

Review

The Hygiene Continuum in Seafood Processing: Integrating Design, Sanitation, and Workforce Safety for Sustainable Food Systems

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Abstract

Seafood processing environments represent some of the most demanding hygienic settings in the global food sector. High humidity, variable temperatures, and heavy organic residues promote the persistence of *Listeria monocytogenes*, *Vibrio* spp., and *Salmonella* spp., making sanitation both critical and inherently complex. This review synthesizes recent advances in hygienic design, sanitation technologies, and workforce safety as interconnected elements of a single “hygiene continuum.” Building upon Codex, FDA, and European hygiene frameworks (2020–2024), the review examines how engineering design, Sanitation Standard Operating Procedures (SSOPs) and Good Manufacturing Practices (GMPs) systems, and occupational hygiene jointly determine microbial control, sustainability, and workforce well-being. Particular focus is given to biofilm dynamics, emerging disinfection technologies, and automation through cleaning-in-place (CIP) and cleaning-out-of-place (COP) systems. Recent trends—including digital monitoring, eco-efficient cleaning, and human-centered facility design—are discussed as drivers of next-generation hygiene management. Collectively, these insights demonstrate that hygienic performance in seafood processing is not a fixed endpoint but a living system linking design, management, and human behavior toward safe, sustainable, and resilient seafood production.

Keywords: hygienic design; Sanitation Standard Operating Procedures (SSOPs); Good Manufacturing Practices (GMPs); seafood processing; biofilm control; occupational hygiene; sustainability



Academic Editor: Fernando Pérez-Rodríguez

Received: 26 October 2025

Revised: 1 January 2026

Accepted: 9 January 2026

Published: 2 February 2026

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1. Introduction

Food hygiene and seafood safety are inseparable disciplines, grounded in the biological perishability of marine raw materials. Even brief lapses in cleaning or temperature control can trigger rapid microbial proliferation and irreversible product loss [1]. Processing plants operate under high humidity, fluctuating temperatures, and constant organic loading—conditions ideal for the survival and spread of *Listeria monocytogenes*, *Vibrio* spp., and *Salmonella* spp. [2,3]. Persistent contamination often arises from surface biofilms and inaccessible areas of equipment, where microorganisms gain resistance to standard cleaning procedures.

The physical structure of a facility fundamentally determines the success of sanitation. Bridger et al. [4] emphasized that hygiene management is only as robust as the infrastructure supporting it. Hygienic design thus extends beyond visual cleanliness, encompassing spatial zoning, airflow, drainage, and material selection engineered for cleanability and

microbial control [5]. In seafood facilities, sloped and drainable floors, sealed wall–floor junctions, and unidirectional product flow from raw to ready-to-eat (RTE) areas remain essential safeguards against cross-contamination [6]. Marriott et al. [7] broadened this principle under “sanitary design,” integrating personnel flow, zoning, and ergonomic accessibility into contamination prevention strategies.

Over the last decade, hygienic design philosophy has evolved from a purely mechanical approach to a system-level model uniting engineering, microbiology, and human factors. Bowser [8] underscored that equipment configuration must accommodate the realities of human work; difficult-to-access surfaces or poorly placed valves often translate into incomplete cleaning. Empirical audits across seafood plants repeatedly identify poor drainage, ventilation, and spatial bottlenecks as leading design deficiencies affecting sanitation performance [9,10].

Complementing design, Good Manufacturing Practices (GMPs) and Sanitation Standard Operating Procedures (SSOPs) constitute the operational backbone of hygiene systems. GMPs define general facility and personnel expectations—personal hygiene, maintenance, pest control—while SSOPs prescribe the exact sequence, frequency, and validation of cleaning tasks [11,12]. Đukić et al. [13] emphasized that the durability of sanitation performance depends not merely on technical execution but on management’s capacity for feedback and continuous improvement.

Biofilm formation remains one of the most intractable obstacles in seafood hygiene. These structured microbial communities, embedded in extracellular polymeric matrices, resist standard disinfection and desiccation [14]. Once established on stainless steel, rubber, or polymeric surfaces, biofilms perpetuate contamination cycles despite repeated cleaning. Prevention requires proactive surface design—minimizing crevices, maintaining dryness—and alternating compatible sanitizers, validated by methods such as ATP bioluminescence [15–17].

Chemical and physical disinfection technologies have expanded considerably. Alongside chlorine and quaternary ammonium compounds, ozone, electrolyzed water, and peracetic acid offer potent microbial reduction with fewer residues [18,19]. Integrated within automated CIP and COP systems, these methods reduce variability, improve worker safety, and conserve water. Yet, their performance remains dependent on organic load, contact time, and material compatibility—requiring periodic validation [20].

The human dimension of sanitation is equally vital. Sanitation crews operate under physically demanding and sometimes undervalued conditions. Fatigue, repetitive strain, and chemical exposure can directly impair cleaning thoroughness [21]. Regular ergonomic evaluation, coupled with safety-oriented training, promotes both compliance and engagement. Soon et al. [22] demonstrated that hygiene education and a supportive culture significantly improve sanitation outcomes in small seafood enterprises.

Finally, sanitation practices increasingly align with sustainability and policy imperatives. Regulatory bodies and markets now emphasize environmental accountability, driving the adoption of resource-efficient cleaning and low-impact chemicals [23]. The use of biodegradable detergents, water-reuse systems, and energy-efficient CIP design illustrates how hygiene and sustainability converge [24]. In this integrated context, sanitation becomes a continuous improvement process that simultaneously protects public health, workers, and the environment [15,25,26].

In summary, effective hygiene in seafood processing is a multidisciplinary continuum linking design, technology, management, and human behavior. The strength of this continuum ultimately defines not only microbial safety but also the sustainability and resilience of the seafood industry [27,28] (Figure 1).

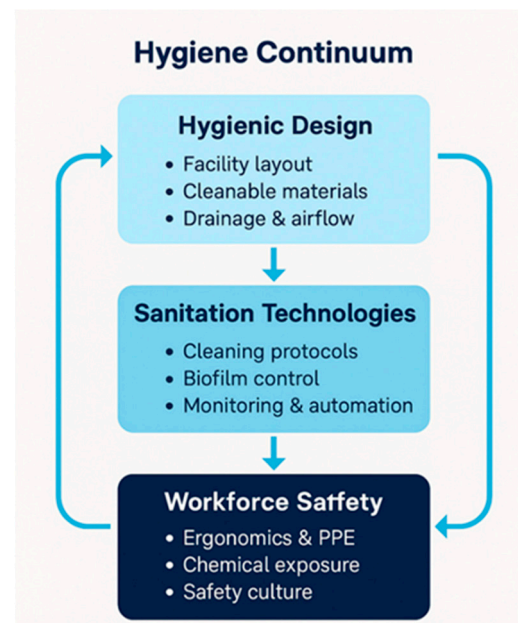


Figure 1. Hygiene Continuum Conceptual Model integrating facility design, sanitation technologies, and workforce safety within a dynamic seafood-safety system.

While the Hygiene Continuum is presented as a conceptual framework, it can be operationalized through structured auditing rather than treated as an abstract model. The proposed audit structure and example evaluation criteria used to operationalize the Hygiene Continuum are provided in Appendix A. In practice, quality assurance managers may evaluate the integration of hygienic design, sanitation execution, and workforce behavior using weighted audit criteria such as design compliance, SSOP performance, environmental monitoring outcomes, and personnel hygiene adherence. This approach enables benchmarking of hygiene-system maturity over time without reliance on a single prescriptive index, translating the continuum into a practical management concept.

This narrative review was developed through a structured literature search conducted in Scopus, Web of Science, and PubMed databases. Peer-reviewed articles, regulatory guidance documents (FDA, Codex, EFSA), and authoritative technical reports published primarily between 2010 and 2025 were considered. Search terms included combinations of “seafood hygiene,” “hygienic design,” “sanitation technologies,” “biofilm control,” “SSOP,” “GMP,” and “occupational hygiene.” Studies were selected based on relevance to seafood-processing environments, demonstrated application at an industrial scale, and contribution to understanding hygiene as an integrated system linking design, operations, and workforce factors.

While concepts such as zoning, biofilm control, and ergonomics recur across subsequent sections, they are intentionally revisited to highlight their distinct roles at different levels of the hygiene continuum—facility design, sanitation execution, and workforce behavior.

2. Hygienic Design Principles

Hygienic design forms the structural and operational foundation of contamination control in seafood processing, where engineering, microbiology, and human factors converge. It represents a proactive philosophy—anticipating contamination before it occurs—rather than a reactive set of cleaning responses. As Brider et al. [4] articulated, “a sanitation program is only as effective as the environment in which it operates.” This environment is

a dynamic system in which air, water, product, and personnel continuously interact, often under challenging thermal and moisture conditions [2,5].

The seafood industry faces unique hygienic challenges due to frequent wet cleaning, salt exposure, and temperature cycling. These stressors accelerate corrosion, damage protective coatings, and facilitate microbial persistence. Consequently, hygienic design must combine functional cleanability with durability, ensuring that surfaces withstand mechanical stress and chemical agents over years of operation. Modern frameworks such as the European Hygienic Engineering & Design Group (EHEDG, [29] and FDA [11] guidelines emphasize this dual mandate—constructing facilities that are not only cleanable but maintainable within sustainable limits [16,30].

2.1. Layout and Product Flow

Facility layout defines the basic hygienic logic of seafood processing. A unidirectional product flow—from raw receiving to finished, ready-to-eat (RTE) packaging—is universally regarded as the cornerstone of hygienic facility architecture [6,12,17]. Each transition between process stages must reduce, not increase, microbial load.

Zoning is the principal tool for achieving this logic. Modern facilities divide operations into distinct hygiene zones:

Zone 1: direct product-contact surfaces (e.g., cutting tables, conveyors);

Zone 2: near-contact surfaces (e.g., equipment frames, control panels);

Zone 3: non-contact production areas (e.g., floors, drains);

Zone 4: peripheral areas (e.g., hallways, offices) (Figure 2).

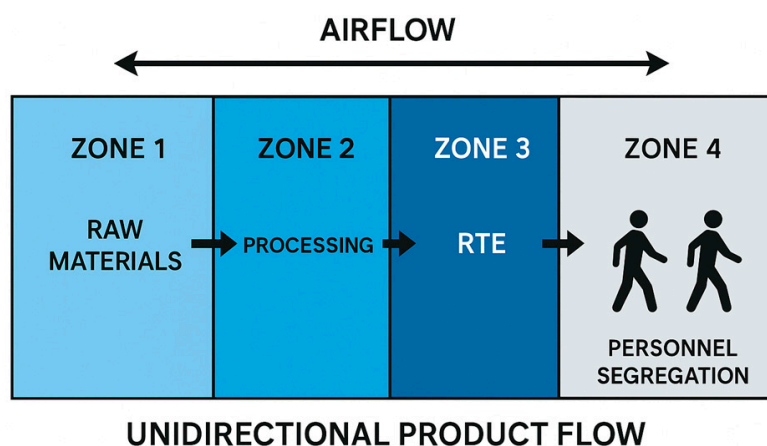


Figure 2. Schematic layout of seafood facility hygienic zones (Zones 1–4) with unidirectional flow and ventilation barriers.

Separation between raw and RTE zones should be reinforced by physical barriers, differential air pressure, and dedicated personnel and equipment. Positive-pressure ventilation into high-hygiene areas and negative pressure in raw zones prevent airborne microorganisms from migrating via condensate or dust [5,11].

Spatial design should also integrate ergonomic flow to minimize cross-path movement. Girmay et al. [9] reported that poor zoning and shared walkways correlated with higher *Listeria* prevalence in Ethiopian fish-processing plants. Automated door systems, restricted-access controls, and visible signage can further enhance zone integrity.

In addition to food safety, optimal product flow contributes to energy efficiency and worker safety by reducing movement distances and thermal losses. Computational tools such as discrete-event simulation and process-mapping software now allow visualization of potential contamination routes during design [29].

2.2. Surface Materials and Equipment Geometry

Surface material selection dictates the facility's long-term cleanability and microbial resilience. Seafood processing imposes severe conditions—constant wetting, saline aerosols, and organic residues that can accelerate corrosion. While austenitic stainless steels (AISI 304 and 316L) remain the industry benchmark due to durability, corrosion resistance, and regulatory acceptance, emerging antimicrobial surface coatings (e.g., silver- or titanium-dioxide-based systems) have demonstrated reduced microbial adhesion under laboratory conditions. However, long-term performance under seafood-processing conditions—characterized by high salinity, frequent wet cleaning, and mechanical abrasion—remains insufficiently validated, reinforcing stainless steel as the preferred hygienic material for industrial use [15].

Surface roughness is a critical determinant of microbial attachment. Surfaces with arithmetic roughness (Ra) values below 0.8 μm prevent bacterial colonization and facilitate cleaning [31–33]. Electropolished stainless steel further minimizes crevice corrosion and provides superior resistance to *Listeria* attachment. For equipment exposed to acidic brines or chlorides, duplex stainless steels (e.g., 2205) offer improved mechanical and corrosion properties [7].

Equipment geometry should eliminate horizontal ledges, lap joints, hollow supports, and unsealed welds—all of which create harborage sites for residues and moisture. Continuous welds, radiused internal corners ($>3\text{ mm}$), and self-draining surfaces prevent microbial entrapment. Mounting clearances of 15–20 cm above the floor allow visual inspection and cleaning access [6,15].

New research emphasizes the role of material–microbe interactions. Peña-Juárez et al. [34] demonstrated that stainless steel modified with titanium dioxide or silver nanoparticles can reduce microbial adherence by up to 80% without affecting cleanability, though such technologies must be balanced with regulatory and cost constraints [35].

Equipment should also be designed for disassembly without tools, allowing complete sanitation of concealed parts. The EHEDG [29] certification program increasingly requires manufacturers to test equipment for “cleanability by design” using riboflavin or soil-retention tests under realistic conditions.

2.3. Drainage, Condensation, and Environmental Controls

Persistent moisture is the root cause of most hygiene failures in seafood facilities. Standing water enables biofilm formation and microbial dispersal through aerosols or footwear. The recommended floor slope of 1–2% reflects validated hygienic-engineering standards shown to promote effective drainage and minimize standing water in wet-processing environments. Site-specific verification through water-flow testing and environmental microbial mapping remains essential to confirm drainage performance and hygiene outcomes [4].

Drains must be fitted with removable grates, water seals, and backflow-prevention valves. “Drain mapping”—a spatial diagram of drainage routes and interconnections—enables rapid identification of contamination pathways during environmental investigations [11]. Multiple facility-specific investigations have identified drainage systems as dominant reservoirs for *L. monocytogenes* in seafood-processing plants. Reported prevalence varies by facility, emphasizing drains as high-risk niches requiring targeted sanitation rather than supporting a single industry-wide quantitative estimate [36,37].

Condensation control is equally vital. Refrigeration coils, ceilings, and cold lines frequently harbor condensate droplets that drip onto food-contact surfaces. Insulated sandwich panels, vapor barriers, and air curtains can prevent condensation and maintain surface dryness [10,25,38,39]. Maintaining relative humidity below 80% and using posi-

tive air exchange rates of 6–10 air changes per hour in chilled rooms minimizes droplet formation and mold growth [5].

Environmental hygiene must also consider airborne particulate management. HEPA filtration, ultraviolet germicidal irradiation (UVGI), and monitored differential pressure contribute to microbiological air quality control in high-risk areas [40]. Regular microbiological air sampling using impactors or settle plates provides verification data for environmental monitoring programs.

2.4. Personnel Hygiene Infrastructure

Humans remain one of the most significant contamination vectors in food facilities. Hygienic design must therefore embed behavior into architecture. Personnel entry points should incorporate hygienic “airlocks” featuring sequential zones: locker → hand-wash → boot-dip → gowning → production entry [41–43].

Touch-free faucets, automatic soap dispensers, and visual cues such as illuminated compliance indicators reduce cross-contact and improve behavioral adherence [7]. Integrating hygiene infrastructure within workflow routes increased hand hygiene compliance by 40% [44,45].

Locker rooms and cafeterias should be located outside of production zones, with distinct entrances for high- and low-hygiene areas. Protective clothing and tools should be color-coded by zone (e.g., blue for raw, white for RTE), ensuring immediate visual recognition. Facilities may also adopt radio-frequency identification (RFID) systems to control personnel access to specific zones [5].

Hygienic design extends beyond equipment—it reflects institutional culture. Layouts that facilitate compliance convey an organizational commitment to hygiene, whereas poorly designed workflows inadvertently promote rule-breaking. Thus, human-centered infrastructure reinforces procedural compliance through spatial logic rather than enforcement alone [4,22,46].

2.5. Ergonomics and Human-Centered Design

Ergonomics and hygiene are inseparable: discomfort and fatigue degrade sanitation quality and worker safety. Cleaning seafood equipment involves repetitive motions, awkward postures, and exposure to cold and moisture. Habib and Fathallah [21] showed that musculoskeletal disorders among seafood sanitation workers are among the highest in the food sector.

Ergonomic interventions—adjustable platforms, retractable hose reels, and anti-fatigue mats—can reduce strain and enhance task consistency. Illumination exceeding 500 lux in cleaning areas improves visual detection of residues, while color-contrast lighting aids verification [8,29].

Human-centered design also involves psychological ergonomics. Participatory design approaches, where sanitation crews contribute to layout and tool configuration, foster ownership and long-term compliance. The integration of social ergonomics—considering worker feedback in redesign cycles—creates alignment between microbiological control and occupational well-being [22].

This convergence of human and microbial factors reflects the emerging concept of “hygiene ergonomics,” recognizing that the safest systems are those that people are physically and mentally able to maintain.

2.6. Validation, Monitoring, and Continuous Improvement

Hygienic design validation is a continuous, evidence-based process that extends across the entire operational life of a processing facility, ensuring that initial design assumptions are translated into measurable and sustained performance outcomes. Within this frame-

work, validation establishes that hygienic design features achieve their intended effects, whereas verification confirms that these effects are consistently maintained under routine, real-world operating conditions [11,38]. Comprehensive validation programs therefore integrate multiple complementary tools, including microbiological surface mapping conducted before and after cleaning to assess residual contamination, airflow and condensation analyses using computational fluid dynamics to identify zones of moisture accumulation or cross-contamination risk, soil-retention testing with riboflavin or fluorescein tracers to visualize cleaning efficacy on complex geometries, and ATP bioluminescence assays to provide rapid, actionable feedback on sanitation performance. Together, these approaches create a robust, data-driven foundation for continuous improvement in hygienic facility design and operation. Additional methodological details, extended validation elements, and supporting examples are provided in Appendix B.

Data from environmental monitoring (swab zones 2–4) should feed directly into design reviews and corrective and preventive action (CAPA) systems. Integrating these datasets into digital “hygiene dashboards” to visualize contamination trends is recommended for higher efficacy [47,48].

Emerging digital twin technologies simulate water flow, temperature gradients, and airflow in three-dimensional models, allowing designers to pre-empt hygiene “dead zones” before construction. Facilities employing predictive analytics and PDCA (Plan–Do–Check–Act) cycles report sustained reductions in cleaning time, chemical use, and microbial loads [5,7].

Ultimately, hygienic design is not a one-time engineering achievement but a continuous learning system that evolves with operational insight, workforce feedback, and scientific progress.

3. Sanitation Technologies and Biofilm Control

Sanitation in seafood processing is both a scientific discipline and an operational practice executed under difficult conditions—low temperatures, saline aerosols, high organic loads, and frequent wet cleaning—each of which promotes biofilm formation and persistence. The aim is not cosmetic cleanliness but demonstrable risk reduction, evidenced by objective verification data and trending (ATP, culture/qPCR, indicator counts) that connect sanitation to hazard control and continuous improvement [2,49,50].

3.1. Fundamentals of Cleaning and Disinfection

Effective cleaning and disinfection outcomes depend on multiple interrelated variables that influence both soil removal and microbial inactivation. These determinants—often summarized within the “TTCM + M” framework (time, temperature, chemical concentration, mechanical action, and material interactions)—govern the reproducibility and sustainability of hygiene performance. Their optimization requires systematic validation during commissioning and continuous verification during production [7]. Key determinants of performance include:

The physicochemical nature of soils dictates detergent chemistry and process parameters. In seafood environments, proteinaceous residues, lipid matrices, and brine films dominate the contamination spectrum. Protein and polysaccharide aggregates bind water and shield embedded microorganisms, while lipids reduce wettability and hinder sanitizer penetration. Alkaline detergents fortified with emulsifiers, chelators, and surfactants (such as sodium metasilicate, nonionic surfactants, or EDTA) are typically required to disperse fish oils and protein films [7]. However, excessive organic load can neutralize oxidants (e.g., chlorine, peracetic acid) by rapid chemical demand, leading to sublethal exposure and potential tolerance selection. Therefore, validation trials should replicate worst-case

soiling—full organic loading, low temperature, and limited flow—to ensure real-world efficacy under process conditions [20].

Water is both a cleaning medium and a reactive component of detergent and sanitizer chemistry. Hardness ions (Ca^{2+} , Mg^{2+}) precipitate with anionic surfactants and form residues that protect microorganisms or promote corrosion. pH governs the antimicrobial speciation of halogens ($\text{HOCl} \leftrightarrow \text{OCl}^-$) and the oxidative stability of peroxygen compounds; for example, peracetic acid decomposes more rapidly under alkaline conditions. Maintaining controlled pH (6.0–8.0) and conductivity targets ensures consistent detergent strength and sanitizer efficacy [5]. Consequently, SSOPs should document water-source treatment, filtration, and disinfection procedures, with periodic verification of hardness, total dissolved solids, and temperature to standardize baseline conditions.

The surface microtopography of equipment materials strongly influences microbial attachment and biofilm initiation. Stainless-steel surfaces with arithmetic roughness (R_a) $< 0.8 \mu\text{m}$, especially those that are electropolished, exhibit lower surface energy and reduced hydrophobic interaction sites for cell adhesion [17]. Polished and passivated surfaces also resist corrosion in saline environments, preventing the formation of micro-pits that harbor soils and bacteria. Equipment geometry should support self-drainage and accessibility, while materials such as high-density polyethylene (HDPE) or food-grade polymers used in non-contact areas must resist cracking and absorbency. Periodic integrity audits—visual inspection, dye penetrant testing, or profilometry—help ensure surfaces remain within hygienic specifications.

Analytical verification of sanitation requires accurate detection of surviving microorganisms, which depends on effective neutralization of residual sanitizers. Without validated neutralizers, residual chlorine, peracetic acid, or quaternary ammonium compounds may continue to inactivate cells during sampling, leading to false-negative results. Neutralizer formulations (e.g., sodium thiosulfate for halogens, catalase for peroxides, Tween-lecithin blends for QACs) should be validated under plant-specific sanitizer concentrations. Method choice must align with the verification question: culture-based enumeration reflects viable survivors, while qPCR detects DNA from both viable and non-viable cells—valuable for confirming presence/absence but not lethality [11].

Modern hygiene systems rely on multi-tiered monitoring: (1) ATP bioluminescence or colorimetric swabs for near-instant process release, (2) culture or qPCR assays for microbiological verification, and (3) trend analysis of microbial indicators (aerobic plate counts, *Listeria* spp.) to identify emerging risks. Rapid ATP tools provide real-time control but must be correlated with microbial baselines to interpret thresholds meaningfully [7]. Over time, integrated databases linking ATP, microbial counts, and environmental metadata enable predictive modeling of sanitation performance.

Together, these determinants emphasize that sanitation validation cannot rely solely on chemical label claims. True hygienic control arises from a system-level understanding—where chemistry, materials, design, and measurement converge to produce consistent microbial outcomes across varying environmental and operational conditions.

3.2. Chemical Sanitizers and Innovations

Legacy chemistries—chlorine, quaternary ammonium compounds (QACs), and iodophores—remain widely used in seafood processing due to their low cost and operational familiarity. However, their limitations, including sensitivity to organic soils, residue potential, and material compatibility concerns, have driven broader adoption of alternative oxidizing agents such as peracetic acid (PAA), ozone, and electrolyzed water. These agents offer strong oxidative activity with minimal persistent residues and

favorable low-temperature efficacy, which is particularly relevant for seafood-processing environments [7,18,19].

The effectiveness of a sanitizer in seafood-processing facilities depends not only on its intrinsic antimicrobial properties but also on application method, contact conditions, material compatibility, worker exposure, and environmental sustainability. Sanitizer selection should therefore be evidence-based, incorporating validation data generated under representative soil loads, temperatures, and facility geometries [7,49]. Each sanitizer category presents distinct operational, regulatory, and occupational considerations.

Despite technological advances, no single sanitation chemistry is universally optimal. Efficacy, material compatibility, worker safety, cost, and environmental impact must be balanced on a facility-specific basis, underscoring the need for critical, context-dependent selection rather than prescriptive adoption.

Peracetic acid remains one of the most versatile oxidizing agents for seafood applications. Its mechanism of action involves oxidative cleavage of cellular membranes, denaturation of proteins, and interference with metabolic enzymes. Unlike free chlorine, PAA maintains efficacy in the presence of moderate organic load and retains activity at refrigeration temperatures [7]. It is highly effective against bacterial spores, biofilms, and viruses, making it valuable for ready-to-eat (RTE) areas.

From an environmental standpoint, PAA decomposes into acetic acid, oxygen, and water, leaving no harmful residues—a key advantage for wastewater compliance and sustainability [49]. However, vapor exposure above 0.4 ppm can irritate mucous membranes; thus, local exhaust ventilation, chemical-specific PPE, and air monitoring are required. Gaskets and soft seals should be verified for EPDM or silicone compatibility, as PAA may degrade natural rubber or nitrile compounds over time. Continuous validation of dilution ratios and contact times (typically 1500–2000 ppm for 5–10 min) ensures reproducible microbial reductions under cold, wet conditions.

Ozone (O_3) is an extremely potent, triatomic oxidant generated on-site by corona discharge or electrolysis. It acts through oxidation of sulfhydryl groups and unsaturated bonds in microbial membranes, producing rapid microbial death even at low concentrations [18,19]. Its gaseous and aqueous forms are both relevant: aqueous ozone serves as a no-residue sanitizer for tanks and CIP loops, whereas gaseous ozone can sanitize air spaces and conveyors between shifts.

The absence of residuals makes ozone particularly suitable for facilities seeking zero-chemical-footprint sanitation. However, it demands stringent off-gassing control: exposure above 0.1 ppm poses respiratory risk, and continuous ambient monitoring is mandatory. Material compatibility testing is crucial because ozone oxidizes natural rubber, some plastics, and carbon-steel components. In practice, stainless-steel 316L, PTFE, and EPDM show high tolerance [18]. Integration into automated CIP cycles, with feedback sensors for oxidation-reduction potential (ORP), can ensure safe, reproducible operation.

Electrolyzed oxidizing (EOW) water, or electrochemically activated water, offers an on-demand sanitizer alternative produced by passing dilute saline through an electrolysis cell, generating hypochlorous acid (HOCl) and minor peroxides. The solution's microbicidal activity stems from the oxidation potential of free available chlorine and its low pH (5.5–6.5), which stabilizes HOCl [7].

EOW reduces the need for manual chemical handling and transport, lowering worker risk and carbon footprint. Its short half-life (hours to days) necessitates on-site generation and frequent verification of FAC (Free Available Chlorine) and pH using handheld meters. The technology is particularly effective for adjunct rinses, equipment exteriors, and contact surfaces between major sanitation cycles. Limitations include reduced efficacy under heavy organic load and lower stability at elevated temperatures or light exposure.

Foam-based hydrogen-peroxide systems combine the oxidative potential of peroxygen compounds with the physical advantages of film-forming wetting agents. These foams cling to vertical, overhead, and irregular surfaces—drain walls, piping networks, and freezer coils—prolonging contact time and enabling visual confirmation of complete coverage [5]. The foaming also facilitates mechanical lift of debris and biofilm residues, particularly after pre-cleaning.

Decomposition to water and oxygen leaves no residues, aligning with eco-efficient sanitation goals [49]. However, effectiveness is contingent on prior removal of organic matter, as hydrogen peroxide radicals are rapidly quenched by proteins and lipids. Regular gasket inspection and staff training on foam stability, dilution, and dwell time are critical to maintain both safety and efficacy [7].

In industrial seafood facilities, enzymatic detergents are most often applied in targeted applications rather than as full replacements for oxidizing sanitizers. Common uses include periodic pre-cleaning of drains, slicers, and complex assemblies with recurring biofilm contamination. Although enzyme formulations are typically more expensive per unit, reduced corrosion, improved EPS disruption, and lower re-cleaning labor frequently result in favorable cost-benefit outcomes when applied strategically [4,5]. Enzyme-based detergents represent a biologically inspired approach to soil and biofilm control. Formulations combining proteases, amylases, lipases, and DNases target diverse biofilm components—proteins, polysaccharides, and extracellular DNA—facilitating detachment and subsequent oxidant penetration [14,50]. Enzymes operate optimally under mild pH and temperature conditions (pH 6.5–8.5, 30–50 °C), reducing corrosion and extending equipment life.

They are best used in rotation with oxidizing sanitizers to avoid microbial adaptation and to manage recurring contamination. Enzymatic pre-cleaning of drains, slicers, and complex assemblies significantly enhances biofilm disruption efficiency in seafood plants [2]. New-generation enzyme systems, stabilized via encapsulation or lyophilization, are expanding use in mobile processing units and remote operations where cold storage and reagent stability are challenges [49].

Optimal sanitizer selection and integration should be grounded in robust comparative validation data generated under the facility's own operating conditions (Table 1). Selection must account for the spectrum of antimicrobial activity, including effectiveness against relevant spoilage and pathogenic microorganisms as well as established biofilms, while also considering material compatibility to ensure that long-term use does not compromise seals, gaskets, or stainless-steel surfaces. Equally critical are worker safety considerations, such as permissible exposure limits, ventilation requirements, and the adequacy of personal protective equipment, alongside the environmental fate of the sanitizer, including its degradation products, aquatic toxicity, and potential impacts on wastewater systems. Verification data demonstrating microbial log reductions under realistic conditions—such as the presence of process soils and low-temperature environments typical of seafood processing—provide essential evidence of real-world efficacy [7,49]. Integrating these technical and operational considerations into SSOP documentation promotes consistency in implementation, facilitates regulatory inspection, and reinforces the continuous-improvement framework that underpins sustainable seafood sanitation programs.

In high-chloride seafood environments, electrolyzed oxidizing water (EOW) may accelerate pitting and crevice corrosion of AISI 304 stainless steel, whereas AISI 316L exhibits superior resistance due to its molybdenum content; therefore, salt-related material compatibility should be considered when selecting novel oxidizing sanitizers for saline processing operations.

Table 1. Comparison of Common Sanitizers Used in Seafood Processing.

Sanitizer	Mode of Action	Typical Use Temp Range	Residue/By-Products	Material Compatibility & Operational Notes	Worker Safety/Environmental Notes	Key References
Chlorine (free chlorine/HOCl)	Strong oxidant; damages membranes, proteins, nucleic acids	2–25 °C	Forms chlorides; potential chloramines/THMs	Corrosive at low pH; efficacy pH-dependent (HOCl favored at pH 6–7)	Irritant vapors; ventilation needed; wastewater by-products to manage	[7,11]
Peracetic acid (PAA)	Peroxygen oxidant; rapid protein/enzyme denaturation; biofilm/spore active	0–25 °C	Decomposes to acetic acid, O ₂ , H ₂ O	Compatible with 304/316L; check gaskets (avoid some elastomers)	Vapor irritant—local exhaust, PPE; environmentally favorable	[7,12,51]
Ozone	Very strong oxidant; reacts with sulfhydryl/unsaturated bonds	0–25 °C	No residual; reverts to O ₂	Incompatible with rubber/plastics; stainless/PTFE good; needs ORP control	Strict off-gassing control (≤0.1 ppm); no chemical transport footprint	[12,50]
Electrolyzed oxidizing water (EOW/HOCl)	Oxidation by free available chlorine in low-pH matrix	2–25 °C	Minimal; short half-life	High chloride and low pH conditions may accelerate pitting corrosion of AISI 304 stainless steel; AISI 316L demonstrates improved resistance due to molybdenum content. Not recommended for prolonged use on 304 surfaces in saline environments without corrosion monitoring.	Reduced handling risk; on-demand generation	[7,11]
Hydrogen-peroxide foams	Peroxide radicals; foam increases contact/coverage	2–25 °C	Water + O ₂ after decomposition	Excellent on vertical/complex surfaces; pre-clean essential	Low residue; train for foam stability and dwell time	[12,50–52]
Enzymatic detergents	Protease/amylase/lipase/DNase hydrolyze EPS and soils (biofilm disruption)	20–50 °C; pH 6.5–8.5	Biodegradable components	Use in rotation; follow with oxidant; verify compatibility	Low corrosivity; strong sustainability fit; requires validation	[53–55]

3.3. Biofilm Prevention and Control Strategies

Biofilm formation represents one of the most persistent and complex hygiene challenges in seafood-processing environments. Unlike planktonic microorganisms, biofilm-associated cells adhere firmly to processing surfaces—such as stainless steel, conveyor belts, drains, and cutting boards—through extracellular polymeric substances (EPSs) composed of polysaccharides, proteins, and nucleic acids [2,14] (Figure 3). Once established, these microbial communities exhibit increased resistance—often by several orders of magnitude—to cleaning agents, disinfectants, and environmental stressors. In seafood plants, the combination of high organic loads, moist and cold conditions, and irregular cleaning schedules creates an ideal ecological niche for the proliferation of *L. monocytogenes*, *Pseudomonas* spp., and *Vibrio* spp. within biofilms. Mixed bacterial–fungal biofilms, such as *Candida* spp. co-existing with *L. monocytogenes*, pose additional challenges due to yeast-derived EPS rich in β -glucans that may resist protease-only treatments. In such cases, multi-enzyme systems (e.g., protease, DNase, and glucanase) followed by oxidizing sanitizers are recommended [3]. The consequences extend beyond microbiological persistence: biofilms serve as reservoirs for cross-contamination, spoilage enzymes, and allergens that compromise both food safety and product shelf life. Understanding biofilm dynamics—initiation, maturation,

and dispersal—is therefore critical to developing effective, validated sanitation programs that combine surface engineering, chemical innovation, and behavioral control [16,49,51].

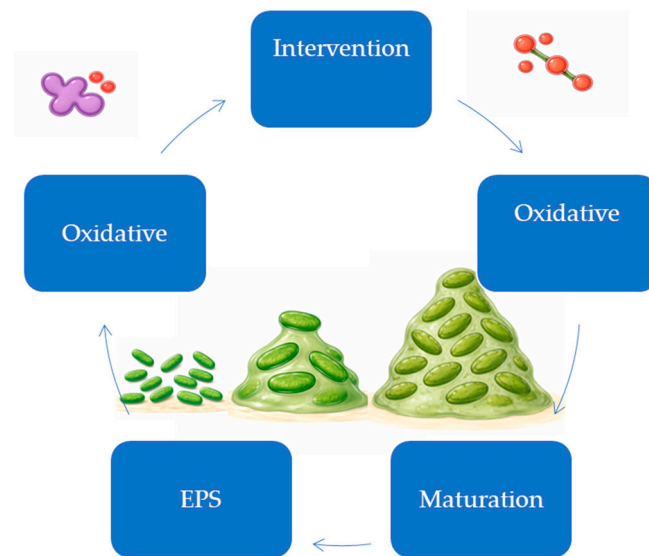


Figure 3. Biofilm formation and control cycle showing adhesion, EPS maturation, and intervention strategies (enzymatic and oxidative).

An effective sanitation program integrates multiple, complementary control layers to address both contamination risk and persistence mechanisms. Primary prevention is achieved through hygienic design principles that maintain dry, drainable surfaces, eliminate harborage points, control airflows and condensation, and ensure strict segregation between wet raw areas and post-lethality zones [15,17]. To address established biofilms, matrix disruption strategies such as periodic acid or enzymatic shock treatments (e.g., protease or DNase phases) are applied to disrupt the extracellular polymeric substance, followed by oxidizing sanitizers, with effectiveness verified through ATP reductions and targeted microbiological swabbing [7,50]. Rotation of sanitizer modes of action, for example, alternating quaternary ammonium compounds with oxidizing agents such as peracetic acid or ozone, reduces the risk of microbial adaptation and should be formally documented within SSOPs [7]. Mechanical energy, delivered through strategic manual scrubbing, turbulent clean-in-place flow, or low-abrasion media where equipment geometry permits, enhances soil and biofilm removal, provided that tools are themselves hygienically managed to prevent cross-seeding [16,17]. Finally, targeted verification programs intensify environmental monitoring at known or emerging “persistent” niches, including drains, slicers, under-belly frames, and gaskets, with trend mapping used to inform equipment redesign and corrective actions [11] (Table 2).

Combined biofilm-control strategies should follow a defined sequence: (1) mechanical soil removal, (2) enzymatic disruption of extracellular polymeric substances, and (3) application of oxidizing sanitizers for microbial inactivation.

Adjunct physical methods (e.g., pulsed light, low-frequency ultrasound) may assist detachment where materials allow, but should be treated as complements—not substitutes—for robust chemistry and design [15,52].

Table 2. Biofilm Control Strategies in Seafood Processing Environments.

Approach	Mechanism/Key Actions	Advantages	Limitations/Considerations	Validation/Key References
Mechanical (scrubbing, high-pressure rinsing, agitation)	Physically disrupts biofilm matrix and removes surface soils; reduces organic load and enhances subsequent treatment penetration	Immediate reduction in biomass; no chemical residue; low cost	May aerosolize pathogens; incomplete removal in micro-crevices; labor-intensive	[7,13,56,57]
Chemical (oxidizers: chlorine, PAA, ozone, EOW)	Oxidative denaturation of proteins and polysaccharides; cell membrane rupture	Broad spectrum; rapid action; effective in cold environments	Organic load sensitivity; corrosive potential; requires PPE and ventilation	[49,58,59]
Enzymatic (protease, amylase, DNase, lipase blends)	Hydrolyze biofilm extracellular polymeric substances (EPSs), facilitating biofilm detachment and increased sanitizer access	Targets biofilm core; synergistic with oxidants; biodegradable and sustainable	Requires specific pH/temperature; slower kinetics; higher cost than oxidants	[50,60,61]
Physical (steam, UV, plasma, ultrasonication)	Thermal or energy-based destruction of microbial cells and EPS	Residue-free; suitable for dry or heat-tolerant equipment	Energy-intensive; may damage surfaces or seals; variable penetration depth	[20,52]
Combined/Integrated methods	Sequential application: mechanical cleaning → enzymatic EPS degradation → oxidizing sanitizer (±physical treatment)	Enhanced penetration; faster kill rates; improved residue and biofilm control	Requires validation of compatibility and safety; more complex SSOPs	[50,62]

3.4. Automation and Digital Monitoring

CIP/COP platforms increasingly employ inline flow, temperature, and conductivity sensors to verify detergent concentration, contact time, and rinse completeness. Coupled with SCADA systems, these parameters generate auditable records and alarms for deviation management. Linking environmental monitoring (EM) trend data to sanitation cycles enables adaptive scheduling (e.g., intensified cleaning following EM alerts), moving beyond fixed timetables toward risk-responsive hygiene management [11,51].

Digital dashboards integrating ATP series, swab results, and CIP telemetry support root-cause analysis and Plan–Do–Check–Act (PDCA) cycles, while also informing preventive maintenance actions such as pump calibration when conductivity drift is detected [7,38,63].

Digital transformation in sanitation should be viewed along a scalability continuum. For small and medium seafood enterprises (SMEs), low-capital, cloud-based solutions—such as digital SSOP logs, mobile ATP data capture, barcode-verified chemical tracking, and cloud dashboards for environmental monitoring—offer immediate gains in traceability, compliance, and verification with minimal infrastructure investment. In contrast, advanced tools such as digital twins, computational fluid dynamics-based hygiene modeling, and fully integrated predictive analytics platforms remain capital-intensive and are currently more feasible for large processors or new facility builds. For SMEs, phased adoption beginning with cloud-enabled documentation and monitoring systems provides a pragmatic pathway toward data-driven hygiene without prohibitive cost or technical burden.

Cleanability and hygienic design verification of packaging equipment can be further strengthened through simple, scalable validation tools. Riboflavin fluorescence testing provides objective confirmation of sanitation coverage on complex packaging machinery and can be integrated into commissioning protocols or periodic verification following maintenance. When paired with targeted environmental monitoring results, these approaches support data-driven refinement of SSOPs and early identification of design-related sanitation failures before contamination becomes systemic.

3.5. Product-Specific and Supply-Chain Hygiene Considerations

Hygienic design verification and testing: Packaging machinery, particularly vacuum chambers, thermoformers, and seal-bar assemblies, represents one of the most critical post-lethality contamination risks for RTE seafood. These systems operate under cold, wet conditions and contain multiple structural interfaces—gaskets, chamber corners, belt returns, and frame junctions—that may retain moisture and organic residues, creating favorable niches for *Listeria monocytogenes* persistence if hygienic design and verification are insufficient [11,26,35].

Environmental monitoring tests around packaging machinery: Hygienic design of packaging equipment should be validated through cleanability and drainability testing in addition to routine sanitation verification. Cleanability of vacuum chambers, lid undersides, seal-bar mounts, and conveyor return paths can be assessed using riboflavin fluorescence coverage testing, which is widely applied in hygienic-engineering validation to visualize shadow zones and incomplete wetting during CIP or foam application [29,31,38]. Riboflavin testing is particularly valuable during equipment commissioning, following maintenance or modification, and when persistent environmental positives indicate potential design-related sanitation failures.

Drainability should be verified through post-sanitation visual inspection and wipe checks to confirm the absence of standing water in chamber floors, frame members, and guarding. Persistent water retention is a well-established risk factor for *Listeria* survival in RTE environments and should be treated as a hygienic design deficiency rather than a procedural failure [11,36,52].

Integration into SSOPs and corrective action: Verification of *Listeria* control in packaging areas should rely on risk-based environmental monitoring (EM) with emphasis on Zones 2 and 3 surrounding vacuum packaging equipment, consistent with FDA and Codex recommendations for RTE foods [11,30]. High-risk sampling sites include seal-bar mounts and gasket interfaces, chamber edges and corners, belt return paths at infeed and outfeed points, equipment frame junctions, and adjacent floor–drain interfaces. Multiple investigations have demonstrated that belt returns, drains, and equipment understructures near packaging lines serve as persistent reservoirs for *Listeria* spp. in seafood and other RTE food facilities [35–37].

Where Zone 1 sampling of direct product-contact packaging surfaces is incorporated into the monitoring plan, results should be linked to defined hold-and-release or corrective-action procedures, as recommended for post-lethality exposed RTE products [11,35]. Positive findings should trigger root-cause investigations that evaluate both sanitation execution and hygienic design factors, including worn gaskets, inaccessible joints, hollow structures, or condensation sources [26,36].

Integration into SSOPs and corrective action: SSOPs for packaging machinery should explicitly document disassembly points (e.g., seal bars and gaskets), cleaning sequence, inspection criteria, and reassembly verification. Corrective actions for EM positives should clearly distinguish between procedural gaps (e.g., incomplete cleaning) and structural deficiencies (e.g., non-drainable geometry or inaccessible components), ensuring that repeated contamination events prompt engineering or design modifications rather than repeated chemical escalation alone [7,11,29].

Water, Ice, and Incoming Raw Material Controls: Water and ice can be vectors or mitigations depending on control. Potable systems require verified treatment (filtration, UV, or approved oxidants) and point-of-use protection (hose/nozzle hygiene, anti-backflow). Ice production should be enclosed, with dedicated scoops/bins and documented cleaning [7].

Incoming control begins at the supplier: harvest-area classification, temperature documentation, and parasite/*Vibrio* risk tied to season and source. At receiving, segregated

docks, calibrated thermometry, and continuous logging provide objective evidence for acceptance or rejection [11,51].

Vessel, Landing Site, and Mobile Processing Hygiene: Space and utility constraints require pragmatic, drainable, corrosion-resistant solutions. On vessels and quays, maintain clean/dirty zoning, smooth nonporous surfaces, and accessible cleaning ports. Provide potable-water connections with backflow protection; document end-of-shift sanitation and verification before redeployment [5,17].

Distribution and Transport Hygiene: Cold-chain hygiene is an extension of plant control. Vehicles should be pre-cooled, inspected, and cleaned prior to loading; mixed loads require physical segregation of raw and RTE products; temperature logging and cleaning records accompany shipments. Sustainability measures—route optimization, reduced water, and verified rinse/dry—reconcile cost and hygiene [64].

3.6. Integration of Sanitation Technologies Within SSOP Frameworks

Technologies deliver value only when embedded in well-written, verified SSOPs that specify who, what, when, how, and how verified. Tablet-based checklists, e-signatures, and automatic data capture strengthen accountability. Training must explicitly cover sensor interpretation and deviation response. EM results should be formally linked to sanitation CAPA and, where relevant, to HACCP/Preventive Controls for *Listeria* in RTE operations [49,63,65].

3.7. Toward Sustainable and Resilient Sanitation

Sustainability entails resource-efficient cleaning (optimized water/energy use), chemistry with favorable environmental fate, and life-cycle thinking in equipment and agent selection. CIP energy audits and sanitizer life-cycle assessments can prioritize lower-impact options without compromising efficacy [64]. Ultimately, resilient sanitation integrates worker safety, design for cleanability, and transparent governance, aligning food safety with environmental and social performance.

4. SSOPs, GMPs, and Operational Hygiene Integration

4.1. The Role of Procedural Systems in Seafood Hygiene

Hygienic design provides the physical substrate for sanitation, but day-to-day control of hazards depends on the rigor of SSOPs and GMPs. Together, they translate architectural intent into repeatable behaviors and auditable records, connecting facility design, personnel conduct, and verification into a coherent control system [11,64,65].

SSOPs operationalize “what, how, when, and by whom” for each cleaning and disinfection task, while GMPs sustain sanitary conditions between cleans—covering personal hygiene, equipment maintenance, pest management, allergen/utensil control, chemical storage, and zone segregation [51]. In mature programs, SSOPs and GMPs are treated as living documents that evolve with process changes, environmental monitoring (EM) findings, and corrective-action trends [49].

4.2. Core Components and Documentation

A robust SSOP system is built on four interdependent pillars that together ensure clarity, traceability, and continuous improvement. First, clearly written procedures must define unambiguous operational parameters, including detergent and sanitizer identity, dilution, contact time, temperature or flow conditions, tool selection, and required safety precautions; the use of visual work aids such as flow diagrams, color-coded equipment maps, and photographic examples of “clean versus not clean” markedly improves reproducibility, particularly for equipment with complex geometries. Second, execution records

are essential to demonstrate task completion and capture critical process data, using tools such as checklists, electronic logs, and clean-in-place conductivity or temperature curves. Third, verification activities conducted at defined frequencies provide assurance of effectiveness, combining rapid ATP screening for line release with culture-based or qPCR methods for outcome confirmation, supplemented by direct observation where appropriate to verify adherence to procedural steps. Fourth, CAPA systems must include explicit root-cause pathways—such as training deficiencies, access or tool limitations, or chemical dosing failures—along with clearly assigned action owners, timelines, and effectiveness checks. Underpinning these pillars, rigorous document control through versioning, approval signatures, and change histories prevents divergence between written procedures and actual practice, while linking SSOP codes to specific equipment identifiers and hygiene zones enables meaningful data trending across assets and sanitation areas [65].

4.3. Integration with Hazard Analysis and Preventive Controls

Under the FDA Fish and Fishery Products Hazards and Controls Guidance and Codex HACCP frameworks, sanitation functions as a prerequisite program and, when supported by validation data, as a preventive control, particularly for *L. monocytogenes* in ready-to-eat (RTE) seafood operations [11]. Environmental monitoring (EM) and SSOP verification outcomes should therefore be actively integrated into the hazard analysis rather than treated as standalone compliance activities. For example, persistent Zone 3 or Zone 4 positives in or around RTE areas may indicate deficiencies in airflow management, personnel or equipment traffic patterns, or hygienic zoning, thereby triggering targeted design or zoning modifications. Similarly, trend analysis revealing repeated ATP or culture failures following specific production shifts or product runs may point to elevated soil loads, inadequate changeover sanitation, or scheduling conflicts that necessitate procedural redesign. This closed-loop system—linking monitoring results to hazard reassessment, engineering controls, and management review—ensures that sanitation performance evolves in step with operational realities and remains aligned with risk-based preventive control principles [65].

4.4. Operational Hygiene and Human Factors

Sanitation procedures are effective only when they are aligned with human capabilities and embedded within a strong, supportive safety culture, as knowledge, motivation, and peer norms remain among the most influential predictors of compliance [22]. Training programs should therefore combine structured classroom instruction with hands-on, line-side coaching, explicitly explaining the rationale behind procedural sequencing—such as the need to rinse between detergent and oxidizing sanitizer steps to prevent chemical neutralization and loss of efficacy. Incorporating behavior-based safety (BBS) principles, including standardized checklists for body posture, hose handling, and appropriate chemical PPE use, has been shown to reduce injury rates while simultaneously improving cleaning completeness; in this context, near-miss reporting and ergonomic strain indicators should be integrated into routine hygiene performance dashboards [21]. In parallel, thoughtful work design that optimizes tool weight, reach distances, and lighting conditions reduces both cognitive and physical workload, thereby lowering error rates, minimizing rework, and supporting sustained sanitation performance under demanding operational conditions [8,47,65].

4.5. Digitalization and Continuous Improvement

Digital transformation strengthens oversight and accelerates learning cycles. Tablet-based SSOPs with e-signatures, barcode/QR validation of chemicals, and cloud dashboards for EM trends provide near-real-time visibility [65].

Core KPIs—% on-time sanitation cycles, mean/95th-percentile ATP readings by asset, EM action-closure time, sanitizer concentration conformance—enable benchmarking within and across facilities. Correlating KPIs with production variables (product type, shift, ambient conditions) supports predictive scheduling and targeted deep-clean windows before a deviation escalates.

4.6. Auditing and Third-Party Verification

Internal audits verify alignment between what is written and what is done on the floor; external audits (regulatory, customer, or certification-scheme assessments) provide independent assurance and market credibility. Contemporary audit models evaluate management commitment and improvement evidence, not only checklist completion [65]. Sampling by third-party laboratories—strategically targeted to drains, conveyors, slicers, and air handling—adds objectivity to trend analyses and can validate internal methods and neutralizers.

4.7. Linking Procedures to Design and Technology

Procedures and plant design must co-evolve. New CIP skids, belt types, or slicer geometries require SSOP updates (e.g., sensor calibration, detergent strength verification, disassembly steps). Conversely, stubborn sanitation failures should trigger design modifications—additional drains, improved accessibility, or equipment replacement—to remove root causes [2,5]. This bidirectional adaptation is the practical expression of the hygiene continuum: design informs procedure; procedure data refine design.

5. Occupational Hygiene and Worker Safety

5.1. The Human Dimension of Sanitation

Sanitation in seafood plants is physically demanding, frequently conducted in cold, wet environments under time pressure. These conditions elevate risks of musculoskeletal strain, slips, and respiratory/dermal exposure to aerosols or chemical vapors [21,65]. A robust occupational-hygiene program protects workers and stabilizes sanitation performance; perceived organizational support is consistently associated with higher hygiene adherence and lower absenteeism [22].

5.2. Chemical Safety and Exposure Control

Oxidizing agents such as peracetic acid and chlorine, along with alkaline and acidic cleaning chemistries, necessitate task-specific worker training, readily accessible Safety Data Sheets, and the implementation of appropriate engineered controls to mitigate exposure risks. Best practices include the use of closed-loop chemical delivery systems and automated dosing to eliminate manual mixing, the installation of local exhaust or targeted ventilation at foam and spray application points to capture chemical mists, and the selection of personal protective equipment that is matched to the specific hazard profile and properly fit-tested, including eye and face protection, chemical-resistant gloves, and impermeable aprons or boots. Facilities that consistently implement these controls report lower rates of occupational illness and improved worker retention in sanitation roles, outcomes that contribute directly to greater consistency and stability in hygiene performance across processing operations [5].

5.3. Ergonomic Design and Work Organization

Leading ergonomic risks include awkward postures around conveyors/slicers, handling heavy or high-recoil hoses, and working on slippery floors. Interventions—adjustable platforms, retractable hose reels, anti-fatigue/anti-slip surfaces, mechanical aids for bin

tipping or disassembly—reduce strain and improve cleaning thoroughness [21,47]. Work organization matters: task rotation between high- and low-exertion activities and planned micro-breaks sustain vigilance without extending shifts. Incorporating ergonomic checks into SSOP verification sustains attention to human factors [7] (Table 3).

Table 3. Ergonomic and Safety Interventions in Seafood Processing Sanitation.

Risk Factor	Engineering/Administrative Control	Performance Outcome	Reference
Repetitive motions, awkward postures	Adjustable platforms, anti-fatigue mats, ergonomic hose nozzles, rotation of tasks	Reduced musculoskeletal strain; improved cleaning reach and compliance	[8,21]
Cold and wet environments	Insulated gloves and boots, micro-breaks, pre-shift warm-up routines	Decreased fatigue and cold-related discomfort; higher sanitation precision	[63]
Chemical exposure (oxidants, acids, alkalis)	Closed-loop dispensing, ventilation hoods, PPE, automatic dosing	Reduced respiratory and dermal irritation; fewer lost-time incidents	[52,64]
Slip and fall hazards	Textured anti-slip floors, rapid-drain systems, visual wet-area markers	Lower incident rates and insurance claims	[66]
Heavy lifting and hose handling	Mechanical lifts, retractable hose reels, lightweight equipment design	Reduced fatigue and worker compensation cases	[8,21]
Psychosocial stress, shift fatigue	Team-based cleaning schedules, cross-training, recognition programs	Enhanced motivation and lower absenteeism	[22]

5.4. Training, Competency, and Safety Culture

Competence requires iterative learning: structured onboarding, supervised practice, and periodic refreshers. Competency assessments—direct observation, brief quizzes focused on critical steps, and ATP “demo” exercises—connect knowledge to measurable performance. Visible leadership (supervisors modeling correct PPE and chemical handling, constructive responses to incident reports) strengthens accountability and trust [22]. Multilingual, pictorial work aids support diverse teams, common in seafood operations.

5.5. Psychosocial and Organizational Factors

Stress, time pressure, and low perceived control erode attention to detail. Evidence links job satisfaction with lower contamination events among sanitation crews [21]. Practical measures include balanced workloads, clear feedback channels, and involving sanitation workers in equipment and chemical selection. Participation converts compliance into commitment, improving both morale and outcomes.

5.6. Integration of Occupational and Food-Hygiene Programs

Worker protection and product protection are mutually reinforcing. Safe chemical handling prevents injuries and product contamination; ergonomic access ensures complete cleaning of hidden surfaces. Joint audits—combining PPE checks, spill response, ventilation performance, and microbial outcomes—provide a holistic view of hygiene maturity. In advanced systems, safety indicators (e.g., near-miss, strain metrics) serve as leading indicators for sanitation reliability [5] (Figure 4).

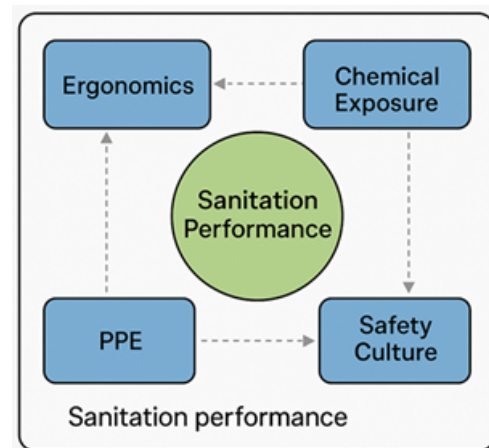


Figure 4. Integration of occupational hygiene and food hygiene systems connecting ergonomics, safety culture, and sanitation outcomes.

5.7. Resilience, Retention, and Workforce Development

Seafood processing faces chronic labor constraints; retaining skilled sanitation staff preserves institutional knowledge and reduces variability. Cross-training, clear career pathways, and formal recognition programs improve retention and hygiene continuity. Investments in ergonomics and mental health build the human infrastructure on which sustainable sanitation depends [22].

6. Future Directions and Policy Implications

6.1. Emerging Trends in Seafood Hygiene

Seafood hygiene is converging with broader agendas in automation, sustainability, and data transparency. Networked sensors embedded in CIP/COP systems, refrigeration units, and air handling can continuously track temperature, humidity, flow, and conductivity, generating high-frequency data that strengthens sanitation verification and deviation response. When combined with routine environmental monitoring (EM) results, these data streams enable leading indicators of hygienic drift (e.g., rising ATP baselines or detergent-strength deviations) so that interventions are scheduled before contamination manifests.

Parallel consumer and buyer expectations for resource efficiency and traceability are reshaping sanitizer choice, equipment design, and packaging practices. Life-cycle assessment (LCA) now informs selection among oxidants and enzymatic cleaners, favoring agents with lower aquatic toxicity and shorter environmental persistence where efficacy is equivalent [66]. The literature on biofilms and microbial interactions underpins these choices by clarifying where chemistry, surface engineering, and operations yield the best risk reduction [2].

6.2. Climate Change and Environmental Resilience

Climate-linked shifts in sea temperature, salinity, and extreme weather influence the ecology of *Vibrio*, *Listeria*, and other hazards in harvest waters and along supply chains. Variability in raw-material quality and temperature at landing necessitates adaptive hygiene strategies—flexible SSOPs, modular cleaning routines that accommodate higher soil loads, and risk-based EM that scales with seasonal risk [1].

Policy responses should integrate environmental surveillance (coastal monitoring of *Vibrio* risk, harmful algal blooms, runoff events) with inspection and certification systems, ensuring that hazard analyses reflect current ecological conditions rather than static historical profiles [67].

6.3. Digital Transformation and Regulatory Evolution

Digital traceability platforms and tamper-evident record systems are becoming mainstream in seafood supply chains. When SSOP, EM, and HACCP/Preventive Controls records are time-stamped and securely maintained, remote auditing and rapid verification are feasible. As regulators increasingly accept digital logs as legal equivalents to paper (with appropriate authentication and privacy protections), the next step is the selective recognition of predictive analytics—for example, statistical triggers that escalate sanitation intensity after specific EM patterns. This evolution blurs boundaries between quality management and regulatory science, but it is consistent with risk-based oversight [11].

6.4. Harmonization and Capacity Building

Fragmentation among national hygiene requirements increases compliance costs and complicates training—especially for small and medium enterprises. Closer alignment between Codex guidance and regional frameworks (e.g., U.S. Seafood HACCP) would streamline audits and documentation while improving public-health outcomes. Capacity-building should emphasize practical, low-cost interventions—portable sanitation tools, simplified EM plans for high-risk zones, and competency-based training—shown to lift hygiene performance in resource-constrained settings [3,22]. Partnerships among universities, extension services, and authorities can deliver context-specific guidance without sacrificing scientific rigor.

6.5. Sustainability and Circular-Economy Approaches

Sustainable sanitation extends beyond chemical substitution to system design: closed-loop CIP with solution recovery, targeted foams that reduce water and energy, and biodegradable/enzymatic detergents, where validated [17] (Figure 5). Waste-to-energy and water-reclamation systems incorporated into plant utilities can reduce life-cycle impacts while maintaining hygienic outcomes. Aligning SSOPs with LCA-informed chemical and resource decisions embeds environmental performance into routine operations, rather than treating it as an external reporting exercise [68] (Table 4).



Figure 5. Sustainability–hygiene nexus showing circular resource flows linking sanitation performance, environmental stewardship, and human welfare.

Table 4. Sustainability Metrics in Sanitation: Resource Efficiency and Performance Indicators.

Metric Category	Indicator/Unit	Description and Relevance	Example Target/Benchmark	Reference
Water Use Efficiency	L of water used per kg of product	Quantifies process and sanitation water consumption; major sustainability driver in seafood processing.	<3.0 L/kg (efficient RTE seafood operation)	[65,66]
Energy Consumption	kWh per sanitation cycle	Tracks power used for heating water, pumps, and CIP/COP systems.	≤10% of total facility energy budget	[66]
Chemical Footprint	kg active ingredient per 1000 kg product	Measures sanitizer and detergent inputs; lower footprint indicates efficient dosing and low environmental residue.	Reduction of ≥25% compared to baseline	[52,64]
Effluent Quality	BOD/COD (mg/L), residual chlorine (ppm)	Evaluates waste discharge and treatment compliance; essential for sustainability audits.	BOD < 50 mg/L; residual chlorine < 1 ppm	[66]
Recycling and Reuse	% of cleaning water recycled	Assesses process water recapture and reuse for non-contact purposes.	>40% reuse feasible with filtration/UV treatment	[49]
Waste Management	kg solid waste per sanitation shift	Evaluates waste segregation and recovery of packaging and PPE materials.	Reduction trend of ≥10% annually	[65]
Worker Welfare & Safety	Incident rate, training hours per employee	Social sustainability measure linking human well-being to hygiene outcomes.	<3.0 lost-time injuries per 100 FTEs	[21,22]
Composite Indicator (conceptual)	Weighted sustainability index (0–1)	Composite indicators are increasingly used to summarize hygiene performance by combining outcomes from design compliance, sanitation effectiveness, and workforce adherence. While weighting schemes may vary by facility, such indicators are best used as internal benchmarking tools rather than standardized metrics, supporting continuous improvement without prescriptive calculation requirements.	≥0.8 indicates sustainable operation	[66]

While resource-efficiency metrics are essential for evaluating the environmental footprint of sanitation systems, their practical value depends on robust verification of hygienic performance. Sustainable sanitation strategies must therefore be supported by objective, routine monitoring tools that confirm effective microbial control, chemical dosing accuracy, and residue removal under real operating conditions. Integrating verification outcomes with sustainability indicators enables facilities to balance environmental performance with food safety assurance. Key sustainability and hygiene-related performance indicators commonly applied in seafood sanitation systems are summarized in Table 5.

Table 5. Key Verification Tools and Targets for Hygiene Monitoring in Seafood Processing.

Verification Tool	Measurement Principle	Typical Threshold/Action Limit	Primary Application	Reference
ATP Bioluminescence	Measures organic residue via light emission from ATP-luciferase reaction	<10× baseline RLU for post-clean verification	Rapid on-site hygiene validation for equipment and surfaces	[11,64]
Aerobic Plate Count (APC)	Culture enumeration on non-selective media (35 °C/48 h)	<1 CFU/cm ² (RTE zones)	Quantitative verification of cleaning effectiveness	[61,69]
<i>Listeria</i> spp./ <i>L. monocytogenes</i> qPCR	Molecular amplification of species-specific DNA sequences	Not detected in 25 g sample or RTE zone surface	Environmental monitoring and pathogen control verification	[61,70]
<i>Vibrio</i> spp. qPCR/MPN	Detection and enumeration of <i>Vibrio</i> parahaemolyticus/ <i>V. vulnificus</i>	Not detected or <3 MPN/g (raw seafood)	Verification of raw-material hygiene and process-water control	[67,68]
<i>Salmonella</i> spp. ELFA/qPCR	Antigen-antibody or nucleic acid-based detection	Not detected in 25 g	Finished product and environmental verification	[71]
Residual Sanitizer Concentration	Colorimetric titration or digital sensor measurement	±5% of target concentration	Confirms chemical dosing accuracy and avoids product residues	[64,66]
Allergen Swab (Lateral Flow or ELISA)	Immunoassay detecting protein residues (e.g., tropomyosin)	<1 ppm on cleaned surfaces	Cross-contact prevention in mixed seafood facilities	[11]
Biofilm Activity (Staining/Microscopy)	Qualitative visualization of EPS presence on coupons or drains	Relative absorbance OD ₅₉₀ < 0.1 (research-level)	Validation of cleaning efficacy and biofilm removal trials	[50,60]

6.6. Human Capital and Next-Generation Training

Effective next-generation hygiene requires multidisciplinary skills that join microbiology, data interpretation, and sustainability. Modular e-learning, augmented-reality simulations for complex disassembly/cleaning tasks, and micro-credentials in sanitation or hygienic design can address skill gaps and stabilize sanitation staffing. Extension networks and university programs remain pivotal for transferring applied methods—such as drain mapping, sanitizer rotation schemes, and verification statistics—into day-to-day plant practice [22,47].

6.7. Policy Implications and Research Priorities

Policy frameworks should consolidate a risk-based, outcome-oriented model of seafood hygiene that aligns sanitation performance with broader sustainability and public-health objectives. Priority areas include the development of harmonized metrics for sanitation effectiveness—such as site-specific environmental monitoring action thresholds and ATP-based control charts—integrated with environmental sustainability indicators to enable holistic performance assessment [11,72]. Policy instruments should also incentivize the adoption of validated, low-impact cleaning and sanitation technologies through mechanisms such as grants or tax credits, thereby accelerating industry-wide implementation. In parallel, targeted research investment is needed to advance understanding of biofilm ecology in seafood-processing environments, with particular emphasis on extracellular

polymeric substance disruption strategies and complex multi-species interactions that drive persistence [2,14]. Finally, collaborative surveillance models that integrate environmental monitoring, occupational health, and public-health data streams can facilitate earlier detection of systemic risks and more proactive interventions [22]. Ultimately, a systems-thinking approach—recognizing the interdependence of food safety, worker safety, and ecological protection—will be central to shaping the next decade of hygienic and sustainable seafood production.

7. Conclusions

Seafood hygiene represents a continuous interplay between design, technology, and human behavior rather than a fixed endpoint of compliance. This review highlights that achieving reliable sanitation in seafood processing requires not only effective chemical or mechanical cleaning but also a deeply integrated system of facility design, procedural discipline, and workforce engagement. Structural integrity and sanitary layout determine whether cleaning can succeed at all, while well-structured SSOPs and GMPs translate those design intentions into measurable daily performance.

Contemporary hygiene management has evolved from manual routines toward digitally supported, data-driven operations. The adoption of automated cleaning-in-place (CIP) systems, sensor-based verification, and environmental monitoring dashboards reflects this transition from reactive sanitation to predictive hygiene control. However, these technologies only reach their potential when they are embedded in a culture that values continuous learning, ergonomic safety, and accountability. In this sense, the human dimension remains central: sanitation quality depends as much on worker well-being and training as on engineering or chemistry.

Sustainability considerations now redefine what constitutes “good hygiene.” Reducing water and chemical consumption, optimizing energy use, and selecting biodegradable or recyclable sanitation agents are not optional refinements but emerging regulatory and market imperatives. Environmental metrics—once peripheral—are becoming key indicators of operational excellence, linking hygiene performance with broader goals of corporate responsibility and resource stewardship.

Looking ahead, the convergence of hygiene science, occupational safety, and environmental management offers the most promising path toward resilient and transparent seafood systems. Facilities that adopt a systems-thinking approach—where microbial control, worker health, and ecological impact are treated as interdependent outcomes—will be best positioned to meet future regulatory, ethical, and consumer expectations. Hygiene in seafood processing, therefore, should no longer be viewed as a narrow technical exercise but as a foundational element of sustainable food-system design.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The author declares no conflict of interest.

Appendix A

Practical Facility Inspection Checklist

Purpose. To standardize hygiene audits in seafood-processing facilities by consolidating design, operational, and verification criteria derived from Codex and FDA guidance and from applied extension materials [6,11].

Category	Inspection Item	Verification Details/Questions	Compliance (✓/✗)	Comments/Corrective Actions
1. Facility Design & Structure	Wall–floor junctions	Are junctions coved, sealed, and cleanable?		
	Floor slope & drainage	Do floors slope 1–2% toward trapped drains? Is a drain map available?		
	Ventilation & condensation	Is airflow zoned (positive in RTE, negative in raw)? Any evidence of condensate?		
2. Equipment & Utensils	Materials & finish	Are contact surfaces smooth, corrosion-resistant, and weld-sealed?		
	Accessibility	Can all surfaces be cleaned without tools? If not, are COP steps documented?		
	Sanitation design	Are cleaning ports, self-drainage, and removable guards provided?		
3. Personnel Hygiene Facilities	Handwash/sanitizer	Are stations at all hygiene-zone transitions and maintained?		
	Locker rooms & uniforms	Are welfare areas separated from processing? Are uniforms color-coded by zone?		
4. Sanitation & SSOP Implementation	Schedules & records	Are SSOPs current, signed, verified? Are e-logs complete?		
	Chemical management	Are containers labeled, dilutions documented, dosing calibrated?		
	Verification methods	Are ATP/microbial tests conducted at defined frequencies with neutralizers validated?		
5. Environmental Monitoring	Sites & frequency	Are sites/tiers defined (zones 1–4), with action thresholds and resample rules?		
	Corrective action	Are root causes and CAPA documented for positives?		
6. Worker Safety & Ergonomics	PPE & ventilation	Is PPE appropriate and maintained? Are mists/aerosols captured at source?		
	Ergonomic aids	Are platforms, hose reels, and mats used to minimize strain?		
7. Documentation & Records	HACCP/SSOP linkage	Are sanitation and EM outcomes linked to HACCP verification?		
	Management review	Are trends analyzed and escalated to management monthly?		

Scoring guidance. ✓ Compliant; Partially compliant: corrective action required; ✗ Noncompliant: immediate action and follow-up verification.

Use and frequency. Include SSOP record checks, operator interviews, and photographic evidence for deviations. Minimum quarterly audits; monthly for high-risk RTE lines [67].

Supplementary tools and resources supporting the operational hygiene framework are provided in the following appendices.

Appendix B. Recommended Analytical Methods for Verification

Purpose. To summarize, validated analytical methods used to verify sanitation outcomes and to support EM programs in seafood plants are aligned with FDA guidance and international standards [2,11,52].

Target Parameter	Analytical Method/Kit	Detection Limit/Range	Typical Sample Type	Reference/Validation Source
1. ATP (rapid hygiene check)	Hygiena EnSURE Touch; 3M Clean-Trace	Facility-specific baseline; typical noise 1–10 RLU	Food-contact & adjacent surfaces	Internal validation; [11]
2. Aerobic plate count (APC)	Standard Plate Count, 35 °C/48 h	~1 CFU/cm ² (method-dependent)	Surface swabs, rinse water	[11]
3. <i>Listeria monocytogenes</i>	qPCR (Bio-Rad iQ-Check, Thermo SureTect)	<10 CFU/25 g (post-enrichment)	RTE surfaces, drains, foods	[11,70]
4. <i>Vibrio parahaemolyticus</i> / <i>V. vulnificus</i>	qPCR (GeneDisc/ Applied Biosystems) or MPN; ISO 21872-1	1–3 MPN/g (method-dependent)	Raw seafood, seawater, ice	[67,68]
5. <i>Salmonella</i> spp.	ELFA (VIDAS) or qPCR (SureTect) after enrichment	<1 CFU/25 g (presence/absence)	Raw seafood, env. swabs	[71]
6. Allergen residues	Sandwich ELISA (Neogen, R-Biopharm)	1–5 ppm (kit-dependent)	Product surfaces, rinse water	[11]
7. Residual sanitizer	Titrimetric kits or colorimetric strips	±5% of target	Rinse water, CIP return	[63]
8. Biofilm assessment	Crystal-violet or fluorescent staining (R&D)	Relative OD590	Coupons, drains (pilot studies)	[50,60]
9. Allergen verification (surface)	Lateral-flow immunoassay	~1 ppm threshold	Work benches, slicers	[11]

Interpretation thresholds

ATP > 10 × baseline at a site: re-clean and re-test; investigate for soil/agent mismatch.

Pathogen detection (e.g., *Listeria* in RTE zones): initiate root-cause analysis, escalate EM frequency, review SSOP steps and hygienic design.

Cleanability validation (packaging equipment): Riboflavin fluorescence coverage testing applied to vacuum chambers, seal-bar assemblies, and conveyor return paths to confirm sanitation reach and identify shadow zones.

Sanitizer out-of-spec: Recalibrate dosing systems and verify sanitizer recovery and neutralization during microbiological sampling to prevent false-negative results.

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