RESEARCH ARTICLE

Frontiers in Advanced Materials Research

DOI: 10.34256/famr2612

Filter-Blocking Tendency of Biodiesel and Biodiesel-Diesel Blends in Compression-Ignition Fuel Systems: Mechanisms, Test Methods and Mitigation

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Received: 29-01-2026, Revised: 16-04-2026, Accepted: 24-04-2026, Published: 07-05-2026

Abstract: Biodiesel can reduce petroleum dependence and improve the lubricity and renewable content of compression-ignition fuels, but its field reliability is strongly influenced by filterability. Filter blocking is not produced by a single contaminant or temperature threshold. It results from coupled effects of feedstock fatty-acid composition, incomplete transesterification, saturated monoglycerides, sterol glucosides, soaps, residual metals, particulate matter, water, microbial growth, oxidative ageing and low-temperature crystallisation. This review critically synthesises the mechanisms by which these species form, agglomerate and deposit within vehicle and dispenser filters. It distinguishes filter-blocking tendency from cloud point, cold-filter-plugging point, particulate contamination and cold-soak filtration, and explains why no individual laboratory method reproduces every field failure. ASTM D2068 evaluates the filtration behaviour of middle-distillate fuels and biodiesel blends, whereas ASTM D7501 targets cold-soak filter-blocking potential of B100. Their outputs should be interpreted together with oxidation stability, glyceride composition, particulate loading and actual thermal history. Evidence from B20 and higher blends shows that pressure-drop growth depends on feedstock, fuel age, temperature cycling and contaminant interactions rather than biodiesel concentration alone. Mitigation is most effective when implemented as a hierarchy: rigorous conversion and purification, removal of minor precipitating species, oxidation control, dry and clean storage, climate-appropriate blending, validated cold-flow improvers, suitable filter design and condition-based maintenance. A research framework is proposed for deposit-resolved chemical analysis, standardised accelerated ageing, pressure-drop sensing and predictive filter-life modelling. The review

concludes that filterability must be treated as a systems property linking fuel chemistry, logistics, climate and engine hardware, rather than as a pass/fail property of freshly produced biodiesel.

Keywords: Biodiesel, Cold-Flow Operability, Compression-Ignition Engine, Filter Blocking Tendency, Fuel Quality, Oxidation Stability, Saturated Monoglycerides.

1. Introduction

Biodiesel consists of mono-alkyl esters of long-chain fatty acids produced principally by transesterification of vegetable oils, animal fats, waste cooking oils and related lipid feedstocks. It can be used as neat B100 or blended with petroleum diesel in compression-ignition engines. Its principal advantages include renewable origin, biodegradability, oxygen content, lubricity and generally lower carbon monoxide, hydrocarbon and particulate emissions than petroleum diesel, although the net environmental effect depends on feedstock and production pathway [1-3].

Fuel-system reliability remains a major barrier to higher biodiesel blending. Modern high-pressure common-rail systems use fine filtration to protect pumps and injectors with small clearances. A modest increase in insoluble material or crystal population can therefore create a steep pressure drop, fuel starvation, hard starting, power loss, pump cavitation and injector deterioration. Similar failures occur in terminal and retail dispenser filters, where temperature cycling and long residence times may allow marginally soluble compounds to precipitate [4-6].

Filter-blocking tendency (FBT) describes the propensity of a fuel to restrict flow through a defined filter under controlled conditions. It should not be confused with particulate concentration alone. A low particle count at the time of sampling does not ensure stable filterability because dissolved or colloidal compounds can precipitate during cooling, ageing or blending. Conversely, a fuel with visible haze may pass a specific laboratory test if the particles are deformable, smaller than the test medium or weakly retained.

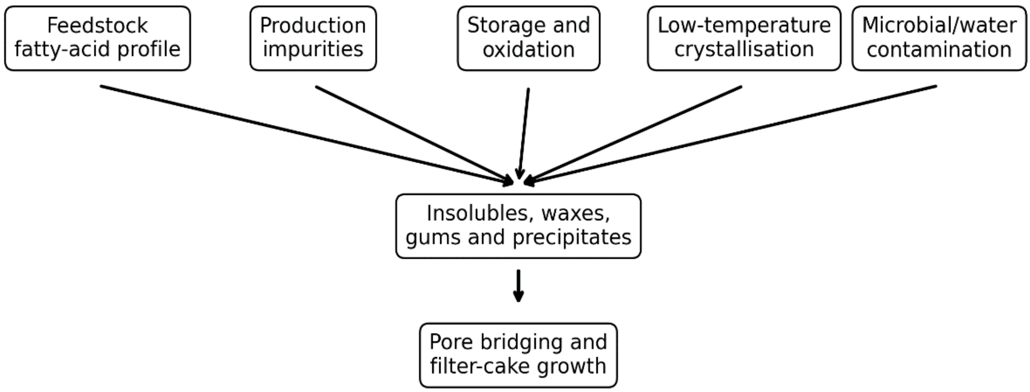

Figure 1. Coupled chemical and operational pathways leading to filter blockage in biodiesel-containing fuels.

The scientific challenge is that filter blocking arises from several overlapping mechanisms. Saturated monoglycerides and sterol glucosides can crystallise or agglomerate; sodium and potassium soaps can form poorly soluble complexes; oxidation produces acids, oligomers and gums; water supports microbial growth and destabilises interfaces; and cold temperature induces wax crystallisation from both fossil and biodiesel fractions [5-9]. Filter media may also change mechanically or chemically after prolonged fuel exposure [10].

This review develops a systems-level account of biodiesel filter blocking for CI engines. It analyses precursor chemistry, precipitation and cake formation, standards and test limitations, effects on fuel-system components, mitigation options, and priorities for predictive monitoring. Particular attention is given to the gap between fresh-fuel qualification and field behaviour after storage and repeated thermal cycling.

2. Review Scope and Methodology

The review focused on peer-reviewed studies, fuel standards, government guidance and field investigations addressing biodiesel filterability, cold-flow operability, oxidation, minor contaminants, filtration pressure drop and CI-engine fuel-system compatibility. Recent literature was prioritised, while foundational work was retained where it established contaminant mechanisms or standard methods.

Figure 2. Representative filter-blocking-tendency apparatus used for controlled filtration tests.

Evidence was organised into six domains: (i) feedstock and production chemistry, (ii) storage and oxidation, (iii) temperature-dependent precipitation, (iv) filter and engine response, (v) laboratory and field test methods, and (vi) prevention and monitoring. Because test procedures differ in filter pore size, sample conditioning, pressure, endpoint and fuel volume, numerical FBT values were not pooled across incompatible methods. Trends were evaluated only where the test basis and fuel composition were sufficiently clear.

The source manuscript used a photograph of a Tamson FBT apparatus but did not explain the standardised measurement logic in sufficient detail. In the revised review, the apparatus is placed within a broader test framework: the fuel is passed through a specified membrane under controlled pressure or flow, and blockage is inferred from pressure increase, flow loss or filtration time according to the selected procedure.

3. Biodiesel Chemistry Relevant to Filterability

3.1 Feedstock Fatty-Acid Profile

Feedstock composition controls both cold-flow behaviour and oxidation stability. Biodiesel rich in saturated fatty-acid methyl esters generally has higher cloud and pour points because straight-chain saturated molecules pack efficiently into crystals. Biodiesel rich in polyunsaturated esters usually remains fluid at lower temperature but oxidises more readily because double bonds accelerate radical-chain reactions [11, 12]. This creates a fundamental trade-off: improving cold flow through greater unsaturation can reduce storage stability, whereas hydrogenation or use of saturated feedstocks can worsen crystallisation.

Animal-fat, palm and certain waste-derived biodiesels may contain larger fractions of high-melting saturated esters and saturated monoglycerides. Soybean and other plant-derived biodiesels may contain sterol-derived minor components. Consequently, equal blend ratios prepared from different B100 sources can show markedly different filterability.

3.2 Residual Glycerides and Incomplete Conversion

Transesterification converts triglycerides to fatty-acid esters and glycerol. Incomplete reaction or inadequate separation leaves mono-, di- and triglycerides. Saturated monoglycerides are especially important because their solubility can decrease sharply during cooling or long storage. Once nucleated, they form platelets or networks that bridge filter pores and trap smaller contaminants. ASTM D6584 is commonly used to quantify free and total glycerin and individual glyceride classes in B100 [13].

The relevance of a concentration limit depends on molecular identity, not only total mass. A small quantity of a high-melting saturated monoglyceride can be more damaging than a larger quantity of an unsaturated glyceride that remains dissolved. Quality-control programmes should therefore examine glyceride profile and cold-soak response rather than total glycerin alone.

3.3 Sterol Glucosides, Soaps and Inorganic Residues

Free sterol glucosides originate from plant sterols and can have limited solubility in biodiesel and biodiesel-diesel blends. They act both as precipitating species and as nucleation sites for other compounds. Acylated sterol glucosides, free fatty acids and fatty-acid sterol esters have also been identified in filter-blocking residues [5, 14].

Residual sodium or potassium from alkaline catalysis can react with free fatty acids to form soaps. Calcium and magnesium contamination from water, adsorbents or handling systems can generate less soluble carboxylate salts. These species may remain dispersed initially and then flocculate after blending or exposure to water. Phosphorus, catalyst residues and corrosion particles further increase deposit complexity.

3.4 Water and Microbial Contamination

Biodiesel is more hygroscopic than hydrocarbon diesel and can hold additional dissolved water. When temperature decreases, dissolved water may separate and collect at tank bottoms. The fuel-water interface supports bacteria, yeasts and fungi. Biomass, extracellular polymeric substances and corrosion products can then enter filters as a cohesive sludge. Microbial blockage should be differentiated from low-temperature crystallisation because the mitigation methods differ: drying and biocide management address biological growth, whereas cold-flow treatment does not. Water also accelerates hydrolysis and promotes corrosion. Routine drainage, Karl Fischer water measurement, tank inspection and microbiological testing are therefore part of filterability management, especially for low-turnover fleets and standby generators.

4. Oxidation, Ageing and Deposit Formation

4.1 Oxidative pathways

Autoxidation begins with hydrogen abstraction adjacent to double bonds, followed by oxygen addition and hydroperoxide formation. Hydroperoxides subsequently decompose into aldehydes, ketones, acids and radicals that create higher-molecular-weight oligomers. As ageing progresses, acidity, viscosity, gum and insoluble sediment can increase. Metals, light, heat and air exposure accelerate these reactions [12, 15]. Oxidation products may remain soluble in B100 but become less soluble after blending with paraffinic diesel. This means that blending can reveal instability not apparent in the neat biodiesel. Compatibility should therefore be evaluated on the finished blend, not inferred solely from B100 quality.

4.2 Storage Variables

Temperature, headspace oxygen, tank material, light exposure, water, residence time and repeated fuel turnover determine ageing severity. Copper and certain transition metals catalyse oxidation, while partially filled tanks provide larger oxygen exposure. Antioxidants are most effective when added before significant oxidation has occurred; they cannot reverse polymerisation or remove existing sediment [15].

The 2024 field investigation of low-temperature dispenser-filter blockage demonstrated that even B7 fuels can experience non-microbial blockage and that diagnosis requires long-term comparison of affected and reference filters, temperature histories and location-specific conditions [6]. This finding reinforces the need to trace logistics rather than assuming that only high biodiesel blends are vulnerable.

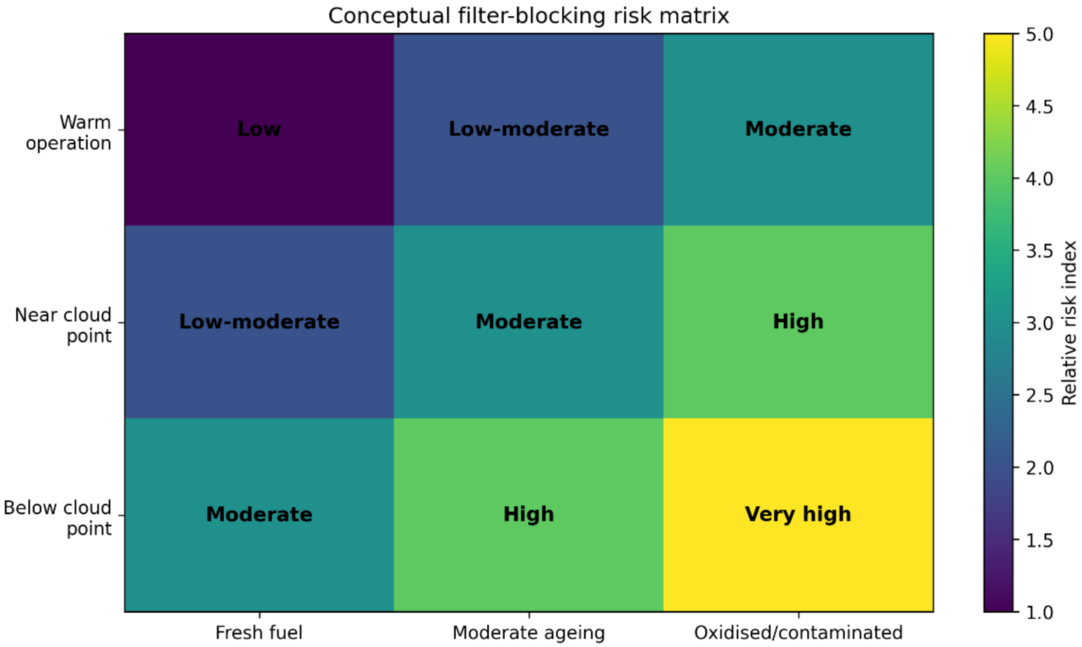

Figure 3. Conceptual interaction between temperature and storage condition. The matrix illustrates relative risk and is not a substitute for a fuel-specific test.

5. Low-Temperature Crystallisation and Operability

5.1 Cloud Point, CFPP and Actual Filter Blockage

The cloud point is the temperature at which crystals first become visibly detectable under a defined method. The cold-filter-plugging point (CFPP) measures the temperature at which a cooled fuel fails to pass through a standardised filtration device within a specified time. Both are useful, but neither fully reproduces a vehicle filter, flow history or prolonged cold soak. Barba *et al.* showed that cloud point and CFPP may not always predict actual cold-start operability of biodiesel blends [16].

Crystallisation is governed by cooling rate, dwell time, agitation, nucleation sites and thermal cycling. Slow cooling can produce fewer, larger crystals; rapid cooling can generate many small crystals. Rewarming does not always immediately restore filterability because metastable aggregates or settled deposits may persist.

5.2 Cold Soak and Room-Temperature Precipitation

Some minor compounds appear soluble at room temperature but precipitate after extended standing or after cooling to temperatures still above the measured cloud point. ASTM D7501 was developed to assess the cold-soak filter-blocking potential of B100 by measuring filtration time after specified conditioning [17]. The method is particularly valuable for detecting minor precipitating constituents that conventional cold-flow tests may miss.

Cold-soak filtration should be interpreted as a B100 quality-control screen. Finished blends may behave differently because diesel solvency, aromatic content and additive package alter precipitation. Field validation remains necessary for severe climates or unusual feedstocks.

5.3 Cold-Flow Improvement

Physical methods include blending with low-cloud-point diesel, winterisation and fractionation. Chemical approaches include pour-point depressants and wax-crystal modifiers. Biological and feedstock-selection strategies can alter fatty-acid composition. A recent review concluded that cold-flow improvement must be evaluated alongside viscosity, density and oxidation stability because an intervention that suppresses crystals can adversely affect another fuel property [11].

Additive performance is strongly fuel-specific. A product effective for one ester distribution or diesel base stock may be ineffective in another. Additives should therefore be qualified in the final blend using the expected temperature profile and storage duration.

6. Filter-Blocking Mechanisms

6.1 Pore Blocking and Cake Filtration

At the beginning of filtration, particles smaller than the nominal pore rating may penetrate the medium, while larger particles bridge pore entrances. Progressive capture forms a surface cake that increases hydraulic resistance. For approximately constant viscosity and flow, pressure drop rises as cake thickness and specific cake resistance increase. Soft organic deposits can compress under pressure, causing a nonlinear and sometimes rapid terminal increase in pressure drop.

The character of the deposit is as important as its mass. Needle-like crystals, platelets, gels and microbial polymers create different permeabilities. Mixed deposits often produce the most severe blockage because small particles fill voids between larger crystals.

6.2 Filter-Media Interaction

Filter media differ in fibre chemistry, pore distribution, depth, pleat geometry, water-separation layer and surface treatment. Biodiesel can alter elastomers, adhesives and media tensile properties after prolonged contact. Thangamani *et al.* combined experiment and simulation and reported higher-pressure drop for biodiesel blends and changes in filter-media behaviour after exposure [10].

A laboratory membrane is therefore a reproducible screening tool, not a direct replica of every vehicle filter. Correlation requires knowledge of the service filter's effective area, pore structure, flow pulsation, fuel viscosity and contaminant-holding capacity.

6.3 Consequences for CI Engines

Filter restriction reduces inlet pressure to the low-pressure pump and can introduce cavitation or aeration. In common-rail systems, insufficient feed pressure compromises rail-pressure control, injection timing and delivered quantity. Symptoms include difficult starting, hesitation, derating and shutdown. Persistent contamination that bypasses or damages the filter can accelerate wear of high-pressure pumps and injectors.

Combustion and emissions effects are secondary consequences of unstable fuel delivery. Apparent changes in brake-specific fuel consumption or smoke during a filter-blocking event should not be interpreted as intrinsic biodiesel-combustion characteristics unless fuel pressure and injection quantity are monitored.

7. Standardised and Complementary Test Methods

ASTM D2068 covers procedures for determining FBT and filterability of middle-distillate fuels, biodiesel and biodiesel blends over a specified viscosity range. The test is intended for cleanliness and quality-control applications, and a change after storage or pretreatment can indicate a change in fuel condition [18]. ASTM D8386 provides an enhanced FBT approach designed to be more sensitive to certain fuel constituents in high-pressure common-rail contexts [19].

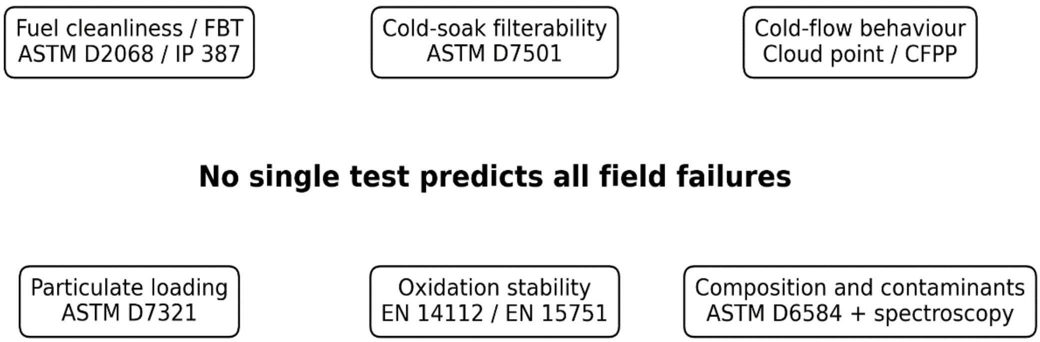

Figure 4. Complementary test framework for evaluating biodiesel filterability and its root causes.

Table 1. Roles and limitations of the principal tests relevant to filter blocking.

Method/property	Primary question	Strength	Main limitation
ASTM D2068 / IP 387 FBT	How rapidly does a fuel block a specified filter under controlled filtration?	Direct filtration response for distillates and blends	Condition-specific; not a complete cold-soak or field simulation
ASTM D7501 CSFT	Will B100 form filterable precipitate after cold soak?	Sensitive to minor precipitating components	Applies to conditioned B100, not every finished blend
ASTM D7321	How much particulate contamination is retained?	Quantitative mass-based cleanliness measure	Does not predict future precipitation from dissolved species
Cloud point	When do crystals first become visible?	Simple climate-screening property	Does not measure filter throughput
CFPP	At what temperature does a cooled fuel fail a standard filter test?	Operationally oriented cold-flow metric	May not predict all vehicle or long-soak failures
Oxidation stability	How resistant is the fuel to accelerated oxidation?	Supports storage-life control	Accelerated chemistry differs from every field condition
ASTM D6584	What glycerides and free/total glycerin are present?	Identifies production-conversion quality	Composition alone does not define deposit morphology
Deposit microscopy/ spectroscopy	What actually blocked the filter?	Root-cause identification	Requires representative sampling and specialist analysis

8. Evidence from Biodiesel Blends and Field Studies

Fersner and Galante-Fox demonstrated that saturated monoglycerides, sterol glucosides and carboxylate salts can contribute strongly to filter blockage, with severity depending on feedstock [5]. Komariah *et al.* observed greater clogging for B100 and higher blends than for diesel and reported lower FBT values for B20 than B100 under their test conditions [20]. These findings support blend-ratio control but do not establish a universal safe concentration.

A study using Ceiba pentandra biodiesel reported filterability comparable to diesel up to B20, with greater restriction above this level [21]. Paryanto et al. developed a B20 filter-clogging model based on precipitate measurement and filter-blocking tests, highlighting the influence of monoglyceride content, conditioning temperature and storage-derived precipitate [22].

Table 2. Root-cause matrix for biodiesel-related filter blockage

Driver	**Typical effect on filterability**	**Diagnostic evidence**	**Control priority**
High saturated FAME/ monoglycerides	Crystal and platelet formation during cooling	GC glyceride profile; microscopy; CSFT	Feedstock control, conversion and winterisation
Sterol glucosides	Fine precipitate and nucleation	LC/MS, FTIR, residue extraction	Adsorptive purification and supplier control
Soaps/metals	Flocs and inorganic-organic salts	ICP, ash, ion analysis	Washing, ion exchange and water control
Oxidation	Gum, acid and oligomer formation	Acid value, oxidation stability, GPC/FTIR	Antioxidants, oxygen/heat control, turnover
Water/microbes	Sludge, corrosion debris and biofilm	Karl Fischer, ATP/culture, tank inspection	Dry storage, drainage and hygiene
Cold temperature	Wax/crystal growth and pore bridging	Cloud point, CFPP, CSFT, thermal history	Climate-specific blending/additives
Incompatible additive package	Agglomeration or reduced solvency	Blend compatibility and filtration test	Finished-fuel validation
Filter-media degradation	Lower mechanical integrity or altered pores	Tensile test and microscopy	Material compatibility and replacement interval

High-pressure common-rail rig testing has shown that the least stable blend component can govern deposit formation and filter response [23]. Nano-additive studies indicate that additives can improve combustion-related properties while increasing filter-blocking risk at excessive concentration; therefore, additive dosage must be validated through filtration rather than selected solely from engine-performance results [24].

Collectively, these studies show that B20 often presents a manageable compromise when prepared from specification-compliant B100 and stored correctly. However, B20 is not inherently immune to blockage. Poor B100 quality, incompatible diesel, cold exposure, water or prolonged ageing can cause failure even at lower blend levels.

9. Mitigation Strategies

9.1 Production and Purification

The most robust intervention is to prevent unstable species from entering the distribution chain. Complete transesterification, efficient glycerol separation, water washing or dry washing, removal of catalyst and soaps, and final polishing reduce the precursor inventory. Distillation can produce high-purity biodiesel but increases energy demand and cost. Adsorbents and ion-exchange media can remove polar contaminants, though spent-material disposal and breakthrough monitoring are required.

Release testing should include not only properties required by ASTM D6751 or EN 14214 but also cold-soak filtration and, where field risk justifies it, finished-blend FBT. Supplier traceability should preserve feedstock, production lot, antioxidant treatment and storage history.

9.2 Storage and Distribution

Tanks should be clean, dry and protected from excessive heat and water ingress. Dead stock and long residence times should be minimised. Copper, brass, bronze, lead and zinc-containing materials can accelerate oxidation or produce deposits and are generally avoided in biodiesel service. Tank bottoms should be sampled because settled water and precipitate may not appear in top samples. Fuel received warm can remain clear while containing material that precipitates after overnight cooling. Quality programmes should condition representative samples at the lowest expected temperature and repeat filtration after storage. Good turnover and first-in/first-out management reduce ageing.

9.3 Blending and Additives

Blending with diesel reduces the concentration of biodiesel-derived precursors and usually improves low-temperature flow, but solvency changes can also force compounds out of solution. Splash blending at low temperature can produce local high-B100 zones and incomplete mixing. Controlled in-line blending at appropriate temperature is preferable.

Antioxidants delay radical oxidation, while cold-flow improvers modify crystal growth. Dispersants may keep particles suspended but can transfer deposits from tanks to vehicle filters. Additive compatibility, dosage and timing must therefore be established with the final fuel and service conditions. Nanoparticles require particular caution because agglomeration can directly increase particulate loading [24].

9.4 Filter Design and Maintenance

A staged system with water separation and appropriate upstream and final filtration can extend service life. Increasing filter area lowers superficial velocity and pressure drop, but oversized filters do not correct unstable fuel. Differential-pressure indicators enable condition-based replacement and can distinguish gradual loading from abrupt cold-weather precipitation. During transition from petroleum diesel to biodiesel blends, filters may initially clog because biodiesel's solvency mobilises historic tank deposits. A planned early filter-change interval and tank cleaning can prevent misclassification of this event as fresh-biodiesel instability.

10. Predictive Modelling and Monitoring

Filter-life models should couple precipitation kinetics with porous-media resistance. Inputs include saturated monoglyceride and sterol-glucoside concentration, oxidation state, particle-size distribution, viscosity, temperature-time history, flow rate and filter geometry. Paryanto *et al.* showed that precipitate measurements can be linked to blockage time with modest model error under the tested B20 conditions [22].Transfer to other fuels requires recalibration.

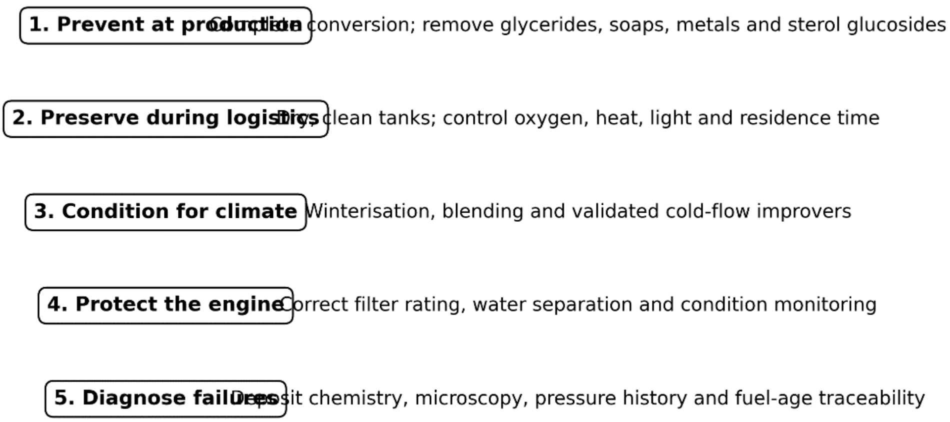

Figure 5. Hierarchy of controls for preventing and managing biodiesel-related filter blockage.

On-board or fleet monitoring can use differential pressure, fuel temperature, pump duty and flow demand. A rising pressure at constant temperature suggests progressive loading; a sharp pressure increase during cooling followed by recovery on warming suggests crystallisation; persistent pressure after warming indicates retained cake or irreversible deposit. Combining sensor history with fuel-lot data could support predictive maintenance. Machine-learning methods may identify nonlinear interactions, but physically meaningful inputs and external validation are essential. Models trained on one feedstock, filter or climate should not be assumed transferable.

11. Research Gaps and Future Directions

First, field-relevant accelerated ageing protocols are needed. Current oxidation, cold-soak and filtration tests isolate different mechanisms, whereas service fuels experience simultaneous oxygen exposure, temperature cycling, water and material contact.

Second, deposits should be chemically resolved. Reporting only pressure drop or filtration time does not identify whether failure was caused by monoglycerides, sterol derivatives, oxidation polymers, microbes or inorganic particles.

Third, standard reference materials containing controlled concentrations of known blocking species would improve interlaboratory comparison and model calibration.

Fourth, research should compare laboratory membranes with actual depth filters and water-separating media used in modern common-rail systems.

Fifth, additive studies must include filtration and long-term stability. Improvements in combustion, viscosity or emissions do not demonstrate compatibility with fine filters.

Sixth, low-cost differential-pressure and temperature logging should be validated across fleets to establish early-warning thresholds.

Finally, future standards should link fresh-fuel quality, conditioned-fuel response and finished-blend compatibility so that a fuel passing one test is not assumed safe under all storage and climate conditions.

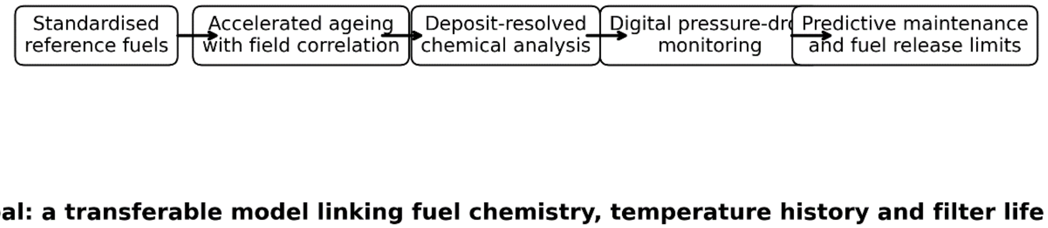

Figure 6. Research roadmap for predictive control of biodiesel filter blockage.

12. Conclusion

Filter blocking is one of the most operationally important but frequently oversimplified limitations of biodiesel use in compression-ignition engines. It is not determined by biodiesel concentration alone. Feedstock fatty-acid profile, saturated monoglycerides, sterol glucosides, soaps, metals, water, microorganisms, oxidation products, diesel solvency, thermal history and filter architecture interact to determine whether a deposit forms and whether it produces a critical pressure drop.

ASTM D2068, ASTM D7501, ASTM D7321, cloud point, CFPP, oxidation-stability testing and glyceride analysis provide complementary information. None independently predicts every field failure. A defensible quality programme therefore combines compositional analysis with conditioned filtration and uses the finished blend whenever compatibility is uncertain.

B10-B20 blends often show lower risk than B100 and can perform reliably when produced from specification-compliant biodiesel, blended correctly and stored under controlled conditions. Nevertheless, lower blend ratio is not a substitute for purification and storage management. The most effective strategy is hierarchical: remove precursors during production, preserve stability during logistics, adapt the fuel to climate, use compatible filters and monitor differential pressure.

Future progress requires deposit-resolved analysis, standardised ageing protocols, actual-filter validation and predictive models that combine fuel chemistry with temperature and pressure histories. Treating filterability as a systems property will improve engine reliability and allow biodiesel deployment decisions to be based on measurable risk rather than blend percentage alone.

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Conflict of interest: The Authors have no conflicts of interest to declare that they are relevant to the content of this article.