
SILICA-BASED MATRICES FOR MICROBIAL CELL ENCAPSULATION AND IMMOBILIZATION: A REVIEW

Utibeabasi Okonbaba¹, H. I. Atta¹, A.y. Atta¹, B. J. El-Yakubu^{1,*}

¹Ahmadu Bello University, Zaria

Email: utibeabasiokonbaba@gmail.com, hiatta@abu.edu.ng, ayatta@abu.edu.ng, byjibril@gmail.com*

*Corresponding author: B. J. El-Yakubu

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ABSTRACT

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Microbial cell immobilization confers protection, reusability, and enhanced tolerance to toxic and fluctuating environments, and is increasingly applied in bioremediation, biocatalysis, and fermentation. Silica and silica-hybrid matrices are attractive due to their mechanical strength, chemical stability, biocompatibility, and ability to shield cells from ultraviolet light and heavy-metal ions. This review examines silica-based precursors and matrices for microbial encapsulation, spanning sol–gel silicas (tetraethyl and tetramethyl orthosilicate, and the water-miscible THEOS), aminosilane (APTES) coatings applied layer-by-layer to alginate beads, silica–alginate hybrids, silica–poly(ethylene glycol) composites, and low-cost biosilica recovered from agro-industrial residues such as rice husk ash and sugarcane bagasse ash. Reported systems are compared by precursor purity, microbial compatibility, and encapsulation efficiency, cell viability, and mechanical stability. A recurring theme is the trade-off between porosity and stability: high porosity eases substrate diffusion but weakens the capsule, while dense matrices protect cells at the expense of mass transport, so that pore-forming additives are used to create this balance. Biosilica precursors offer low cost, antimicrobial character, and circular-economy benefits, though feedstock variability and purification remain limitations. The review confirms that silica matrices, especially porosity-engineered silica–alginate systems, are well suited to encapsulating hydrocarbon-degrading microorganisms to treat petroleum refinery effluent, and identifies controlling diffusivity, mechanical stability, and scale-up as the principal challenges to wider application.

Keywords: microbial encapsulation; silica–alginate matrices; cell immobilisation; sol–gel silica; hydrocarbon biodegradation

1. INTRODUCTION

Microbial cell immobilization retains viable microorganisms within a supporting phase while allowing access to substrates and products. Free cells can be lost through washout, sedimentation or shear, and may be inhibited by toxic pollutants in environmental biotechnology. Immobilized systems enhance biomass retention, boost recovery and permit repeated operation, depending on carrier properties and operating conditions (Partovinia & Rasekh, 2018; Wadhawan *et al.*, 2026; Abdulmumin *et al.*, 2025).

This review critically examines silica-based matrices for microbial cell encapsulation and immobilization, with emphasis on precursor chemistry, microbial compatibility, encapsulation performance, porosity, mass transfer, mechanical stability, reusability and hydrocarbon biodegradation. The specific objectives are to: (i) compare major silica and silica-hybrid matrix classes; (ii) identify agreements, disagreements and limitations in published studies; (iii) examine APTES-derived silica coatings on alginate capsules; (iv) assess the relevance of microbial consortia and low-cost biosilica; (v) identify engineering requirements for applying immobilized hydrocarbon-degrading microorganisms to petroleum-refinery effluent.

2. METHODOLOGY

The relevant literature concerning microbial encapsulation, immobilization, and silica-based matrices was found through targeted searches using keywords. Studies published mostly between 2018 and 2026 were chosen, and in some cases older foundational studies were included as well. Articles were selected on the basis of their relevance to microbial compatibility, matrix properties, mass

transfer, stability, hydrocarbon biodegradation, and wastewater treatment. The information from these studies was then arranged in structured literature tables and thematically combined in order to compare the different types of matrix, microbial performance, and application potential.

2.1 Silica-Based Matrices for Microbial Cell Encapsulation and Immobilization

Studies establish that microorganisms can remain metabolically active after incorporation into silica-based matrices. (Holzmeister et al., 2018) reviewed inorganic biohybrids, while (Li et al., 2020) investigated viable bacteria related to sawdust–silica for phenanthrene removal in soil. These findings support immobilization but highlight a major challenge: silica synthesis and matrix formation must be compatible with living cells. Alkoxide hydrolysis can generate alcohol, while sol–gel processing may involve conditions that stress microorganisms. (Wadhawan et al., 2026) emphasized that matrix chemistry, processing conditions and matrix properties determine the performance and useful lifetime of immobilized cells.

2.2 Sol–Gel Silica and Precursor Chemistry

TEOS and TMOS are common alkoxide precursors for sol–gel silica, while APTES introduces amine functionality and participates in silica–alginate hybrid formation. (Hernández-González et al., 2020) showed that TEOS/APTES ratios, water, and catalyst conditions affect silica–alginate hybrid structure and mechanical properties. (Abdulmumin et al., 2025) demonstrated that hydrolyzed APTES forms silica coatings on alginate capsules and that glucose can be used as a pore-forming agent to increase diffusivity. The evidence supports mixed precursor chemistry over absolute choice for one precursor. For microbial applications, precursor concentration, hydrolysis conditions, and coating architecture must be selected with cell tolerance and mass transfer requirements. (Dragomirescu et al., 2021)

2.3 Silica–Alginate and APTES-Based Hybrid Matrices

Alginate and silica provide complementary functions. Alginate offers mild ionic gelation and a hydrated environment, while silica reinforces the capsule and provides mechanical stability (Szopa et al., 2022; Hernández-González et al., 2020). Hybridization represents a rational compromise rather than a simple replacement of polymer by inorganic material. APTES is particularly relevant because it participates in silica formation and introduce surface functionality. (Abdulmumin et al., 2025) demonstrated that pore engineering of APTES-derived silica–alginate capsules increases diffusion. However, performance reported for fermentation systems should be transferred with caution to hydrocarbon treatment because hydrocarbons differ in solubility, hydrophobicity and partitioning behaviour. The transferable principle is that pore architecture should be designed around the actual substrate and process.

2.4 Porosity, Diffusion and the Protection–Transport Trade-Off

Mass transfer is a principal mechanism linking matrix architecture to biological performance. As illustrated in Figure 1, matrix architecture influences the balance between microbial protection and substrate transport, ultimately affecting biodegradation performance (Abdulmumin et al., 2025). A hydrocarbon must move from the bulk liquid to the capsule surface, traverse external and internal diffusion barriers, reach the cells, and allow metabolites to leave the matrix. A simplified description is given by Fick's first law:

$$J = -D_{\text{eff}} (dC/dx) \quad (1)$$

where J is the diffusive flux, D_{eff} is the effective diffusion coefficient in the matrix, C is the concentration of the transported species, and x is the diffusion distance.

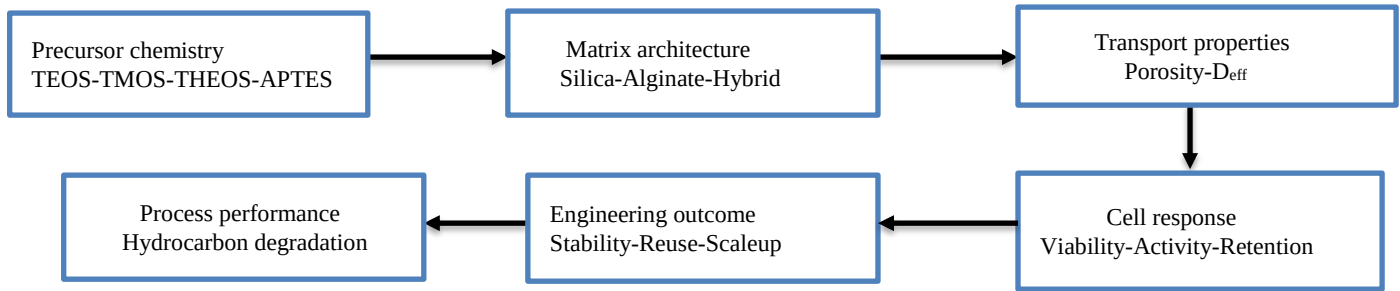


Figure 1: Conceptual relationship between silica precursor chemistry, matrix architecture, mass transfer, microbial response and engineering performance.

(Hernández-González et al., 2020)

2.5 Microbial Consortia and Hydrocarbon Biodegradation

Complex petroleum mixtures of various hydrocarbons justify microbial consortia because different organisms may possess synergistic catabolic pathways. (Tang et al., 2023) described synergistic metabolic functions in crude-oil biodegradation, while (Partovinia et al., 2023) showed that interactions among consortium members can include both synergism and antagonism. (Ganesh Kumar et al., 2019) reported crude-oil degradation using a self-immobilized hydrocarbonoclastic consortium, and (Partovinia et al., 2023) found that immobilization improved crude-oil biodegradation under their conditions. These findings favour functional screening over isolates selection. Consortium design should consider complementary degradation pathways, compatibility growth behaviour, and resistance to the intended wastewater conditions, therefore careful consortium and matrix design are core to improving stability and efficient petroleum hydrocarbon degradation. Consortium design should systematically investigate species ratio, individual and combined growth kinetics, inter-strain compatibility, complementary hydrocarbon-degradation activity, tolerance to relevant wastewater conditions (e.g., pH, salinity and hydrocarbon concentration), and consortium stability over repeated cultivation or treatment cycles. Compatibility can be assessed through pairwise co-culture or interaction tests before selecting the final consortium, while species ratios can be optimized by comparing degradation performance and biomass stability across defined inoculation ratios. (Haq et al., 2024) demonstrated hydrocarbon-removal potential in petroleum-refinery wastewater, while (Al-Mur et al., 2021) reported treatment of refinery wastewater using a hydrocarbon-degrading bacterial consortium under extreme conditions. An additional interpretive issue is the distinction between pollutant removal and biodegradation. Hydrocarbon concentration loss can arise from biological transformation as well as adsorption or partitioning into the carrier. (Younis et al., 2020) demonstrated the importance of partition behaviour in silica–alginate microbeads, while (Zhang et al., 2020) examined degradation by immobilized crude-oil-degrading bacteria. Future validation should therefore include abiotic, free-cell and matrix-only controls so that biological transformation is not inferred from concentration loss alone.

2.6 Evidence and Research Gap

Table 1: Comparative characteristics of some microbial immobilization carriers.

Matrix	Main advantage	Limitation	Evidence implication	Relevance to target
Alginate	Mild, cell-compatible gelation	Swelling; low mechanical strength	Good biological starting phase	High
Sol-gel silica	Rigidity; tunable porosity	Synthesis stress; diffusion barrier	Feasible but chemistry-sensitive	High
Silica-alginate	Combines hydration and strength	Porosity-strength trade-off	Strong hybrid strategy	Very high
APTES-silica coating	Functional coating; tunable architecture	Coating thickness must be controlled	Promising for pore-engineered capsules	Very high
Si-PEG hybrid	Organic-inorganic compatibility	More complex formulation	Useful where flexibility is needed	Moderate
Biosilica	Potentially low-cost and circular	Purity/feedstock variability	Requires standardization	Future option

Table 1 shows the key design trade-offs, silica-alginate hybrids emerge as promising systems because alginate supports microbial compatibility while silica enhances mechanical stability. Biosilica from agricultural residues is also promising and potentially attractive because rice-husk and sugarcane-bagasse residues can provide silica feedstocks, although their feedstock composition and purification require standardization (Nzereogu et al., 2023; September et al., 2023; Taiye et al., 2024). The main research gap lies in enhancing hydrocarbon transport especially for poorly water-soluble petroleum hydrocarbons. This gap justifies evaluating APTES-based encapsulation for treating petroleum-contaminant. Relevance to the target was assessed qualitatively based on material cost, microbial compatibility, suitability for hydrocarbon biodegradation, and maturity of supporting evidence. “Very high” indicates strong overall suitability and evidence, while “Moderate” or “Future option” reflects greater limitations or less mature evidence.

Table 2: Representative microbial immobilization matrices and performances

Carrier / matrix	Target system and microorganism	Reported quantitative performance	Reference
Agar	Waste lubricating-oil-contaminated soil; <i>Paenibacillus</i> sp. OL15	45 ± 3% degradation after 30 days	(September et al., 2022)
Alginate	Diesel-contaminated groundwater; <i>Pseudomonas aeruginosa</i>	71.2% diesel degradation after 10 days; suspended cells achieved 32.0% after 30 days	(Park et al., 2021)
PVA–alginate–clay	Crude-oil system; marine bacterial isolates	74.0–66.6% degradation with PVA–alginate; up to 78.8–75.0% with attapulgate-containing beads	(Farid et al., 2024)
Silica-containing carrier	Phenanthrene-contaminated soil; bacteria immobilized on Sawdust@silica	>95% phenanthrene removal after 48 h; adsorption–degradation was reported as the dominant mechanism	(Li et al., 2020)

Table 2, shows, that immobilized systems outperform free-cells in hydrocarbon removal or degradation under specific conditions. However, comparing matrices is flawed due to differing microorganisms, hydrocarbons, matrix composition, incubation periods and analytical methods. Silica-containing systems stand out combining high pollutant removal with matrix stability and tunable transport characteristics. Quantitative evidence supports their enhanced transport capabilities: pore forming modification of an APTES derived silica–alginate capsule increased characteristics when appropriately engineered; for example, pore-forming modification of an APTES-derived silica–alginate capsule increased the diffusion coefficient by approximately 3.2-fold at 308 K, pH 5, and 150rpm demonstrating that silica reinforcement does not necessarily impose mass-transfer penalty (Abdulmumin et al., 2025).

3. FUTURE OUTLOOK

3.1 Advanced Controlled Matrix and Smart Materials

Future trend should focus on matrices that can be tuned to provide controlled mass transfer, mechanical stability, durability and practical recovery. This includes advances in pore engineering, such as the use of pore-forming agents demonstrated for APTES-derived silica–alginate capsules. (Abdulmumin et al., 2025). Reusability, stability, separation and scale-up are also identified as continuing challenges (Wadhawan et al., 2026; Abdulmumin et al., 2026). Magnetic or other recoverable hybrid matrices may offer additional routes to reuse, but their suitability for refinery wastewater should be established experimentally rather than assumed. Future studies should therefore prioritize long-term repeated-use testing, real-effluent validation and assessment of adsorption versus genuine biodegradation. Immobilized bacterial pellets have also shown promise for petroleum-contaminated soil remediation, although such evidence should be treated as complementary rather than direct evidence for silica systems (Zhao et al., 2024).

4. CONCLUSION

The review shows that silica-based matrices are promising platforms for microbial cell immobilization because their structural and surface properties can be controlled to provide protection while maintaining biological accessibility. The literature supports improved biomass retention and operational robustness with immobilized systems, but it does not establish that immobilization is universally superior to free cells. The principal determinant is whether matrix system permits substrate and product transport while maintaining cell viability and mechanical stability. Various matrix systems each offer unique advantages: sol–gel silica, silica–alginate hybrids, APTES-derived coatings, and other silica–polymer systems. Among these, porosity-controlled silica–alginate systems provide a strong basis for hydrocarbon treatment because they combine a hydrated, cell-compatible phase with an inorganic reinforcing network. APTES is therefore a choice precursor for the proposed silica-coated microbial cell, provided that coating thickness, porosity and synthesis conditions are controlled. Microbial consortia should be selected for synergistic hydrocarbon-degrading functions rather than simply for species number. Future work should experimentally establish diffusivity, viability, mechanical stability, hydrocarbon biodegradation, adsorption controls and reusability under petroleum-refinery conditions before scale-up to continuous treatment.

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