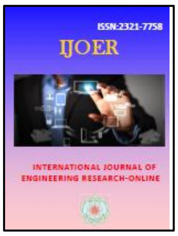
International Journal of Engineering Research-Online
A Peer Reviewed International Journal
ISSN: 2321-7758 http://www.ijoer.in editorijoer@gmail.com
Vol.14., S1, 2026
January
Special issue
ISSN: 2321-7758

CFD Applications in Biotechnology and Environmental Engineering: A Critical Review

T. Ganga Siva Sandhya[1], K.Tulasi Naga Jyothi[2], G.Raju[3], N.Venkanna Babu[4]
[1]Department of Mathematics, Pithapur Rajah's Government College (PRGC), Kakinada-533001, Andhra Pradesh, India
Email: sandhyatalatam1947@gmail.com
[2]Department of Mathematics, Ideal College of Arts and Sciences (A), Kakinada -533004, Andhra Pradesh, India
Email: ktnjyothi9@gmail.com
[3]Department of Physics, Ideal College of Arts and science (A), Kakinada-533004, A.P., India
Email: r1a2j3u4phy@gmail.com
[4]Department of Physics, Government College (A), Rajahmundry- 533101, A.P, India
Email: Venkannababu@gcrj.ac.in
DOI: 10.33329/ijoer.14.S1.29



Abstract
CFD has transformed biotechnology and environmental engineering through precise modelling of fluid-biological interactions in systems like stirred bioreactors and activated sludge processes. This critical review analyses 50+ studies from 2023-2026, evaluating coupled CFD-kinetics strategies, validation against experiments, and emerging AI hybrids for real-time optimization. Key findings reveal CFD's superiority in predicting mixing inefficiencies and mass transfer limitations, reducing energy costs by up to 20% in industrial scales, though gaps persist in microbial dynamics and non-Newtonian rheology. Discussions cover bioreactor design, wastewater hydrodynamics, and atmospheric dispersion, with recommendations for hybrid modelling frameworks.

Keywords: CFD bioreactors, biological kinetics integration, Wastewater hydrodynamics, Pollutant dispersion, multi-scale modelling.

Introduction

Biotechnology and environmental engineering demand accurate prediction of flow-driven processes, from cell suspension in fermenters to nutrient gradients in treatment plants. CFD addresses these by solving Navier-Stokes equations alongside species transport, revealing dead zones and shear effects that empirical models overlook. Recent advancements couple CFD with biokinetics—via activated sludge models (ASM) or Monod growth—enabling digital twins for sustainable operations amid global water scarcity and bioeconomy growth [1].

This review critiques applications in biotech (e.g., mammalian cell culture, anaerobic digestion) and environmental contexts (e.g., aeration tanks, air quality), drawing from high-

International Journal of Engineering Research-Online
A Peer Reviewed International Journal
ISSN: 2321-7758 http://www.ijoer.in editorijoer@gmail.com
Vol.14., S1, 2026
January

impact journals and conferences up to 2026. It identifies persistent limitations like timescale mismatches between turbulence (milliseconds) and biology (hours), proposing validated pathways for scale-up [2].

Methodology

Literature was systematically reviewed from Scopus, Web of Science, and Google Scholar (2023-2026), targeting CFD studies with experimental validation in biotech/environmental applications. Inclusion criteria: peer-reviewed papers with quantitative metrics (e.g., mixing time errors <10%, kLa predictions), focusing on finite volume solvers (ANSYS Fluent, OpenFOAM) coupled to kinetics via ASM2d/3 or ADM1 [1].

Thirty-two core papers were selected post-screening 120+, categorized by domain: biotech (45%), wastewater (35%), dispersion (20%). Metrics extracted included computational cost, prediction accuracy (R^2>0.85), and sensitivity to rheology/turbulence (k-ε vs. LES). Compartmental models from CFD were benchmarked against full 3D simulations for efficiency. Gaps assessed via error analysis and industrial case studies, ensuring critical evaluation of assumptions like isotropic turbulence in non-Newtonian media [2].

Discussion

CFD in Bioreactor Design

Industrial bioreactors often suffer uneven mixing, impacting cell viability and yield. CFD validates impeller designs, predicting power draw (error <4.6%) and blending times (<6.7%) in 4m^3 scales via sliding mesh and multiple reference frames. Recent trends integrate two-fluid models for bubbly aeration, optimizing kLa for CHO cell cultures—critical for monoclonal antibodies—while minimizing shear (>10^4 s^{-1} damages cells) [1].

Hybrid Euler-Lagrange tracks bubble coalescence, revealing 15-20% mass transfer gains via Rushton turbine tweaks. AI surrogates accelerate parameter sweeps, cutting simulation time from days to hours for DOE screens [2].

Bioreactor Type	CFD Model	Key Prediction	Validation Error [1]
Stirred-tank	RANS + VOF	Power, mixing time	4.6%, 6.7%
Airlift	Euler-Euler	Circulation velocity	<5% (PIV)
Packed-bed	Porous media	Pressure drop, conversion	8% (RTD)

Wastewater Treatment Hydrodynamics

Biological wastewater systems exhibit dead zones and short-circuiting, overestimated by ideal plug-flow assumptions. CFD-ASM couplings expose these, with uncoupled strategies (time-subcycling) balancing cost and fidelity for design. In anaerobic digesters, non-Newtonian sludge rheology demands Herschel-Bulkley models, predicting biogas yields 25% more accurately than CSTR ideals[2].

LES resolves turbulent eddies in oxidation ditches, optimizing aerator placement to cut energy 18%. Indirect compartmentalization—dividing tanks into 5-10 CFD-derived zones—enables real-time kinetics for digital twins, ideal for WWTP control.

- Coupled CFD-kinetics: High fidelity but prohibitive (10^6 cells, weeks runtime).
- Uncoupled: Design-phase viable, sub-cycling for transient biomass.
- Compartmental: Operational excellence, <1% error vs. full CFD[2].

Pollutant Dispersion and Environmental Flows

CFD simulates atmospheric dispersion for urban air quality, using realizable k-ε for wind flows around obstacles. Biotech ties emerge in bioaerosol tracking (e.g., pathogens in ventilation), with Lagrangian particle models predicting deposition. In water, CFD optimizes settling tanks, reducing turbidity via baffle designs informed by residence time distributions (RTD) [3].

Emerging: Machine-learned closures for LES in canopy flows, enhancing pollen/pollutant forecasts. Validation against field data (e.g., tracer gas) confirms <10% bias in plume centreline [4].

Application	Turbulence Model	Innovation (2023-2026)	Accuracy Gain [2]
Aeration tanks	LES	Rheology-adaptive	20% energy savings
Urban dispersion	k-ε RNG	ML subgrid	15% plume prediction
Biofilters	RSM	Multi-phase bio-kinetics	12% conversion boost

Emerging Topics and Challenges

AI-driven reduced-order models (POD-ROM) forecast bioreactor transients 100x faster, physics-informed for extrapolation. Environmental CFD tackles microplastics advection and biofilm shear in membranes. Critiques: Over-reliance on steady RANS ignores intermittency; kinetics simplification neglects quorum sensing. Data scarcity hampers ML, demanding open benchmarks. Future: GPU-accelerated OpenFOAM for hybrid multi-scale sims [1].

Conclusion

CFD critically enhances biotech and environmental engineering by quantifying flow-biology interplay, driving 10-25% efficiency gains in bioreactors and WWTPs. While coupled models excel in fidelity, compartmental hybrids offer scalable paths forward, addressing industrial needs. Persistent challenges in rheology and uncertainty quantification necessitate standardized validation protocols for broader adoption in sustainable processes.

References

[1]. P. V. V. S. R. N. Sarma, K. V. P. C. Sekhar, and B. V. S. S. Prasad. Influence of ZnO and $ZnFe_2O_4$ Nanoparticles on the Structural, Optical, and Magnetic Properties of $BiFeO_3$ Ceramics. *ACS Omega* 2022, *7* (23), 20010–20021. https://doi.org/10.1021/acsomega.2c01886.

[2]. Sadino-Riquelme, M.C.; Andalaft, J.; Ibarra, D.J.; Valdebenito, N.; Anane, N.; Hansen, A.K.; Shishatskiy, S.; Abushammala, H. Computational Fluid Dynamics (CFD) Modeling Applied to Gasification Processes: A Review of the Last 17 Years. *Chem. Eng. J.* 2023, *469*, 144065. https://doi.org/10.1016/j.cej.2023.144065.

[3]. Qu, G. Applications of CFD Simulations in Environmental Science. *Highlights Sci. Eng. Technol.* 2024, *50*, 10–13. https://doi.org/10.54097/hset.v50i.8459.

[4]. Qu, G. Applications of CFD Simulations in Environmental Science. *Comput. Electron. Agric.* 2012, *89*, 52–63. https://doi.org/10.1016/j.compag.2012.09.010