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Microbial biodeterioration of diesel and biodiesel during storage

Biodeterioração microbiana de diesel e biodiesel durante o armazenamento

Biodeterioro microbiano de diésel y biodiésel durante el almacenamiento

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ABSTRACT

Objective: To critically examine the scientific structure, thematic evolution, and emerging monitoring and mitigation strategies of microbial biodeterioration in diesel, biodiesel, and diesel–biodiesel storage systems. **Methods:** An integrative review with bibliometric and scientometric analysis used records from the Web of Science Core Collection. Studies were screened according to PRISMA 2020 and analysed with VOSviewer. **Results:** The final corpus comprised 51 original research articles published up to December 31, 2025. Scientific production increased markedly between 2020 and 2025, with a transition from studies focused on fuel instability and microbial contamination toward an interdisciplinary field integrating microbial ecology, biofilm formation, fuel degradation, sludge and deposit accumulation, microbiologically influenced corrosion, and mitigation strategies. Water accumulation and the fuel–water interface emerged as central factors in microbial colonization and biofilm development, while molecular detection, spectroscopy, biosensors, corrosion assessment, and predictive modelling gained increasing relevance. **Final considerations:** The evidence indicates persistent fragmentation among microbiological, physicochemical, corrosion, and operational assessments. Future research should prioritize standardized sampling and integrated monitoring combining molecular methods, FTIR/NIR spectroscopy, biosensors, corrosion monitoring, deposit characterization, and predictive modelling to support early warning, preventive control, and data-driven fuel-storage management.

Keywords: Biofilms, Biofuels, Environmental monitoring, Corrosion, Biodegradation, Environmental.

RESUMO

Objetivo: Analisar a estrutura científica, a evolução temática e as estratégias emergentes de monitoramento e mitigação da biodeterioração microbiana em sistemas de armazenamento de diesel, biodiesel e misturas diesel–biodiesel. **Métodos:** Foi realizada uma revisão integrativa com análise bibliométrica e cienciométrica utilizando registros da Web of Science Core Collection. Os estudos foram triados segundo o PRISMA 2020 e analisados com o VOSviewer. **Resultados:** O corpus final compreendeu 51 artigos originais publicados até 31 de dezembro de 2025. A produção científica aumentou entre 2020 e 2025, acompanhada por uma transição de estudos centrados na instabilidade do combustível e na contaminação microbiana para um campo interdisciplinar que integra ecologia microbiana, formação de biofilmes, degradação do combustível, acúmulo de lodo e depósitos, corrosão influenciada microbiologicamente e estratégias de mitigação. O acúmulo de água e a interface combustível–água emergiram como fatores centrais na colonização microbiana e no desenvolvimento de biofilmes, enquanto detecção molecular, espectroscopia, biossensores, avaliação

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da corrosão e modelagem preditiva ganharam relevância. **Considerações finais:** Persistem fragmentações entre avaliações microbiológicas, físico-químicas, de corrosão e operacionais. Pesquisas futuras devem priorizar amostragem padronizada e monitoramento integrado para apoiar alerta precoce, controle preventivo e gestão orientada por dados.

Palavras-chave: Biofilmes, Biocombustíveis, Monitoramento Ambiental, Corrosão, Biodegradação Ambiental.

RESUMEN

Objetivo: Analizar la estructura científica, la evolución temática y las estrategias emergentes de monitoreo y mitigación del biodeterioro microbiano en sistemas de almacenamiento de diésel, biodiésel y mezclas diésel–biodiésel. **Métodos:** Se realizó una revisión integrativa con análisis bibliométrico y cienciométrico utilizando registros de Web of Science Core Collection. Los estudios fueron seleccionados según PRISMA 2020 y analizados con VOSviewer. **Resultados:** El corpus comprendió 51 artículos publicados hasta el 31 de diciembre de 2025. La producción aumentó entre 2020 y 2025, con una transición desde estudios centrados en la inestabilidad del combustible y la contaminación microbiana hacia un campo interdisciplinario que integra ecología microbiana, formación de biopelículas, degradación del combustible, acumulación de lodos y depósitos, corrosión influenciada microbiológicamente y mitigación. La acumulación de agua y la interfaz combustible–agua surgieron como factores centrales en la colonización microbiana y el desarrollo de biopelículas, mientras que la detección molecular, la espectroscopia, los biosensores y la modelización predictiva adquirieron relevancia. **Consideraciones finales:** Persisten fragmentaciones entre evaluaciones microbiológicas, fisicoquímicas, de corrosión y operativas. Las investigaciones futuras deben priorizar muestreo estandarizado y monitoreo integrado para favorecer la alerta temprana, el control preventivo y la gestión basada en datos.

Palabras clave: Biopelículas, Biocombustibles, Monitoreo ambiental, Corrosión, Biodegradación ambiental.

INTRODUCTION

The increasing incorporation of biodiesel into diesel fuels has created new challenges for fuel quality during storage and distribution. Although biodiesel is a renewable component with low sulfur content and favorable biodegradability, its composition, predominantly fatty acid methyl esters, increases susceptibility to oxidation, hydrolysis, water retention and microbial colonization. These processes are especially relevant during prolonged storage, when water accumulation and changes in fuel composition can promote physicochemical instability, acidity, deposit formation and biological growth. Consequently, deterioration of diesel–biodiesel blends should be understood as the result of interacting chemical and biological mechanisms rather than as a single fuel-property alteration (KNOTHE G, 2010; ATABANI AE, et al., 2012; OGUNKUNLE O e AHMED NA, 2019).

Microbial biodeterioration is a dynamic process governed by fuel composition, water availability, temperature, storage time, nutrient availability and the materials present in tanks, pipelines and distribution systems. Free or emulsified water is particularly important because it favors bacterial and fungal growth at the fuel–water interface. Microbial metabolism can generate biomass, extracellular products and metabolites associated with sludge, filter clogging, acidity and compositional changes (BENTO FM e GAYLARDE CC, 2001; PASSMAN FJ, 2013; KOMARIAH LN, et al., 2022). Biofilms further increase microbial persistence on tank walls, pipelines, filters and metallic surfaces and may contribute to microbiologically influenced corrosion (MIC). Under oxygen-limited conditions, sulfate-reducing bacteria and other corrosive consortia can intensify material deterioration and threaten storage-system integrity (FLEMMING HC, et al., 2016; ENNING D e GARRELFS J, 2014; LEE JS, et al., 2010; KNISZ J, et al., 2023).

Despite substantial advances, fuel instability, microbial ecology, biofilm development, deposit formation, corrosion and mitigation are frequently investigated as separate domains. This fragmentation limits comparison among studies and complicates the establishment of standardized monitoring criteria and preventive strategies. Technical guidance such as ASTM D6469-24 emphasizes the need to recognize the occurrence, consequences, detection and control of microbial contamination in fuels, but current evidence remains

distributed across microbiological, physicochemical and engineering approaches (ASTM D6469-24, 2024). Bibliometric and network-based analyses can help integrate these domains by identifying influential studies, collaboration patterns, thematic clusters and emerging technologies while supporting a critical synthesis of unresolved gaps (VAN ECK NJ e WALTMAN L, 2010; DONTHU N, et al., 2021).

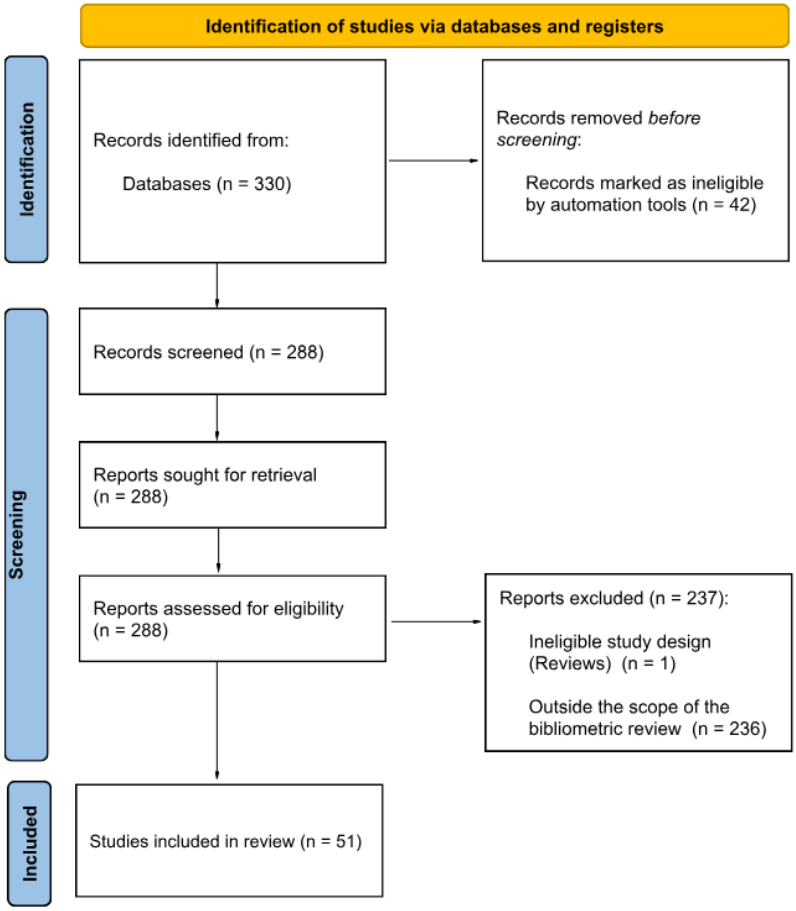
Accordingly, the guiding question was: how have scientific production, thematic axes and monitoring and mitigation strategies for microbial biodeterioration in diesel, biodiesel and diesel–biodiesel storage systems evolved, and which scientific and technological gaps remain? This integrative review with bibliometric and scientometric analysis aimed to characterize the structure and temporal evolution of the field, relate microbial contamination, biofilms, degradation, deposits and MIC, identify emerging analytical and control technologies, and define priorities for integrated, preventive and predictive fuel-storage management.

METHODS

Study design and guiding question

This study was designed as an integrative literature review with bibliometric and scientometric analysis. The review addressed the guiding question defined in the Introduction and combined a structured literature search, predefined eligibility criteria, critical synthesis and network analysis. Study identification, screening, eligibility assessment and inclusion were reported with reference to PRISMA 2020 to improve transparency, traceability and reproducibility of the selection process (PAGE MJ, et al., 2021). PRISMA was used as a reporting framework and not to classify the study as a conventional systematic review. No formal review protocol was registered. The study-selection process is summarized in **Figure 1**.

Figure 1 - PRISMA flow diagram of the study selection process.



Source: Silva GVC, et al., 2026.

Information source and search strategy

The literature search was performed on June 5, 2026, in the Web of Science Core Collection (WoSCC), selected because of its standardized multidisciplinary citation metadata and compatibility with bibliometric tools (BIRKLE C, et al., 2020; MONGEON P e PAUL-HUS A, 2016). The Web of Science Topic field was used, covering titles, abstracts, author keywords and Keywords Plus. The search combined descriptors for fuels, biodeterioration structures and control processes. The final strategy was: (("biodiesel" OR "diesel" OR "biofuel*") AND ("biofilm*" OR "sludge" OR "gum*") AND ("origin*" OR "formation*" OR "composit*" OR "biocide*" OR "antimicrobial*" OR "control*" OR "mitigat*") NOT ("production" OR "waste water" OR "sewage" OR "soil*" OR "jet")). The unrestricted search retrieved 330 records. Automated filters limited the dataset to publications issued through December 31, 2025 and to original research articles containing primary empirical data. Reviews, conference proceedings, book chapters, letters and editorials were excluded, and no language restriction was applied. After filtering, 288 records remained for manual screening.

Eligibility criteria and study selection

Original studies were included when they directly addressed microbial biodeterioration, microbial contamination, biofilm formation, sludge or deposit formation, microbial degradation, MIC, or mitigation and control in diesel, biodiesel or diesel–biodiesel systems. Studies centered on biofuel production, wastewater treatment, soil bioremediation, crude hydrocarbons, aviation fuels or general hydrocarbon degradation without a direct connection to diesel or biodiesel fuel systems were excluded. Titles and abstracts were screened sequentially, with full texts evaluated when scope or eligibility remained uncertain. A total of 237 records were excluded, and 51 original articles composed the final analytical corpus.

Data extraction and bibliometric analysis

The included records were exported as tab-delimited “Full Record and Cited References” files. Extracted metadata comprised authors, article titles, publication years, journals, institutional affiliations, countries, abstracts, author keywords, Keywords Plus, citation counts and cited references. These variables supported analyses of productivity, impact, collaboration, thematic organization and intellectual structure. Bibliometric mapping was performed in VOSviewer version 1.6.20 using full counting and association-strength normalization (VAN ECK NJ e WALTMAN L, 2010; PERIANES-RODRIGUEZ A, et al., 2016). Analyses included document citation (minimum five citations), organizational co-authorship (minimum one document), country-level bibliographic relationships (minimum one document), keyword co-occurrence (minimum two occurrences; 32 terms) and bibliographic coupling (minimum six citations; 30 structurally relevant documents). A customized thesaurus standardized synonyms, acronyms, spelling variants, plural forms and taxonomic inconsistencies, including MIC/biocorrosion and SRB/sulfate-reducing bacteria. Generic or tangential terms with limited analytical relevance were excluded from the keyword network. Scientific productivity was assessed by document counts, citation impact by total and mean citations, and network connectivity by total link strength. The resulting maps and indicators were interpreted together with the selected literature to categorize thematic fronts, technological transitions, industrial implications and research gaps (DONTHU N, et al., 2021; KESSLER MM, 1963).

RESULTS AND DISCUSSION

Selection of studies and general characterization of the corpus

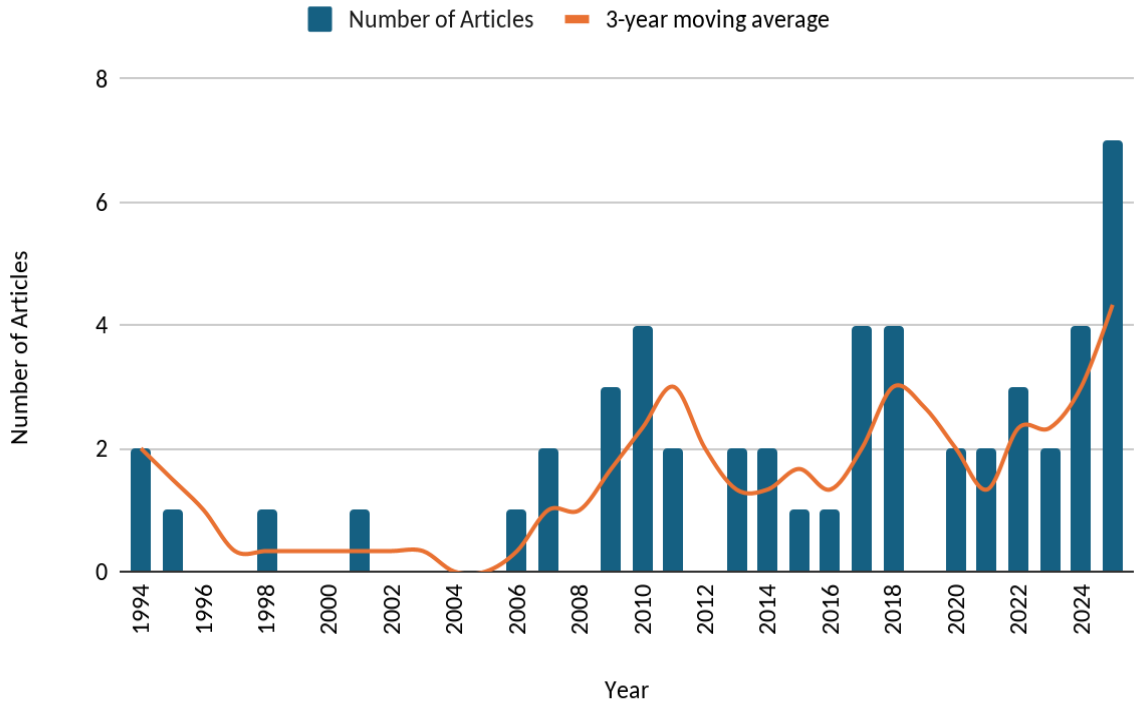
The structured search identified 330 records. Automated filtering by publication period and document type retained 288 original articles for manual eligibility assessment. Sequential screening of titles, abstracts and, when necessary, full texts excluded 237 records outside the predefined thematic criteria, resulting in a final corpus of 51 original articles published through December 31, 2025 (**Figure 1**). The high exclusion rate reflects the intentionally narrow focus on storage-associated microbial biodeterioration rather than adjacent topics such as biofuel production, wastewater treatment, soil bioremediation, crude hydrocarbons or aviation fuels. The final dataset supported all subsequent bibliometric and critical analyses of temporal evolution, scientific influence, collaboration, thematic organization and technological development (PAGE MJ, et al., 2021).

Changes in scientific production over time

Scientific production showed an irregular but progressively expanding trajectory (**Figure 2**). Four broad phases were evident. From 1994 to 2006, publications were sparse and focused mainly on fuel instability, sediment formation, oxidative deterioration and early recognition of microbial contamination.

Between 2007 and 2012, more regular publication activity accompanied wider biodiesel adoption, with greater attention to water retention, biodegradation and microbial proliferation. The increase observed around 2009–2010 marked growing concern with the biological susceptibility of diesel–biodiesel blends and with the role of interfacial water in colonization and corrosion (PASSMAN FJ, 2013; LEE JS, et al., 2010; SØRENSEN G, et al., 2011).

Figure 2 -Temporal evolution of scientific production on microbial biodeterioration in diesel and biodiesel systems.



Note: The blue line shows the annual number of articles included in the final corpus, while the orange line indicates the three-year moving average.
Source: Silva GVC, et al., 2026.

From 2013 to 2018, the field shifted from descriptive contamination surveys toward mechanistic and applied studies of interfacial biofilms, microbial community structure, biocide efficacy and simulated storage. Influential investigations connected diesel–biodiesel degradation, sessile biofilms and antimicrobial control, demonstrating that biodeterioration depends on both fuel composition and microbial persistence (ZIMMER A, et al., 2013; BÜCKER F, et al., 2014; ZIMMER AR, et al., 2017).

The 2020–2025 period exhibited the most sustained growth and culminated in the highest annual output in 2025. Research increasingly connected fuel chemistry, microbial ecology, MIC, materials science and diagnostic monitoring.

Overall, the trajectory indicates a transition from isolated instability and contamination studies toward integrated risk management in which water accumulation, biofilm persistence, sludge formation, fuel degradation and corrosion are treated as interacting processes. The contemporary emphasis on early detection and predictive monitoring reflects the need to protect both fuel specification and storage infrastructure (KNISZ J, et al., 2023).

Journals, influential documents, and institutional organization

Publication and citation patterns confirm the multidisciplinary structure of the field. Fuel was the most productive journal in the corpus, with four articles and 72 citations, whereas Energy & Fuels accumulated 120 citations. International Biodeterioration & Biodegradation remained a central venue for microbial degradation and biofilm studies, while Industrial & Engineering Chemistry Research showed high citation density. Together, these venues position biodeterioration at the intersection of fuel science, applied microbiology, corrosion engineering and storage reliability.

Citation analysis identified Lee JS, et al. (2010) as the most cited document in the corpus (57 citations), followed by Bücker F, et al. (2014) (42), Zimmer A, et al. (2013) (30) and Zimmer AR, et al. (2017) (19). Collectively, these studies established key links among microbial contamination, alternative fuel formulations, biodegradation, biofilm formation, corrosion and biocide-based control. Their influence shows that the intellectual core of the field is organized around three applied concerns: contamination and fuel-specification loss, biofilm persistence and deposits, and technological mitigation.

Institutional productivity was similarly concentrated. Institut Teknologi Bandung led with five articles; Universidade Federal do Rio Grande do Sul published three articles and accumulated 91 citations; and the National Research Centre reached 104 citations. The presence of Ipiranga Produtos de Petróleo among the leading institutions also indicates direct industrial participation in research on fuel degradation, specification compliance and microbial control. Overall, scientific influence is organized around specialized journals, seminal applied studies and a limited number of institutional hubs, consistent with a field moving from isolated microbiological observations toward multidisciplinary fuel-quality and asset-management research (PASSMAN FJ, 2013; DONTHU N, et al., 2021).

Geographical distribution and collaboration networks

The geographic distribution was broad but collaboration remained uneven. Brazil led the corpus with 12 articles and 251 citations, followed by the United States with nine articles and 165 citations; China and Indonesia contributed six articles each. Network connectivity differed from publication volume: Indonesia had the highest total link strength (9), followed by the United States (6) and China (5). Thus, Brazil functioned as the principal production and citation hub, whereas other countries showed stronger relative integration in the collaboration network.

Brazil's prominence is consistent with the expansion of national biodiesel blending and the operational importance of storage stability under a regulated fuel market. Increasing biodiesel fractions can intensify water affinity and oxidative susceptibility, reinforcing interest in microbial contamination, sludge, filter blockage and biocorrosion. National fuel specifications and surveillance further connect academic research with industrial risk management (PASSMAN FJ, 2013; ZIMMER A, et al., 2013; BÜCKER F, et al., 2014; AGÊNCIA NACIONAL DO PETRÓLEO, GÁS NATURAL E BIOCOMBUSTÍVEIS, 2025; BRAZIL, 2024; MINISTÉRIO DE MINAS E ENERGIA, 2025).

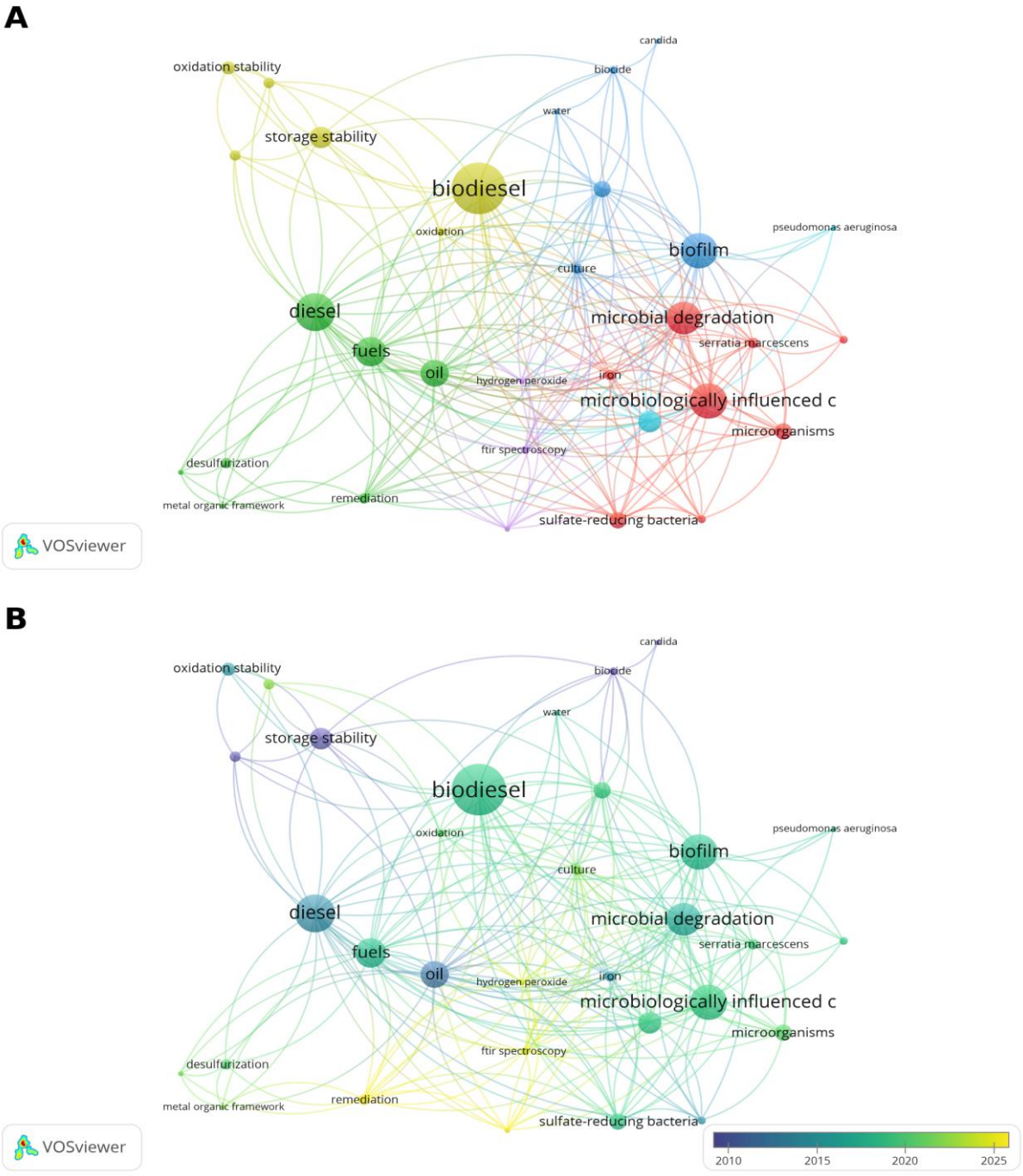
The international pattern also indicates that biodeterioration is not a localized problem. Similar mechanisms-water accumulation, microbial colonization, biofilm development, sludge deposition, filter clogging and MIC-occur across storage systems, but their severity may vary with feedstock, climate, blend policy, infrastructure and maintenance. The fragmented collaboration network and methodological heterogeneity limit direct comparison among regions. International efforts should therefore prioritize harmonized sampling, common microbiological and corrosion endpoints, comparative blend evaluations and shared datasets suitable for predictive modeling under diverse storage conditions.

Thematic developments and emerging technologies

Keyword co-occurrence produced a network of 32 terms distributed across six clusters (**Figure 3A**; **Table 1**). Central terms included biodiesel, diesel, biofilm, microbial degradation, microbiologically influenced corrosion, storage stability and fuels, showing that the field connects fuel composition and aging with microbial activity, interfacial biofilms, deposits and metallic deterioration. The six clusters organize these relationships

into biodegradation and active consortia; advanced refining and remediation technologies; water–fuel interface and contamination; physicochemical stability and aging; analytical monitoring and metabolic dynamics; and biocorrosion of metallic surfaces. This structure confirms that microbial biodeterioration is increasingly interpreted as a system-level process rather than solely as detection of microbial presence.

Figure 3 - Keyword mapping of the bibliometric corpus on microbial biodeterioration in diesel and biodiesel systems: (A) co-occurrence network and thematic clusters; (B) temporal overlay showing the average occurrence period of the keywords.



Note: Node size represents keyword occurrence and lines indicate co-occurrence relationships. In panel A, colours represent thematic clusters. In panel B, the colour scale represents the average occurrence period of terms between 2010 and 2025; bluish colours indicate older average occurrence, whereas greenish and yellowish colours indicate more recent terms in the analysed corpus. **Source:** Silva GVC, et al., 2026.

Temporal overlay mapping (**Figure 3B**) showed a clear technological progression. Earlier research emphasized storage stability, oil, culture-based contamination assessment and biocides. A consolidation phase centered on biodiesel, water, biofilms, microbial degradation and MIC, reflecting recognition of the fuel–water interface as a key ecological and corrosion zone. More recent terms, including FTIR spectroscopy, remediation and advanced materials, indicate growing interest in rapid diagnostics and targeted treatment. This evolution does not eliminate conventional methods; culture, visual inspection and physicochemical assays remain operationally useful, but increasingly serve as baseline tools complemented by molecular and instrumental approaches (ASTM D6469-24, 2024).

Molecular methods are central to this transition. qPCR and multiplex qPCR can improve sensitivity and reduce the time required to quantify microbial loads compared with culture alone, supporting earlier detection of bacteria, fungi and archaea in fuel systems (MARTIN-SANCHEZ PM, et al., 2018; RADWAN O, et al., 2018). High-throughput sequencing further characterizes complex communities and treatment-associated shifts, supporting interpretation of multispecies biofilms, microbial succession and potential tolerance mechanisms (BÜCKER F, et al., 2014). These tools are especially relevant because biodeterioration is driven by interacting communities rather than by a single organism.

In parallel, FTIR and NIR spectroscopy provide rapid, non-destructive information on fuel composition and degradation and can be coupled with chemometric models. Established applications include assessment of biodiesel content and physicochemical properties, while biodeterioration studies can exploit spectral changes associated with oxidation, hydrolysis, metabolites and sludge precursors (FERRÃO MF, et al., 2011; FELIZARDO P, et al., 2007). Biosensors add potential for rapid, on-site detection of fuel biocontamination, although routine industrial deployment still requires validation against matrix interference, detection limits and variable storage conditions (PAVLYUK OM e RUIZ ON, 2017).

Taken together, the thematic and temporal evidence indicates a shift from reactive contamination diagnosis toward multimodal, preventive monitoring. The main unresolved challenge is not the absence of diagnostic options, but their integration. Microbial quantification, fuel chemistry, water dynamics, corrosion indicators and operational history must be combined in standardized protocols validated beyond laboratory conditions. Such integration would allow technologies represented in the thematic clusters to contribute to early warning, condition-based maintenance and predictive fuel-storage management.

Table 1 - Thematic clusters and technological interpretation of keyword co-occurrence analysis.

Cluster	Main keywords	Thematic focus	Technological interpretation
Cluster 1	*hydrocarbons, iron, microbial degradation, microbiologically influenced corrosion, microorganisms, Serratia marcescens, stainless steel, sulfate-reducing bacteria*	Biodegradation and active microbial consortia	Transition from isolated microbial identification to community-level interpretation of degradation and MIC
Cluster 2	*desulfurization*, *diesel, fuels*, *ion exchange*, *metal organic framework*, *oil*, *remediation*	Advanced refining, purification, and remediation technologies	Emergence of functional materials and treatment strategies for fuel-related contaminants
Cluster 3	*biocide*, *biofilm*, *candida*, *culture*, *microbial contamination*, *water*	Water-fuel interface and contamination triggers	Conventional culture and biocide testing are being complemented by qPCR, sequencing and biosensing
Cluster 4	*antioxidants*, *biodiesel*, *oxidation*, *oxidation stability*, *sludge formation*, *storage stability*	Physicochemical Stability and Fuel Aging	Spectroscopy and chemometrics may support faster assessment of fuel degradation and sludge formation
Cluster 5	*Bacillus megaterium*, *FTIR spectroscopy* (*Fourier-transform infrared spectroscopy*), *hydrogen peroxide*	Analytical monitoring and metabolic dynamics	FTIR-based monitoring points to rapid, non-destructive detection of compositional changes
Cluster 6	*carbon steel*, *Pseudomonas aeruginosa*	Biocorrosion and the Integrity of Metallic Surfaces	MIC studies are moving toward surface-specific and biofilm-mediated corrosion mechanisms

Note: The clusters were identified through an analysis of keyword co-occurrence performed in VOSviewer. The final network consisted of 32 items distributed across six thematic clusters.
Source: Silva GVC, et al., 2026.

Bibliographic linkages, intellectual framework, and unresolved challenges

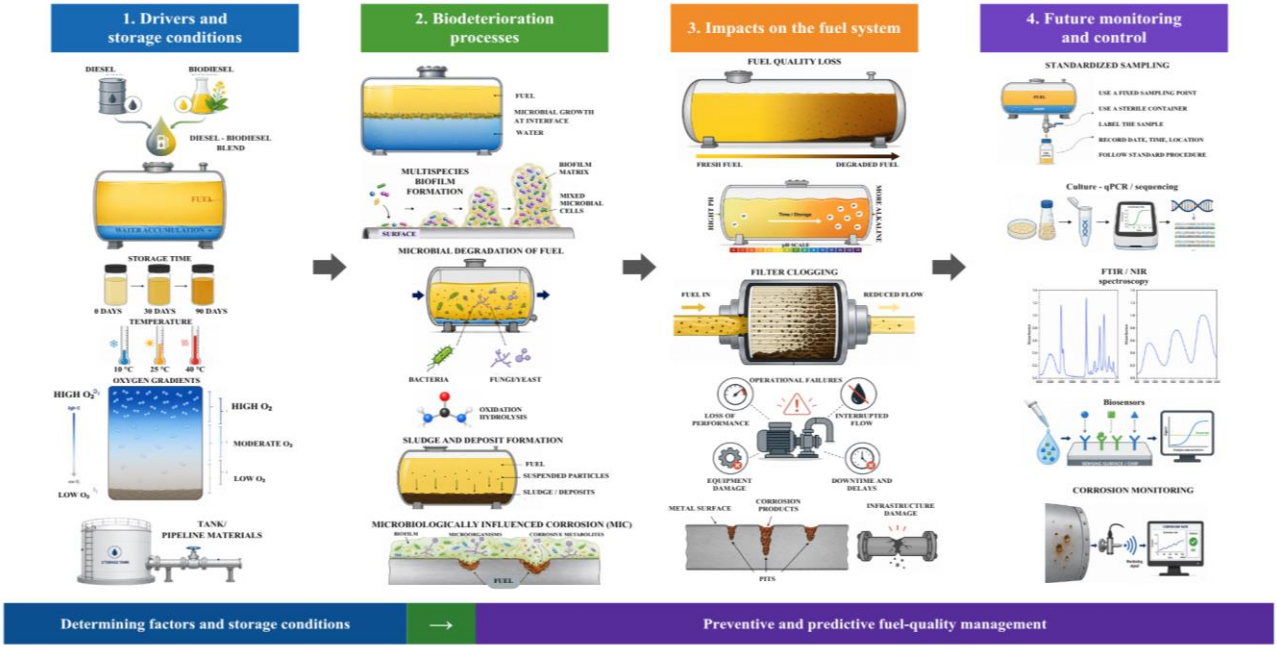
Bibliographic coupling mapped the intellectual proximity of the corpus and revealed four interconnected research fronts: (i) oxidative instability, thermal degradation and deposit formation; (ii) microbial contamination, interfacial biofilms and MIC; (iii) biocide-based mitigation and storage simulation; and (iv) physical mitigation and preventive engineering. High-connectivity studies, including Liang R, et al. (2018), Bücker F, et al. (2014) and Zimmer A, et al. (2013), functioned as bridges among biodegradation, corrosion, biofilm ecology and antimicrobial testing (VAN ECK NJ e WALTMAN L, 2010; KESSLER MM, 1963).

The first front shows that oxidation, hydrolysis and insoluble deposits remain important pathways of fuel-specification loss, but these processes are not consistently integrated with microbiological measurements (HARDY DR e WECHTER MA, 1994; CONCEIÇÃO MM, et al., 2007; AGARWAL S, et al., 2018). The second highlights polymicrobial biofilms and corrosive consortia but leaves uncertainty about active functional groups, community succession and localized corrosion under real storage conditions (RAJASEKAR A, et al., 2010; LIANG R, et al., 2018; KNISZ J, et al., 2023). The third demonstrates the value of biocides and multifunctional additives while exposing uncertainties about long-term performance across variable water contents, blend ratios, recurrent contamination and mature biofilms (ZIMMER A, et al., 2013; BÜCKER F, et al., 2014; ZIMMER AR, et al., 2017). The fourth addresses water removal, sludge control and filtration but often evaluates these measures separately from microbiological and corrosion processes.

Across these fronts, the recurring gaps are methodological fragmentation, limited representation of industrial storage conditions, incomplete characterization of active multispecies biofilms and the absence of standardized thresholds linking microbial burden, deposit formation and corrosion. Laboratory models do not always reproduce fluctuating temperature, intermittent condensation, variable blend chemistry and extended storage times. Moreover, separate evaluation of microbial growth, fuel chemistry and corrosion makes it difficult to determine when contamination becomes operationally relevant. These gaps explain why specialized research fronts have advanced in parallel without yet producing a unified predictive framework.

Figure 4 integrates these findings into a conceptual pathway connecting storage drivers, biodeterioration mechanisms, fuel-system impacts and future monitoring strategies. It emphasizes that effective management requires coordinated control of water and fuel condition together with molecular detection, chemical monitoring, corrosion assessment and predictive analysis rather than reliance on a single diagnostic or mitigation measure.

Figure 4 - Conceptual framework linking storage drivers, biodeterioration mechanisms, fuel-system impacts and future monitoring strategies in diesel and biodiesel storage systems.



Note: The schematic illustration was created using Inkscape. **Source:** Silva GVC, et al., 2026.

Industrial implications and research priorities

The practical implication of the review is that microbial biodeterioration should be managed as a fuel-quality and infrastructure problem rather than as an isolated contamination event. Water accumulation, microbial activity, biofilm formation, physicochemical degradation, deposits, filter blockage and MIC are interdependent; therefore, monitoring should combine microbiological, molecular, physicochemical, electrochemical and operational indicators. Conventional culture, visual inspection and standard fuel assays remain useful because they are accessible and established, but they often identify problems after biomass or degradation has progressed. Their integration with qPCR, spectroscopy, biosensors and corrosion monitoring can support earlier diagnosis, risk classification and preventive intervention (PASSMAN FJ, 2013; FLEMMING HC, et al., 2016; MARTIN-SANCHEZ PM, et al., 2018; RADWAN O, et al., 2018).

The main barriers to industrial translation are summarized in **Table 2**. They include non-standardized sampling of fuel, bottom water, sludge and biofilms; weak integration between microbiology and fuel chemistry; insufficient characterization of active biofilms and deposits; separation of microbial and corrosion assays; limited real-time monitoring; dependence on conventional biocides; and scarce predictive models for higher biodiesel blends.

Because these matrices and processes represent distinct microenvironments within the same storage system, inconsistent sampling and isolated measurements reduce comparability among studies and make it difficult to define reproducible thresholds for intervention.

Table 2 - Research gaps, fuel-system impacts and priorities for future investigations on microbial biodeterioration in diesel and biodiesel systems.

Research gap	Impact on fuel systems	Industrial consequence	Priority
Lack of standardized sampling for fuel, water, sludge and biofilms	Low comparability among studies and storage conditions	Difficulty defining reproducible monitoring protocols	High
Limited integration between microbiology and fuel chemistry	Partial understanding of biodeterioration mechanisms	Weak prediction of fuel quality loss during storage	High
Insufficient molecular characterization of active biofilms	Poor identification of functional microbial consortia	Inefficient microbial control and late contamination diagnosis	High
Incomplete characterization of sludge and sedimented deposits	Limited understanding of deposit origin and composition	Filter clogging, operational failures and poor maintenance decisions	High
Separation between microbial studies and corrosion assays	MIC mechanisms remain underexplored in fuel systems	Risk of tank, pipeline and metallic surface degradation	High
Limited use of real-time monitoring tools	Late detection of microbial proliferation and fuel deterioration	Reactive rather than preventive management of storage systems	High
Dependence on conventional biocides	Environmental, regulatory and resistance-related concerns	Need for safer multifunctional additives and combined mitigation strategies	Medium - High
Scarce predictive models for biodiesel blends	Low capacity to anticipate deterioration in B10, B20, B30 or higher blends	Limited preventive maintenance and risk classification	High

Note: Research gaps were derived from the bibliometric mapping and critical synthesis of the included studies. Priority levels indicate the expected relevance of each gap for fuel storage, quality control, biodeterioration monitoring and operational risk reduction. MIC, microbiologically influenced corrosion; B10, B20 and B30, diesel blends containing 10%, 20% and 30% biodiesel, respectively. **Source:** Silva GVC, et al., 2026.

Future work should prioritize standardized sampling across storage microenvironments and experimental designs that reproduce fluctuating water, temperature, blend composition and residence time. Active biofilms require particular attention because community composition, succession and metabolic activity influence degradation, sludge formation, localized corrosion and treatment efficacy.

Molecular tools and sequencing can improve detection and characterization of these communities, while FTIR/NIR, biosensors, deposit analysis and electrochemical measurements can provide complementary information on fuel degradation and material integrity. Safer multifunctional additives and combined mitigation

strategies should be evaluated not only for microbial inhibition, but also for effects on fuel stability, sludge formation, corrosion risk and environmental compatibility (PAVLYUK OM e RUIZ ON, 2017).

Predictive models represent the logical endpoint of this integration. For B10, B20, B30 and higher blends, risk models should combine microbial burden, fuel chemistry, water content, temperature, storage time, corrosion indicators and operational history. Such models could support preventive maintenance and targeted intervention before severe fuel-quality loss or infrastructure damage. However, predictive approaches will require datasets generated with comparable methods and validated under real storage conditions. Thus, the main research priority is to move from late corrective treatment toward standardized, real-time and data-driven management, using the multimodal framework summarized in **Figure 4** and the priorities ranked in **Table 2**. This strategy preserves the usefulness of conventional monitoring while linking it to more sensitive tools capable of early warning and condition-based decision-making.

FINAL CONSIDERATIONS

This integrative review with bibliometric and scientometric analysis shows that research on microbial biodeterioration of diesel and biodiesel has evolved from isolated studies of fuel instability and contamination toward an interdisciplinary field linking water accumulation, microbial communities, biofilms, fuel degradation, deposits, MIC and monitoring technologies. The principal gap is the persistent separation of microbiological, physicochemical, corrosion and operational approaches, which limits comparability, threshold definition and predictive management. The review is limited by the use of a single database and by a deliberately specific search strategy focused on biofilms, sludge, gums and related control terms, which may have excluded relevant studies using different descriptors. Future investigations should prioritize standardized sampling and integrated validation of molecular methods, sequencing, FTIR/NIR spectroscopy, biosensors, deposit characterization, corrosion monitoring and predictive models under industrially representative conditions. Integrating these tools with conventional assays can support earlier warning, preventive intervention and data-driven protection of fuel quality and storage infrastructure.

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