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Optimization of Substrate Removal in Multi-Stage Complete Mix Biofilm Reactors Using Pseudo-Analytical Solutions

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Abstract:

A biofilm is an aggregation of microorganisms attached to a surface that plays a crucial role in natural and engineered ecosystems. This study applies a pseudo- analytical model to analyze the substrate removal efficiency and overall flux in different configurations of a Complete Mix Biofilm Reactor (CMBR). Configurations include single-stage, two-stage (series and parallel), and three-stage parallel reactors. A sensitivity analysis evaluates the influence of various parameters such as substrate concentration and reactor volume. Results demonstrate that multi-stage configurations outperform single-stage designs in substrate removal efficiency, with three-stage parallel configurations offering the best performance.

Keywords — **Biofilm, Pseudo-analytical model, Complete Mix Biofilm Reactor (CMBR), Substrate Flux, Sensitivity Analysis, Efficiency**

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Highlights

- Pseudo analytical modeling applied to CMBR configurations
- Single, two-stage (series/parallel), and three-stage parallel analyzed
- Sensitivity analysis conducted on inflow concentration and volume
- Efficiency calculated using substrate flux and output concentration
- Three-stage parallel configuration showed highest substrate removal

I. INTRODUCTION

Biofilms are structured communities of microorganisms embedded in a self-produced extracellular polymeric matrix. They adhere to interfaces and are commonly encountered in natural, medical, and industrial settings. In wastewater treatment, biofilms facilitate degradation of organic matter through microbial activity. Mathematical modeling is essential for predicting biofilm behavior and optimizing bioreactor configurations.

A schematic diagram of a biofilm structure typically includes the bulk liquid, boundary layer, biofilm, and substratum. Figure 1 illustrates this multi-layered system, showing the interactions between mass transfer and microbial zones.

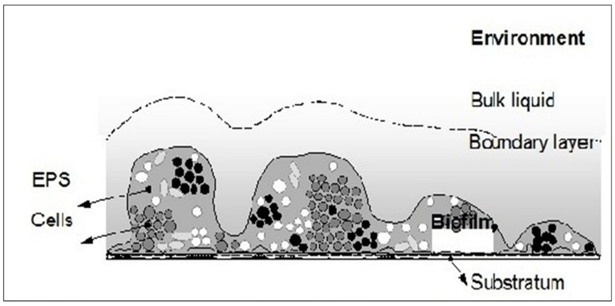

Figure 1: Biofilm structure showing bulk liquid, boundary layer, and substratum

II. METHODOLOGY

A. *Pseudo Analytical Solution*

The pseudo-analytical model is based on:

i. Monod kinetics for substrate utilization:

$$R = q_{max} \cdot \frac{S}{K_s + S} \cdot X$$

ii. Fick's law for diffusion:

$$\frac{d^2S}{dz^2} = \frac{1}{D} \cdot R$$

At steady state, the model reduces to algebraic equations involving dimensionless variables S^*, K^*, J^*, etc.

B. *Biofilm Conceptual Model*

The biofilm conceptual model includes substrate transport from the bulk fluid into the biofilm layer, internal diffusion, microbial growth, and decay. Figure 2 illustrates both the concentration profile and mass transport processes.

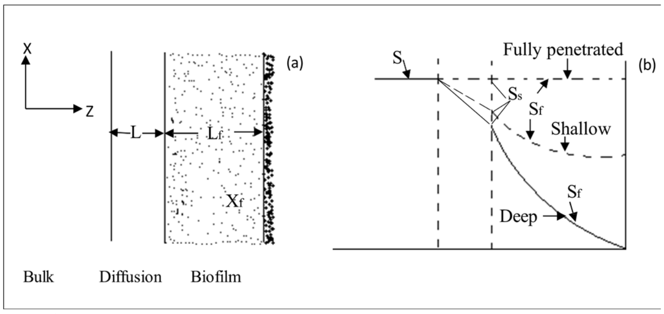

Figure 2: Substrate concentration profile, Mass transport and biofilm dynamics

4CMBR Configurations Analysed

i. Single-Stage
ii. Two-Stage Series
iii. Two-Stage Parallel
iv. Three-Stage Parallel

C. *Sensitivity Analysis*

A sensitivity analysis was performed for:

i. Substrate concentration (S^0)
ii. Reactor volume ratio (V_1/V)

III. RESULT AND DISCUSSION

The substrate flux (J_{ss}) and corresponding outlet concentration (S') were computed for each configuration. Efficiency was calculated as:

$$Efficiency = \left(\frac{S^0 - S'}{S^0}\right) \times 100\%$$

Graphs such as Efficiency vs. Volume Ratio for all configurations are shown in Figures 3 to 5.

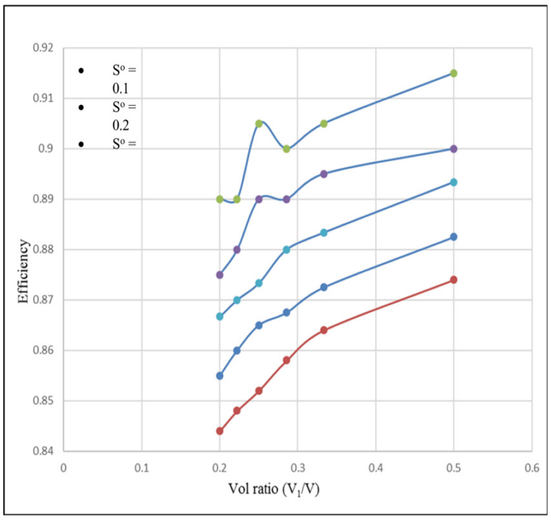

Figure 3: Efficiency vs Volume Ratio for Two-Stage Series Configuration

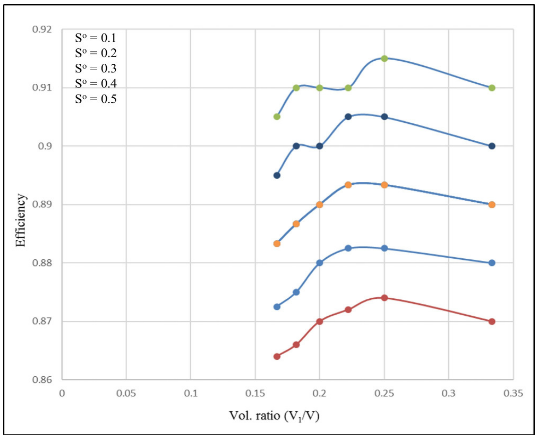

Figure 4: Efficiency vs Volume Ratio for Two-Stage Parallel Configuration

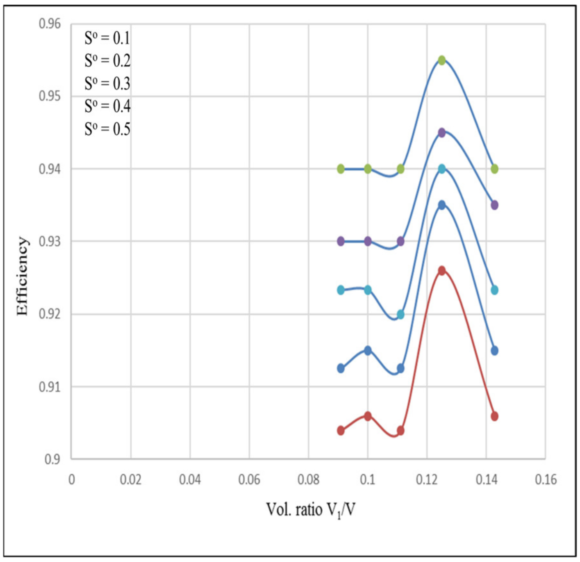

Figure 5: Efficiency vs Volume Ratio for Three-Stage Parallel Configuration

IV. CONCLUSIONS

The pseudo-analytical model offers a robust framework for evaluating different CMBR configurations. Sensitivity analysis indicates that substrate concentration and reactor volume are critical to optimizing reactor performance. Among the configurations tested, the three-stage parallel configuration consistently showed the highest substrate removal efficiency, making it ideal for advanced wastewater treatment systems.

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