Impact of Shock Loading on Biological Wastewater Treatment Systems: A Review

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Abstract—Biological wastewater treatment plants operate under intrinsically unsteady influent conditions, and sudden increases in organic loading can destabilize carbon removal, nitrification, sludge structure and membrane filtration. This focused critical review synthesizes three complementary investigations covering a two-stage activated sludge-biofilm reactor, nitrifying sludge exposed to variable organic loading rates, and a membrane bioreactor subjected to repeated shock events. The reviewed evidence shows that apparent recovery of chemical oxygen demand removal can occur considerably earlier than recovery of nitrogen conversion, making organic removal alone an insufficient indicator of biological resilience. In the hybrid reactor, short-term influent chemical oxygen demand shocks of approximately two to four times the normal concentration produced progressively higher effluent peaks and recovery periods of about 7-27 h, while severe shocks suppressed nitrification and shifted the dominant cultured bacterial morphology. In nitrifying sludge, increasing organic loading modified loosely bound extracellular polymeric substances, reduced protein content and the protein-to-polysaccharide ratio, deteriorated aggregation and separation properties, and caused system collapse at 0.75 kg COD kg^{-1} MLVSS d^{-1} with incomplete recovery after load reduction. In the membrane bioreactor, higher shock magnitude accelerated residual fouling and transmembrane-pressure jumps; increasing filament abundance indicated that clogging and fouling acted synergistically. Across configurations, dissolved-oxygen competition, heterotrophic overgrowth, extracellular polymeric substance composition, biofilm retention and filamentous growth emerge as the principal mechanisms governing resistance and recovery. The review concludes that robust design requires multi-parameter monitoring, protection of nitrifying populations, equalization of peak loads and reactor-specific control of solids separation. The limited three-study evidence base also reveals a need for standardized shock-loading protocols, full-scale validation and integrated microbial, hydraulic and filtration diagnostics.

Keywords— organic shock loading; activated sludge-biofilm reactor; nitrifying sludge; extracellular polymeric substances; membrane bioreactor; process resilience.

I. INTRODUCTION

Wastewater treatment plants are designed around representative hydraulic and organic loads, yet their biological reactors are repeatedly exposed to departures from those design conditions. Industrial discharges, diurnal domestic patterns, production cycles and accidental releases can raise influent organic strength for periods ranging from minutes to days. Such disturbances are commonly described as organic shock loads. Their significance is not limited to temporary deterioration of effluent chemical oxygen demand (COD): they can alter oxygen distribution, select different microbial populations, suppress slow-growing nitrifiers, change extracellular polymeric substances (EPS), weaken sludge-water separation and accelerate membrane fouling or clogging.

The engineering question is therefore not simply whether a reactor can remove an increased mass of substrate. A resilient treatment system must attenuate the effluent peak, preserve critical microbial functions, avoid irreversible changes in biomass properties and recover rapidly after normal loading resumes. These criteria are configuration dependent. Suspended-growth systems respond through changes in mixed-liquor activity and solids inventory; attached-growth systems add protected biomass and diffusion gradients; nitrifying systems are particularly sensitive to competition from heterotrophs; and membrane bioreactors couple biological stability with a filtration barrier whose resistance can continue increasing after water-quality indicators improve.

This paper provides a focused critical review of three supplied studies that address these complementary dimensions. Seetha, Bhargava and Kumar evaluated short-term COD shocks in a two-stage activated sludge-biofilm system [1]. Yang et al. examined organic-loading-rate (OLR) disturbances in nitrifying sludge treating high-strength ammonia wastewater, with emphasis on EPS and physicochemical sludge properties [2]. Alimoradi, Valizadeh and Torabian assessed repeated OLR shocks in a membrane bioreactor (MBR), focusing on transmembrane pressure (TMP), fouling and clogging [3]. Because the review is intentionally restricted to these references, it should be interpreted as a comparative focused review rather than an exhaustive systematic review of the entire field.

The objectives are to: (i) compare how the three biological systems were stressed and monitored; (ii) synthesize the mechanisms linking organic loading to carbon removal, nitrification, EPS, floc structure and membrane resistance; (iii) distinguish reversible performance deterioration from incomplete or cumulative recovery; (iv) identify operational indicators that provide earlier warning than effluent COD alone; and (v) formulate research priorities grounded in limitations demonstrated by the reviewed experiments.

II. REVIEW SCOPE AND ANALYTICAL APPROACH

The review follows a structured comparative approach. Information was extracted from each source on reactor configuration, influent characteristics, loading protocol, duration of disturbance, hydraulic retention time (HRT), biomass state, monitored variables, principal outcomes and reported limitations. The studies were then compared across four response domains: treatment performance, microbial competition, sludge physicochemistry and solids-separation or membrane-filtration behaviour.

Direct numerical comparison requires caution because the studies used different normalization bases and disturbance durations. Study [1] expressed shocks mainly as influent COD concentrations and multiples of normal feed for a six-hour pulse. Study [2] expressed OLR as kilograms COD per kilogram mixed-liquor volatile suspended solids per day and maintained each loading condition for four weeks during both increasing and decreasing sequences. Study [3] imposed repeated shocks of increasing relative magnitude during a 75-day MBR run and interpreted the resulting TMP gradients. Accordingly, values are compared as evidence of system response within each experimental design rather than as interchangeable threshold limits for full-scale plants.

A further methodological distinction concerns recovery. Study [1] defined recovery primarily by return to pseudo-steady-state effluent conditions after the pulse. Study [2] deliberately tested hysteresis by reducing OLR after reaching a destabilizing maximum, showing that returning the input to its previous value did not necessarily restore the previous sludge state. Study [3] demonstrated cumulative filtration resistance through progressively higher initial TMP after physical cleaning and residual resistance after chemical cleaning. Together, these approaches show that recovery should be assessed at functional, structural and operational levels.

III. ORGANIC SHOCK LOADING: MECHANISMS AND INDICATORS

A. Substrate Surplus and Oxygen Competition

A sudden increase in biodegradable COD increases the food-to-microorganism ratio and stimulates heterotrophic respiration. The immediate consequence is a rise in oxygen demand that may exceed aeration transfer capacity, producing a temporary dissolved-oxygen (DO) deficit even when aeration equipment is unchanged. In study [1], DO fell below 1 mg L^{-1} during shock periods before gradually recovering after normal loading resumed. This low-DO interval is especially damaging to nitrifiers because autotrophic ammonia oxidizers grow more slowly than heterotrophs and compete less effectively for oxygen and surface area.

The separation between carbon-removal recovery and nitrification recovery is a central finding. Heterotrophs can rapidly metabolize excess carbon and restore effluent COD once the shock is removed. Nitrifying populations, however, may have been displaced, inhibited or washed out. Consequently, a plant can appear recovered based on COD while ammonia oxidation remains impaired. The evidence in study [1], where nitrification deteriorated after the 1170 mg COD L^{-1} shock and remained absent after COD returned to pseudo-steady state, demonstrates why ammonia, nitrite and nitrate must be included in post-shock monitoring.

B. Biomass Retention and Biofilm Protection

Attached growth can improve resistance by increasing total biomass concentration and retaining slow-growing microorganisms independently of suspended-solids washout. The two-stage reactor in study [1] used plastic-net carriers occupying about 30% of each 35-L reactor volume. The biofilm offered a protected microbial reservoir, while the series arrangement distributed readily biodegradable substrate removal primarily to the first stage and provided polishing in the second stage.

Protection is not absolute. Substrate and oxygen penetration change during a shock, and a sufficiently high load can expose deeper biofilm layers to concentrations outside their acclimated range. The reviewed hybrid reactor maintained organic removal under moderate shocks but produced a large effluent COD peak at the highest influent concentration. Thus, biofilm increases buffering capacity but does not eliminate the need for upstream equalization or adequate aeration reserve.

C. EPS and Floc Stability

EPS bind cells into aggregates and influence flocculation, hydrophobicity, surface charge, settling and dewatering. Study [2] separated EPS into loosely bound (LB-EPS) and tightly bound (TB-EPS) fractions. TB-EPS remained comparatively stable across OLR changes, whereas LB-EPS changed substantially. Protein (PN) concentrations and PN-to-polysaccharide (PS) ratios declined as OLR increased, while fluorescence signatures shifted from tryptophan protein-like material toward humic- and fulvic-like substances at high loading.

The distinction between total EPS quantity and composition is important. A reactor may retain a similar total amount of bound material while losing the protein-rich matrix associated with cohesion and stable aggregation. Correlation analysis in study [2] identified PN and PN/PS ratio as key factors associated with sludge physicochemical properties. These measurements therefore provide mechanistic information that conventional bulk indicators such as MLSS or COD cannot supply.

D. Filtration Resistance, Fouling and Clogging

In MBRs, the membrane retains solids and decouples effluent quality from sludge settling, but organic shocks can still impose an operational penalty through TMP increase. Study [3] distinguished reversible, residual, irreversible and irrecoverable resistance using the rate of TMP increase and the response to relaxation, physical cleaning and chemical cleaning. The residual fouling rate rose from about 10 mbar d^{-1} before shock loading to approximately 20, 30, 40 and 50 mbar d^{-1} following progressively stronger shocks.

The authors argued that fouling alone could not explain every TMP jump. The filamentous index increased from 1 to 5 over the run, and sludge accumulated particularly at membrane-module corners. Filamentous ragging or sludging can obstruct flow passages and create non-uniform pressure distribution, producing clogging that overlaps with residual fouling. For operation, this means that TMP trend analysis should be combined with microscopic sludge observations and module inspection rather than interpreted as a purely pore-scale fouling signal.

TABLE 1. COMPARISON OF THE REVIEWED STUDIES

Study	System	Shock protocol	Key monitored variables	Main response	Recovery/legacy
[1]	Two-stage AS-biofilm, 2 × 35 L; 30% carrier volume	COD raised to 808, 1170, 1358 and 1900 mg L^{-1} for 6 h	COD, NH4-N, NO3-N, DO, pH, cultured morphology	Effluent COD peaks increased; nitrification more sensitive than COD removal	Approx. 7, 17, 20 and 27 h COD recovery; nitrification deterioration persisted
[2]	20-L SBR with nitrifying sludge	OLR increased 0 to 0.75 and then decreased; each stage 4 weeks	Nutrients, SVI, floc size, FA, SRF, RH, zeta potential, LB/TB-EPS, EEM	Sludge destabilization, altered EPS composition and nutrient performance	System collapse at 0.75 kg COD kg^{-1} MLVSS d^{-1}; incomplete recovery
[3]	MBR at constant flux 9 L m^{-2} h^{-1}	Four repeated relative OLR shocks during 75 d	TMP, dTMP/dt, FI, COD, ammonia, visual module condition	Faster residual-fouling jumps and increasing filament abundance	Physical cleaning left rising TMPi; chemical cleaning reduced but did not erase resistance

IV. TWO-STAGE ACTIVATED SLUDGE-BIOFILM RESPONSE

A. Baseline Operation and Stage Function

The hybrid system in [1] treated synthetic medium-strength domestic wastewater at an overall HRT of 6 h after stepwise start-up. Influent COD was typically 350-500 mg L−1, the recycle ratio was one, and DO was maintained at approximately 3-3.5 mg L−1 in the first reactor and 4-4.5 mg L−1 in the second under normal conditions. At pseudo-steady state, the first reactor achieved approximately 72-73% COD removal and the second contributed a further 12-15%, giving an overall removal of about 76%.

This unequal distribution reflects substrate quality rather than poor second-stage performance. Reactor 1 received the readily biodegradable fraction and therefore removed most of the COD. Reactor 2 received effluent of roughly 100-130 mg COD L−1 containing a larger proportion of slowly biodegradable or residual material. The two-stage arrangement thus created functional specialization: bulk carbon removal upstream and polishing plus additional nitrogen transformation downstream.

Ammonium removal was approximately 31% in the first stage and 13% in the second, with overall removal around 38-39%. Nitrate concentrations remained low relative to ammonium disappearance, which the authors interpreted as evidence of denitrification within anoxic zones of the biofilm. The attached matrix can support aerobic nitrification near the oxygenated surface and anoxic denitrification deeper inside, allowing coupled nitrogen transformations within nominally aerated reactors.

B. Effluent Peaks and Recovery

During each six-hour shock, effluent COD increased with exposure time. At influent shocks of 808, 1170, 1358 and 1900 mg COD L−1, maximum final-effluent COD concentrations were approximately 169, 169, 250 and 617 mg L−1, respectively. The comparable final effluent for the first two shocks suggests a substantial buffering range at moderate loading; the sharp rise at 1900 mg L−1 indicates that this reserve was exceeded.

After the normal feed was restored, the reactor returned to pseudo-steady COD conditions in about 7, 17, 20 and 27 h, respectively. Recovery duration therefore increased with shock magnitude. A practical interpretation is that resilience should be characterized by both the peak excursion and the integral duration of impaired performance. A reactor with a moderate peak but slow recovery can discharge a larger cumulative pollutant mass than one with a short high peak.

The first stage remained responsible for most carbon removal during the shocks, confirming that upstream biomass absorbed the largest metabolic burden. The second stage provided attenuation but could not fully compensate at the highest shock. For design, this supports maintaining reserve capacity in the lead stage and protecting the polishing stage from direct high-strength influent through equalization or staged feeding.

C. Nitrification and Microbial Selection

Nitrification was largely maintained during the lowest shock but became markedly inhibited after the 1170 mg COD L−1 event. Once heterotrophs expanded under elevated carbon and DO declined, autotrophic nitrifiers were outcompeted for oxygen and attachment space. The subsequent 1358 and 1900 mg L−1 tests were therefore conducted with an already weakened nitrifying function, which complicates attributing later ammonia behaviour solely to the instantaneous shock magnitude.

Culture-based observations showed a shift from dominant Gram-positive rods under baseline conditions toward Gram-negative oval-shaped bacteria after shock loading. Although this technique cannot resolve community composition at modern taxonomic depth, it demonstrates selection pressure. The finding also warns that effluent recovery can coincide with a different microbial state; functional redundancy may restore carbon removal even when the original community has not recovered.

A major limitation is that the study did not quantify attached and suspended contributions separately during each shock or apply molecular tools to track nitrifying guilds. Nevertheless, the observed decoupling of COD and ammonia recovery remains robust and directly relevant to full-scale monitoring.

V. NITRIFYING SLUDGE, EPS AND PHYSICOCHEMICAL DESTABILIZATION

A. Experimental Loading Path and Hysteresis

Study [2] used a 20-L sequencing batch reactor seeded with laboratory-grown autotrophic nitrifying sludge and treating synthetic wastewater containing 200 mg L−1 ammonium. MLSS was maintained at 2500-3000 mg L−1, pH at 7.5-8.0 and temperature at 25 °C. The 12-h cycle included feeding, anoxic reaction, oxic reaction, settling and decanting, with an HRT of 24 h.

The OLR was adjusted using sodium acetate at 0, 0.15, 0.30, 0.45 and 0.75 kg COD kg−1 MLVSS d−1. Each condition lasted four weeks. After reaching the maximum, the sequence was reversed toward zero loading. This design is particularly valuable because it tests whether the sludge follows the same pathway during loading and unloading. The reported incomplete recovery shows hysteresis: the biological and physical state depended on prior exposure, not only on the current OLR.

The highest OLR caused collapse of the nitrifying sludge system. Reducing OLR thereafter did not fully restore the original performance or sludge characteristics. In plant terms, a severe disturbance may move biomass into a new state requiring reseeding, prolonged acclimation or operational intervention even after influent quality returns to normal.

B. Nutrient Removal and Population Competition

The nitrifying inoculum had been cultivated on inorganic ammonium medium for nearly one year, so the early addition of organic carbon caused a pronounced transitional response. Heterotrophic populations increased as OLR rose, changing the competition for oxygen and substrate while the ammonia concentration remained fixed. The system therefore provides a controlled demonstration of how an organic intrusion can destabilize a biomass selected for nitrification.

At lower OLRs, acclimation allowed partial stabilization, but increasing carbon progressively impaired nitrogen-removal performance. The change cannot be explained solely by oxygen limitation; microbial composition, aggregate architecture and EPS chemistry also evolved. This is important because simply increasing aeration during a shock may not reverse structural changes that reduce floc stability or alter retention of nitrifiers.

C. LB-EPS, TB-EPS and Matrix Composition

The study's strongest contribution is its fractionated EPS analysis. TB-EPS quantities remained relatively stable, whereas LB-EPS changed significantly as OLR varied. Because LB-EPS is located at the floc-water interface, it strongly affects interactions among aggregates and between sludge and the surrounding liquid. Large changes in this fraction can therefore influence settling, dewatering and dispersion before gross biomass concentration changes become obvious.

Both LB-EPS and TB-EPS showed declining protein content and PN/PS ratio with increasing OLR. Three-dimensional excitation-emission matrix spectra indicated that tryptophan protein-like substances dominated at low OLR, while humic- and fulvic-acid-like signals increased at high OLR. The shift suggests that severe organic loading changed the biochemical nature of the matrix, not merely its mass.

Protein and PN/PS ratio showed the strongest relationships with physicochemical sludge properties. Protein-rich EPS contributes to hydrophobic interactions and cohesive binding within aggregates. A reduction can weaken floc integrity, increase fragmentation and worsen solid-liquid separation. Thus, PN and PN/PS are plausible early-warning indicators of deteriorating nitrifying sludge.

D. Sludge Surface and Separation Properties

The authors monitored floc-size distribution, flocculating ability, sludge volume index, specific resistance to filtration, relative hydrophobicity and zeta potential. This multi-parameter characterization demonstrates that 'sludge quality' is not a single property. Organic loading can simultaneously alter particle size, charge, water binding and mechanical cohesion, with different implications for clarifier performance and downstream dewatering.

The observed destabilization at high OLR reinforces the need to monitor solids separation when evaluating shock resistance. A reactor may continue converting some pollutants while producing sludge that settles poorly or is difficult to dewater. In a conventional plant, this can lead to solids loss and reduced effective sludge age, further weakening nitrification. In an MBR, the same changes are transferred to membrane resistance rather than final-clarifier failure.

VI. MEMBRANE BIOREACTOR FOULING AND CLOGGING UNDER SHOCKS

A. TMP Development and Fouling Classification

Study [3] operated an MBR at a constant flux of 9.0 L m^{-2} h^{-1} and an HRT of 12 h over 75 days. Four OLR shocks were imposed while TMP and filamentous index were tracked. The constant-flux mode is useful because rising filtration resistance appears directly as increasing TMP.

The reported TMP profile distinguished reversible resistance removed by relaxation or aeration, residual resistance requiring physical cleaning, irreversible resistance remaining after physical cleaning but removable chemically, and irrecoverable resistance persisting after chemical cleaning. This hierarchy converts a pressure trend into operational consequences: energy demand, cleaning frequency, chemical use and eventual membrane replacement.

Before the first shock, residual fouling developed at roughly 10 mbar d^{-1}. After the 2× shock, the rate increased to about 20 mbar d^{-1} and TMP reached 600 mbar within four days. Following stronger shocks, residual rates of approximately 30, 40 and 50 mbar d^{-1} were reported. Higher shock intensity therefore shortened the time available for operational response.

B. Cumulative Resistance and Cleaning Response

Initial TMP after successive physical cleanings increased from about 100 mbar for the new membrane to 110, 130 and 180 mbar. This progressive baseline increase indicates accumulation of resistance that physical cake removal could not reverse. Chemical cleaning on day 65 reduced initial TMP to about 110 mbar, leaving a small persistent difference from the new membrane that the authors interpreted as irrecoverable fouling.

The paper extrapolated the observed irrecoverable rate to a membrane-replacement interval, but such extrapolation should be treated cautiously because the experimental period was short relative to the predicted service life and shock history may not remain linear. The more defensible conclusion is that repeated shock events produced measurable cumulative resistance and increased cleaning demand.

C. Filamentous Growth and Clogging

The filamentous index rose from 1 to 5 during the run. After each high-load pulse ended, the return to lower F/M conditions may have favoured filamentous growth. Filaments can increase viscosity, bridge flocs, form ragging and obstruct channels within hollow-fibre modules. The visual accumulation of sludge at membrane corners supported non-uniform hydraulic obstruction.

The unexpected TMP jump after one 8× event was therefore interpreted as combined residual fouling and clogging rather than fouling alone. The distinction matters operationally: chemical cleaning targeted at pore or surface foulants may not correct module-scale flow obstruction, while mechanical cleaning may remove accumulated ragging but leave irreversible membrane resistance. Diagnosis should combine pressure trends, aeration distribution, sludge microscopy and direct inspection of the module.

VII. CROSS-SYSTEM CRITICAL SYNTHESIS

A. What Recovers First?

Across the three studies, bulk carbon removal was the most rapidly recoverable function. In [1], COD returned to pseudo-steady state within 7-27 h depending on shock magnitude, while nitrification remained impaired. In [2], lowering OLR did not fully restore the original nitrifying sludge properties. In [3], water-quality performance could be maintained by the membrane barrier even as TMP and cleaning requirements worsened. These results establish a hierarchy: effluent COD may normalize before microbial community, nitrogen conversion, floc structure or filtration resistance.

A credible recovery assessment should therefore include at least four dimensions: (1) effluent compliance, (2) biological function, particularly nitrification, (3) biomass physical state, including EPS and separation properties, and (4) operational burden, including aeration, cleaning and pressure. Declaring recovery from a single parameter risks overlooking latent instability.

B. Protective and Destabilizing Mechanisms

Biofilm retention is the principal protective mechanism in [1]. It increases biomass inventory, prevents complete washout and creates microenvironments supporting multiple redox processes. In contrast, the specialized nitrifying sludge in [2] was vulnerable to carbon-driven heterotrophic expansion and EPS transformation. The MBR in [3] retained all solids, protecting biomass age but transferring separation problems into the membrane system.

The same biological response can therefore have different plant-level consequences. Heterotrophic growth may temporarily improve carbon uptake, but it consumes oxygen and suppresses nitrifiers. Increased polymeric material or filaments may assist aggregation under some conditions, yet excessive or compositionally altered EPS can worsen settling, dewatering or membrane resistance. Reactor resilience is a balance rather than a universally beneficial increase in biomass.

C. Thresholds versus Loading History

The reviewed experiments caution against treating a single OLR threshold as universally safe. The hybrid reactor tolerated moderate six-hour pulses that might be damaging if prolonged. The nitrifying SBR collapsed at a sustained normalized OLR of 0.75 kg COD kg^{-1} MLVSS d^{-1}. The MBR experienced cumulative effects from repeated shocks even when individual events were temporary. Shock duration, repetition, acclimation state and prior damage are therefore as important as peak magnitude.

Loading history also affects interpretation of sequential experiments. In [1], nitrification impairment from an earlier shock influenced the starting condition of later shocks. In [2], the descending OLR sequence differed from the ascending sequence. In [3], each shock occurred on a membrane with a different accumulated resistance and sludge community. Future protocols should include replicate reactors or independent runs to separate instantaneous shock effects from history-dependent deterioration.

TABLE 2. ENGINEERING INTERPRETATION OF RESPONSE INDICATORS

Indicator	What it reveals	Potential misinterpretation	Recommended companion measurement
Effluent COD	Immediate carbon-removal performance	May recover while nitrification or sludge structure remains damaged	NH4-N, NO2-N, NO3-N and oxygen uptake
DO	Balance between oxygen transfer and biological demand	Bulk DO may not represent biofilm or floc microzones	Aeration rate, OUR and biofilm-depth information
PN/PS in EPS	Cohesion and matrix-composition change	Total EPS alone can hide compositional deterioration	LB-EPS/TB-EPS fractionation, hydrophobicity, zeta potential
SVI / floc size	Settling and aggregate condition	Not directly applicable to membrane effluent quality	Solids loss, SRF and microscopy
TMP and dTMP/dt	Filtration resistance and rate of deterioration	Cannot alone distinguish fouling from module clogging	FI, viscosity, cleaning response and visual inspection
Recovery time	Duration of functional impairment	Depends strongly on the chosen endpoint	Use multi-domain recovery criteria

VIII. IMPLICATIONS FOR DESIGN AND OPERATION

The first practical implication is the value of influent equalization. None of the reviewed reactors was immune to severe shocks. Equalization basins, controlled industrial discharge, staged feeding and diversion of exceptionally high-strength streams can reduce peak substrate concentration and extend the time available for biological adaptation.

Second, aeration systems should be evaluated against peak oxygen demand rather than average load alone. The DO collapse in [1] links organic shocks directly to nitrification loss. However, excess aeration is not a complete solution because it increases energy use and cannot reverse all EPS or community changes. Feed-forward control based on influent COD or surrogate sensors, combined with ammonia feedback, would be more effective than fixed aeration.

Third, nitrification protection deserves explicit priority. Options supported by the mechanisms in the reviewed papers include maintaining adequate sludge age, retaining attached biomass, providing staged reactors and avoiding sustained high F/M conditions. Following a shock, operators should not reduce monitoring once COD improves; ammonia conversion may require a longer stabilization period.

Fourth, solids-separation diagnostics should match reactor configuration. Clarifier-based systems require attention to SVI, floc size and sludge loss. Nitrifying systems benefit from EPS composition and surface-property monitoring. MBRs require TMP-gradient analysis, filament observation and distinction between membrane fouling and module clogging. A common dashboard cannot rely on the same single indicator for all technologies.

Finally, cleaning and recovery procedures should be selected from diagnosis. Physical cleaning addresses removable cake or accumulated sludge; chemical cleaning targets strongly attached foulants; neither necessarily restores a biologically destabilized sludge. After a severe event, the recovery plan may need to combine load reduction, aeration adjustment, sludge wasting control, reseeding and membrane cleaning.

IX. LIMITATIONS OF THE AVAILABLE EVIDENCE

The focused evidence base is small and heterogeneous. All three studies used laboratory or pilot systems and synthetic or controlled feeds, limiting direct extrapolation to full-scale municipal-industrial wastewater containing particulate COD, toxic compounds, surfactants and changing temperature. The reactor volumes, shock durations and loading units differed substantially.

The studies also evaluated different endpoints. Study [1] emphasized short-term effluent and cultured bacterial morphology; [2] provided detailed sludge physicochemistry over long loading stages; [3] emphasized membrane pressure and filamentous index. Their complementarity enables mechanism synthesis, but it prevents statistical meta-analysis or derivation of a universal safe OLR.

Microbial characterization was limited. Culture-based morphology in [1] cannot identify unculturable organisms or functional genes. Study [2] counted nitrifiers and heterotrophs but the reviewed findings do not provide high-resolution community succession comparable to modern sequencing. Study [3] used filamentous index without species-level identification. Consequently, proposed microbial mechanisms are plausible and consistent with performance data but not fully resolved taxonomically.

Finally, recovery definitions were not standardized. Return of COD, recovery of nitrification, restoration of EPS composition, reduction of TMP and recovery after cleaning represent different endpoints. This variation is itself a key conclusion: future studies should report a recovery vector rather than a single recovery time.

X. RESEARCH GAPS AND FUTURE DIRECTIONS

Standardized shock protocols are needed to distinguish peak magnitude, duration, mass loading and repetition. At minimum, studies should report baseline F/M, normalized OLR, pulse duration in HRT units, cumulative excess COD, aeration capacity, SRT and the biological condition before each shock. Independent replicate reactors would reduce confounding by loading history.

Future experiments should integrate online process signals with detailed biomass analysis. High-frequency COD surrogates, ammonia, nitrate, DO, oxidation-reduction potential, oxygen uptake rate, TMP and permeability should be synchronized with EPS fractionation, particle-size analysis, microscopy and microbial sequencing. This would connect an operational alarm to the biological mechanism causing it.

Full-scale and long-term validation is especially important for MBR clogging and for nitrifying-sludge hysteresis. Repeated disturbances over seasonal temperature ranges may produce adaptation that short studies cannot capture. Conversely, cumulative damage may become more severe than laboratory pulse tests suggest.

Predictive control represents a promising direction, but models should not be trained solely on effluent COD. A useful resilience model would predict the probability and duration of ammonia breakthrough, floc deterioration and TMP acceleration from influent strength, loading history, DO reserve and biomass indicators. The three studies collectively show that a multi-output model is necessary.

Hybrid configurations also deserve systematic comparison. The protection observed in the activated sludge-biofilm system suggests that attached biomass could stabilize nitrifying populations, while membrane retention could prevent washout. Yet combining biofilm and membranes may increase carrier-associated scouring benefits as well as clogging complexity. Controlled comparisons are required to establish when added process complexity yields genuine resilience.

Finally, research should connect process resilience with life-cycle cost. Shock tolerance has value only if it reduces non-compliance, aeration demand, sludge handling, cleaning chemicals, downtime and membrane replacement. Reporting these operational consequences would make laboratory findings more actionable for civil and environmental engineers.

XI. CONCLUSIONS

The reviewed studies demonstrate that organic shock loading affects biological wastewater treatment through a connected sequence of substrate surplus, increased heterotrophic activity, oxygen competition, microbial selection, EPS modification and deterioration of solids separation or membrane filtration. Reactor configuration determines how these mechanisms appear operationally.

The two-stage activated sludge-biofilm reactor buffered moderate six-hour COD shocks and recovered carbon removal within hours, but recovery time increased to about 27 h at the largest shock and nitrification remained more vulnerable than COD removal. The nitrifying SBR showed that sustained OLR increases can alter LB-EPS composition, reduce protein and PN/PS ratio, destabilize sludge properties and produce incomplete recovery after system collapse. The MBR study showed that repeated shocks accelerate residual fouling and TMP jumps, while increasing filament abundance and visual sludge accumulation implicate clogging as a synergistic mechanism.

Three overarching conclusions follow. First, effluent COD alone is not a sufficient measure of recovery. Second, resilience depends on protected biomass, oxygen reserve and matrix quality rather than biomass concentration alone. Third, shock history and duration must be considered together with peak load. A robust operating strategy should therefore combine influent equalization, multi-parameter monitoring, protection of nitrifying populations, configuration-specific solids-separation diagnostics and recovery procedures selected from the actual failure mechanism.

Because the present review is restricted to three supplied references, its conclusions should guide focused interpretation rather than define universal design thresholds. Nevertheless, the convergence of findings across hybrid, nitrifying and membrane systems provides a coherent framework for designing more resilient wastewater treatment processes and for structuring broader systematic reviews.

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