The Economics of Microbial Control in Poultry Processing

From disappointing carcass results to integrated process engineering, resource efficiency and emerging water technologies

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Abstract

Poultry processors operate at the intersection of two demanding objectives: reducing microbial contamination and maintaining the economics of high-throughput production. Recent European surveillance shows why neither objective can be treated as solved. In 2024, 24.3% of samples taken during competent-authority monitoring exceeded the Campylobacter process-hygiene threshold of 1,000 CFU/g; the corresponding proportion reported through operators' own checks was 16.4%. Meanwhile, research synthesis reveals inconsistent effects of washing, chilling and newer interventions, with recontamination at defeathering and evisceration offsetting upstream reductions. This study develops a decision framework that prices microbiological performance alongside water, energy, carcass yield, throughput, product loss and regulatory eligibility. A transparent hypothetical plant model shows how apparently attractive interventions can become financially inferior when costs or modest performance losses are included. Finally, it examines reactive mineral transformation of process water, including INTABIOTECH's KNAMAX™/AAI platform, as a testable integration opportunity rather than an independently verified solution. The industrial objective is safer production with demonstrable net value, not another laboratory-only reduction claim.

Keywords: *poultry processing; Campylobacter; Salmonella; process hygiene; techno-economic assessment; water efficiency; reactive mineral systems; regulatory compliance*.

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I. The uncomfortable evidence: an expensive problem has not disappeared

A food-safety programme should not be declared successful merely because it has accumulated interventions. Modern poultry plants invest in farm biosecurity, scalding, automated evisceration, washing, chilling, environmental hygiene, sanitation and testing. Yet the European Union One Health 2024 Zoonoses Report, published by EFSA and ECDC in 2025, records an outcome that warrants serious industrial scrutiny: among 15,431 official-control Campylobacter process-hygiene samples, 24.3% exceeded 1,000 CFU/g, compared with 16.0% in the official data for 2023. Among 67,042 samples collected under food-business operators' monitoring programmes, 16.4% exceeded that threshold, compared with 15.8% in 2023. In the eleven Member States providing both sampling series, the contrast was 26.0% against 14.7% [1]. These are consequential results even allowing for methodological differences. They are not evidence that every processing plant is failing, and they are not a European-wide measured rate of non-compliant establishments. They demonstrate that substantial microbial burdens persist and that sampling design matters.

The same report recorded 168,396 confirmed human campylobacteriosis cases in the EU in 2024, an 11.9% increase in the reported notification rate compared with 2023. Changes in ascertainment, surveillance coverage, exposure and healthcare reporting limit direct attribution to poultry processing. The burden nevertheless makes the performance of control programmes a public-health as well as commercial concern. Salmonella offers a different warning: only fourteen Member States met all their poultry-population Salmonella reduction targets in 2024, compared with nineteen in 2022 [1]. These signals justify rigorous investigation; they do not justify an indiscriminate claim that every conventional treatment is ineffective.

The legal threshold also has a precise meaning. Commission Regulation (EU) 2017/1495 amended Regulation (EC) No 2073/2005 to establish a Campylobacter process-hygiene criterion for chilled broiler carcasses. Since 1 January 2025, the sampling plan is n = 50, c = 10, with the criterion expressed as a maximum of ten individual results above 1,000 CFU/g. Unsatisfactory outcomes call for improvement of slaughter hygiene, review of process controls, origin of animals and farm biosecurity [2]. The criterion is not a blanket zero-tolerance food-safety limit, nor is a single result above 1,000 CFU/g, by itself, proof that the complete 50-sample process criterion has failed. The distinction is central when costing product dispositions and regulatory consequences.

Perhaps the most instructive fact is that the variability is not small. The EFSA/ECDC account describes official-sample exceedance proportions across Member States ranging from almost none to very high percentages, while operator monitoring commonly yields lower figures. Differences in geographical conditions, flock status, risk-based official sampling, sampling frequency, analytical practices and choice of establishment can influence such comparisons. The official-versus-operator gap cannot legitimately be sold as evidence of deliberate underreporting. It is instead a reason to conduct independent, stratified and blinded assessments of interventions under real manufacturing conditions.

For the financial director, the implication is uncomfortable: the absence of a failed customer audit this quarter does not establish low exposure to future interruption or commercial loss. For the technical director, it is equally uncomfortable: a modest average log reduction measured in a laboratory cannot guarantee that a high-variance industrial process has moved sufficiently below a regulatory action threshold. The useful unit of evaluation is the distribution of results across time, flocks and lines, not a single mean value.

II. Why the processing line repeatedly gives back what an intervention removes

The microbial ecology of poultry slaughter explains why apparently promising control points can underperform. A flock arrives with a variable biological load. Holding, transport crates and feathers can contribute environmental transfer before the bird encounters the principal process. Scalding may reduce organisms substantially, but plucking equipment can redistribute contamination. Evisceration may transfer intestinal contents, while carcass-to-carcass contact, process water, aerosols, conveyors and contact surfaces provide additional routes. Chilling reduces temperature and can lower counts, yet the effect depends on the method, organic burden, residence time and cross-contamination control. Sanitation applied at the wrong stage can therefore reduce a count temporarily while leaving the dominant later transfer mechanism untouched.

The UK's Food Standards Agency published an umbrella review in 2026 synthesising systematic reviews of Campylobacter interventions in slaughterhouses. The synthesis found meaningful reductions during scalding, but increases in contamination associated with defeathering and inconsistent effects at evisceration. It also reported very high heterogeneity across many pooled estimates, including physical interventions. Water-only post-chill immersion had a pooled reduction of approximately 0.42 log10 in the studies discussed, but with an I^2 of 96%; this is evidence of variability, not a transferable universal performance coefficient. Another physical-intervention synthesis reported about 0.46 log10 reduction with I^2 of 99%. In contrast, tests of ozonated water spray and cold plasma under specified study conditions produced small or statistically unpersuasive changes. These results should neither disqualify a whole technology family nor be hidden when presenting its industrial promise [3].

An independent 2026 systematic review and meta-regression encompassing 71 studies and 1,256 observations provides further context. The authors reported mean reductions of approximately 0.898 log10 after scalding, 0.523 log10 after carcass rinsing with water, and 0.692 log10 after combined sanitisation and chilling. Organic-acid interventions had larger reported average effects in the assessed studies, but study design, application mode, concentration, product and matrix strongly moderated outcomes [4]. Such pooled estimates are not engineering guarantees. They are evidence that stage selection and consistent process control matter at least as much as the nominal choice of agent.

A one-log reduction represents a tenfold decrease in a measured count; it does not mean a 90% decrease in the probability of a process-hygiene failure, consumer illness or product rejection. Those probabilities depend on the entire underlying distribution. Nor can log reductions for separate stages simply be added as though the stages were independent. A reduction achieved before defeathering may disappear after subsequent transfer. A microbial change at slaughter may not predict spoilage during distribution, because the organisms and storage conditions governing sensory shelf life are not the same as those governing Campylobacter risk. Campylobacter generally does not proliferate under normal refrigeration conditions, whereas spoilage populations may grow. A shelf-life claim therefore requires its own longitudinal evidence.

The weakness of single-point comparisons is illustrated by the difference between concentration and prevalence. An intervention may reduce high Campylobacter counts without changing the proportion of test-positive samples, or lower prevalence with only a small change in average concentration. Either may be useful, but the selected commercial endpoint must match the risk it is intended to manage. An intervention optimised to move a carcass distribution below 1,000 CFU/g may be economically preferable to one delivering a larger mean log reduction while leaving a problematic upper tail. That is a distribution-management problem rather than a competition over the largest number reported in a laboratory paper.

III. The real cost of control: water, power, yield and capacity

In a slaughter plant, microbial control consumes or influences scarce resources even when its direct chemical cost is small. Water is purchased, cooled or heated, pumped, monitored and ultimately discharged or treated. Heat applied to carcasses may improve a microbial endpoint while contributing to surface damage, moisture loss or changes in skin appearance. A misting or immersion stage can alter retained water and weight, while tighter sanitation may add changeover time. An apparent microbiological gain may therefore be purchased with lost saleable kilograms or an unplanned throughput bottleneck. Conversely, improving contamination control can prevent reworking, retained lots, customer downgrading and loss of shelf life. The finance department must be allowed to observe both sides of that equation.

The European Commission's 2023 best-available-techniques (BAT) conclusions for slaughterhouses provide a useful resource benchmark, though their associated performance levels must not be mistaken for plant-specific prices, universal design minima or permitted limits applicable without regard to permit conditions. For chicken slaughterhouses, the BAT-associated environmental performance range for specific net energy consumption is 170–490 kWh per tonne of carcasses (also expressed as 0.25–0.90 kWh per animal); the associated specific wastewater discharge range is 1.45–6.30 m^3 per tonne of carcasses (or 0.002–0.013 m^3 per animal), subject to the decision's notes and applicability [5]. These are particularly valuable for screening an innovation claim: an intervention that saves 2% of process water but adds a large refrigeration or thermal penalty may deliver negligible net value.

Water intake, wastewater discharge and reuse are separate quantities. A reduction in discharge does not automatically equal a reduction in freshwater abstraction. Reuse may require filtration, microbiological safeguards, equipment, energy and separate authorisation. Water that comes into contact with food must meet applicable requirements, and a proposal to recycle or chemically condition it cannot be evaluated exclusively through its utility bill. Product losses are similarly multi-causal: microbial-control improvements should receive economic credit only for losses causally affected by the intervention, not for all inventory shrinkage or all retail returns.

An investment model must distinguish contribution margin from selling price. If improved control retains an extra kilogram for sale, the economic benefit is ordinarily the incremental contribution or avoided loss, not the entire retail price of that kilogram. Likewise, the value of an extra hour of line availability is large only where demand, labour, chilling and packaging capacity allow that production to be sold. In a demand-constrained plant, additional line speed may have little value; in a capacity-constrained plant, lost minutes can dominate chemical costs. The engineering and finance teams need the same process map.

Three sources of value merit separate ledgers. First is direct resource expenditure; water, wastewater, electricity, heat, chemical or mineral concentrate, labour and consumables. Second is manufacturing contribution; yield, line availability, rework, quality downgrades, cleaning downtime and avoidable rejection. Third is risk; probability-weighted consequences of a regulatory intervention, major recall, loss of an export approval, retailer delisting or a foodborne incident. The third category has potentially severe consequences but is the easiest to exaggerate. Without reliable local frequency and severity data, expected-loss estimates should be reported as scenarios, not added to an ROI calculation as though they were realised savings.

IV. A transparent industrial model: when a good microbial result is a poor investment

Consider a deliberately hypothetical EU broiler plant processing 30 million birds a year. Assume 2.0 kg of saleable carcass equivalent per bird, 9 litres of incoming water per bird, and 0.55 kWh of net electricity equivalent per bird. Suppose water plus wastewater treatment costs €2.80/m^3 and electricity €0.16/kWh.

For this illustrative plant, 270,000 m^3 of water-related throughput costs €756,000 annually; energy at the assumed rate costs €2.64 million. These numbers are transparent assumptions selected for economic illustration and are not the measured results of an INTABIOTECH customer. The energy assumption falls within the BAT-associated range noted earlier; the selected water intake is not the same measure as the BAT wastewater-discharge range [5].

A proposed integrated microbial-control upgrade is assumed to require €950,000 of initial capital and €420,000 of incremental annual operating expense. Those figures are not a KNAMAX™ quotation or cost estimate. They are placeholders that include potential equipment, monitoring, maintenance, process preparation and validation expenses. The hypothetical current plant incurs €0.024 per bird in microbiologically attributable rework, holding or downgrade costs, equivalent to €720,000 annually. It also incurs €0.006 per bird in demonstrably attributable downstream spoilage loss, equivalent to €180,000. If only part of those losses can be credibly linked to the proposed intervention, only that part should be credited to it.

ILLUSTRATIVE BASELINE

Metric	Assumption	Annual implication
Annual production	30,000,000 birds	60,000 tonnes carcass equivalent
Water intake	0.009 m^3/bird	270,000 m^3/year
Water + wastewater unit cost	€2.80/m^3	€756,000/year
Energy	0.55 kWh/bird at €0.16/kWh	€2,640,000/year
Microbiologically attributable rework/hold/downgrade	€0.024/bird	€720,000/year
Attributable downstream spoilage loss	€0.006/bird	€180,000/year
Candidate upgrade	€950,000 capital	€420,000 extra annual operating cost

Under a central scenario, assume that the intervention avoids 70% of rework/hold/downgrade costs (€504,000), recovers 0.20 percentage points of saleable yield (€264,000 using €2.20 incremental contribution per recovered kilogram), reduces water expenditure by 4% (€30,240) and prevents 25% of the specifically attributable downstream spoilage losses (€45,000). Total gross annual benefit would then equal €843,240; subtracting €420,000 of incremental running costs yields €423,240 of annual net operating benefit. At a 10% discount rate over five years, and ignoring terminal value and taxes, the net present value would be approximately +€654,000 after the €950,000 capital expenditure. That is a conditional result: if the plant cannot substantiate a yield change, or if reduced microbiological counts do not translate to saved rework or waste, the value falls sharply.

FIVE-YEAR SCENARIOS

Metric	Downside	Central	Strong execution
Avoided attributable rework costs	20%	70%	85%
Saleable yield gain (percentage points)	0.00	0.20	0.35
Water-related expenditure saved	0%	4%	10%
Avoided attributable downstream spoilage	0%	25%	50%
Gross annual benefit	€144,000	€843,240	€1,239,600
Incremental annual operating expense	€420,000	€420,000	€420,000
Net annual operating benefit	−€276,000	€423,240	€819,600
Five-year NPV at 10%, after €950,000 capex	−€2,000,000 approx.	+€654,000 approx.	+€2,157,000 approx.

The asymmetry is instructive. The same technology can be an unattractive investment in one plant and financially compelling in another, even when the microbiological laboratory result is identical. In this illustrative model, retaining the central assumptions for yield, water and attributable spoilage, the fraction of the current €720,000 annual rework/hold/downgrade cost that must be avoided for a non-negative five-year NPV is approximately 46%. This is a decision threshold, not an efficacy prediction. If it proves

implausible under a rigorous plant trial, capital approval should fail regardless of how promising the mechanism sounds.

For an operator comparing three or four interventions, the correct question is not simply which method gives the greatest log reduction. It is which legally admissible and validated configuration delivers the best risk-adjusted five-year value without worsening the variability of food-safety performance. Scenario analysis should stress-test utility prices, yield effects, line-speed loss, chemical consumption, water quality, seasonal flock burdens and equipment reliability. A technology that requires a continuous operator intervention and a chemical delivery system has different failure modes from a passive hygienic design upgrade. These failure modes deserve explicit cost and risk allowances.

V. From published log reductions to regulatory probability (and the limits of that translation)

A useful statistical exercise demonstrates why mean reductions cannot be treated as compliance probabilities. Imagine, purely as a mathematical example, that the probability that an independently sampled carcass exceeds 1,000 CFU/g is p. For a fifty-sample assessment permitting at most ten exceedances, the probability of more than ten is $P[X > 10]$ for X following a Binomial(50, p) distribution. At $p = 0.24$, that simple model gives approximately 68%; at $p = 0.16$, approximately 17%; and at $p = 0.10$, less than 1%. Moving the tail of the distribution may therefore create an economically meaningful difference even when the average count changes only moderately.

These values must not be confused with real-world failure rates inferred from EFSA's 24.3% and 16.4% aggregate surveillance results. The mathematical example assumes independent and identically distributed samples. Industrial carcasses are commonly clustered by flock, slaughter day, farm, line and sanitation status; autocorrelation and overdispersion can change the probability substantially. A hierarchical beta-binomial or logistic mixed-effects framework, rather than an unqualified binomial model, is often more suitable for plant datasets. Nor should different sampling populations be combined as though they were randomised arms of an experiment. The model illustrates the importance of distributional outcomes, not a claim that European plants face a 68% legal failure probability.

The trial should quantify at least four separate microbiological endpoints. One is log10 concentration of Campylobacter on chilled carcass neck skin by the relevant reference method, including high percentiles and the fraction above the process threshold. Another is Salmonella incidence and relevant serovar behaviour where the legal and hazard assessment requires it. A third is the hygiene trajectory across scalding, defeathering, evisceration, wash and chill, so that reductions and subsequent reacquisition are visible. The fourth covers spoilage populations and sensory life during distribution; this endpoint is necessary before crediting shelf-life savings. Without that last analysis, assigning higher commercial shelf-life value to a Campylobacter intervention is speculation.

A well-designed industrial experiment also needs proper unit selection. Taking many swabs from one flock does not create many independent farm-level replicates. For a time-series or stepped-wedge trial, treatment and control periods must account for season, flock origin, equipment drift and changes in chemical cleaning. All validation should quantify recoveries, neutralisation of residual treatment effects in the microbiological assay, and the cost of increased testing. A small absolute improvement may be worth a great deal if it prevents a recurring bottleneck, but only if the improvement persists over successive independent flocks and within the legal operating regime.

VI. The established control portfolio and the unanswered cost–performance question

Biosecurity and flock management sit upstream of the plant's most expensive interventions. They reduce the challenge entering the line, but the value is distributed between grower, integrator and slaughter plant. When farm and processing are contractually separated, the firm that pays for better biosecurity may not capture the complete processing benefit. Incentives matter. A processing strategy that assumes uniform incoming load will be destabilised by seasonal variation or a shift in supplier mix.

Equipment and hygienic design can outperform a later antimicrobial treatment economically when the primary failure is recontamination. Plucker finger maintenance, evisceration settings, intestinal rupture management, conveyor separation, water flow and removal of organic solids may each change the net microbial balance. Such improvements may have modest capital requirements and avoid chemical or thermal burden, but they require evidence that the actual contamination route has been addressed. They should be tested before adding another intervention to a badly controlled line. The FSA review's evidence of increases during defeathering and inconsistent evisceration outcomes reinforces this sequence [3].

Scalding and thermal surface treatments offer established physical mechanisms and potentially substantial reductions. Their economic cost depends on hot water and steam generation, heat recovery, cooling capacity, line dwell time and carcass quality. Changing scald severity can affect defeathering efficiency and skin integrity, making the intervention a multi-objective process variable. A nominally high log reduction should be priced alongside damaged product, energy and subsequent contamination stages. Treatment temperature also influences occupational safety and equipment design.

Cold water and air-chilling strategies alter microbial loads, product moisture, chilling time and process water use. Immersion chilling can provide additional removal and dilution but creates shared-water-management challenges; air chilling has different capital, energy, moisture-loss and capacity characteristics. Differences among plants, climates, product types and national rules defeat a single universal economic ranking. Likewise, packaging technologies may improve spoilage or distribution outcomes without producing commensurate reductions in the pathogen of interest. A modified-atmosphere package is not a substitute for controlling Campylobacter at slaughter.

Chemical antimicrobial treatments may be commercially attractive where specifically authorised, but their legal availability differs sharply by country and use. Reviews often report important reductions from organic acids and oxidising agents, while also finding high heterogeneity and, in some studies, limited confidence. In the European Union, the central constraint on direct poultry-meat surface decontamination is not merely whether a treatment works. It is whether the specific substance and use are authorised under the animal-origin hygiene framework. The German Federal Institute for Risk Assessment stated in its public 2025 account that chemical decontamination agents had not been permitted for poultry meat in the EU; EFSA's decontaminating-substances topic page identifies lactic acid approval for bovine carcasses, not a general poultry approval [8,9]. A US practice involving peracetic acid cannot be imported as an EU poultry legal precedent.

Emerging platforms, -including high-voltage treatment, pulsed electric fields, plasma, UV and violet-blue light, electrochemically generated media, bacteriophages and membrane-active systems-, deserve study, but not a common performance label. Their energy, contact mechanism, compatibility with meat, post-treatment residues, equipment scale, commercial throughput and legal status differ. Not every physical method has proved effective on whole carcasses; indeed, some FSA-summarised trials reported minimal or non-significant reductions. The value of a novel approach resides in solving a documented bottleneck under plant conditions, not in being novel by description [3].

VII. Reactive transformation of process water: the KNAMAX™/AAI industrial proposition

A particularly relevant line of investigation for INTABIOTECH concerns the deliberate transformation of process water before its point of use. The company's KNAMAX™ platform is described in its technical documentation as a food-grade reactive mineral concentrate used in the water-preparation stage to generate AAI (Activated Alkaline Ionized Water). The intended process sequence is concentrate → controlled reaction within the water → characterised AAI → selected industrial contact point → verification of performance. This is materially different from describing the business model as applying an undiluted chemical product onto poultry carcasses, and different from defining the whole technology as simply increasing water alkalinity. The proposed technological variable is the condition of the resulting aqueous medium, including its ionic and interfacial properties and how these interact with the process [17].

The conceptual appeal is genuine. Water already circulates through critical operations, reaches surfaces and transfers heat and particulate matter. If a controlled preparation stage could reproducibly modify the water into a more effective process medium without introducing unacceptable residues, quality damage, extra downstream washing or expensive retrofit constraints, the resulting value could extend beyond microbial counts. Potential benefits worth testing include reduced recontamination, fewer rework events, greater process stability, lower use of additional interventions, improved water management or quality retention. None of these benefits should be booked into a plant's financial forecast before measurement. Moreover, reducing the concentration of a contaminant in a water sample is not equivalent to proving a benefit on skin or meat in a moving industrial line.

The company's IONOFORÉSIS™/ECMD (*Electro-Cell Membrane Disruption®)* model proposes intensive ionic and electrochemical interaction with microbial cell envelopes, potentially disturbing electrochemical gradients, membrane transport, permeability and homeostasis [17]. These were research hypotheses that now has clear described mechanism-specific evidence. An electrolyte-rich aqueous solution exhibit altered conductivity and interfacial behaviour, but conductivity alone does not demonstrate a sustained net electrical charge, an externally generated transmembrane field or electroporation in the precise sense established for controlled applied electric fields. A microbe losing viability after AAI contact would not, by itself, distinguish conventional ionic stress from a specific electromechanical membrane-disruption pathway. A persuasive mechanistic dossier includes matched-pH and matched-ionic-strength controls, membrane-potential and permeability assays, neutralised microbiological recovery and independent physicochemical characterisation. The exact reaction is being documented under controlled confidentiality with mass and charge balance where technically relevant.

Industrial integration normally begins with water-source characterisation: hardness, alkalinity, major ions, organic load, temperature, cleaning carry-over and seasonal variation. The generation stage needs a verified mixing and reaction interval, defined process limits and traceable batch identity. At the application point, contact time, pressure, droplet size or immersion regime, water-to-bird ratio, flow, drainage and renewals determine whether the system can reach the target surface at scale. Trials include in-line monitoring and a comparison of treated water with untreated process water and appropriately matched reference media. The downstream measurements cover poultry quality, residue or ion transfer, microbiology and wastewater effects. Performance should be analysed through an AAI process window rather than a universal dose-response number detached from water chemistry.

An attractive case for the platform could emerge if the water-preparation stage is retrofittable, control signals are inexpensive, and verified microbial improvements are achieved without a thermal energy penalty, measurable meat deterioration or an additional rinse. This is a hypothesis about engineering advantages, not a report of established cost savings. It should be compared against at least two alternatives: an optimised existing water-and-hygiene baseline and a conventional admissible process

modification. Otherwise, any observed improvement may simply reflect that the comparison line was poorly operated. Ideally, commercial trials would report per-bird net costs, independent flock-to-flock variability, treatment stability, changes in water consumption and the proportion of samples in the high-contamination tail.

The regulatory investigation must follow the exact claim and use. Regulation (EU) No 528/2012 defines biocidal products with reference to control of harmful organisms by means other than mere physical or mechanical action; this makes proof of mechanism relevant, but neither the label 'physical' nor an unverified electroporation claim automatically establishes exclusion. Independently, Article 3(2) of Regulation (EC) No 853/2004 restricts the use of substances other than potable water (or clean water when permitted) to remove surface contamination from products of animal origin unless approved by the Commission. The Court of Justice's judgment in Micreos Food Safety, C-745/22, confirmed a broad interpretation extending to a substance used to prevent surface contamination of ready-to-eat foods of animal origin [10–12]. Whether the AAI output legally qualifies as permitted water, or a substance/intervention falling within Article 3(2), requires a case-specific determination based on its actual composition, function and intended contact, supported by the competent authority. Establishing a non-biocidal mechanism would not by itself answer this separate food-hygiene question. By now, this alternative is being treated as processing aid, able to conditioning water with a functional action over poultry.

VIII. A jurisdictional comparison that changes the investment decision

European Union and Spain. Regulations (EC) 852/2004 and 853/2004 provide the core hygiene framework, while Regulation (EC) 2073/2005 contains the relevant microbiological criteria and Regulation (EU) 2017/1495 supplies the Campylobacter amendment. In Spain, Royal Decree 3/2023 and relevant food-business water requirements must also be examined. Process-hygiene results generate corrective-action obligations, not an automatic conclusion that every carcass from a sampling window is unfit for sale. For direct poultry surface decontamination, the Article 3(2) distinction is critical. Spain's Royal Decree 773/2023 on processing aids does not automatically displace the more specific requirements for animal-origin foods. For water reuse, the operator must distinguish reclaimed water from potable process water and assess the intended contact; Royal Decree 1085/2024 includes specific conditions for use in food businesses [2,10–14].

Great Britain and Northern Ireland. UK food-hygiene and biocidal law must be checked in the applicable territorial form. Great Britain's domestic regime cannot simply be inferred from every subsequent EU amendment; Northern Ireland requires separate consideration of relevant EU-linked arrangements. The UK FSA's 2026 research on Campylobacter interventions is a valuable scientific source, but an FSA literature review does not confer approval on a particular new treatment. Where exporting into either territory, the dossier should record the competent authority, product classification, applicable water specifications, treatment authorisations and claims rather than saying only 'UK compliant' [3,15].

United States. USDA-FSIS oversight, rather than direct transplantation of the EU rules, determines the status of poultry interventions. Applicable substances, conditions and processes must be checked against current FSIS safe-and-suitable documentation, federal regulations and establishment requirements. The 2024 proposed Salmonella Framework for Raw Poultry Products was withdrawn in April 2025; it must not be described as currently binding law [16]. A method permitted in a US chilling system does not thereby become permissible in a Spanish poultry plant. Conversely, a European evaluation of a physical process does not replace FSIS conditions of use in the United States. Regulatory divergence produces tangible costs for international suppliers: testing programmes, water-system design and legal substantiation may need destination-specific variants.

REGULATORY DECISION MATRIX

Decision topic	EU / Spain	Great Britain / Northern Ireland	United States
Process hygiene / pathogens	Reg. 2073/2005 and 2017/1495; verify product-specific criteria	Check territorial hygiene instruments and FSA/FSS provisions	FSIS performance standards, verification and HACCP
Poultry surface decontamination	Art. 3(2), Reg. 853/2004; specific approval issue	Domestic provisions, competent authority and territorial status	FSIS safe/suitable substances and conditions
Process or recycled water	Reg. 852/2004; Spain RD 3/2023; reuse rules as applicable	Territory-specific food and water rules	US potable-water and FSIS establishment rules
Novel reactive medium	Chemistry, mechanism, residues and intended function determine classification	Separate territorial evaluation	Substance- and process-specific clearance
Investment gate	Legal permissibility before commercial rollout	Confirm current local law	Confirm FSIS status and conditions

IX. Research & Innovation Opportunity - the Microbial-Control Value Map

The unresolved question is not whether plants need better control: that is already established. The more precise question is whether an integrated process intervention can materially reduce the upper tail of microbial contamination while improving, or at least preserving, the economics of each saleable kilogram. Existing microbiological challenge tests, process monitoring, cost accounting, water analytics and statistical control are established disciplines. There is no defensible basis for presenting their combination as a newly discovered scientific principle. The potential research contribution is a reproducible comparative design that tests whether a linked biological–engineering–economic qualification system improves choices relative to a conventional decision based mainly on a supplier's average log-reduction claim.

A falsifiable hypothesis can be stated: in a defined class of poultry processing lines, interventions qualified using a distribution-aware Microbial-Control Value Map will produce fewer late-stage commercial failures than interventions selected on the basis of mean microbiological reduction alone. A second, narrower hypothesis concerns reactive mineral conditioning of process water: under selected operating windows, independently verified AAI performance may improve the proportion of chilled carcass samples below a prespecified contamination threshold without an unfavourable change in water, energy, meat quality or per-bird processing cost. Neither claim is established by the present article.

The study should have four linked modules. The baseline module collects flock origin, season, incoming contamination, processing stage, water chemistry, line speed, existing sanitation, utilities, yield, waste and quality outcomes. The analytical module characterises the treated water at preparation and point of use, and uses matrix-appropriate microbiological methods with verified neutralisation and recovery. The causal module uses a blocked, randomised or carefully designed stepped-wedge comparison, accounting for flock and line effects, with treatment allocation and acceptance criteria defined before the data are observed. The economic module calculates incremental contribution, water and energy use, labour, consumables, downtime and risk-adjusted outcomes using actual internal accounting records rather than brochure figures.

Crucially, the study should compare **three production states**: the documented current baseline; an optimised baseline with low-cost hygiene and process fixes; and that optimised baseline plus the candidate technology. This prevents the new intervention from being credited for gains that would have been achieved through routine correction of scalding, evisceration, plucker hygiene or chilling. It also ensures that the competitor is not an artificially poor status quo. Independent laboratory verification and

repetition across different seasons would be particularly valuable where microbiological baselines fluctuate sharply.

Success should require a prespecified microbiological effect that persists across independent flocks and materially improves the relevant distributional endpoint, with no unacceptable impact on meat quality, residues or food safety. An economic success additionally requires a positive risk-adjusted value after capital and operating costs, and legal eligibility for the exact process. A statistically significant 0.2-log reduction may be economically important where the process operates close to a compliance threshold; a larger reduction may be immaterial when a later stage promptly recontaminates the product. Both outcomes should be reported. A negative result is useful information when it eliminates an unsuitable deployment or identifies the engineering constraint that must be solved.

The datasets generated could support better predictive modelling. A digital twin or machine-learning system may forecast which combinations of water chemistry, flock contamination and line parameters are associated with elevated post-chill counts, but it must not infer a microbial mechanism solely from correlations or treat model predictions as legal certifications. A disciplined implementation preserves raw records, model version, validation domain, calibration and uncertainty, and triggers human review of out-of-domain situations. Prospective external validation is necessary before any claim that the model predicts failure under unseen commercial conditions.

For a supplier of emerging technologies, this type of programme would have strategic value beyond a single sale. It could identify where the technology works, where it does not, how it scales, which water sources need additional control, what equipment is essential, and which manufacturing claims can survive independent scrutiny. It would also supply a basis for honest techno-economic proposals rather than extrapolating from a laboratory kill curve to an entire national poultry market. When proprietary know-how is involved, the chemical formulation can be disclosed under controlled confidentiality to laboratories and competent authorities without requiring public release of trade-secret details; safety-critical composition and analytical traceability cannot be replaced by secrecy.

X. Conclusions: invest in verified net improvement, not microbial theatre

The poultry industry is not short of antimicrobial ideas. What it lacks in many settings is a sufficiently integrated way to determine why a stage fails, where the next intervention should be placed, and whether the cost of obtaining a result is defensible. EFSA/ECDC surveillance and contemporary systematic reviews show that substantial Campylobacter burdens remain and that conventional operations can both remove and reintroduce contamination. Their message is neither that established methods should be abandoned nor that one new technology will solve every plant's problem. It is that microbial management must become more distribution-aware, process-specific and economically accountable.

The strongest investment decisions will price the full chain of consequences. A sanitary intervention has value when it measurably changes the relevant contamination distribution, protects product quality, reduces avoidable processing losses, conserves resources or lowers a demonstrable business risk. The significance of each outcome varies with the plant's layout, flock mix, water quality, capacity constraint and destination market. A promising technology with an unresolved legal classification or a weak pilot design is not yet a commercially validated solution, regardless of the manufacturer's confidence in its mechanism.

Reactive mineral transformation of process water, including KNAMAX™/AAI, warrants a technically serious place in that investigation. Its proposed value is not a generic claim of high alkalinity or the direct application of a concentrated chemical onto meat; it is the engineering of a functional process medium before use. Whether that promise becomes measurable advantage depends on independent demonstration of the reaction, the resulting water properties, microbial effects, compatibility with food,

legal eligibility and actual cost. If these questions are answered well, the result could become a meaningful industrial contribution. If not, the discipline of the evaluation will at least prevent microbiological enthusiasm from turning into poor capital allocation.

The most important economic conclusion is therefore also a scientific one: a reduction reported in log units acquires industrial meaning only when its causal persistence, distributional effect, resource consequences and lawful use have been established. The next generation of poultry control should be judged by that integrated evidence and not by the novelty of its vocabulary.

Related Knowledge Areas

Food Safety; Biotechnology; Processing Technologies; Mineral Technologies; Regulatory Affairs; AI & Food; Sustainability; Emerging Research.

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