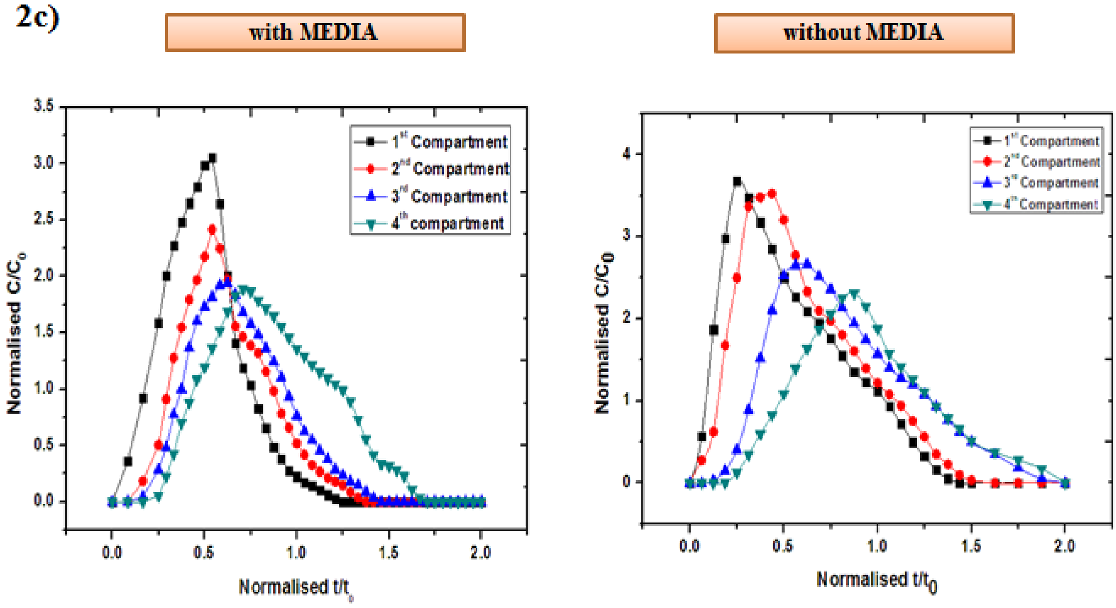


**Fig.2. RTD curves of ABR at a) 4h, b) 8h, c) 12 h**

The peak of normalised concentration appeared at θ = 0.4±0.1 and θ = 0.5±0.1 in the HABR with and without media in the second compartment. Also, the peak of normalised concentration occurs at θ = 0.8±0.1 and θ =0.9±0.1 in the HABR with and without media in the rear compartment. Thus it is evident that, the higher value of tail area in the HABR in the initial compartments leads to increase in dead space (16, 17). From Fig. 2a-2c, the tail-area decreases as the HRT increases, which was the cause of the decrease in dead space by increasing the HRT. Overall, there was only a marginal difference in RTD peaks by varying HRTs and media presence inside the reactor. However, there was a significant difference in RTD peaks by varying the number of compartments in the reactor. Thus the number of compartments in the reactor was the key factor in influencing the hydrodynamic behaviour of the reactor (3).

### 3.2. Dead space

The total dead space of any HABR was the summation of hydraulic dead space and biological dead space. The flow rate and the number of compartments highly influenced the hydraulic dead space whereas biological dead space was a function of biomass and hindrance of biomass particles (1,18). The addition of sludge inside the reactor had a meagre influence on creating biological dead space. Thus, the hydraulic dead space contributed more of the total dead space(19,20). In this study, the hydraulic dead space was calculated for HABR by varying parameters like the number of compartments, presence of media, and HRTs. The dead space ($V_d$) in the reactor is given in Eq. 1

$$V_d\ (\%) = (1- (\tau/HRT)\ ) \times 100 \qquad (1)$$

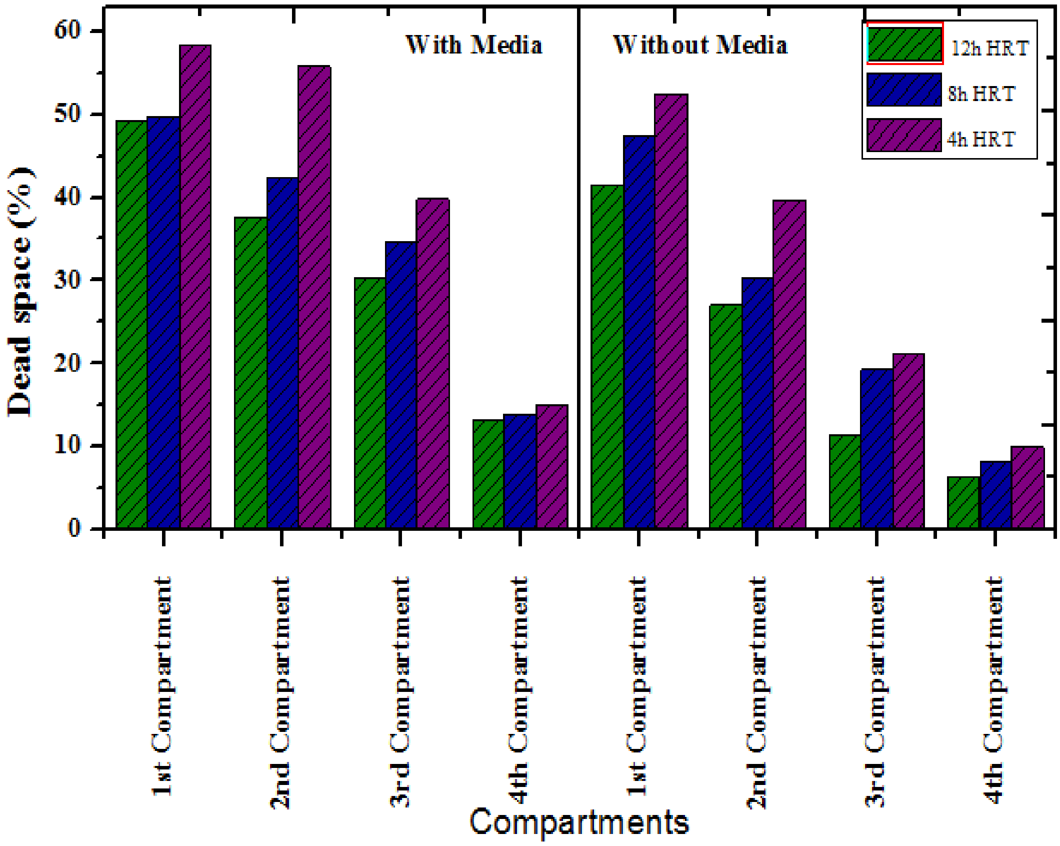


**Fig 3 Variation of Dead space at different conditions**

From Fig 3, it was observed that the dead space ranged from 58.3% to 6.4%. The higher value of dead space in the first compartment for 4 h HRT was due to the channelling effect in the reactor. The channelling causes stagnant eddies formation under weirs and in corners of the reactor. These eddies act as reservoirs where the tracer slowly diffuses in and out inside the reactor(3). The pattern of increase in dead space by decreasing the HRTs and number of compartments was observed to be the same in HABRs with media and without media. The dead space value was slightly higher in HABR with media (58.3% to 13.3%) due to the hindrance of media than in the HABR without media (52.5% to 6.4%). Hence the volume of HABR with media can be efficiently used as the HABR without media. From Fig 3, the number of compartments was the primary factor in creating dead space as the decrease in dead space was higher by increasing the number of compartments compared to the decrease in dead space by increasing the HRT.

### 3.3. Hydraulic models

To increase the treatment efficiency in the reactor, it was necessary to study its flow pattern inside the reactor. The state of flow condition in the reactor was determined by the models with the help of indexes found.

### 3.3.1. Axial Dispersion Model

The dispersion number (d) obtained from the axial dispersion model by varying HRT and the number of compartments is presented in Table 3. By increasing the number of compartments and HRT, the d value decreased. The lower value of d in the ABR with media was due to the media's hindrance, which lowered the dispersion inside the reactor. The hydrodynamic study on the eight chambered ABR was conducted by (3,19) in which they found out that the flow pattern was intermediate between completely mixed flow and plug flow. However, as the HRT or number of compartments increased, the reactor behaved well like a plug-flow reactor. Likewise, for all the runs, the d $= (D|uL)$ values were between 0.2>d>0.002 which leads to large dispersion and was intermediate between mixed flow and plug flow conditions in most of the chambers. But when the HRT increased, there was a decrease in flow rate causing lesser back mixing, which tend the reactor closer to plug-flow condition.

**Table 3 the indices obtained from the axial dispersion model**

| Compartment | HRT (h) | Mean retention time ($\tau$) (h) | Dispersion number (d) | Number of tank in series (N) | Hydraulic efficiency (λ) |
|---|---|---|---|---|---|
| 1(1) | 12 | 7.01 | 0.157 | 3.78 | 0.43 |
| 1(2) | 12 | 6.10 | 0.077 | 7.04 | 0.43 |
| 2(1) | 12 | 8.76 | 0.097 | 5.71 | 0.60 |
| 2(2) | 12 | 7.48 | 0.068 | 7.87 | 0.54 |
| 3(1) | 12 | 10.64 | 0.068 | 7.87 | 0.77 |
| 3(2) | 12 | 8.35 | 0.063 | 8.47 | 0.61 |
| 4(1) | 12 | 10.40 | 0.066 | 8.13 | 0.82 |
| 4(2) | 12 | 6.40 | 0.063 | 8.47 | 0.76 |
| 1(1) | 8 | 4.20 | 0.192 | 3.22 | 0.36 |
| 1(2) | 8 | 4.10 | 0.119 | 5.00 | 0.41 |
| 2(1) | 8 | 4.77 | 0.147 | 4.00 | 0.44 |
| 2(2) | 8 | 4.61 | 0.101 | 5.49 | 0.47 |
| 3(1) | 8 | 6.45 | 0.088 | 6.25 | 0.67 |
| 3(2) | 8 | 5.23 | 0.085 | 6.45 | 0.55 |
| 4(1) | 8 | 6.88 | 0.067 | 8.06 | 0.80 |
| 4(2) | 8 | 8.20 | 0.064 | 8.33 | 0.76 |
| 1(1) | 4 | 1.90 | 0.195 | 3.17 | 0.32 |

| | | | | | |
|---|---|---|---|---|---|
| 1(2) | 4 | 1.67 | 0.140 | 4.17 | 0.32 |
| 2(1) | 4 | 2.41 | 0.152 | 3.88 | 0.44 |
| 2(2) | 4 | 1.77 | 0.126 | 4.54 | 0.34 |
| 3(1) | 4 | 3.15 | 0.100 | 5.51 | 0.64 |
| 3(2) | 4 | 2.41 | 0.100 | 5.55 | 0.49 |
| 4(1) | 4 | 3.60 | 0.068 | 7.93 | 0.79 |
| 4(2) | 4 | 3.40 | 0.067 | 8.06 | 0.75 |

(1) ABR without media (2) ABR with media

### 3.3.2. TIS model

The number of tank in series (N) obtained from the tank in series model, and hydraulic efficiency (λ) is tabulated in Table 3. As the HRT increased, the N value increases, approaching the reactor towards plug flow condition. For all the runs, the N values of first and second compartments mostly lie between 3 and 4, approaching the reactor intermediate between CSTR and plug flow. The N values of the third and fourth compartments were >4 (8.47 to 5.51), indicating the flow in plug flow condition. When comparing the dispersion number (d) and number of tank in series (N) value, there was a major difference in d and N value between compartments and a meagre difference in d and N value when there was a variation in HRT and in presence and absence of media. Thus from the axial dispersion model and tank in series model, it was evident that number of compartments was the primary factor in influencing the hydraulic characteristics in HABR.

The hydraulic efficiency in the reactor explained the uniform distribution of flow within the reactor, optimum treatment efficiency, and the maximum contact time of the pollutant in the reactor [3,9]. From Table 3, it was evident that the flow had good hydraulic efficiency with λ > 0.75 in the fourth compartment in all the conditions, while in the third compartment, the flow had moderate hydraulic efficiency with $0.75< \lambda \geq 0.5$. In the first and second compartment $\lambda < 0.5$ and the flow has poor hydraulic efficiency.

## 4. Statistical Analysis

The response surface methodology had many classes like the Central Composite Design, Box-Behnken Design, Hybrid Design, and Three-Level Factorial Design. The central composite design was the most frequently used RSM design. In this study, the relationship between the variables (HRT, Number of chambers) and hydraulic responses like dead space, dispersion number, hydraulic efficiency, and the number of tank in series was found using the response surface methodology. In this study, all the experimental data obtained from the three runs in HABR with media and without media were analysed by RSM. Here, the HRTs 4h, 8h, 12h, and chambers 1-4 were used as the independent factors in RSM. The central composite design was used to develop a quadratic model for each response such as dead space, hydraulic efficiency, dispersion number and the number of tank in series to quantify the curvature effects for responses (20). The ANOVA results for the responses are tabulated in Table 4.

**Table 4 the ANOVA results obtained from response surface methodology**

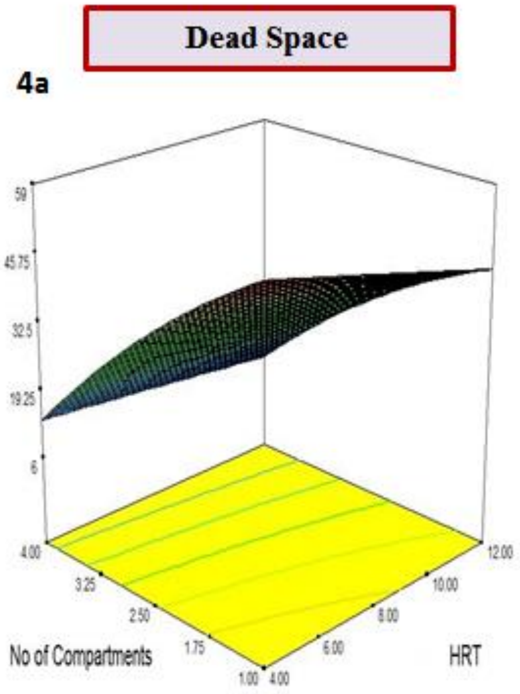
| **Responses** | **Equation** | **$R^2$** | **Adj $R^2$** | **Pred $R^2$** | **AP** | **CV%** | **F value** | **P-value** |
|---|---|---|---|---|---|---|---|---|
| **Dead Space** | $+73.25 -2.00A -8.50B +0.35AB -3.516E\text{-}003A^2 -1.45B^2$ | 0.869 | 0.833 | 0.788 | 14.31 | 21.23 | 24.06 | <0.0001 |
| **Dispersion number** | $+0.24 -2.219E\text{-}003A -0.06B +2.056E\text{-}003AB -4.648E\text{-}004A^2 +3.333E\text{-}003B^2$ | 0.750 | 0.681 | 0.497 | 10.11 | 22.71 | 10.84 | <0.0001 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Number of tank in Series** | $+2.21 -0.05A +0.91B -0.053AB +0.026A^2 +0.16B^2$ | 0.815 | 0.764 | 0.634 | 12.54 | 14.68 | 15.89 | <0.0001 |
| **Hydraulic efficiency** | $+0.14 +0.016A +0.087B -4.063E\text{-}003AB -5.078E\text{-}004A^2 +0.016B^2$ | 0.920 | 0.898 | 0.870 | 19.02 | 9.62 | 14.59 | <0.0001 |

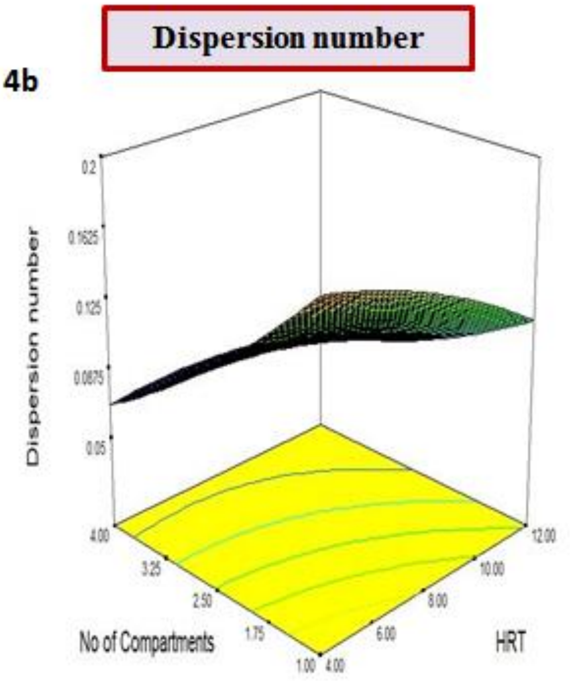
A-HRT (h) B-chambers

The significance of the model was determined by the F-values and values of probability >F. The values of probability >F of less than 0.05 indicated that the model terms were significant statistically. Table 4 P-value (the value of probability) was <0.0001, showing that the independent variables were significant at a 95% confidence level. The model F-value of the responses dead space, dispersion number, number of tank in series, and hydraulic efficiency were 24.06, 10.84, 15.89, and 14.59, and these values imply that the model was significant. Adeq precision measured the signal-to-noise ratio with a value greater than 4 was desirable. The AP values of 14.31 for dead space, 10.11 for dispersion number, 12.54 for number of tank in series, and 19.02 for hydraulic efficiency indicate an adequate signal. The pred R-squared values of 0.788 for dead space, 0.497 for dispersion number, 0.634 for number of tank in series, 0.870 for hydraulic efficiency were in reasonable agreement with the Adj R-squared value of 0.833 for dead space, 0.681 for dispersion number, 0.764 for number of tank in series, 0.898 for hydraulic efficiency. Fig. 4e-4h showed a good convergence between the actual(experimental) and predicted(model) values for the responses like dead space, dispersion number, number of tank in series, and hydraulic efficiency. The actual values were distributed closer to the straight line. The $R^2$ and adj.$R^2$ between the experimental and model predicted were close to 1.0. Hence the fit of model was verified and there was good consistency between the actual and predicted values of response surface assessment(20). The lower values of coefficient of variation (CV) (9.62%-22.71%) indicated reliability and good precision of the experiments. The combined efforts of HRT and different chambers on the dead space, dispersion number, number of tank in series, and hydraulic efficiency in HABR were given in Fig. 4a-4d. It was observed that the dead space was primarily influenced by number of chambers rather than the HRT. As the number of chambers increased, the dead space decreased. Hence, from the curvature effect of responses, it was again proved that number of compartments was the primary factor in influencing the hydraulic characteristics.

**4a**

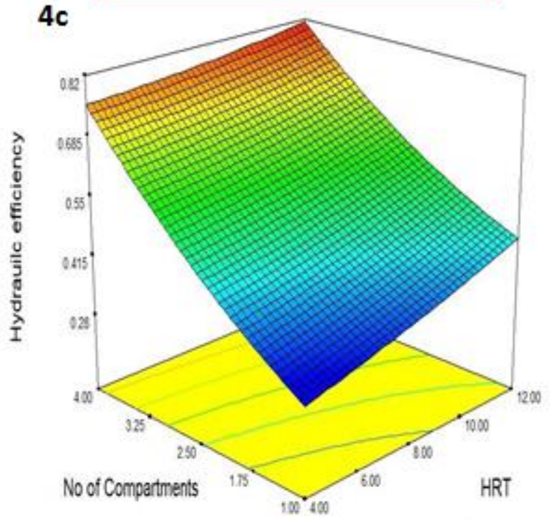


**4b**



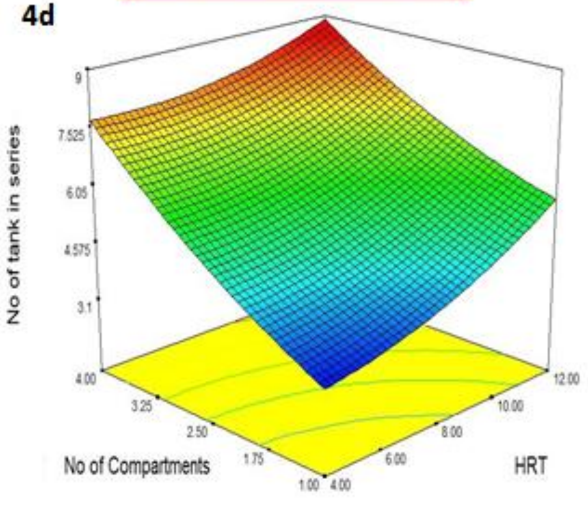
**Number of tank in series**

4c



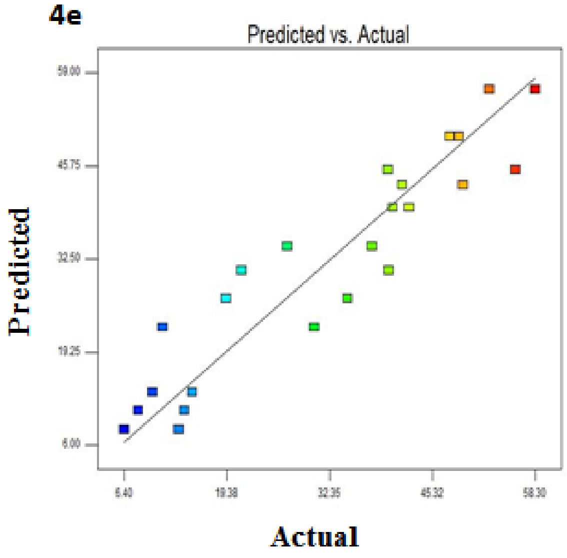
**Hydraulic efficiency**

4d



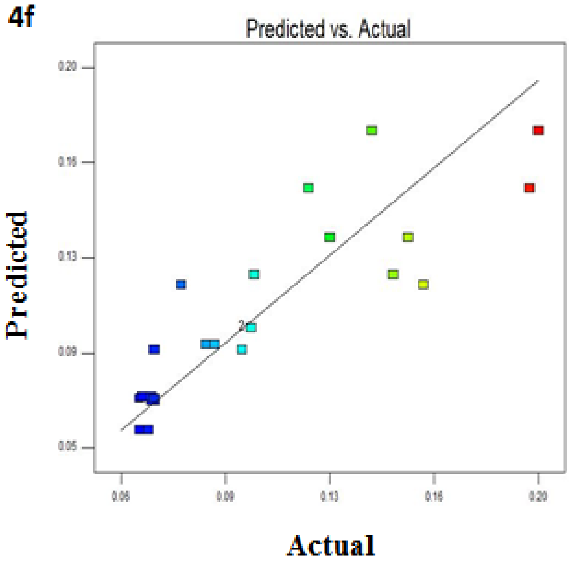
**Dead Space**

4e



**Dispersion number**

4f



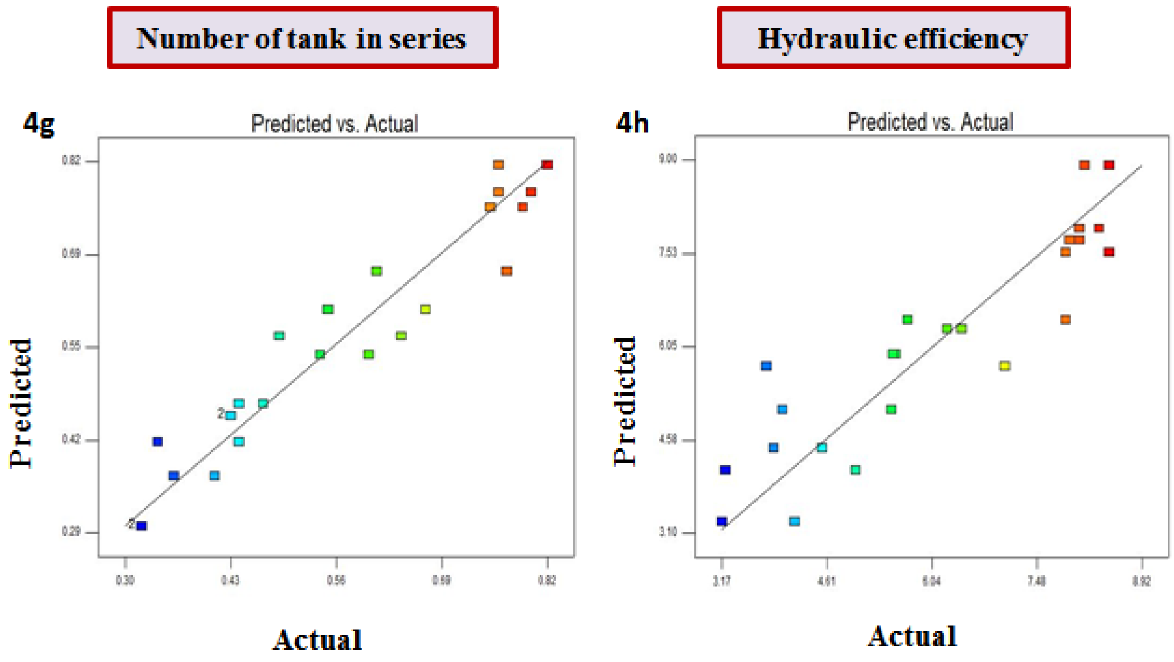


**Fig.4a-4d Surface and Contour plots of responses and 4e-4h Predicted vs Actual values of responses**

## 5. Conclusion

The dead space decreased as the HRT and number of compartments increases, and the dead space in ABR with and without media conditions showed only a marginal difference (within 0.5%). The results obtained show that the number of compartments in the reactor had greater influence in the reactor performance and the creation of dead space rather than the hydraulic retention time and the presence of media. The hydrodynamic characteristics studied by the axial dispersion and TIS model to find the state of condition in the reactor showed that the first, second, and third compartments were intermediate between the CSTR and plug-flow conditions. This condition states higher treatment efficiency in the ABR with media and without media. The ABR also showed a very good hydraulic efficiency after the third compartment with $\lambda>0.75$ by varying the HRTs. Hence the proposed ABR with and without media conditions works well with four compartments and can be effectively used to treat low strength, high strength, and refractory wastewater. The advantage of the presence of media by increasing the biomass contact with the substrate and by the results that the presence of media creates only a merge high dead space compared to the ABR without media, the proposed ABR with media condition has higher treatment efficiency compared to ABR without media condition. The central composite design analysis using RSM determines the interactive effects on the hydraulic responses like the dead space, dispersion number, number of tank in series, and hydraulic efficiency.

## Acknowledgment

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## Symbols

| | |
|---|---|
| $\theta$ | Normalised time, |
| t | Sampling time |
| HRT | Hydraulic retention time |
| $C_\theta$ | Normalised tracer concentration |
| $C(t)$ | Tracer concentration at time t |
| $C_0$ | Initial tracer concentration. |
| $\tau$ | Mean retention time |
| $\sigma_m^2$ | Variance |
| D | Axial dispersion coefficient, |
| $u$ | Average fluid velocity |
| L | Axial distance of the reactor |
| d | Dispersion number |
| Pe | Peclet number |

| | |
|---|---|
| N | Number of the continuous stirred tank in series |
| PI | Plug-flow Index |
| $\lambda$ | Hydraulic efficiency |
| $V_d$ | Dead Volume |
| e | Reactor effective volume |

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