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# Biofouling by *Limnoperna fortunei* in Water-Conveyance Infrastructure: Stage-Specific Risks, Monitoring Signals, and Integrated Management for Sustainable Operation

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## Abstract

The planktonic dispersal of *Limnoperna fortunei* larvae and the byssal attachment of juveniles and adults make this species a major invasive biofouling species in water-conveyance infrastructure, while artificial hydraulic connectivity further facilitates its spread. Dense colonization can reduce conveyance capacity, increase energy consumption, accelerate structural deterioration, and impair water quality, thereby posing multiple risks to infrastructure operation. This narrative and critical review synthesizes evidence from 110 publications retained after screening 537 records retrieved from the Web of Science Core Collection up to 30 June 2026. The review characterizes the stage-specific progression of *L. fortunei* biofouling from propagule input and early settlement to mature fouling and post-treatment residual risks. It compares the applicability of eDNA/qPCR assays, conventional field surveys, and remotely operated vehicle (ROV)-based image inspection, and evaluates the effectiveness and operational limitations of physical, chemical, coating-based, and biological control measures across different risk stages. Current management often targets individual stages, with limited linkage between monitoring results and subsequent intervention. Accordingly, we propose a risk-oriented decision pathway that integrates early warning, settlement confirmation, fouling-load assessment, targeted removal, and post-treatment verification while accounting for hydraulic safety, water-quality constraints, and asset accessibility. By aligning management actions with biofouling stage and asset condition, this framework provides a basis for more sustainable operation and maintenance of water-conveyance systems.

**Keywords:** *Limnoperna fortunei*; biofouling; water-conveyance infrastructure; stage-specific risk; early warning; environmental DNA (eDNA); sustainable infrastructure management

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## 1. Introduction

China has implemented a series of inter-basin water-transfer projects, including the South-to-North Water Diversion Project, to alleviate the spatial and temporal mismatch between water availability and demand. These projects have substantially increased hydrological connectivity. Although such connectivity improves water-resource allocation, it also

creates pathways for the dispersal of aquatic organisms [1,2]. Among them, *Limnoperna fortunei* has spread rapidly through water-transfer networks and has become one of the principal biofouling threats to the safe operation of water-conveyance infrastructure [3–5].

*L. fortunei* is native to river systems in southern China and is characterized by a life cycle that combines planktonic larval dispersal with persistent byssal attachment after settlement. Its larvae can be transported passively with flowing water, whereas settled juveniles and adults attach firmly to submerged concrete, metal, and other hard surfaces [6,7]. This transition enables rapid colonization and the formation of dense fouling layers. Such accumulation can reduce the effective flow area, increase wall roughness and head loss, lower conveyance efficiency, raise energy consumption, and accelerate surface deterioration; under severe conditions, it may obstruct pipelines and critical hydraulic components [8–10]. Compared with zebra mussels, *L. fortunei* has been reported to tolerate a broader range of temperatures and flow conditions and to exhibit high reproductive output, traits that may enhance its invasion potential in engineered water-transfer systems [7]. Surveys of the South-to-North Water Diversion Project and urban water-supply systems indicate that its colonization has extended beyond previously recognized distribution boundaries [2,3,11]. The associated risk therefore no longer concerns isolated facilities alone, but extends across interconnected source waters, intake structures, conveyance corridors, and downstream receiving areas [1]. Accordingly, *L. fortunei* biofouling should be understood as a stage-specific infrastructure risk mediated by engineered hydrological connectivity.

Research on *L. fortunei* has generated substantial evidence in invasion biology, engineering hydraulics, monitoring, and control [8,10,12]. However, operational practice often applies similar responses to biologically and operationally distinct risk states. This reflects the absence of an organizing framework centered on biofouling progression and limits the translation of monitoring signals into asset-level decisions. Previous reviews have summarized the distribution, biology, ecological and engineering impacts, and control of *L. fortunei* from different perspectives [7,13,14]. However, less attention has been given to linking biofouling stages with monitoring evidence and corresponding management actions in water-conveyance infrastructure. This review addresses this issue by organizing biofouling into propagule input, early settlement, mature biofouling, and post-treatment residual biomass, and by linking these stages with monitoring and management requirements (Table 1). This review therefore conceptualizes *L. fortunei* biofouling as a stage-specific infrastructure risk and addresses three objectives: (1) to identify the distinct engineering risks associated with different life-history and biofouling stages; (2) to evaluate the monitoring signals and control measures most appropriate for each risk stage; and (3) to develop an integrated management framework linking early warning, settlement confirmation, fouling-load assessment, targeted removal, and post-treatment verification. By organizing existing evidence around this stage-specific logic, the review aims to support a transition from reactive removal toward risk-informed management of *L. fortunei* biofouling in water-conveyance infrastructure. From a sustainability perspective, this approach seeks to maintain hydraulic performance and water quality while avoiding unnecessary intervention over the service life of water-conveyance assets.

**Table 1.** Comparison of the scope and management perspectives of selected reviews on *L. fortunei.*

| Review | Main Emphasis | Stage–Risk Perspective | Monitoring and Management Link | Post-Treatment Management |
|---|---|---|---|---|
| [13] | Distribution, ecology, impacts, knowledge gaps, and control | Life-history stages and ecological effects are broadly considered, but not organized around risks to water-conveyance infrastructure | Monitoring and control are mainly discussed as separate aspects of invasion management | Limited attention to residual biomass and associated risks |

**Table 1.** *Cont.*

| Review | Main Emphasis | Stage–Risk Perspective | Monitoring and Management Link | Post-Treatment Management |
|---|---|---|---|---|
| [7] | Distribution, environmental tolerance, growth, behaviour, and control methods | Emphasis on biological traits and responses across life stages | Control methods are mainly discussed in relation to biological responses and treatment effects | Not specifically addressed |
| [14] | Impacts on hydraulic structures and ecosystems, invasion factors, and control approaches | Biofouling development and engineering impacts are considered | Monitoring and control are discussed, but are not organized around stage-specific management responses | Limited discussion of residual biomass and post-treatment recovery |
| Present review | Stage-specific biofouling risk and management in water-conveyance infrastructure | Biofouling is divided into propagule input, early settlement, mature biofouling, and post-treatment residual biomass | Monitoring evidence identifies the relevant risk stage, while engineering consequences determine the urgency and intensity of management actions | Residual biomass, biomass removal, water-quality recovery, and post-treatment monitoring are incorporated into the management process |

## 2. Literature Search and Evidence Synthesis

This study was conducted as a narrative and critical review. Relevant literature was searched in the Web of Science Core Collection using the topic query TS = ("*Limnoperna fortune*" OR "golden mussel"). The search covered all records available up to 30 June 2026, with no predefined starting year, and returned 537 records.

Titles and abstracts were screened for relevance, with full texts examined when needed. Studies were retained if they addressed the biology, attachment, monitoring, engineering impacts, control, or management of *L. fortunei* and were relevant to freshwater infrastructure. Studies outside the scope of biofouling or lacking sufficient information for interpretation were excluded. Greater attention was given to evidence from water-conveyance systems, raw-water facilities, reservoirs, pipelines, pumping stations, canals, intake structures, and water-treatment facilities. After screening, 110 publications were retained for qualitative synthesis. The literature was organized according to the main topics addressed in this review. Evidence was interpreted qualitatively on the basis of study design, methodological detail, engineering relevance, and consistency with other studies. Operational and full-scale studies were used primarily to assess engineering applicability, whereas laboratory studies were used mainly to interpret mechanisms and treatment responses.

## 3. Stage-Specific Biofouling Processes in Water-Conveyance Systems

### *3.1. Mussel Attachment Mechanisms and Biofouling Progression*

From the perspective of infrastructure management, the successful invasion of *L. fortunei* in water-conveyance projects is closely associated with its distinctive life-history characteristics. This process can be divided into two key stages: the planktonic larval dispersal stage and the adult attachment and colonization stage, both of which are strongly affected by hydraulic conditions in engineering systems.

The planktonic larval stage has the greatest dispersal capacity in the life cycle of *L. fortunei* and provides the basis for its long-distance transport and range expansion through water-transfer projects [2,15,16]. The relatively high flow velocities in engineered water-conveyance channels provide an efficient carrier for the passive dispersal of larvae (Figure 1b). Their occurrence in the water column, either as larvae or as molecular evidence, can indicate reproductive activity and potential long-distance dispersal before visible

biofouling develops [5,11]. At this stage, the primary concern is not structural blockage but the entry and movement of propagules through vulnerable water-conveyance corridors. In addition, its short developmental period further enhances its invasion advantage: at a suitable temperature of 25 °C, development from a fertilized egg to the end of the planktonic larval stage, when the larva becomes capable of settlement and attachment, requires only approximately 13 days [17]. Although the life cycle includes gametogenesis and several larval stages, such as the trochophore, veliger, and pediveliger stages, the planktonic period from the veliger to early pediveliger stage represents the critical window for downstream dispersal and invasion of water-conveyance systems. During the later developmental stage, approximately after day 6, the mobility of pediveligers decreases, and they tend to sink and search for suitable attachment substrates [17].

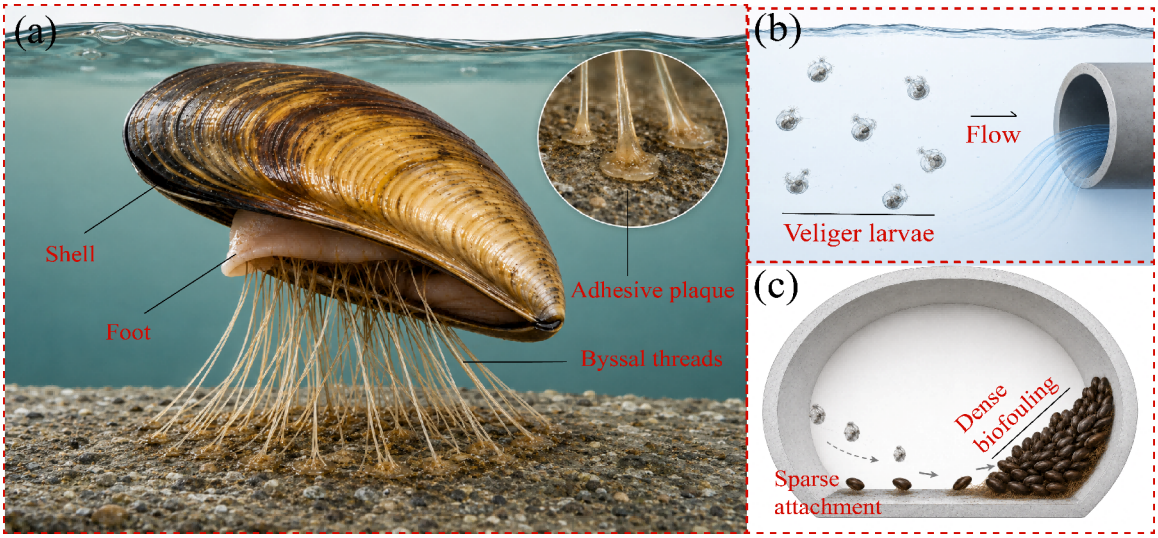



**Figure 1.** Schematic illustration of the formation mechanisms of *L. fortunei* biofouling: (**a**) anatomical structure of underwater anchoring by mussel byssal threads and adhesive plaques; (**b**) transport of larvae into pipelines with flowing water; and (**c**) progression of biofouling inside pipelines from sparse attachment to dense growth.

After entering the attachment stage, *L. fortunei* develops a muscular and highly mobile foot capable of secreting byssal proteins (Figure 1a). The structure and function of the foot are fundamental to its firm attachment and the resulting biofouling of engineering structures. The foot of *L. fortunei* is flattened and muscular, facilitating contact with the surfaces of submerged substrates such as concrete components and steel-pipe structures [18]. Several types of glands, including the accessory gland, collagen gland, and phenol gland, are distributed within the ventral groove of the foot and are responsible for secreting byssal proteins, collagen proteins, and matrix proteins [19,20]. These proteins are released into the water along the ventral groove and rapidly solidify to form byssal threads with strong adhesive capacity. Once stable byssal attachment has been established, individuals enter a relatively sessile juvenile stage and remain attached through adulthood. Adults can reach 2–3 cm in length and have a strong capacity for byssal secretion, with a single individual capable of producing dozens of byssal threads [13,19]. These byssal threads exhibit excellent mechanical adhesion properties, enabling the mussels to form high-density attachment layers on various engineering surfaces (Figure 1c). Such layers provide the basis for subsequent large-scale biofouling and are a major reason why the species is difficult to control [21,22]. As attached populations grow, this accumulation can reduce the effective flow area, increase local hydraulic resistance, interfere with facility operation, and accelerate the deterioration of engineering surfaces [9,10,23].

Therefore, the invasion of *L. fortunei* should not be regarded as a single colonization event but as a stage-specific process consisting of reproduction, larval transport, settlement, attachment, and population growth. The transition from planktonic larvae to attached populations marks a shift in risk from dispersal through the water column to asset-level biofouling, providing a biological basis for distinguishing early-warning requirements from post-settlement control priorities. Seasonal reproductive peaks increase propagule pressure, whereas post-settlement growth determines the development of visible biofouling and damage to infrastructure [7,24,25]. As illustrated in Figure 1, the transition from planktonic transport to substrate attachment represents the key shift from corridor-scale dispersal risk to localized biofouling risk on engineering surfaces. Subsequent population growth then transforms localized attachment into a structural and hydraulic problem.

### *3.2. Stage–Risk Mapping for Infrastructure Management*

Stage–risk mapping provides a practical bridge between mussel biology and operational decision-making (Table 2). The same species can generate distinctly different management problems at different growth stages. At the risk-warning level, the planktonic larval stage represents dispersal and a potential threat. Once the mussels enter the early settlement stage, individual attachment corresponds to the initial formation of surface biofouling. Mature adult populations directly generate severe risks of hydraulic obstruction and material loading. In addition, after fouling organisms have been removed, the residual biomass may cause secondary water-quality deterioration and equipment-maintenance problems. Therefore, an effective management framework must link the different life stages of the mussel with differentiated risk signals, targeted asset types, and specific management actions.

**Table 2.** Stage–risk mapping and management objectives for *L. fortunei* biofouling in water-conveyance infrastructure.

| Risk Stage | Dominant Process | Major Infrastructure Risk | Management Objective |
|---|---|---|---|
| Propagule input | Larval transport through connected water systems | Corridor-scale dispersal before visible fouling | Early detection and pathway surveillance |
| Early settlement | Juvenile attachment and early byssus formation | Surface colonization and localized hotspots | Settlement prevention |
| Mature biofouling | Growth and accumulation of adult fouling layers | Hydraulic impairment and material deterioration | Load assessment and targeted removal |
| Post-treatment residual risk | Accumulation and decomposition of dead mussels, shells, and residual biomass | Water-quality deterioration and maintenance risks | Biomass removal and post-treatment verification |

## 4. Impacts of *L. fortunei* on Water-Conveyance Projects

The high-density attachment of *L. fortunei* to water-conveyance facilities poses serious threats to engineering structures, water quality, conveyance efficiency, and equipment operation through multiple mechanisms (Figure 2).

### *4.1. Concrete Deterioration*

Concrete deterioration associated with *L. fortunei* involves both mechanical and biochemical processes. Mechanically, byssal plaques and threads can penetrate surface irregularities, while removal of strongly attached mussels may cause mortar loss, aggregate exposure, and local fissures [9,26]. Chemically, organic acids associated with byssal secretion and metabolic activity can promote the dissolution of cement hydration products such as calcium hydroxide [27]. Yao et al. [9] further showed that colonized concrete had increased

pore volume and lower apparent density, together with reductions in calcium and calcium carbonate, compared with uncolonized concrete under the same environmental exposure.

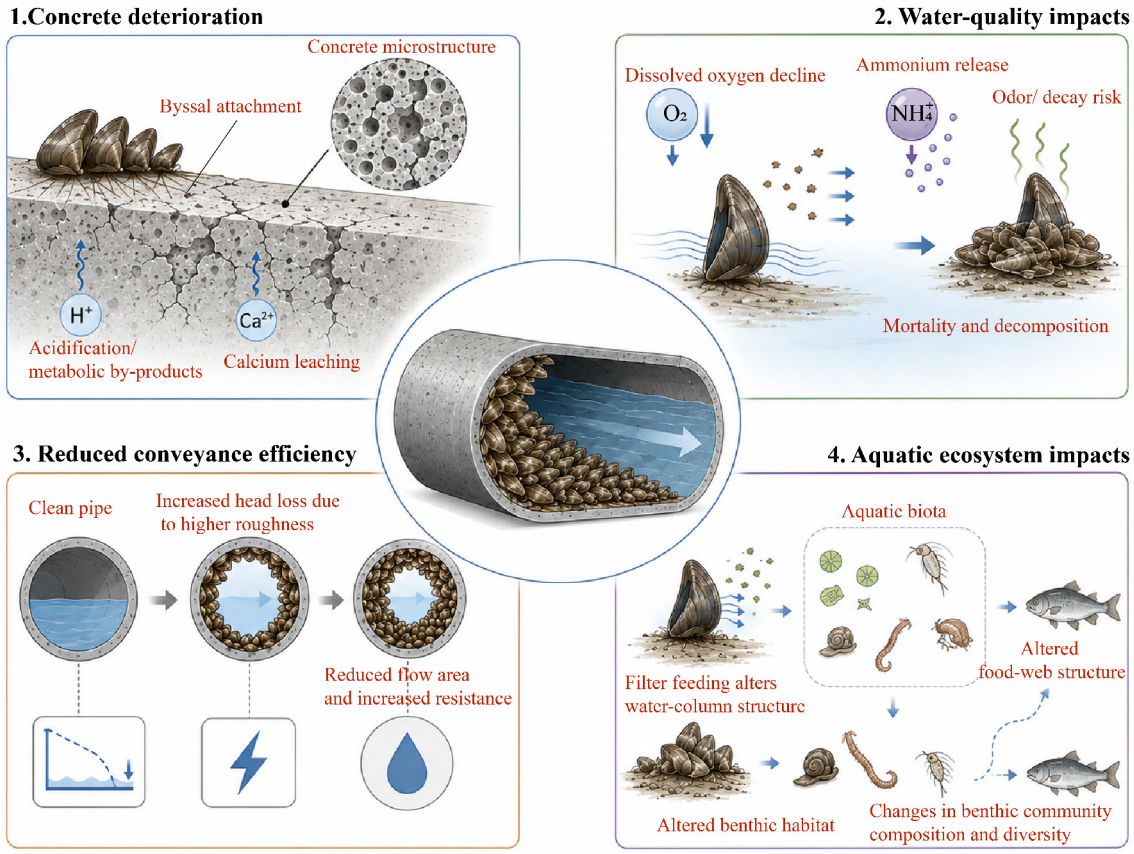



**Figure 2.** Major impacts and mechanisms of *L. fortunei* in water conveyance projects.

The same study measured water absorption after 24 h in accordance with SL 352-2006. After approximately one year of colonization, water absorption increased from 5.21 ± 0.35% in the uncolonized control to 9.30 ± 0.58% in colonized concrete, corresponding to a 79% increase. For in situ concrete colonized for more than 20 years, water absorption increased from 2.88 ± 0.40% to 5.73 ± 0.29%, corresponding to a 99% increase. Biofilms and associated microbial activity may further modify near-surface interfacial conditions and contribute to long-term material deterioration [28].

### *4.2. Water-Quality Impacts*

The biological activities of *L. fortunei* directly affect the quality of conveyed water. Its respiration consumes dissolved oxygen, while its excretion releases substances such as ammonia nitrogen. For example, the proliferation of *L. fortunei* in the collection well of a raw-water treatment plant in Wuxi reduced dissolved oxygen from 6.14 mg/L to 3.8 mg/L [7]. Following mortality, the release of internal metabolites into the water can increase the concentrations of odor-producing compounds, including 3-methylindole (skatole), 1-octen-3-ol (earthy odor), dimethyl disulfide, and dimethyl trisulfide (putrid and fishy odors), thereby impairing water-supply quality [29].

In addition to these direct effects, *L. fortunei* can reshape water-quality and ecological processes through intense filter feeding, nutrient cycling, biodeposition, and biomass decomposition. Studies have shown that its filtration activity can remove suspended particles, phytoplankton, and organic matter, thereby altering resource availability, water transparency, and plankton-community structure [30,31]. These effects vary with individual

size, temperature, food concentration, and flow conditions. High-density populations may therefore create spatially heterogeneous gradients of food resources and organic matter in pipelines, canals, reservoirs, and receiving waters rather than producing uniform ecological effects [32].

Control actions may also generate secondary water-quality risks. Killing adult populations does not necessarily eliminate operational risks because the decomposition of mussel biomass may consume dissolved oxygen, restructure bacterial communities, promote odor formation, and release harmful gases or metabolites under conditions of poor ventilation or limited maintenance accessibility [33–35]. Therefore, successful mortality does not necessarily equate to successful management. Where dense adult fouling mats are present, chemical or physical control should be combined with biomass removal, hydraulic flushing, ventilation during maintenance, monitoring of dissolved oxygen and nutrients, and post-treatment inspection to prevent decomposition-driven water-quality deterioration and occupational-safety risks.

### *4.3. Reduced Water-Conveyance Efficiency*

High-density *L. fortunei* fouling layers, which can reach a thickness of up to 10 cm, can markedly increase the roughness of wetted surfaces and reduce the effective flow area, resulting in greater hydraulic losses, lower water-conveyance efficiency, and increased energy consumption [10,36]. Recent studies have begun to quantify the relationship between biofouling severity and hydraulic performance. Here, $k_s$ denotes the equivalent sand roughness, $L$ the mussel shell length, and N the attachment density (individuals $m^{-2}$). The ratio $k_s/L$ represents equivalent sand roughness normalized by shell length, while $NL^2$ is a dimensionless attachment density obtained by multiplying the areal attachment density $N$ by the squared shell length $L^2$. For continuous regular fouling layers at $NL^2 > 1.2$, $k_s/L$ was approximately 1.5. At $0.5 < NL^2 < 1.2$, irregular continuous fouling produced $k_s/L$ values of up to 2.4. Application of these relationships to a large water-transfer project indicated that even early, patchy colonization could increase overall energy losses by approximately 5%. Under the most severe simulated fouling condition, additional energy losses reached approximately 29% in a trapezoidal channel, 53% in a U-shaped aqueduct, and 91% in a circular pressure pipeline [10]. These results indicate that hydraulic effects are controlled not only by mussel density but also by shell size, fouling-layer continuity, and the geometry of the affected structure. This interpretation is consistent with model experiments on pressurized water-conveyance systems, in which hydraulic roughness increased with both attachment thickness and surface coverage. At relatively low fouling densities, mussel abundance was the dominant factor, whereas attachment thickness became more important as fouling density increased [37]. Biofouling severity should therefore be characterized using a combination of density, coverage, layer thickness, and individual size rather than density alone. In an intake pipeline at a water-treatment plant in Guangzhou, the outlet pressure head increased from 32.5 m to 33.4 m between September 2012 and April 2013, while the unit energy consumption for water intake increased from 0.1240 kWh/$m^3$ to 0.1314 kWh/$m^3$ [38].

### *4.4. Impacts on Aquatic Ecosystems*

The rapid proliferation of *L. fortunei* can also affect aquatic ecosystems in multiple ways [39,40]. On the one hand, it can alter the structure of benthic communities in the original water body. For example, the filtration activity of *L. fortunei* may change the densities of other filter-feeding benthic organisms, while its attachment to native mollusks may cause suffocation and mortality, thereby reducing or eliminating regional differences among benthic assemblages [31,41–43].

On the other hand, *L. fortunei* may affect aquatic food webs. Certain fish that preferentially consume *L. fortunei*, including carp, black carp, catfish, and prochilodontid fishes, may alter their original feeding habits and reduce their predation efficiency on previously consumed prey, thereby affecting the balance of the original aquatic food web [44–46].

## 5. Monitoring and Early Warning Across Risk Stages

### *5.1. Larval Monitoring and eDNA-Based Early Warning*

eDNA monitoring detects trace amounts of genetic material in water and can reveal low-density populations of *L. fortunei* before visible biofouling develops, often with greater sensitivity than conventional morphology-based surveys [3,5,47]. Studies conducted across South America, Japan, and China have demonstrated the ability of eDNA methods to map distributions over broad spatial scales, detect cryptic populations, and identify invasion risks in long-distance water-conveyance systems [48]. In the South-to-North Water Diversion Project and its receiving areas, repeated eDNA surveys have provided spatially explicit evidence of rapid dispersal, giving the method clear operational value for prioritizing inspection and sampling locations [3,5]. However, the current management value of eDNA remains concentrated primarily on early detection and spatial screening rather than on direct estimation of biofouling loads or selection of control intensity [49].

eDNA concentration has been reported to show an exponential relationship with *L. fortunei* density, with this relationship also influenced by water temperature and pH [50]. However, eDNA signals are also influenced by DNA shedding, transport, dilution, degradation, and local hydrodynamic conditions [5], which complicates their interpretation as indicators of population abundance or local attachment density. False negatives may occur when target DNA concentrations are low or unevenly distributed, or when environmental samples contain PCR inhibitors, whereas contamination or non-specific amplification may produce false-positive results [51,52]. In flowing systems, downstream transport means that the location of eDNA detection may not correspond to the location of the source population [53]. These factors limit the direct use of eDNA concentration as an estimate of local abundance or attachment density. Thus, eDNA is better suited to early detection and spatial screening than to direct estimation of local biofouling loads. Positive detections should therefore prompt confirmatory sampling or intensified monitoring rather than serve as the sole basis for large-scale control.

PCR-based larval detection, real-time qPCR, and eDNA analysis have all been applied to *L. fortunei* monitoring, often together with conventional microscopic examination [48,54,55]. PMA-coupled real-time qPCR has also been used to assess tissue damage after ultrasound treatment [56]. This methodological diversity increases operational flexibility but also requires greater standardization of sampling, assay validation, data interpretation, and result reporting. Without such standardization, comparisons among facilities and the development of reliable operational thresholds remain difficult [49].

### *5.2. Conventional Field Surveys*

Conventional field monitoring includes larval sampling, adult-density surveys, artificial-substrate sampling, visual inspection during maintenance periods, and recording of biofouling loads. These approaches provide direct biological or surface-based evidence of propagule occurrence, settlement, and established biofouling. These methods directly document colonization on the surfaces of critical facilities and confirm whether *L. fortunei* has completed settlement and established a persistent attached population. Parameters such as adult density, biomass per unit area, fouling-layer thickness, percentage cover, and population size structure can be used to determine whether biofouling has progressed from early settlement to a structural load and can provide a direct basis for defining clean-

ing frequency, scheduling shutdown maintenance, and protecting critical locations [57]. However, these methods depend on surface accessibility and the availability of maintenance windows, and their spatial coverage is restricted in enclosed pipelines, deep-water structures, and confined spaces [8]. They are also less sensitive to initial larval input and low-density early settlement and are therefore more closely aligned with reactive inspection than with early warning. When used alone, they cannot adequately meet whole-process early-warning requirements.

Within a stage-specific risk-management framework, conventional field monitoring is more appropriately used for settlement confirmation and biofouling-load assessment rather than as an independent whole-process warning method. Larval surveys and eDNA detection can identify propagule-input risks; artificial substrates and material coupons can capture early attachment signals; and adult-density, percentage-cover, and fouling-thickness surveys can quantify established structural loads. Combining these methods according to risk stage can create a continuous monitoring system extending from early warning to operation and maintenance decision-making.

### *5.3. ROV- and Image-Based Inspection*

ROV- and image-based inspection is mainly used for water-conveyance facilities that are difficult or hazardous for personnel to access directly, including intake structures, tunnels, inverted siphons, pumping-station pipelines, gates, deep-water components, and confined spaces. The basic workflow generally includes deploying underwater cameras or ROVs, acquiring images or videos of facility surfaces, interpreting biofouling coverage and attachment extent, and using scale calibration to estimate shell-layer thickness, spatial distribution, and post-treatment residues [8].

The principal advantage of these methods is that they can reduce the need for water-supply shutdowns, dewatering, and personnel entry into confined spaces. They are therefore suitable for rapid screening of inaccessible assets, verification of critical locations, and evaluation of removal effectiveness. For water-conveyance projects, ROV and image data provide spatially explicit information on asset condition and can help identify localized high-density colonies, potential blockage points, and subsequent maintenance priorities [58]. These methods also have clear limitations. Image quality is strongly affected by turbidity, illumination, flow velocity, surface complexity, viewing angle, and equipment stability. Estimation of biofouling thickness and density generally requires scale calibration and manual verification, while automated recognition models depend on representative annotated datasets and validation under operational field conditions [57]. ROV- and image-based inspection should therefore be regarded as a structural-inspection and asset-condition assessment tool rather than as a replacement for larval monitoring, eDNA-based early warning, or direct density sampling. Its principal role in stage-specific risk management is to translate early-warning and field-confirmation results into spatially explicit information for maintenance planning.

### *5.4. Stage-Specific Management Responses to Monitoring Signals*

Risk-oriented monitoring should combine methods according to the stage of biofouling development rather than treat them as interchangeable alternatives (Table 3). eDNA, qPCR, and larval surveys are most informative before local settlement is confirmed, whereas direct surveys and ROV- or image-based inspection become more useful once attached populations are present. Risk models and decision-support tools can further integrate these observations to prioritize monitoring locations and intervention timing.

**Table 3.** Stage-specific applications and key limitations of monitoring methods for *L. fortunei* biofouling.

| Method Category | Primary Management Use | Key Limitation |
| --- | --- | --- |
| Field sampling of larvae and adults | Routine surveillance after invasion and quantitative assessment of biofouling loads [59–61] | Labor-intensive, dependent on accessibility, and relatively insensitive to low-density early invasion |
| eDNA and qPCR detection | Pre-invasion screening, early detection, and early warning during the larval stage [5,11,47,52] | Affected by false-positive/negative detections, DNA transport and persistence, and site-specific environmental conditions |
| ROV- and image-recognition-based inspection | Inspection of inaccessible or hazardous structures during operation or shutdown periods [8,57] | Performance depends on image quality, turbidity, illumination, scale calibration, annotated datasets, and field validation |
| Risk models and decision-support tools | Integrating biological and environmental observations to prioritize monitoring locations and intervention timing [57] | Requires site-specific calibration and long-term operational validation before independent use for management decisions |

The transition from monitoring to management should reflect the strength of the available evidence. Management decisions should consider both biological confirmation and the level of engineering validation. In this review, evidence is considered in increasing order of engineering relevance: laboratory, mesocosm, pilot, full-scale demonstration, and operational studies. Early-warning signals warrant confirmation and closer surveillance, whereas confirmed settlement calls for targeted inspection and assessment of fouling development. If settlement is detected without measurable operational impairment, continued inspection may be more appropriate than immediate intensive treatment. Intervention should be considered when established biofouling is accompanied by measurable deterioration in hydraulic or operational performance. Operational shutdown or hydraulic isolation should be considered only when biofouling interferes with asset operation or when access is required for removal or treatment. Because transferable numerical thresholds are not yet available, action criteria should be calibrated against site-specific operating baselines.

## 6. Control Measures for *L. fortunei*

### *6.1. Physical Control Methods*

Physical defouling methods mainly include manual or mechanical cleaning, flow-velocity regulation, filtration, water-temperature adjustment, hydraulic regulation, ultrasonic treatment, and ultraviolet irradiation [14,37,56,62]. From an environmental perspective, these methods can achieve substantial short-term defouling effects while avoiding the risk of secondary water pollution associated with conventional chemical treatment. However, more detailed studies have revealed considerable economic and technical constraints on their long-term application. On the one hand, these treatments may cause structural damage to treatment facilities; on the other hand, their practical applicability is restricted by multiple factors. Specifically, ultrasonic cavitation and aeration treatments generally require equipment operation to be interrupted, thereby interfering with the continuous operation of engineering systems. The effectiveness of ultraviolet-based treatment is also highly dependent on water transparency and is generally limited to low-turbidity water, which substantially restricts its applicability in complex settings such as inter-basin water-transfer projects.

Physical control remains an important component of *L. fortunei* management because it can reduce reliance on chemical dosing and, in many settings, can be integrated into

planned maintenance windows. Air exposure and desiccation, thermal treatment, mechanical scraping, hydraulic flushing, and turbulence- or flow-assisted removal have all produced varying degrees of mortality or removal under controlled or locally favorable conditions [56,63–65]. The principal limitation is scalability at the operational level. Treatments that are effective in dewatered sections, laboratory systems, or accessible components may be difficult to deploy across long-distance, large-diameter, or continuously operating water-conveyance networks. Physical control should therefore not be regarded as a stand-alone eradication strategy but is more appropriately used as a planned-maintenance or localized-response tool for accessible, high-priority assets where treatment timing, hydraulic isolation, and post-treatment removal can be controlled [14,23,37].

### *6.2. Chemical Control Methods*

Chemical measures include oxidants, copper sulfate, pH adjustment, microencapsulated baits, biomimetic antifouling agents, and various biocides [14,66–68]. At appropriate concentrations and exposure conditions, oxidants such as sodium hypochlorite, potassium permanganate, hydrogen peroxide, and chlorine dioxide can induce valve closure, physiological stress, attachment weakening, or mortality in *L. fortunei*. Chlorfenapyr and several other molluscicides have also shown lethal effects. However, treatment effectiveness depends strongly on application conditions, and mortality of exposed individuals should not be interpreted as system-wide eradication. Commercial molluscicides have also been evaluated against *L. fortunei*. MXD-100 has shown acute toxic effects in adult mussels, whereas BULAB 6002 has been reported to cause mortality and inactivation of larvae [69–71]. Other non-oxidizing molluscicides have also been tested under different concentrations, exposure durations, and temperatures [67]. Treatment outcomes should therefore be distinguished as mortality or inactivation, weakening of byssal attachment, and detachment; none of these endpoints alone demonstrates system-wide eradication. Chemical control remains one of the more established operational approaches for suppressing *L. fortunei* biofouling, particularly in systems where oxidants can be delivered through existing raw-water dosing infrastructure. Studies have shown that sodium hypochlorite can reduce byssus production, decrease byssal-thread breaking force, and promote byssal shedding. Potassium permanganate, particularly at higher exposure levels, appears to act primarily through acute oxidative stress and lethal effects [72,73]. Chemical treatment depends on applied concentration, exposure duration, water temperature, and, in flowing systems, hydraulic retention time. Field application must also consider residual chemicals, treatment by-products, downstream water-quality requirements, and effects on non-target organisms [66,68]. Oxidant treatment should therefore be regarded as a dose–response intervention that depends on operational conditions rather than as a universally effective eradication method.

Chemical control can also be understood from the perspective of attachment weakening. Oxidants such as sodium hypochlorite and hydrogen peroxide can inhibit byssus production and reduce byssal-thread breaking force in *L. fortunei*, indicating that their antifouling effects arise not only from direct toxicity but also from weakening the mechanical basis of attachment [72]. This distinction is operationally important: mussels with weakened attachment may still require flow-assisted or mechanical removal, whereas dead but attached mussels may continue to obstruct flow and decompose in situ on engineering surfaces. Oxidant-based strategies should therefore be combined with hydraulic or mechanical removal and evaluated using multiple endpoints, including mortality, byssus production, detachment rate, breaking force, and residual post-treatment attachment [23].

### *6.3. Coating-Based Control Methods*

Some studies have shown that the attachment characteristics of *L. fortunei* vary among substrates and surface coatings, and that these factors are critical determinants of its biofouling capacity [21,37,74]. On this basis, materials that release biocides to kill attached organisms or interfere with byssus synthesis and adhesion have been proposed as potential control strategies. However, toxic substances can compromise water-use safety and therefore cannot be applied in some water-supply settings. Although natural antifouling agents, such as terpenoid compounds, may provide alternatives to conventional chemical coatings, their high production costs reduce their economic feasibility and constrain large-scale production and application [75–77]. Antifouling coatings provide a prevention-oriented complement to chemical treatment. Their principal function is not to remove established populations but to reduce settlement suitability during the early attachment stage by modifying surface energy, surface roughness, mechanical-release properties, and biofilm–substrate interactions. Studies of *L. fortunei* have emphasized the need for environmentally compatible coating systems. Evidence concerning mussel attachment and deterioration of engineering surfaces further demonstrates the importance of surface protection before high-density colonization develops [37].

Mechanism-oriented antifouling design should be evaluated using both laboratory-based mechanistic endpoints and field-relevant operational indicators. Laboratory tests can help determine how candidate interventions affect byssus production, adhesive-plaque performance, attachment strength, and mortality [19]. However, short-term inhibition under laboratory conditions should not be considered equivalent to control effectiveness at the field scale. Candidate antifouling materials should be tested under realistic flow regimes and exposure conditions rather than evaluated solely through short-term static experiments [22,75]. Longer-term field or semi-field assessments must capture recruitment pulses, coating aging, sediment deposition, variations in operational flow, and repeated attachment pressure. Available evidence supports the use of byssal biology as a mechanistic perspective for material screening and antifouling design, but remains insufficient to establish a mature engineering-control solution. Until field durability, coating-renewal intervals, compatibility with oxidant exposure, and ecological safety have been verified, mechanism-oriented antifouling design should be described as an emerging strategy rather than as a directly deployable engineering technology [37,78].

### *6.4. Biological Control Methods*

Biological control, naturally derived bioactive compounds, and genetic tools remain exploratory approaches in the management of *L. fortunei*. Predator regulation has some empirical support: native fish can consume *L. fortunei*, and field and experimental studies indicate that fish predation may suppress mussel abundance under specific ecological conditions [79]. Naturally derived bioactive compounds, including tannins, algal diterpenes, and aquatic-macrophyte extracts, have also been reported to inhibit survival, attachment, or biofouling development [75,77].

By contrast, RNA interference and CRISPR-related strategies should be regarded as emerging concepts for invasive-mussel control rather than as engineering measures that can be deployed in the near term [44]. Biological and genetic control should therefore not currently be presented as alternatives to physical, chemical, or operational-scheduling methods in water-conveyance infrastructure, but as candidate tools requiring extensive validation and ecological-risk assessment.

### *6.5. Comparison of Control Methods*

Operational control should be treated as a stage-specific and site-specific decision process rather than as a choice among broadly applicable technologies (Table 4). Mechanical removal is most appropriate for accessible components, particularly where adults, shells, or accumulated sediment have already impaired conveyance capacity or equipment performance. Chemical oxidants and molluscicides are better suited to rapid localized suppression in enclosed or controllable systems where dosage, exposure duration, hydraulic retention time, and downstream discharge can be managed [66–68,72]. Preventive coatings and material selection are more relevant before settlement and stable byssal attachment occur. Larval-stage interventions, including ultraviolet treatment, should also be synchronized with reproductive and recruitment windows rather than applied continuously at a constant intensity [14,62].

**Table 4.** Engineering and sustainability comparison of control strategies for *L. fortunei.*

| Control Strategy | Long-Term Performance | Engineering Feasibility | Maintenance and Cost Implications | Environmental Considerations | Preferred Application |
|---|---|---|---|---|---|
| Mechanical removal and flushing | Effective for established fouling, but recolonization may require repeated removal | Suitable for accessible or hydraulically isolated structures; difficult to scale to long or continuously operating systems | Labor, shutdown requirements, repeated cleaning, and biomass disposal increase maintenance demand | Avoids chemical residues, but detached shells and biomass require removal or disposal | Localized mature fouling during planned maintenance |
| Thermal and UV treatment | Effective under suitable exposure conditions; long-term performance depends on repeated treatment | Thermal treatment requires heat delivery and temperature control; UV performance depends strongly on water transparency and exposure conditions | Energy and equipment requirements may constrain large-scale use | No chemical residues; energy demand and operating conditions remain important considerations | Larval-stage treatment or hydraulically controllable sections |
| Chemical oxidants and molluscicides | Effective when adequate dose and exposure time are maintained; repeated dosing may be required | Relatively feasible where existing dosing infrastructure is available | Chemical consumption, monitoring, and residual management contribute to operating costs | Residuals, by-products, downstream water quality, and non-target effects require control | Enclosed pipelines, intakes, and other systems with controllable dosing and retention time |
| Antifouling coatings | Can reduce settlement while coating performance is maintained; long-term field durability remains insufficiently quantified | Most suitable for new construction or accessible surfaces during major maintenance | Costs depend on surface preparation, service life, and recoating frequency; comparative life-cycle cost data remain limited | Environmental performance depends on coating chemistry; non-toxic systems are preferable for water-supply infrastructure | Prevention of settlement on high-risk surfaces |
| Biological or genetic approaches | Long-term effectiveness remains uncertain | Field-scale engineering application is currently limited | Cost-effectiveness cannot yet be assessed because practical deployment remains limited | Ecological effects and non-target risks require further assessment | Research and experimental applications |

Short-term treatment efficacy alone is therefore insufficient for engineering selection. A method that performs well under controlled conditions may be less practical if it requires major retrofitting, frequent shutdowns, repeated treatment, or high chemical or energy

inputs. Long-term feasibility should instead be judged over the maintenance cycle, including retreatment needs, residual-biomass management, and downstream water-quality constraints. Long-term selection should therefore consider both cost and environmental burden over the maintenance cycle, rather than treatment efficacy alone.

## 7. An Integrated Management Framework for Water-Conveyance Assets

Effective management of *L. fortunei* biofouling requires more than the use of a single monitoring method or control technique. Biological evidence needs to be considered together with the condition and operational requirements of the affected infrastructure. We therefore propose a stage-specific management framework for water-conveyance assets that links monitoring, prevention, control, and post-treatment management with routine operation and maintenance (Figure 3).

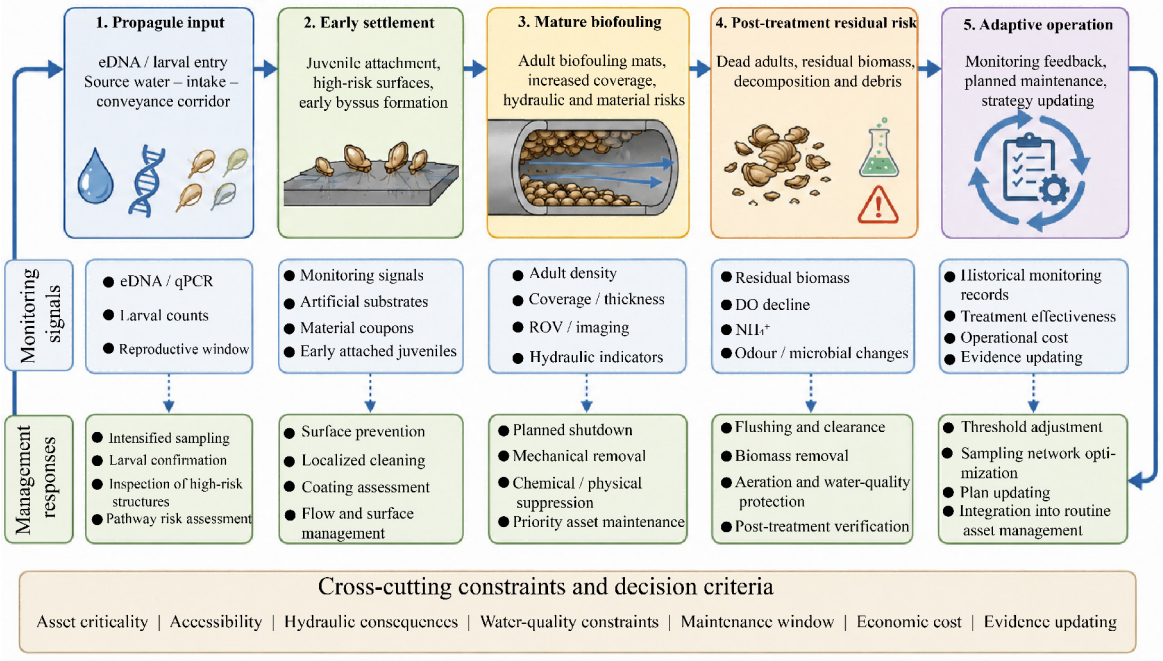



**Figure 3.** Integrated multi-barrier framework for the prevention and control of *L. fortunei* biofouling in water-conveyance projects.

The framework covers four main management functions: dispersal monitoring, settlement prevention, mature biofouling control, and post-treatment risk management. The choice and timing of management actions also depend on engineering conditions. Important considerations include asset criticality, hydraulic effects, facility accessibility, water-quality requirements, maintenance windows, and operating costs. As a result, similar levels of biofouling may require different responses in different parts of a water-conveyance system. Thus, monitoring evidence determines the stage of response, whereas asset condition and operational consequences determine its urgency and intensity. This risk-based approach may reduce unnecessary intervention during long-term operation. Post-treatment management should include residual biomass removal and disposal, flushing, and verification before the system is returned to service. In confined spaces, ventilation and gas monitoring should accompany maintenance, while dissolved oxygen and other relevant water-quality indicators should be checked after treatment. Raw-water systems may resume operation once site-specific hydraulic and water-quality requirements are met, whereas drinking-water systems should additionally undergo required flushing and disinfection and meet applicable microbiological criteria before supply is restored. Field observations show that biofouling risk can vary considerably among components and loca-

tions within the same conveyance system. In Japanese water-supply facilities, operational problems caused by *L. fortunei* occurred mainly in small-diameter sampling, monitoring, and cooling-water pipes [80]. Along a headrace channel connected to an invaded reservoir, larval drift and settlement decreased downstream, with higher settlement observed near the intake [15]. These findings suggest that monitoring and control should focus on vulnerable components and locations with high propagule pressure or settlement intensity rather than be applied uniformly across the system. Effective implementation requires coordination among key stakeholders. Water utilities and asset managers set monitoring and maintenance priorities, facility operators undertake routine inspection and control, and environmental agencies oversee potential effects on water quality, discharge, and non-target organisms. Such coordination helps translate monitoring results into timely management actions.

Management strategies should also be revised as operational experience accumulates. Historical monitoring records, treatment outcomes, and maintenance costs can be used to evaluate whether current monitoring frequency, inspection locations, and intervention schedules remain appropriate. Repeated settlement or rapid recolonization after treatment may indicate the need for more frequent monitoring or earlier maintenance. In contrast, consistently low fouling pressure may justify a lower monitoring frequency. The proposed framework does not introduce new control technologies; its contribution lies in organizing existing measures around stage-specific decisions and operational feedback. This differs from approaches that rely mainly on removal after severe fouling has developed, because greater attention is given to early risk identification, intervention timing, and treatment assessment. However, the effectiveness of this approach still needs to be evaluated through long-term application in operating water-conveyance systems.

## 8. Current Limitations and Research Priorities

### *8.1. Current Limitations*

Although substantial evidence has accumulated regarding the biology, monitoring, and control of *L. fortunei*, the translation of this knowledge into the management of water-conveyance projects remains constrained by two major limitations.

First, reliable quantitative relationships between the severity of biofouling and its engineering consequences remain lacking. Existing studies have demonstrated that *L. fortunei* colonization can affect hydraulic performance and material condition. However, the extent to which different densities, percentage cover, and fouling morphologies correspond to losses in conveyance capacity, increases in energy consumption, or deterioration in material performance has not yet been established in a form that is transferable across engineering systems. Consequently, operators have difficulty determining maintenance priorities and intervention timing on the basis of observed biofouling severity.

Second, explicit criteria for translating monitoring signals into management actions have not yet been established. eDNA detection, larval monitoring, artificial substrates, and adult surveys provide information on different types of risk, but stable relationships among these signals and corresponding action thresholds remain unavailable. In particular, continuous validation is lacking regarding when a propagule signal develops into an actual settlement risk and at what level biofouling requires engineering intervention. Therefore, the stage-specific management framework proposed in this review should currently be regarded as a conceptual management approach developed through a critical interpretation of the available literature, rather than as a fully validated engineering protocol.

### *8.2. Research Priorities*

Future research should prioritize the establishment of quantitative relationships among biofouling loads, engineering performance losses, and management actions. Field investigations in operating water-conveyance projects should simultaneously measure *L. fortunei* density, percentage cover, and fouling morphology together with head loss, conveyance capacity, energy consumption, and material condition. Such data are needed to clarify how risk changes under different asset conditions.

Continuous multi-method monitoring and long-term field validation should also be conducted to determine the temporal relationships among eDNA signals, larval occurrence, early attachment, and mature biofouling. These relationships should then be used to identify key indicators capable of triggering intensified inspection, settlement prevention, or large-scale removal. Further comparison of stage-specific intervention with conventional reactive removal in terms of conveyance efficiency, treatment frequency, shutdown duration, and maintenance costs will be essential for determining whether the proposed management framework has practical value for engineering applications. Taken together, these research needs can be prioritized as follows: first, establishing quantitative relationships between biofouling load and engineering performance; second, developing standardized protocols for cross-site comparison; third, validating the temporal relationships among eDNA signals, larval occurrence, and settlement; fourth, evaluating coating wear and service life under field conditions; and finally, assessing control strategies on a life-cycle cost basis. These priorities would provide the quantitative evidence needed to move stage-specific management from a conceptual framework toward practical engineering application.

## 9. Conclusions

This review examines *L. fortunei* biofouling in water-conveyance systems from an operational perspective, linking invasion stages and monitoring evidence with engineering risk and management response. The main contribution is to clarify how monitoring results can inform the timing and intensity of intervention under different infrastructure conditions. The proposed framework is conceptual and should not be applied using uniform thresholds across systems, because hydraulic conditions, facility type, water-quality requirements, and fouling pressure can vary substantially. Its practical use therefore depends on site-specific monitoring, locally tested decision thresholds, maintenance conditions, water-quality safeguards, and post-treatment verification. Long-term field application is still needed to determine whether the framework can improve intervention timing and reduce unnecessary control effort.

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