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BIOENGINEERING AND HEALTH SERVICE MANAGEMENT IN HOSPITAL WASTEWATER TREATMENT: A NARRATIVE REVIEW OF BIOLOGICAL PROCESS PERFORMANCE AND INSTITUTIONAL DETERMINANTS

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ABSTRACT
Hospital wastewater contains pharmaceuticals, pathogens, and antibiotic-resistant organisms, creating significant public health risks despite the availability of mature biological treatment technologies. This narrative review examines why systems that perform effectively in research settings often underperform in real-world applications, particularly in low- and middle-income countries. It integrates treatment performance with health service management, reviewing suspended-growth and attached-growth systems, membrane bioreactors, aerobic granular sludge, anaerobic treatment, and biological nutrient removal. Evidence indicates that organic-load removal is consistently high, while nitrogen removal is generally achievable. However, phosphorus removal remains challenging because of microbial competition and irregular carbon availability. Conventional disinfection based on indicator organisms may also fail to eliminate clinically important resistant pathogens. Furthermore, sludge management standards often overlook pharmaceuticals and antibiotic-resistance genes. Four key management factors—governance, operating finance, operator competence, and infection prevention—strongly influence treatment outcomes. The review concludes that technology selection should consider not only removal efficiency but also long-term institutional capacity to finance, operate, regulate, and monitor treatment systems.

Keywords:
hospital wastewater; biological treatment; antimicrobial resistance; enhanced biological phosphorus removal; health service management; institutional determinants.

1. INTRODUCTION

1.1 The Dual Nature of the Problem

Hospital wastewater occupies a distinctive and difficult position within the wider field of water pollution control. It is neither ordinary domestic sewage nor classic industrial effluent, but a hybrid stream that concentrates the pharmaceutical residues, pathogenic microorganisms, disinfectant by-products, and antibiotic-resistant bacteria generated by the routine business of clinical care [14]. A single tertiary hospital can discharge a cocktail of cytotoxic drugs, contrast media, antibiotics, and detergents at concentrations that, litre for litre, frequently exceed those found in the municipal sewers into which the effluent is often released [24]. During the COVID-19 pandemic this concern acquired a new urgency, as the possibility that viral genetic material could survive in hospital sewage forced a reappraisal of detection, survival, and disinfection technologies across the sector [1]. The central premise of this review is that hospital wastewater treatment cannot be understood as an engineering problem alone; it is equally a problem of health service management, and the two dimensions determine outcomes jointly rather than separately.

1.2 Biological Treatment as a Mature Field

The biological treatment of wastewater is, in narrow technical terms, a mature field. Activated sludge, membrane bioreactors, anaerobic reactors, granular sludge, biofiltration, and biological nutrient removal are all established technologies with decades of operational history [8, 11, 21]. Each has been demonstrated, in at least some studies, to bring hospital effluent within conventional discharge standards, and several have been validated at full scale on genuine hospital influent rather than synthetic surrogates [7, 18]. If the question is simply whether hospital wastewater can be treated biologically, the answer is settled. Yet the recurring pattern observed in practice, particularly in low- and middle-income settings, is that plants which perform well in a published study perform poorly, intermittently, or not at all once installed in a functioning hospital [6]. The gap between demonstrated capability and delivered performance is the phenomenon this review sets out to explain.

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1.3 The Role of Health Service Management

That explanatory gap is where health service management enters. A treatment plant is an organisational artefact as much as an engineered one. Its performance is bounded by the governance framework that requires it to run, the operating budget that pays for its energy and chemicals, the competence of the staff who operate it, and the institutional attention devoted to its upkeep [6]. These are not peripheral considerations to be addressed after the engineering has been settled; they are determinants of engineering outcome in their own right. A configuration that assumes a reliable electricity supply, a trained operator establishment, and an enforced discharge standard is making institutional assumptions that may or may not hold, and when they do not hold, the biology fails regardless of how sound the reactor design may be.

1.4 Objectives of the Review

This narrative review therefore pursues two interwoven objectives. The first is to assess the reported performance of the principal biological treatment processes applied to hospital wastewater, drawing together evidence on removal efficiency for organic load, nutrients, pathogens, and pharmaceutically active compounds. The second is to identify the institutional and management determinants that mediate whether that performance is realised in practice. By treating bioengineering performance and health service management as a single coupled system, the review aims to offer hospital planners, particularly those working in resource-constrained environments, a more complete account of why treatment succeeds or fails than either an engineering or a management perspective could provide alone.

2. SCOPE AND METHODOLOGICAL APPROACH

2.1 Rationale for a Narrative Approach

This article is a narrative rather than a systematic review, but it adopts several conventions from systematic reporting to strengthen transparency. The PRISMA 2020 statement and its accompanying explanation provided the guiding framework for how sources were identified, screened, and reported, even though the synthesis itself is interpretive rather than quantitative [16, 17]. A narrative approach was chosen deliberately: the evidence base spanning hospital wastewater bioengineering and health service management is heterogeneous, drawn from environmental engineering, microbiology, and public health literatures that do not share a common outcome vocabulary, and it is not amenable to meta-analysis. A narrative synthesis allows the two domains to be brought into dialogue in a way a rigidly quantitative method would not.

2.2 Source Selection Criteria

Sources were prioritised according to several criteria. Primary peer-reviewed research articles were preferred over secondary summaries wherever a primary study addressed the point directly. Studies published within approximately the last five years were favoured, while seminal or foundational works were retained where they remained essential, most notably the microbiological literature on enhanced biological phosphorus removal and the full-scale validation studies for granular and membrane technologies [11, 21, 22]. Each source was required to be directly relevant to the biological processes, institutional constructs, or performance variables under examination. A strict bibliographic verification criterion was applied: sources whose publication details could not be confirmed against a resolvable digital object identifier were excluded rather than reported with reconstructed detail. This criterion had a material effect on the evidence base, reducing an initially larger candidate set and excluding several recent and topically relevant studies whose records could not be verified, a limitation returned to in the discussion.

2.3 Organisation of the Review

The review is organised to move from process to institution. Sections 3 to 8 examine the main biological configurations in turn: suspended-growth systems, membrane bioreactors, aerobic granular sludge, anaerobic treatment, biofiltration and attached-growth systems, and biological nutrient removal, followed by the sludge line where contaminants ultimately concentrate. Section 9 then addresses the health service management interface, mapping each engineering dependency onto a corresponding institutional function. The discussion and conclusion draw the two threads together.

3. THE CHARACTER OF HOSPITAL WASTEWATER

3.1 Chemical Complexity

Any assessment of treatment performance must begin with the nature of the influent, because hospital wastewater differs from municipal sewage in ways that directly shape which biological processes can succeed. The defining feature is chemical complexity. Hospital effluent carries a broad spectrum of pharmaceutically active compounds, including antibiotics, analgesics, cytostatics, and contrast agents, many of which are designed precisely to resist metabolic degradation and therefore pass through conventional biological treatment poorly [14, 24]. Verlicchi and

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colleagues, in an influential review of pharmaceutical occurrence in urban wastewater, established that secondary biological treatment removes many compounds only partially, with removal efficiencies varying enormously between substances and between plants [24]. This variability is not a measurement artefact; it reflects genuine differences in biodegradability that a treatment train must be designed around.

3.2 Microbiological Burden

A second defining feature is the microbiological burden. Hospital effluent is enriched in pathogenic and, critically, antibiotic-resistant organisms, making it a recognised environmental reservoir and potential amplification point for antimicrobial resistance [14]. This places hospital wastewater treatment at the intersection of environmental protection and infection prevention, a dual role that ordinary sewage treatment does not carry. The presence of resistant organisms also complicates disinfection, because a stage validated on bulk indicator bacteria may leave the specific resistant strains of greatest clinical concern intact, a point examined in detail in Section 9 [4]. Emerging biological approaches to resistant organisms, including bacteriophage-based strategies, are being explored across infectious disease and environmental contexts, though their application to wastewater remains largely investigational [34].

3.3 Flow and Load Variability

A third feature is variability itself. Hospital discharge fluctuates with clinical activity, admissions, and time of day, and the resulting swings in flow and composition impose a load-management challenge on any biological process that depends on a stable microbial community [30]. The comprehensive sustainability assessments now being published for hospital wastewater treatment techniques increasingly emphasise that a technology's robustness to this variability, rather than its peak performance under ideal conditions, is the more meaningful measure of suitability [26]. Table 1 summarises the principal contaminant classes and the treatment challenge each presents.

Table 1. Principal contaminant classes in hospital wastewater and the associated biological treatment challenge.

Pharmaceutically active compounds	Designed to resist metabolic breakdown; partial and variable removal in secondary treatment [24]	Recalcitrant fraction requires polishing beyond biology alone
Antibiotic-resistant organisms	Enriched relative to domestic sewage; environmental AMR reservoir [14]	Disinfection on indicator organisms may spare resistant strains [4]
Nutrients (N and P)	Present but with unreliable carbon supply for biological removal [5, 18]	Phosphorus removal underperforms nitrogen consistently
Organic load (COD/BOD)	Generally amenable to biological oxidation [7]	Least problematic; high removal routinely achieved
Flow and load variability	Fluctuates with clinical activity [30]	Destabilises microbial community; demands buffering

4. SUSPENDED-GROWTH AND ATTACHED-GROWTH SYSTEMS

4.1 Extended-aeration activated sludge

Activated sludge remains the workhorse of biological wastewater treatment, and its extended-aeration variant is frequently deployed for hospital effluent because the long solids retention time promotes stable nitrification and a degree of resilience to load variation. Custodio and colleagues reported that a full-scale extended-aeration system treating hospital wastewater achieved biochemical oxygen demand removal of 97.5%, suspended solids removal of 92.0%, and faecal coliform removal of 99.99% [7]. Those are strong figures by any standard, and they establish that suspended-growth biology, properly operated, can meet conventional discharge criteria for organic load and indicator pathogens on real hospital influent. The qualifier properly operated is doing considerable work, however, because extended aeration is energy-intensive: the aeration demand that sustains the long-sludge-age biology is a recurring operating cost that falls squarely on the hospital budget, a theme developed in Section 9.

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4.2 Integrated fixed-film activated sludge

A refinement of conventional suspended growth is the integrated fixed-film activated sludge process, which introduces carrier media into the aeration basin so that attached biofilm supplements the suspended biomass. Kuśnierz and colleagues examined the application of this approach in a conventional treatment plant and found that it increased the effective biomass inventory without a corresponding increase in tank volume, improving treatment capacity within an existing footprint [12]. For hospitals, where space is often constrained and retrofitting is more feasible than new construction, this footprint efficiency is attractive. The trade-off is added operational complexity in managing the carrier media and the biofilm, which again returns the analysis to the question of operator competence rather than pure process capability.

4.3 Biofiltration and nitrification–denitrification

Attached-growth biofiltration offers another route, particularly where nitrogen removal is a priority. Hassen and colleagues investigated a basic nitrification–denitrification biofiltration system for primary wastewater treatment and demonstrated that the sequential creation of aerobic and anoxic conditions could drive biological nitrogen transformation effectively [10]. The broader challenge of biological nitrogen removal, especially from low-carbon wastewater where the electron donor for denitrification is in short supply, has become a distinct research focus, with the recognition that carbon limitation is frequently the binding constraint on nitrogen removal performance [5]. Hospital effluent, with its erratic carbon supply, is precisely the kind of stream in which this constraint bites, and it foreshadows the nutrient-removal difficulties examined in Section 7.

5. MEMBRANE BIOREACTORS

5.1 Principle and Performance

Membrane bioreactors combine biological treatment with membrane filtration, replacing the secondary clarifier with a physical barrier that retains all suspended biomass and produces a high-quality, effectively particle-free effluent. This configuration is especially relevant to hospital wastewater because the complete biomass retention permits very long sludge ages, which in turn allows the slow-growing microbial communities capable of degrading recalcitrant pharmaceuticals to establish and persist. The foundational demonstration remains that of Kovalova and colleagues, who operated a pilot membrane bioreactor for a full year at a Swiss hospital on influent drawn directly from the sanitary collection system, assessing the elimination of sixty-eight target analytes including fifty-six pharmaceuticals [11]. The study's enduring value lies in its design: full-year operation captured seasonal and clinical variation, and direct influent abstraction avoided the dilution that renders many hospital wastewater studies difficult to interpret. Although now more than a decade old, no subsequent study in this evidence base matches its analytical breadth.

5.2 Operational Limitations

The principal limitation of membrane bioreactors is not biological but economic and operational. Membranes foul, requiring energy for cross-flow or aeration to control the fouling layer, periodic chemical cleaning, and eventual replacement. Each of these is a recurring cost, and each demands a level of operator diagnostic skill that exceeds what a conventional activated-sludge plant requires. The performance advantage of membrane and related advanced processes is therefore contingent on sustained operational input rather than being intrinsic to the hardware, a distinction that is easily lost when a technology is selected on the basis of its reported removal efficiency alone [26].

5.3 Hybrid Oxidative Configurations

Hybrid configurations extend the biological stage with oxidative polishing to address the recalcitrant fraction that biology alone cannot degrade. Vo and colleagues coupled a sponge membrane bioreactor with an ozonation step and reported enhanced removal of persistent pharmaceutical compounds beyond what the biological stage achieved on its own [25]. The logic generalises across the field: biological treatment handles bulk organics and readily degradable pharmaceuticals efficiently, while a downstream oxidative step targets the residue. The cost of this improvement is additional energy and complexity, both of which fall on the operating budget and both of which are more readily secured at the point of commissioning than sustained into the third year of operation. Dynamic modelling and process-control approaches are increasingly proposed as a means of optimising these coupled biological and advanced-oxidation trains, though such control systems themselves presuppose institutional and technical capacity that many facilities lack [30].

6. Aerobic Granular Sludge

6.1 Process Principle

Aerobic granular sludge represents a distinct bioreaction regime rather than a variant of activated sludge. Biomass self-aggregates into dense, fast-settling granules with stratified redox zones, so that aerobic, anoxic, and anaerobic reactions proceed simultaneously within a single granule. Settling is rapid, the reactor footprint is reduced, and

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secondary clarification requirements fall. Pronk and colleagues established the full-scale viability of the process for municipal sewage treatment, and their work remains the reference point for the technology's engineering credibility [21].

6.2 Application to Hospital Wastewater

The application of granular sludge to hospital wastewater is more recent and, for this review, pivotal. Pérez-Bou and colleagues treated real hospital effluent with aerobic granular sludge and reported chemical oxygen demand removal of 75%, biochemical oxygen demand removal of 100%, nitrogen removal in the range of 70 to 90%, and phosphate removal of up to 50%, alongside a characterisation of the microbial dynamics that sustained these outcomes [18]. This is arguably the single most informative entry in the hospital wastewater evidence base, because it addresses aerobic bioreaction and biological nutrient removal within one study on one real substrate. Read carefully, however, it also carries a warning. The phosphate removal figure is roughly half the nitrogen figure, and this asymmetry between nitrogen and phosphorus removal is not incidental; it recurs across the nutrient-removal literature and is examined mechanistically in Section 7. Table 2 consolidates the reported performance of the biological configurations reviewed here.

Table 2. Reported performance of biological configurations treating hospital or comparable wastewater. Blank entries indicate outcomes not reported in the cited study, not zero performance.

Extended-aeration activated sludge [7]	Full scale, hospital effluent	—	97.5%	99.99% faecal coliform removal
Aerobic granular sludge [18]	Real hospital effluent	75%	100%	N 70–90%; PO_4 up to 50%
Pilot membrane bioreactor [11]	One year, Swiss hospital, direct influent	—	—	68 analytes incl. 56 pharmaceuticals assessed
Sponge MBR + ozonation [25]	Hospital wastewater	—	—	Enhanced pharmaceutical removal vs. biology alone
Integrated fixed-film activated sludge [12]	Conventional plant	—	—	Increased biomass inventory within existing footprint

7. BIOLOGICAL NUTRIENT REMOVAL: THE PHOSPHORUS PROBLEM

7.1 Nitrogen Versus Phosphorus

Biological nutrient removal is where the coupling between microbial ecology and process performance is most consequential, and where hospital wastewater treatment most often falls short. Nitrogen removal, achieved through sequential nitrification and denitrification, is generally the more tractable of the two, provided a sufficient carbon source is available for the denitrifying step [5, 10]. Phosphorus removal is a different matter. Enhanced biological phosphorus removal depends on a specialised group of polyphosphate-accumulating organisms that take up phosphate in excess of their immediate metabolic needs, storing it so that its removal with the waste sludge exceeds what ordinary growth would achieve. The microbiology of this process has been studied intensively yet remains incompletely understood.

7.2 The Microbial Competition

Seviour and colleagues, in a foundational review of the microbiology of biological phosphorus removal, cautioned that the process can be achieved in practice but that its microbiological and biochemical basis was not fully resolved, and that caveat has proved durable rather than dated [22]. Two decades of subsequent work have refined the picture without closing it. The central mechanistic difficulty is competition. Polyphosphate-accumulating organisms deliver phosphorus removal, but glycogen-accumulating organisms consume the same volatile fatty acid substrate without removing any phosphorus. Albertsen and colleagues identified a novel glycogen-accumulating organism abundant in full-scale enhanced biological phosphorus removal plants, demonstrating that

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the competing population in real plants is more diverse than laboratory models had assumed [2]. McIlroy and colleagues went further, showing through genomic and in-situ analysis that certain fermentative glycogen-accumulating organisms are more abundant and more metabolically versatile than the textbook account allows, implying that current models of the competition may be too simplistic [15].

7.3 Implications for Hospital Effluent

For hospital wastewater the practical implication is direct. Volatile fatty acids are the currency of this microbial competition, and hospital effluent supplies them unreliably and intermittently. The 50% phosphate removal reported by Pérez-Bou and colleagues, set against 70 to 90% nitrogen removal in the same reactor on the same substrate, is entirely consistent with a phosphorus pathway that is carbon-starved rather than poorly designed [18]. The operational lesson is that hospitals discharging to phosphorus-sensitive receiving waters should plan for chemical polishing rather than assume biological removal will suffice, and should budget for it at the design stage rather than discover the need after commissioning. This is a case where a microbiological reality, the PAO–GAO competition under intermittent carbon, translates directly into a capital and operating-budget decision, illustrating in miniature the coupling that this review argues runs throughout the field.

8. ANAEROBIC TREATMENT, SLUDGE, AND RESOURCE RECOVERY

8.1 Anaerobic Treatment

Anaerobic biological treatment offers a fundamentally different energy balance from aerobic processes: rather than consuming energy to supply oxygen, it produces energy in the form of methane-rich biogas. Dutta and colleagues, in a comparative review of the upflow anaerobic sludge blanket reactor and other anaerobic configurations, documented both the strong organic-load removal these systems can achieve and the load-management and granule-husbandry demands they impose on operators [8]. This dual character, energy-positive treatment coupled with real operational demands, makes anaerobic technology simultaneously attractive for resource-constrained settings and risky where operator competence is limited. A further caution specific to hospital effluent is that most full-scale anaerobic performance figures derive from domestic or industrial substrates that lack the pharmaceutical and disinfectant loads characteristic of hospital wastewater, so the transferability of those figures is not assured.

8.2 Sludge Stabilisation and Pretreatment

Sludge is where hospital wastewater treatment most often stops being treated as an engineering problem, and it is where the trace-organic and pathogen burden ultimately concentrates. Contaminants removed from the water line are not destroyed; they are transferred to a solid phase that must then be stabilised and disposed of. A treatment assessment that stops at effluent quality has assessed only half a system. Anaerobic digestion is the standard stabilisation route, and hydrolysis is its rate-limiting step, which is why pretreatment to accelerate hydrolysis has become the main line of process development. Li and colleagues reported a pilot-scale thermal–alkali pretreatment study that is unusually useful because it quantifies energy cost alongside yield, reporting a 31.2% increase in methane yield over thermal hydrolysis alone at a defined energy input [13]. Reporting the energy figure alongside the yield figure is what makes such a result actionable; a great many pretreatment studies report only the latter. Guo and colleagues provide an independent pathway, combining potassium ferrate with ultrasound pretreatment to enhance methane production from waste activated sludge [9]. Having two independently reported routes matters more than either result alone, because it allows a hospital to weigh a thermal–chemical option against an oxidative–physical one rather than accepting a single vendor-adjacent claim. Table 3 compares these pretreatment routes.

Table 3. Pretreatment routes for enhancing anaerobic digestion of waste activated sludge.

Thermal–alkali [13]	31.2% higher methane yield than thermal hydrolysis alone, at a quantified energy input	Energy cost reported, enabling a genuine cost–benefit judgement
Potassium ferrate + ultrasound [9]	Enhanced methane production from waste activated sludge	Oxidative–physical alternative; requires chemical dosing and sonication

8.3 Disposal and Regulatory Gaps

The disposal end of the sludge line is governed less by process performance than by regulation, and the regulation is frequently ill-matched to the hazard. Pozzebon and Seifert, in a scoping review of the health risks of land-

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applied biosolids, note that prevailing biosolids standards focus on a limited set of inorganic metals, pathogens, and vector attractiveness, while pharmaceutical residues, resistant organisms, and resistance genes fall largely outside their scope [20]. Those excluded constituents are precisely the ones that distinguish hospital sludge from municipal sludge. Popoola, Olawale, and Salami reinforce this point in a review of the fate and effects of contaminants in land-applied biosolids, situating the analysis within government regulatory policy and giving it particular weight for the West African context [19]. The consequence is that a hospital can comply fully with an applicable biosolids standard while land-applying material that carries exactly the contaminants that motivated on-site treatment in the first place. Against this backdrop, the growing interest in integrating sludge treatment with resource recovery, recovering nutrients and energy rather than merely disposing of a hazard, offers a more sustainable framing, though it does not by itself resolve the regulatory blind spot [39].

9. THE HEALTH SERVICE MANAGEMENT INTERFACE

The preceding sections describe what biological processes can do. This section addresses why they frequently do not. The argument is that treatment outcome is determined jointly by engineering capability and institutional capacity, and that four management dependencies structure the relationship. Figure 1 sets out this conceptual framework, in which each bioengineering construct has a corresponding institutional determinant.

Figure 1. Conceptual framework linking bioengineering unit processes to health service management functions. Treatment outcome is determined jointly by the two domains rather than by either alone.

Discharge standard defines required process train	↔	Governance and regulation: a national healthcare-waste framework that requires and enforces treatment
Aeration, membranes, carbon dosing, sludge pretreatment energy	↔	Operating finance: a recurrent budget that sustains energy and chemical costs beyond commissioning
Anaerobic load control, EBPR troubleshooting, membrane fouling diagnosis	↔	Operator competence: training matched to process complexity
Disinfection stage validation and monitoring	↔	Infection prevention and control: monitoring specified for clinically relevant organisms

9.1 Governance and Regulation

The first dependency is governance. Where national guidelines for healthcare waste are absent, treatment obligations rest on general environmental regulation that was not written with hospital effluent in mind. Chisholm and colleagues document exactly this deficit across African developing countries, situating it within underfunded health systems and limited staff training [6]. Where regulation is absent, capital investment in treatment becomes discretionary, and discretionary spending in a resource-constrained hospital does not readily flow towards sewage. The regulatory framework is thus not a backdrop to the engineering decision but a precondition for it.

9.2 Operating Finance

The second dependency is finance, and it operates on the operating budget more than the capital budget. Every configuration reviewed above carries a recurring cost: aeration energy for activated sludge, membrane replacement and fouling control for membrane bioreactors, external carbon where nitrogen removal is carbon-limited, chemicals for phosphorus polishing, and the energy demanded by sludge pretreatment [13]. Capital grants and donor-funded plants routinely fail, and the technology is rarely the reason; nothing in the grant funds the electricity bill in the third year. This distinction between capital and operating finance is, in the author's synthesis of the evidence, the single most under-appreciated determinant of long-run performance.

9.3 Operator Competence

The third dependency is operator competence. Anaerobic reactors require load management and granule husbandry [8]; enhanced biological phosphorus removal requires an operator to interpret a microbial competition that the research literature is itself still revising [15]; membrane systems require fouling diagnosis. Limited training is named explicitly among the constraints on medical waste management in the African context [6]. Specifying a process that a facility cannot run is a design error rather than an operator failing, and it is a decision made at the design stage, not at the plant. The corollary is that process selection should be constrained by available competence, and that a simpler process reliably operated will outperform a sophisticated one intermittently operated.

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9.4 Infection Prevention and Control

The fourth dependency is infection prevention and control, and it is where the two domains meet most concretely. Azuma and Hayashi report that on-site chlorination inactivated most antimicrobial-resistant and susceptible bacteria in hospital wastewater, with the notable exception of methicillin-resistant Staphylococcus aureus and Staphylococcus aureus [4]. That exception is the citable result: a disinfection stage validated on bulk indicator organisms may leave intact the specific resistant organisms of greatest clinical concern. Faecal coliforms may be removed at 99.99% [7] while a clinically critical resistant organism persists, and compliance monitoring built on indicator organisms will not detect the discrepancy. This makes disinfection validation an infection-prevention matter rather than purely an environmental-compliance one, and it argues for monitoring regimes specified jointly by the environmental and infection-control functions rather than by either alone. Table 4 maps each management function to its engineering dependency and the associated evidence gap.

Table 4. The bioengineering–management interface: institutional dependencies and evidence gaps.

Governance and regulation	Discharge standard defines the required process train	National healthcare-waste guidelines absent in several African countries [6]
Operating finance	Aeration, membranes, carbon and chemical dosing, pretreatment energy	Recurring cost quantified in few studies; rarely reported [13]
Operator competence	Anaerobic load control; EBPR troubleshooting; membrane fouling	PAO–GAO competition models acknowledged as too simplistic [15]
Infection prevention and control	Disinfection validation and monitoring	Chlorination ineffective against MRSA specifically [4]
Residuals policy	Sludge stabilisation and disposal routing	Biosolids standards omit pharmaceuticals and resistance genes [20]

10. DISCUSSION

10.1 Key Findings

10.1.1 Phosphorus Removal as the Consistent Weak Point

Four findings cut across the sections above. The first is that phosphorus removal is the consistent weak point of biological hospital wastewater treatment. Nitrogen removal reaches 70 to 90% on real hospital effluent while phosphate removal in the same reactor reaches only about 50% [18], and the mechanistic literature explains why: the polyphosphate-accumulating pathway depends on volatile fatty acids that hospital effluent supplies erratically, under a competitive dynamic with glycogen-accumulating organisms that current models describe imperfectly [2, 15]. Hospitals discharging to phosphorus-sensitive waters should not rely on biological removal alone, and should treat chemical polishing as a design assumption rather than a contingency.

10.1.2 Disinfection and Clinically Relevant Organisms

The second finding is that disinfection validated on indicator organisms is not equivalent to disinfection validated on organisms of clinical concern. The result that chlorination spares methicillin-resistant Staphylococcus aureus while inactivating most other bacteria [4] is the clearest example, and its implication reaches beyond disinfection: any treatment stage validated on proxy parameters should be assumed unvalidated for the hazards those proxies do not track. This reframes a routine compliance activity as a patient-safety concern and locates it squarely at the bioengineering–management interface.

10.1.3 Heterogeneous Outcome Reporting

The third finding is that outcome reporting across the field is heterogeneous enough to obstruct comparison. Verlicchi and colleagues established reporting conventions for removal efficiency and mass load that would make cross-study synthesis tractable [24], yet those conventions have been adopted unevenly, as the blank cells in Table 2 attest. Until studies routinely report a common minimum outcome set, comprising chemical oxygen demand, biochemical oxygen demand, suspended solids, total nitrogen, total phosphorus, an indicator organism, and specific energy consumption, statements about the relative merit of process configurations will continue to rest

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on partial evidence. Sustainability assessments that attempt to standardise comparison across techniques are a welcome corrective but cannot substitute for consistent primary reporting [26].

10.1.4 The State of the Evidence Base

The fourth finding concerns the evidence base itself, and this review is an instance of the problem as much as an observer of it. Applying a strict bibliographic verification criterion reduced the candidate set and excluded several recent and directly relevant studies whose records could not be confirmed. Combined with the observation that the developing-country literature is thin to begin with [6], this means the synthesis available to a hospital planner in a low-resource setting is narrower than the apparent volume of publication suggests. Several priorities follow. Primary anaerobic treatment studies on genuine hospital effluent are needed, since existing full-scale figures derive from substrates without comparable pharmaceutical and disinfectant loads. Phosphorus removal under intermittent volatile fatty acid supply requires targeted study rather than incidental reporting. Seasonal and worst-case performance reporting should become standard, because compliance margins based on annual averages conceal the periods when receiving waters are most at risk. And economic reporting, specific energy consumption, chemical cost per cubic metre, and membrane replacement interval, should be treated as a primary outcome rather than an afterthought, because Section 9 suggests these are the variables on which real plants actually fail.

10.2 Limitations

A limitation of this review should be stated plainly. As a narrative synthesis drawing on a verified but bounded set of sources, it does not claim the exhaustive coverage of a systematic review, and its interpretive conclusions, particularly regarding the primacy of operating finance and operator competence, reflect a reasoned reading of the evidence rather than a quantified effect size. The coupling it proposes between bioengineering and health service management is offered as an analytical frame to be tested, not as a settled empirical result.

11. CONCLUSION

Biological treatment of hospital wastewater is technically mature and institutionally fragile. Each of the process families reviewed here, suspended-growth and attached-growth systems, membrane bioreactors, aerobic granular sludge, anaerobic treatment, and biological nutrient removal, has demonstrated performance adequate to conventional discharge standards, in several cases on genuine hospital effluent at full scale [7, 11, 18, 21]. The engineering question of whether hospital wastewater can be treated biologically is, in that sense, settled.

Three qualifications nonetheless remain. Phosphorus removal underperforms nitrogen removal consistently and for identifiable mechanistic reasons rooted in microbial competition and carbon supply [2, 15, 18]. Disinfection can leave specific resistant organisms intact in ways that indicator-based monitoring will not reveal [4]. And the sludge line, where the trace-organic and pathogen burden concentrates, is governed by standards that do not measure the contaminants that make hospital sludge distinctive [19, 20]. Each qualification sits at the boundary between engineering and institution.

The broader argument of this review is that process selection cannot be settled on removal efficiency alone. A configuration that performs well in a study and poorly in a hospital has usually failed for reasons the study did not measure: an operating budget that could not sustain aeration, an operator establishment that could not diagnose a fouled membrane, or a regulatory framework that never required the plant to run in the first place. These are health service management variables, and treating them as external to the engineering problem is what produces the recurring pattern of capable plants performing below their design potential. Integrating them, as the conceptual framework in Figure 1 attempts, does not soften the engineering question; it states that question more completely. For hospital planners in resource-constrained settings in particular, the practical implication is that the right process is the one the institution can finance, staff, regulate, and monitor over its whole life, not the one with the highest removal efficiency in a published trial.

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