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Expert-Based Prioritization of Control Measures for Salmonid Rickettsial Septicemia in Chilean Salmon Aquaculture

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ABSTRACT

Piscirickettsiosis (SRS) remains the main infectious disease affecting salmon aquaculture in Chile. This study evaluated expert perceptions of the effectiveness of SRS control measures and the level of agreement among industry professionals. A structured cross-sectional expert-elicitation survey was conducted with nine head fish health managers representing more than half of the Chilean Atlantic salmon and rainbow trout production. Experts scored 67 control measures using a 5-point Likert scale, and effectiveness and consensus were assessed using descriptive and variability metrics. Measures related to biosecurity, mortality management, and production practices ranked highest and showed strong agreement. Therapeutic and vaccination-related measures showed heterogeneous levels of agreement: several specific antimicrobial protocols (oral florfenicol, injectable oxytetracycline monotherapy, and combination florfenicol + oxytetracycline therapy) reached high consensus, while other therapeutic measures and most vaccination strategies exhibited substantially greater variability. The integration of effectiveness and consensus enabled classification of measures into priority tiers, consistently highlighting preventive strategies as high priority. These findings provide a structured, practice-oriented framework to support decision-making and reinforce the importance of management-based approaches for SRS control under field conditions.

1 | Introduction

Piscirickettsiosis, or Salmonid Rickettsial Septicemia (SRS), caused by *Piscirickettsia salmonis*, remains one of the most important infectious constraints for the Chilean salmon aquaculture. It was first reported in 1981 in farmed coho salmon (Bravo and Campos 1989) and was subsequently isolated and characterized in 1992 (Fryer et al. 1992). Nearly four decades after its original recognition, the disease is still considered endemic during the marine phase of production and continues to generate substantial biological, operational, and economic losses. Its persistence has been associated with the intracellular lifestyle of the pathogen, the inconsistent field performance of currently available vaccines, and the continued dependence on antimicrobial therapy as part of outbreak control (Rozas and Enriquez 2014; Rozas-Serri 2022; Valenzuela-Aviles et al. 2022).

The epidemiological understanding of SRS has evolved beyond the concept of isolated farm-level outbreaks. Between-farm transmission of *P. salmonis* in seawater production systems has been demonstrated, with spread detected at distances of up to 10 km (Rees et al. 2014). This understanding was further refined by subsequent studies that identified hydrodynamic connectivity, water temperature, and salinity as major drivers of prevalence and transmission among salmonid farms in Chile (Bravo et al. 2020). Production-level factors have also

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been implicated: a recent retrospective cohort analysis of 571 Atlantic salmon production cycles found that antibiotic treatment initiated at higher SRS-attributable mortality thresholds (≥0.03%) was associated with significantly earlier outbreak onset compared with earlier treatment initiation, and that autumn stocking carried higher outbreak risk than spring stocking, with median time to outbreak ranging from 26 to 51.5 weeks post-stocking depending on these factors (Gaete-Carrasco et al. 2026). Together, these studies support the view that SRS behaves as a spatially connected disease, in which risk is shaped not only by conditions at the individual farm, but also by its position within a broader marine epidemiological network.

Official surveillance data reinforce this interpretation. In December 2012, Chile launched the Specific Health Programme for the Surveillance and Control of Piscirickettsiosis (PSEVC-SRS), aimed at early detection, case tracking, and the implementation of timely and progressive control measures by the National Fisheries and Aquaculture Service (Sernapesca). Data generated under this programme indicate that the prevalence of piscirickettsiosis was only 0.28% in freshwater fish but reached 58.1% in seawater farms (Gaete-Carrasco et al. 2019).

Strong regional differences were also reported, with higher prevalence in Aysén and Los Lagos than in Los Ríos and Magallanes, together with clear seasonal signals. On average, the first detection after seawater transfer occurred 105 days or even less after entry to sea, indicating that disease occurrence is not randomly distributed in time but tends to emerge within a recognizable production window (Gaete-Carrasco et al. 2019).

Host species and farm characteristics further modulate the epidemiology of SRS. Transmission models parameterized with historical outbreak data estimated shorter recovery times for coho salmon farms than for Atlantic salmon or rainbow trout farms and found higher relative infectiousness for rainbow trout farms (Wada et al. 2021). More recent regional modelling in Aysén suggested that the most effective theoretical strategies for incidence reduction would include immediate depopulation of infected farms, strategic removal of highly connected farms, or highly efficacious long-duration vaccination; however, these authors also warned that the most epidemiologically effective options may not be the most economically feasible for the industry (Lam et al. 2025).

Another important layer of complexity concerns pathogen population structure. The LF-89-like and EM-90-like genogroups are now recognized as epidemiologically relevant entities rather than simply genotypic variants. EM-90-like isolates have been shown to be highly prevalent and widely distributed in Chilean marine farming, with a marked host preference for Atlantic salmon (Saavedra et al. 2017). Subsequent studies demonstrated substantial spatiotemporal variability, co-infection by both genogroups at the farm, fish, and tissue levels, and a significant increase in LF-89-like detections between 2017 and 2021 (Rozas-Serri et al. 2023). These findings imply that surveillance, clinical interpretation, and control strategies should increasingly consider genogroup composition. According to surveillance data generated by ADL Diagnostic Chile between 2020 and 2025, the predominant genogroup detected in marine-phase Atlantic salmon has been LF-89-like (ADL Diagnostic Chile, unpublished data).

SRS also interacts with other sanitary and environmental cofactors. A significant association has been reported between adult female *Caligus rogercresseyi* abundance and subsequent *P. salmonis*-attributed mortality (Arriagada et al. 2019), while sea lice burden and warm-season conditions have been identified as key predictors of both weekly mortality risk and the hazard of the first SRS outbreak within a production cycle (Diethelm-Varela et al. 2025). In parallel, native and non-salmonid reservoirs remain relevant to epidemiological reasoning. *P. salmonis*-related sequences have been detected in native fish from southern Chile (Contreras-Lynch et al. 2015), and horizontal transmission from *Eleginops maclovinus* to rainbow trout has been experimentally demonstrated (Quintanilla et al. 2021).

Surveillance has also become progressively more molecular and more sensitive. qPCR diagnostic sensitivity for *P. salmonis* has been estimated to be 5- to 30-fold greater than bacteriological culture, particularly when compatible gross lesions are present (Laurin et al. 2020). New assays aimed at distinguishing LF-89-like and EM-90-like strains, including LAMP-based approaches, suggest that routine surveillance may increasingly evolve from simple species-level detection toward genogroup-informed monitoring (Isla et al. 2024; Rozas-Serri et al. 2023).

Taken together, the available evidence indicates that SRS is a multifactorial disease shaped by between-farm connectivity, host species, pathogen genogroup dynamics, environmental and parasitic cofactors, and imperfect prevention and treatment tools. In Chile, this complexity is addressed within a formal regulatory framework anchored in the PSEVC-SRS, which mandates routine and risk-based surveillance, epidemiological categorization of farms, rapid action plans for alert and high-dissemination centres, and increasing oversight of antimicrobial use and susceptibility monitoring.

However, although the epidemiological and regulatory context of SRS is increasingly well described, there is limited evidence on how control measures are comparatively prioritized by field experts under real Chilean production conditions. Structured information on perceived effectiveness and levels of consensus remains scarce. Structured expert elicitation provides a practical approach to address this gap in complex systems where empirical data are limited (Diamond et al. 2014). Applications in aquaculture have demonstrated the value of this approach for informing disease management, including the estimation of key epidemiological parameters and the identification of risk factors and control priorities (Estevez et al. 2019; Verdugo et al. 2020).

Accordingly, the objective of the present study was to assess expert opinion on a broad set of SRS control measures currently relevant to Chilean salmon farming using a structured cross-sectional expert-elicitation survey. Specifically, we aimed to rank measures according to perceived effectiveness, quantify the degree of consensus among experts, and identify thematic areas with stronger or weaker agreement. By doing so, this study seeks to complement the formal epidemiological literature with structured expert judgment and to provide a practice-oriented

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prioritization of SRS control options within the Chilean industry context.

2 | Materials and Methods

2.1 | Expert Selection and Study Design (Cross-Sectional Expert-Elicitation Survey)

This study employed a structured cross-sectional expert-elicitation survey to assess expert consensus on control measures for SRS. Nine experts from independent salmon aquaculture companies were recruited based on their professional experience in SRS management, fish health, and aquaculture operations. Expert selection criteria included: (1) a minimum of 10 years of experience in salmon aquaculture, (2) veterinarian by profession, (3) direct involvement in SRS control programs, and (4) current professional roles as fish health managers in salmon production. Responses were anonymised among participants: each expert completed the questionnaire independently and had no access to the ratings of other respondents. The research team could link responses to companies but reported all results in aggregated, de-identified form. Expert identities were not disclosed to other participants or in any study output (Table S2).

2.2 | Development of the Control-Measure Questionnaire and Literature-Support Mapping

The questionnaire included 67 candidate control measures for SRS, grouped into 20 thematic domains: general biosecurity measures, SRS regulations, vaccination, therapies, diagnostics, neighbourhood meetings, predator control, use of functional foods, neighbourhood rest (fallowing period), culture densities, presence of concomitant diseases with SRS, smolt quality, smolt origin, smolt from SRS-resistance breeding programs, nets, production sites, mitigation of low oxygen levels, animal (fish) welfare, smolt weight at sea-site entry, and fattening production cycle (Table S1). The questionnaire was developed by the study team before expert recruitment. No members of the expert panel participated in the construction, wording, selection, or pre-ranking of the questionnaire items (Table S2). The item list was generated through a structured literature-informed process combined with the authors' clinical, diagnostic, epidemiological, and operational experience in Chilean salmon farming. Searches were performed in Web of Science, Scopus, PubMed, Google Scholar, and Chilean regulatory sources using combinations of terms including "*Piscirickettsia salmonis*", "piscirickettsiosis", "SRS", surveillance, vaccination, antimicrobial therapy, fallowing, neighbourhood management, Caligus, smolt quality, and regulatory control, among others. Because several SRS control practices are based on field use, biological plausibility, or regulatory requirements rather than intervention trials, the questionnaire was not restricted to measures directly supported by published SRS-specific evidence. The thematic sections were defined by the study team by grouping measures by management domain, drawing on the structure of the Chilean PSEVC-SRS regulatory programme and the thematic organization used by Estevez et al. (2019). The questionnaire was reviewed internally by the study team for completeness and clarity; no formal external pilot was conducted, which we acknowledge as a limitation. A *post hoc* literature-support mapping was conducted during manuscript revision, classifying each measure according to the strength and directness of its supporting evidence. The full mapping is provided as Table S3.

2.3 | Data Collection and Rating Scale

Each expert independently evaluated all 67 control measures using a 5-point Likert scale based on perceived effectiveness for SRS control: 0 = No effectiveness, 1 = Slightly effective measure (provides little benefit), 2 = Moderately effective measure (benefits are partial), 3 = Effective measure (benefits are evident), 4 = Highly effective measure (benefits are notable). No pre-specified definition of effectiveness was provided to participants. Experts were therefore free to interpret effectiveness in terms of different outcomes (e.g., prevention of infection, delay to first outbreak, reduction in mortality, reduction in antimicrobial use, or reduction in economic losses). The questionnaire also did not formally separate preventive measures from those applied after clinical diagnosis. These aspects are acknowledged as limitations in Section 4. Data were collected using structured survey forms and compiled into a data matrix with measures as rows and experts as columns. Missing responses were handled using pairwise deletion for statistical analyses.

2.4 | Statistical Analysis Framework

All statistical analyses were performed using R version 4.3.3 (R Core Team 2026) with the following packages: tidyverse v2.0.0 for data manipulation and visualization (Wickham et al. 2019), readxl v1.4.3 for data import (Wickham and Bryan 2026), psych v2.4.3 for descriptive statistics and reliability analysis (Revelle 2026), irr v0.84.1 for inter-rater reliability metrics (Gamer et al. 2026), corrplot v0.92 for correlation visualization (Wei and Simko 2024), FactoMineR v2.11 for multivariate analysis (Le et al. 2008), factoextra v1.0.7 for PCA visualization (Kassambara and Mundt 2020), and cluster v2.1.6 for clustering analysis (Maechler et al. 2026). Statistical significance was set at $\alpha = 0.05$ for all analyses.

2.5 | Descriptive Statistics and Consensus Assessment

For each control measure, descriptive statistics were calculated including mean effectiveness score, median, standard deviation (SD), coefficient of variation (CV), interquartile range (IQR), minimum and maximum scores, and response rate. Expert consensus was evaluated using multiple metrics. As the primary, scale-appropriate measures of dispersion we report the interquartile range (IQR), the average absolute deviation from the median (AD index), and the Tastle and Wierman (2007) ordinal consensus index (Cns), all of which are mean-independent and suitable for bounded ordinal data. The coefficient of variation (CV = SD/mean) is reported as a secondary, descriptive quantity; its use as a primary consensus measure is not appropriate for ordinal scales because measures with lower mean scores are mathematically

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predisposed to higher CV values even when absolute dispersion is similar. Combined consensus criteria defined high consensus as both CV ≤ 0.3 AND IQR ≤ 1.0 (boundary values treated inclusively; a CV of exactly 0.300 qualifies as meeting this threshold). Moderate consensus was defined as CV ≤ 0.4 AND IQR ≤ 1.5. Effectiveness categories were established as: Highly effective (mean ≥ 4.0), Effective (3.0 ≤ mean < 4.0), Moderately effective (2.0 ≤ mean < 3.0), Slightly effective (1.0 ≤ mean < 2.0), and No effectiveness (mean < 1.0).

2.6 | Inter-Rater Reliability and Agreement Analysis

Inter-rater reliability was assessed using three complementary approaches: Intraclass Correlation Coefficient (ICC) with both ICC (2,1) for single measures and ICC (2,k) for average measures calculated using a two-way random effects model with absolute agreement (McGraw and Wong 1996; Shrout and Fleiss 1979), Kendall's Coefficient of Concordance (W) to assess overall agreement among all experts across all measures (Kendall 1955), and Krippendorff's Alpha for ordinal data (Krippendorff 2004). ICC values > 0.75 were considered excellent, 0.60–0.75 good, 0.40–0.59 fair, and < 0.40 poor reliability (Cicchetti 1994). Pairwise expert correlations were computed using Spearman's rank correlation coefficients to identify patterns of agreement between individual experts (Zar 2010).

2.7 | Multivariate Analysis and Priority Classification

Differences in effectiveness ratings between thematic sections were evaluated using one-way analysis of variance (ANOVA) with Tukey's honestly significant difference (HSD) post hoc tests when significant differences were detected (Tukey 1949). K-means clustering was performed on standardized expert ratings to identify groups of measures with similar effectiveness patterns, with optimal cluster number determined using the elbow method (Hartigan and Wong 1979). A priority matrix was developed combining effectiveness and consensus metrics to classify measures into implementation tiers: Tier 1 (High Priority, mean score ≥ 3.5 AND high consensus), Tier 2 (Medium Priority, mean score ≥ 3.0 AND moderate consensus), Tier 3 (Consider, mean score ≥ 2.5), and Tier 4 (Low Priority, mean score < 2.5 OR low consensus). Visualization approaches included forest plots showing mean scores ±1 standard deviation (SD), capped at the scale maximum of 4, scatter plots of effectiveness versus consensus, heatmaps of expert ratings, box plots for section comparisons, and correlation matrices for expert agreement patterns. All plots were generated using ggplot2 v3.4.4 (Wickham 2016).

3 | Results

3.1 | Overall Expert Ratings and Effectiveness Distribution

A total of 67 SRS control measures were evaluated by nine experts (Table 1). Mean effectiveness scores ranged from approximately 1.0 to above 3.5 on the 0–4 scale, with most measures distributed between 2.5 and 3.5. The distribution of effectiveness scores across thematic sections is shown in Figure 1. Sections related to nets, predator control, general biosecurity measures, and therapies exhibited higher central tendency values. In contrast, sections such as vaccination, smolt origin, and animal welfare displayed lower median scores and greater dispersion. A one-way ANOVA of measure means across the 20 thematic sections did not detect significant differences ($F(19,47) = 0.76$, $p = 0.74$); no Tukey post hoc test was therefore performed. Figure 1 is presented as a descriptive distribution of scores by section.

3.2 | Consensus and Variability Among Measures

Consensus levels, assessed using the coefficient of variation (CV) and interquartile range (IQR), varied across control measures. CV values ranged from low (< 0.2) to high (> 0.6), indicating heterogeneous agreement among experts. The relationship between mean effectiveness and consensus (expressed as 1/CV) is shown in Figure 2. Measures with higher effectiveness scores (≥ 3.0) were frequently associated with higher consensus (lower CV), while measures with lower effectiveness scores exhibited greater variability. Several measures with moderate effectiveness scores (2.5–3.0) also showed relatively low variability.

3.3 | Ranking of Control Measures

The ranking of control measures based on mean effectiveness scores is presented in Figure 3. The highest-ranked measures included:

- Maintenance of net cleanliness (M54)
- Shorter production cycles at sea (M65)
- Regular removal of moribund fish (M06)
- Necropsy and mortality classification (M02)
- Effective *Caligus* control to prevent SRS outbreaks (M33)
- Implementation of smolt quality programs (M44)

These measures had mean scores above 3.5 and relatively low standard deviations.

Additional measures with mean scores ≥ 3.0 included:

- Effective use of netting systems to prevent sea lions (M24)
- Daily mortality removal (M01)
- Neighbourhood fallowing (M28)
- Net replacement (M53)
- Regular PCR monitoring (M18)

Therapeutic measures, including injectable and oral antimicrobial treatments, were also represented among the higher-ranked interventions but generally showed slightly lower mean scores and wider variability compared to top-ranked management measures.

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TABLE 1 | Expert ratings of 67 SRS control measures, ranked by mean effectiveness score and grouped into 20 thematic sections. For each measure, the table reports the mean, median, standard deviation (SD), and coefficient of variation (CV) of effectiveness scores; the minimum and maximum scores observed; the interquartile range (IQR); two mean-independent measures of dispersion, the average absolute deviation from the median (AD Index) and the Tastle and Wierman (2007) ordinal consensus index (Cns); the number of expert responses; the overall consensus classification; and the effectiveness category. Consensus level was classified as High (CV ≤ 0.3 AND IQR ≤ 1.0), Moderate (CV ≤ 0.4 AND IQR ≤ 1.5, but not meeting the High criteria), or Low (neither the High nor the Moderate criteria were met); boundary values were treated inclusively. Effectiveness category was classified as Highly Effective (mean ≥ 4.0), Effective (3.0 ≤ mean < 4.0), Moderately Effective (2.0 ≤ mean < 3.0), Slightly Effective (1.0 ≤ mean < 2.0), or No Effectiveness (mean < 1.0).

Ref	Section	Measure	Mean score	Median score	SD score	CV score	Min score	Max score	IQR	AD Index	Cns (Tastle-Wierman)	N responses	Consensus level	Effectiveness category
M54	Nets	Maintain mesh (net) cleanliness at all times	3.78	4	0.44	0.117	3	4	0	0.22	0.867	9	High	Effective (3.0–3.9)
M02	General biosecurity measures	Necropsy and mortality classification	3.67	4	0.5	0.136	3	4	1	0.33	0.829	9	High	Effective (3.0–3.9)
M06	General biosecurity measures	Regular removal of moribund fish in the event of an outbreak	3.67	4	0.5	0.136	3	4	1	0.33	0.829	9	High	Effective (3.0–3.9)
M65	Fattening production cycle	Have shorter production cycles at sea	3.67	4	0.5	0.136	3	4	1	0.33	0.829	9	High	Effective (3.0–3.9)
M33	Presence of concomitant diseases with SRS	Effective Caligus control to prevent SRS outbreaks[a]	3.56	4	0.53	0.148	3	4	1	0.44	0.81	9	High	Effective (3.0–3.9)
M44	Smolt quality	Create/maintain an effective smolt quality program	3.56	4	0.53	0.148	3	4	1	0.44	0.81	9	High	Effective (3.0–3.9)
M24	Predator control	Effective use of netting systems to prevent sea lions	3.56	4	0.73	0.204	2	4	1	0.44	0.76	9	High	Effective (3.0–3.9)
M01	General biosecurity measures	Daily mortality removal	3.56	4	0.73	0.204	2	4	1	0.44	0.76	9	High	Effective (3.0–3.9)

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TABLE 1 | (Continued)

Ref	Section	Measure	Mean score	Median score	SD score	CV score	Min score	Max score	IQR	AD Index	Cns (Tastle-Wierman)	N responses	Consensus level	Effectiveness category
M28	Neighbourhood rest (fallowing period)	Neighbourhood rest (fallowing period)	3.5	3.5	0.53	0.153	3	4	1	0.5	0.807	8	High	Effective (3.0–3.9)
M53	Nets	Net replacements	3.44	4	0.73	0.211	2	4	1	0.56	0.752	9	High	Effective (3.0–3.9)
M18	Diagnostics	Regular monitoring (PCR), with or without SRS signs	3.44	4	0.73	0.211	2	4	1	0.56	0.752	9	High	Effective (3.0–3.9)
M16	Therapies	OTC inj + oral FFC combination therapy	3.38	3	0.52	0.153	3	4	1	0.38	0.819	8	High	Effective (3.0–3.9)
M15	Therapies	OTC injectable therapy	3.33	3	0.5	0.15	3	4	1	0.33	0.829	9	High	Effective (3.0–3.9)
M45	Smolt quality	Absence of non-good adapted fish	3.33	3	0.5	0.15	3	4	1	0.33	0.829	9	High	Effective (3.0–3.9)
M61	Animal welfare	The absence of skin lesions reduces the risk of SRS outbreaks	3.33	3	0.5	0.15	3	4	1	0.33	0.829	9	High	Effective (3.0–3.9)
M63	Smolt weight at sea-site entry	Smolt weight at sea-site entry (large smolts, e.g., > 400 g)	3.33	3	0.71	0.212	2	4	1	0.56	0.762	9	High	Effective (3.0–3.9)
M31	Culture densities	Stocking at final density	3.33	3	0.71	0.212	2	4	1	0.56	0.762	9	High	Effective (3.0–3.9)
M55	Cultivation sites	Use high-energy sites	3.25	3.5	0.89	0.273	2	4	1.25	0.75	0.692	8	Moderate	Effective (3.0–3.9)
M57	Mitigation of low oxygen levels	Use of automatic oxygen control and supply systems	3.22	3	0.67	0.207	2	4	1	0.44	0.792	9	High	Effective (3.0–3.9)

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TABLE 1 | (Continued)

Ref	Section	Measure	Mean score	Median score	SD score	CV score	Min score	Max score	IQR	AD Index	Cns (Tastle-Wierman)	N responses	Consensus level	Effectiveness category
M13	Therapies	Oral therapy with Flofenicol (FFC)	3.11	3	0.33	0.107	3	4	0	0.11	0.924	9	High	Effective (3.0–3.9)
M22	Neighbourhood meets	Regular neighbourhood meetings	3.11	3	0.33	0.107	3	4	0	0.11	0.924	9	High	Effective (3.0–3.9)
M34	Presence of concomitant diseases with SRS	Absence of Tenacibaculum co-infections	3.11	3	0.33	0.107	3	4	0	0.11	0.924	9	High	Effective (3.0–3.9)
M38	Presence of concomitant diseases with SRS	Algal bloom mitigation measures	3.11	3	0.6	0.193	2	4	0	0.33	0.84	9	High	Effective (3.0–3.9)
M23	Predator control	Use of nets to protect cages (from birds)	3.11	4	1.05	0.339	2	4	2	0.89	0.59	9	Low	Effective (3.0–3.9)
M62	Animal welfare	Absence of gill disorders	3	3	0.5	0.167	2	4	0	0.22	0.908	9	High	Effective (3.0–3.9)
M04	General biosecurity measures	Routine mortality sampling (for PCR)	3	3	0.87	0.289	2	4	2	0.67	0.723	9	Low	Effective (3.0–3.9)
M17	Diagnostics	Monitoring (PCR) due to suspicious symptoms of SRS	3	3	0.87	0.289	2	4	2	0.67	0.723	9	Low	Effective (3.0–3.9)
M21	Diagnostics	MIC determination in each outbreak.	3	3	0.87	0.289	2	4	2	0.67	0.723	9	Low	Effective (3.0–3.9)
M30	Culture densities	Use max densities lower than those established by regs	3	3	0.87	0.289	2	4	2	0.67	0.723	9	Low	Effective (3.0–3.9)

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TABLE 1 | (Continued)

Ref	Section	Measure	Mean score	Median score	SD score	CV score	Min score	Max score	IQR	AD Index	Cns (Tastle-Wierman)	N responses	Consensus level	Effectiveness category
M26	Use of functional foods	Use of functional foods according to the risk period	2.89	3	0.6	0.208	2	4	0	0.33	0.84	9	High	Moderately Effective (2.0–2.9)
M58	Mitigation of low oxygen levels	Use of an oxygen measurement system per cage	2.89	3	0.78	0.271	2	4	1	0.56	0.757	9	High	Moderately Effective (2.0–2.9)
M29	Culture densities	Use the maximum densities established by regulations.	2.89	3	0.78	0.271	2	4	1	0.56	0.757	9	High	Moderately Effective (2.0–2.9)
M36	Presence of concomitant diseases with SRS	Effective AGD control	2.89	3	0.78	0.271	2	4	1	0.56	0.757	9	High	Moderately Effective (2.0–2.9)
M03	General biosecurity measures	Integrated neighbourhood management	2.89	3	0.93	0.321	2	4	2	0.78	0.673	9	Low	Moderately Effective (2.0–2.9)
M47	Smolt quality	Achieve the highest Smolt Index values or scores	2.89	3	1.05	0.365	1	4	2	0.78	0.647	9	Low	Moderately Effective (2.0–2.9)
M19	Diagnostics	Genogroup classification (PCR)	2.78	3	0.83	0.3	2	4	1	0.67	0.717	9	High	Moderately Effective (2.0–2.9)
M37	Presence of concomitant diseases with SRS	Effective PGD control	2.78	3	0.83	0.3	2	4	1	0.67	0.717	9	High	Moderately Effective (2.0–2.9)
M27	Use of functional foods	Use of additives (definition/ acquisition) from the company	2.67	3	0.71	0.265	2	4	1	0.56	0.762	9	High	Moderately Effective (2.0–2.9)

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TABLE 1 | (Continued)

Ref	Section	Measure	Mean score	Median score	SD score	CV score	Min score	Max score	IQR	AD Index	Cns (Tastle-Wierman)	N responses	Consensus level	Effectiveness category
M43	Presence of concomitant diseases with SRS	Absence of BKD in the farm	2.67	3	0.87	0.325	1	4	1	0.56	0.72	9	Moderate	Moderately Effective (2.0–2.9)
M67	Fattening production cycle	Use fast-growing strains	2.67	3	0.87	0.325	1	4	1	0.56	0.72	9	Moderate	Moderately Effective (2.0–2.9)
M07	SRS Regulations	Center Categorization (Surv., Alert, High Dissem.-CAD)	2.67	3	1	0.375	1	4	1	0.78	0.654	9	Moderate	Moderately Effective (2.0–2.9)
M40	Presence of concomitant diseases with SRS	Absence of HSMI	2.67	3	1	0.375	1	4	1	0.78	0.654	9	Moderate	Moderately Effective (2.0–2.9)
M51	Smolts from SRS-resistance breeding programs	Smolt obtained from a breeding genetic program	2.67	3	1.12	0.419	1	4	1	0.78	0.612	9	Low	Moderately Effective (2.0–2.9)
M09	SRS Regulations	Integrated Zone Management	2.67	3	1.22	0.459	1	4	2	1	0.546	9	Low	Moderately Effective (2.0–2.9)
M11	Vaccination	Use of a live attenuated vaccine	2.56	2	0.73	0.284	2	4	1	0.56	0.752	9	High	Moderately Effective (2.0–2.9)
M35	Presence of concomitant diseases with SRS	Control and/or absence of Ulcerative Vibriosis	2.56	3	0.88	0.345	1	4	1	0.67	0.702	9	Moderate	Moderately Effective (2.0–2.9)

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TABLE 1 | (Continued)

Ref	Section	Measure	Mean score	Median score	SD score	CV score	Min score	Max score	IQR	AD Index	Cns (Tastle-Wierman)	N responses	Consensus level	Effectiveness category
M10	Vaccination	Use of a polyvalent vaccine (including *P. salmonis* bacterin)	2.44	2	0.73	0.297	2	4	1	0.44	0.76	9	High	Moderately Effective (2.0–2.9)
M25	Use of functional foods	Use of permanent functional foods in on-growing	2.33	2	0.71	0.303	2	4	0	0.33	0.787	9	Moderate	Moderately Effective (2.0–2.9)
M66	Fattening production cycle	Use photoperiod	2.33	2	0.87	0.371	1	4	1	0.56	0.72	9	Moderate	Moderately Effective (2.0–2.9)
M39	Presence of concomitant diseases with SRS	Absence or negligible presence of jellyfish in the farm	2.33	2	1	0.429	1	4	1	0.78	0.654	9	Low	Moderately Effective (2.0–2.9)
M46	Smolt quality	Comply with summer photoperiod schedules (w/ out ext.)	2.33	2	1.12	0.479	0	4	1	0.78	0.63	9	Low	Moderately Effective (2.0–2.9)
M56	Cultivation sites	Avoid growing in low-energy area	2.25	2	0.46	0.206	2	3	0.25	0.25	0.855	8	High	Moderately Effective (2.0–2.9)
M42	Presence of concomitant diseases with SRS	Coho: absence of Icteric Syndrome in the farm	2.22	2	0.67	0.3	1	3	1	0.44	0.792	9	High	Moderately Effective (2.0–2.9)
M20	Diagnostics	Genovariant classification (PCR)	2.22	2	1.09	0.492	0	4	1	0.67	0.661	9	Low	Moderately Effective (2.0–2.9)

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TABLE 1 | (Continued)

Ref	Section	Measure	Mean score	Median score	SD score	CV score	Min score	Max score	IQR	AD Index	Cns (Tastle-Wierman)	N responses	Consensus level	Effectiveness category
M48	Smolt quality	Low mortality rates during the freshwater cycle	2.22	2	1.09	0.492	0	4	1	0.67	0.661	9	Low	Moderately Effective (2.0–2.9)
M49	Smolt origin	Transfer smolt to ongrowing from open-flow hatcheries	2.22	2	1.2	0.541	0	4	1	0.89	0.586	9	Low	Moderately Effective (2.0–2.9)
M64	Smolt weight at sea-site entry	Entry into the sea of smolts of typical weight (e.g., 100–200 g)	2.11	2	0.78	0.37	1	3	1	0.56	0.757	9	Moderate	Moderately Effective (2.0–2.9)
M41	Presence of concomitant diseases with SRS	Low prevalence of PRV	2.11	2	0.93	0.44	1	3	2	0.78	0.673	9	Low	Moderately Effective (2.0–2.9)
M60	Animal welfare	The absence of damaged fins reduces the risk of SRS outbreaks[a]	2.11	2	1.05	0.499	1	4	2	0.78	0.647	9	Low	Moderately Effective (2.0–2.9)
M50	Smolt origin	Transfer smolt to ongrowing from RAS hatcheries	2.11	2	1.17	0.553	0	4	1	0.78	0.626	9	Low	Moderately Effective (2.0–2.9)
M08	SRS Regulations	PROA Program	2.11	2	1.27	0.601	0	4	2	1	0.543	9	Low	Moderately Effective (2.0–2.9)
M14	Therapies	Oral therapy with Oxytetracycline (OTC)	2	2	0.87	0.433	1	3	2	0.67	0.723	9	Low	Moderately Effective (2.0–2.9)
M05	General biosecurity measures	Use of disinfectants (footbath, handbath)	1.89	2	0.93	0.491	1	3	2	0.78	0.673	9	Low	Slightly Effective (1.0–1.9)

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TABLE 1 | (Continued)

Ref	Section	Measure	Mean score	Median score	SD score	CV score	Min score	Max score	IQR	AD Index	Cns (Tastle-Wierman)	N responses	Consensus level	Effectiveness category
M59	Animal welfare	Absence of cataracts reduces the risk of SRS outbreaks[a]	1.78	2	0.83	0.469	1	3	1	0.67	0.717	9	Low	Slightly Effective (1.0–1.9)
M52	Nets	Net In situ cleaning	1.78	2	1.09	0.615	0	4	1	0.67	0.661	9	Low	Slightly Effective (1.0–1.9)
M32	Culture densities	Stocking smolts and subsequent splitting	1.56	2	0.53	0.339	1	2	1	0.44	0.81	9	Moderate	Slightly Effective (1.0–1.9)
M12	Vaccination	Revaccinate at sea (with or without antibiotic therapy)	1.25	1.5	0.89	0.709	0	2	1.25	0.75	0.692	8	Low	Slightly Effective (1.0–1.9)

[a]Item wording incorporates an implied conclusion rather than a neutral description of the intervention and may have introduced acquiescence bias; ratings for these items should be interpreted with caution (see Limitations).
Abbreviations: AD Index, average absolute deviation from the median; Cns, Tastle–Wierman ordinal consensus index; CV, coefficient of variation; IQR, interquartile range; SD, standard deviation; N, number; OTC, oxytetracycline; FFC, florfenicol; PCR, polymerase chain reaction; MIC, minimum inhibitory concentration; BKD, Bacterial Kidney Disease; HSMI, Heart and Skeletal Muscle Inflammation; PRV, Piscine Orthoreovirus; AGD, Amoebic Gill Disease; PGD, Proliferative Gill Disease; RAS, Recirculating Aquaculture System; PROA, Programa de Reducción del Uso de Antimicrobianos; CAD, Centro de Alta Diseminación.

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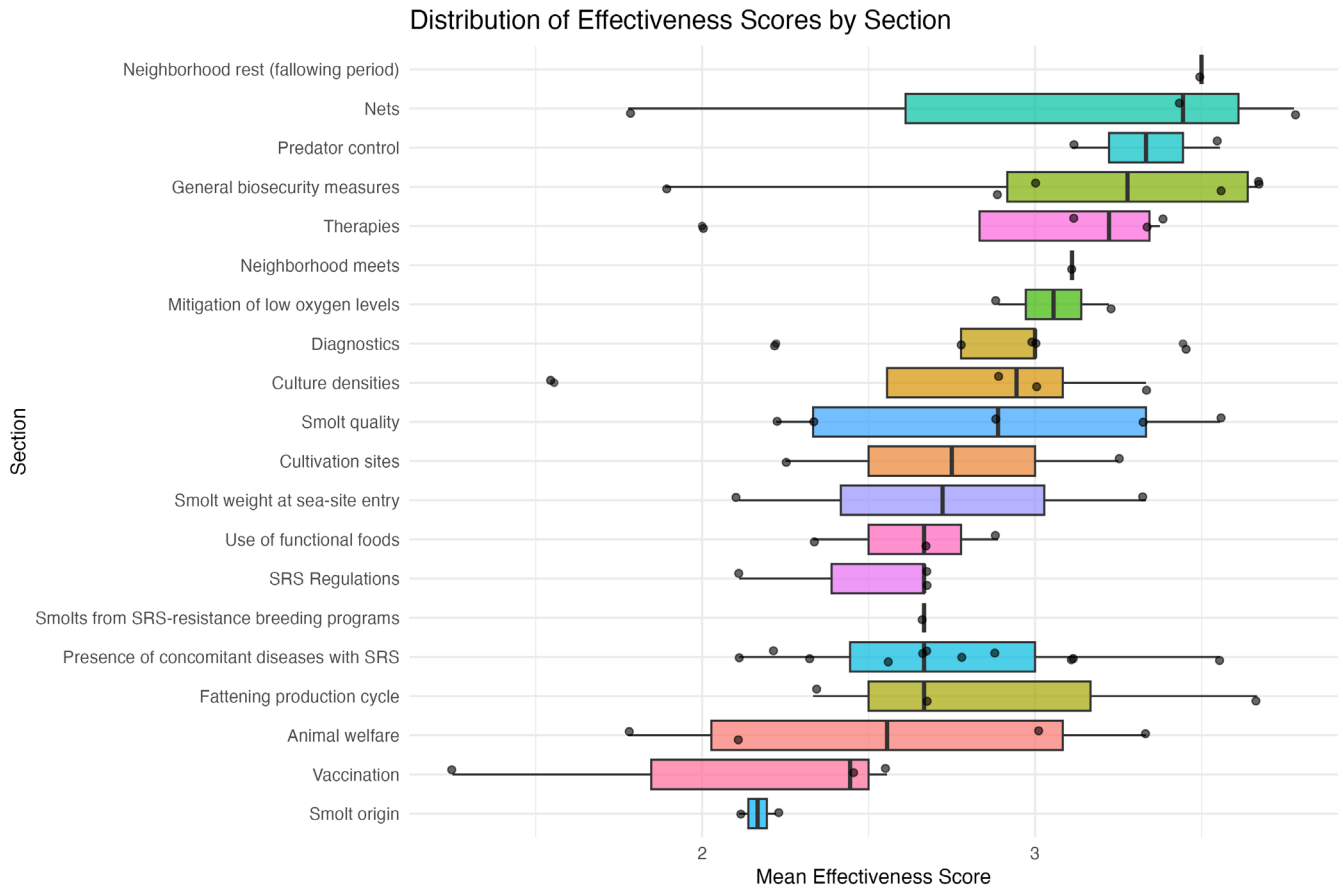

FIGURE 1 | Distribution of mean effectiveness scores across thematic sections of SRS control measures.

3.4 | Priority Classification of Control Measures

Control measures were classified into four priority tiers based on mean effectiveness and consensus metrics (Figure 4):

- Tier 1 (High Priority): Measures with mean ≥ 3.5 and high consensus (low CV), located in the lower-right region of the plot
- Tier 2 (Medium Priority): Measures with mean ≥ 3.0 and moderate consensus
- Tier 3 (Consider): Measures with mean ≥ 2.5 and variable consensus
- Tier 4 (Low Priority): Measures with mean < 2.5 and/or high variability

Tier 1 measures were concentrated among biosecurity, mortality management, and production-related interventions. Tier 4 measures were primarily located in the lower effectiveness range with higher dispersion.

3.5 | Inter-Expert Agreement

Pairwise agreement between experts, assessed using Spearman's rank correlation coefficients, ranged from 0.12 to 0.54 (Figure 5). Most pairwise correlations were positive and within the range of 0.25 to 0.45. Higher correlations were observed among specific expert pairs, while lower correlations indicated differences in scoring patterns across participants. Inter-rater reliability was assessed using three complementary approaches. The intraclass correlation coefficient for a single rater (ICC (2,1)) was 0.30 (95% CI 0.21–0.41), indicating poor reliability at the individual expert level by Cicchetti's (1994) criteria. For the nine-rater panel average, ICC (2,k) was 0.79 (95% CI 0.71–0.86), indicating excellent reliability for aggregate scores. Kendall's coefficient of concordance was $W = 0.31$ ($p < 0.001$), and Krippendorff's ordinal alpha was 0.275. These results indicate that individual experts diverged substantially, while the nine-expert panel average is reliable enough to support aggregate prioritization. Of the 67 measures, 34 (50.7%) met the high-consensus criteria (CV ≤ 0.3 AND IQR ≤ 1.0), 10 (14.9%) met moderate-consensus criteria, and 23 (34.3%) were classified as low-consensus. The low single-rater reliability also implies that the prioritization of low-consensus measures should be interpreted with caution.

4 | Discussion

This study provides a structured assessment of expert judgement on SRS control measures in Chilean salmon aquaculture, integrating perceived effectiveness with levels of agreement across a wide range of interventions. The panel of nine experts, all serving as head fish health managers from independent companies, is assumed to reflect an aggregated industry-level perspective. Collectively, these companies represent 59.3% of Atlantic salmon

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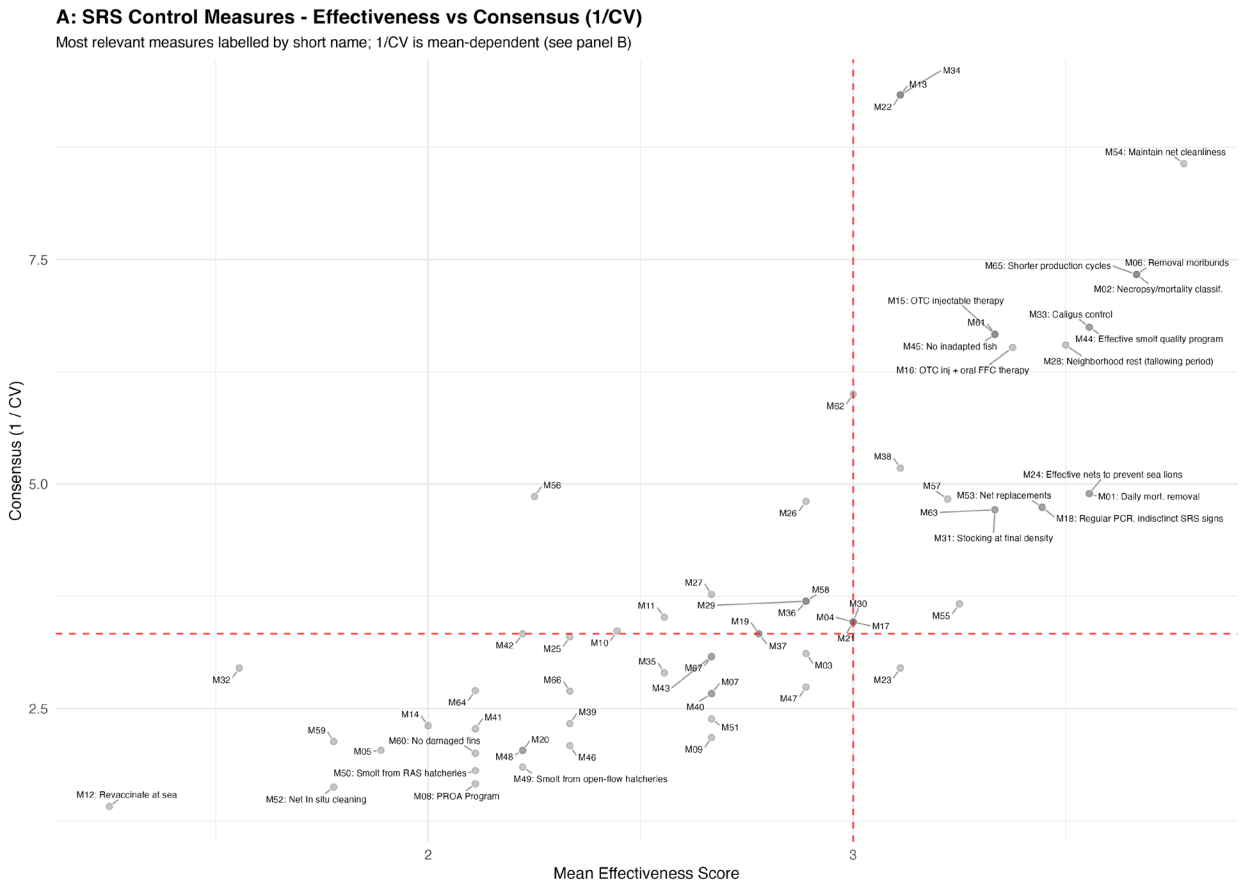

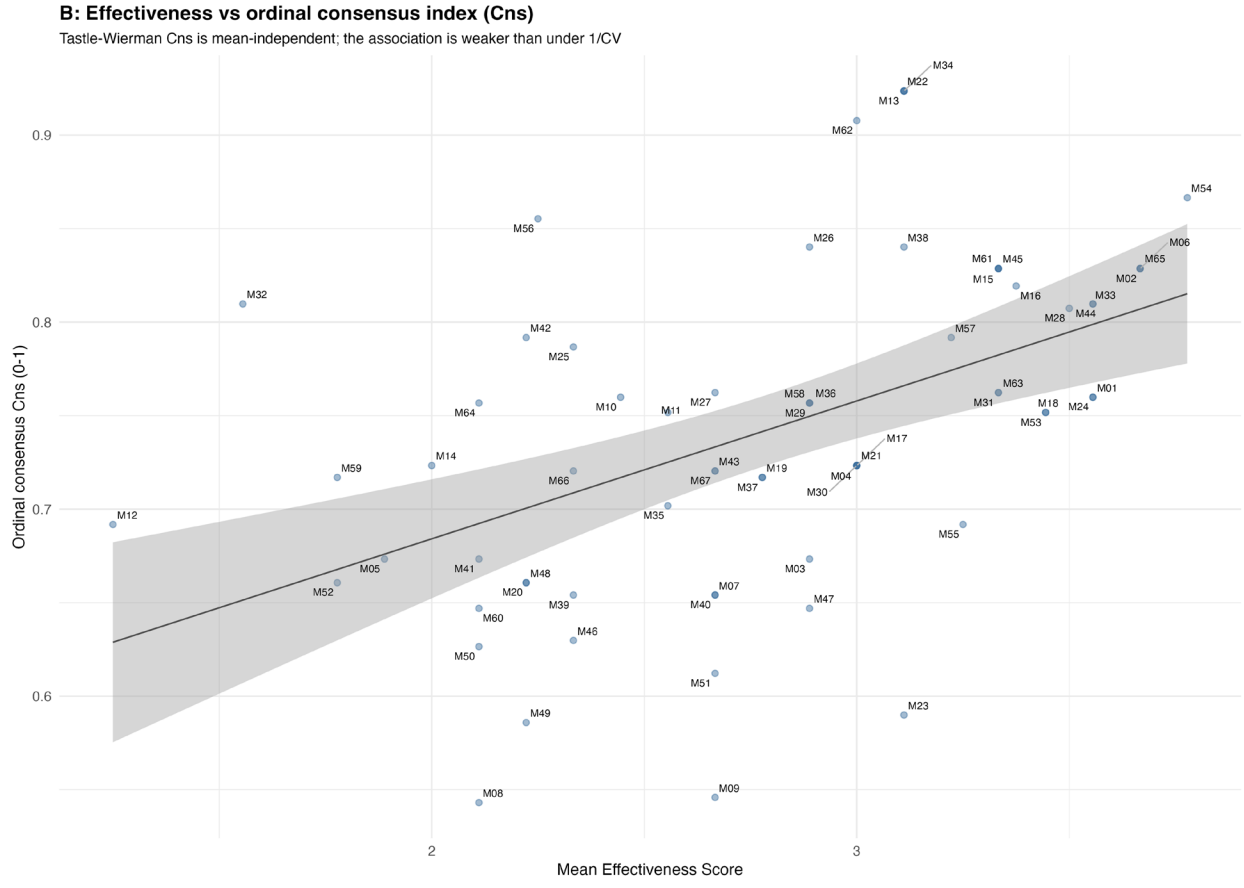

FIGURE 2 | Legend on next page.

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FIGURE 2 | Relationship between mean effectiveness and consensus for SRS control measures. (A) Effectiveness vs. CV-based consensus (1/CV); mean-dependent and shown for comparison with prior literature. (B) Effectiveness vs. the Tastle–Wierman ordinal consensus index (Cns); mean-independent. The most relevant measures are labeled with their code and a short descriptive name; less central measures are labeled by code only.

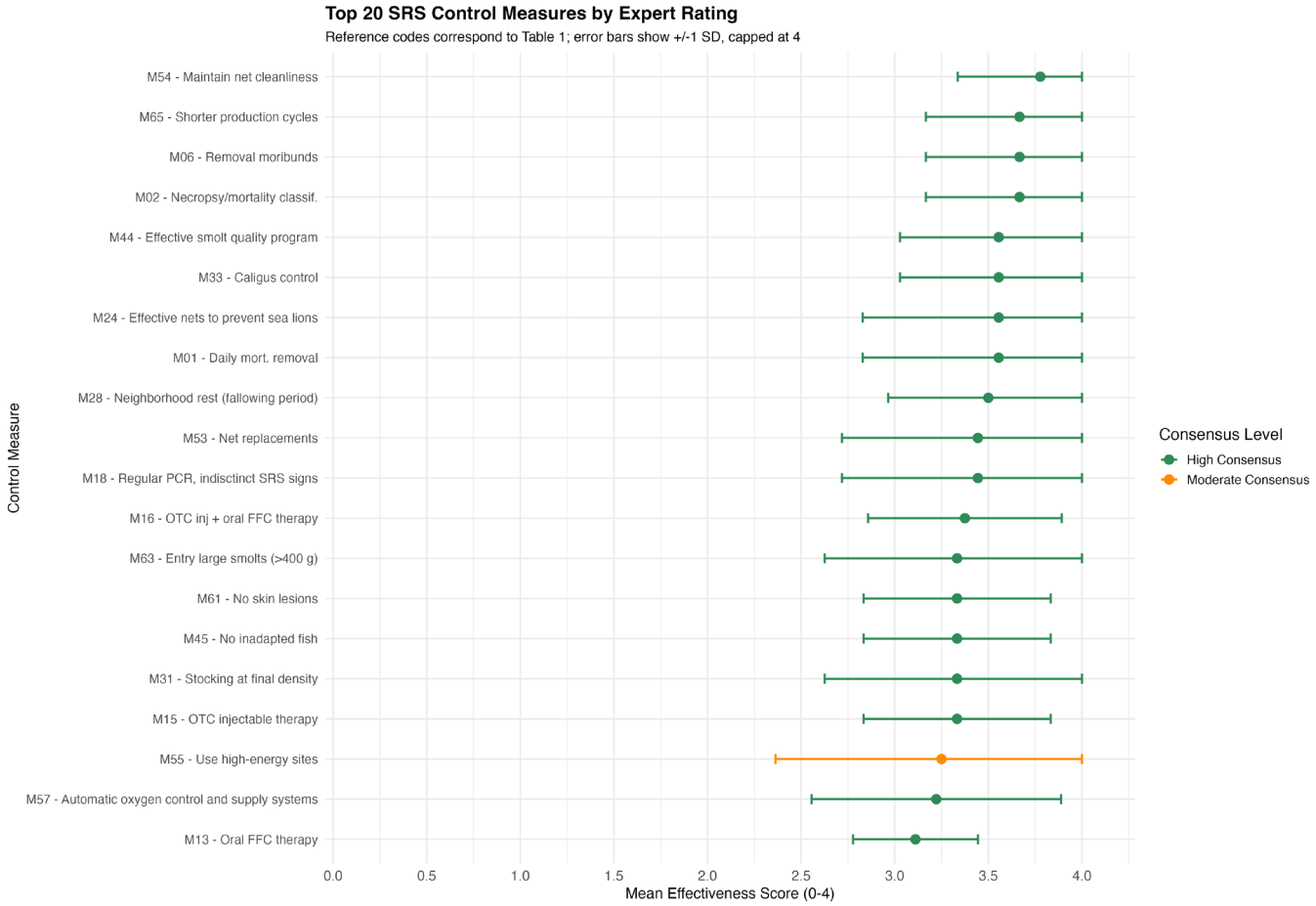

FIGURE 3 | Top 20 SRS control measures ranked by mean effectiveness score (±1 standard deviation (SD); bars are capped at the scale maximum of 4).

production and approximately 65% of rainbow trout production in Chile (Sernapesca 2025), supporting the relevance of the elicited responses as a proxy for prevailing operational knowledge and decision-making in the sector. Coho salmon, the species in which SRS was first described and which has a distinct disease profile, was not represented among the participating companies. Our prioritization framework should therefore be interpreted as most applicable to Atlantic salmon and rainbow trout production.

A consistent pattern emerging from the results is the prioritization of management-driven and preventive strategies over therapeutic interventions. Measures related to biosecurity, mortality management, and production practices, such as net cleanliness, removal of moribund fish, and shorter production cycles, were ranked highest and showed strong agreement among experts for 34 of 67 measures (50.7%) that met the prespecified high-consensus criteria (CV $\leq$ 0.3 AND IQR $\leq$ 1.0). This aligns with previous expert elicitation studies that identified operational factors, including cage fouling, mortality management, and neighbourhood-level practices, as key determinants of SRS risk (Estevez et al. 2019). It is also consistent with the structure of national surveillance and control programs in Chile, where early detection, mortality removal, and biosecurity are central components of disease management (Gaete-Carrasco et al. 2019). In contrast, therapeutic interventions, including antimicrobial treatments, were positioned below top-ranked measures and exhibited greater variability in expert ratings. This finding is consistent with previous studies reporting heterogeneous effectiveness of antimicrobial treatments under field conditions and strong dependence on outbreak dynamics and timing of intervention (Happold et al. 2020; Price et al. 2016; Rozas and Enriquez 2014). This is further supported by recent survival analysis evidence showing that delaying antibiotic initiation until SRS-attributed mortality reaches $\geq$ 0.03% is associated with significantly earlier outbreak onset compared with earlier intervention (HR = 1.37, $p < 0.001$), underscoring that timely diagnosis and early treatment decisions, rather than treatment choice alone, are critical determinants of therapeutic effectiveness in the

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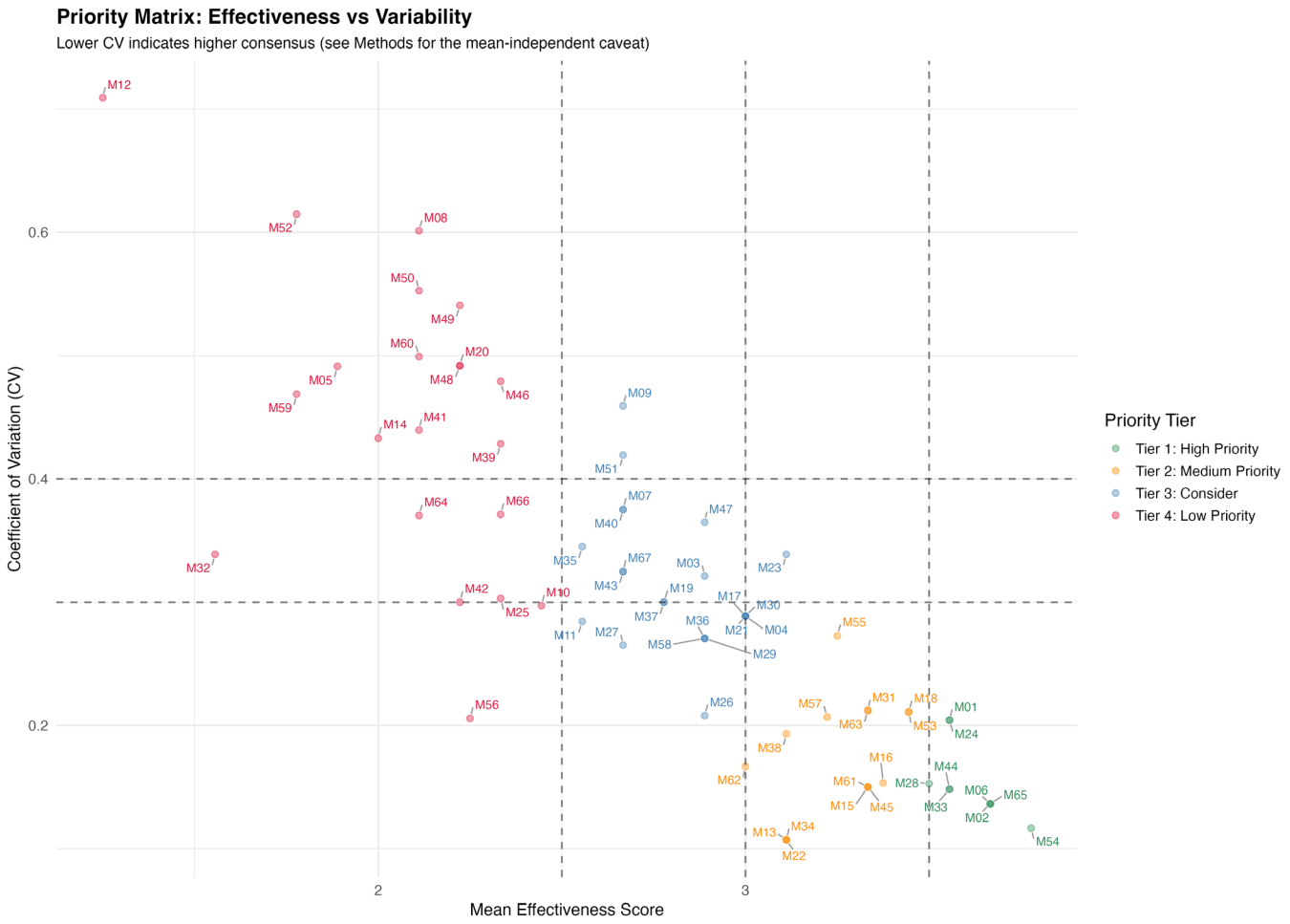

FIGURE 4 | Priority matrix of SRS control measures based on effectiveness and variability (CV), showing four implementation tiers.

field (Gaete-Carrasco et al. 2026). The variability observed among experts likely reflects differences in farm-level conditions, pathogen dynamics, and historical treatment outcomes. From a broader perspective, this reinforces the role of antimicrobial use as a reactive rather than primary control strategy. Furthermore, continued reliance on antimicrobial treatments raises concerns regarding the emergence of antimicrobial resistance in aquaculture systems, with potential implications beyond the farm level (Avendaño-Herrera et al. 2023; Rozas and Enriquez 2014). Similarly, vaccination-related measures showed lower and more variable effectiveness scores compared to management-based interventions. This is consistent with the current understanding that available vaccines tend to delay rather than prevent SRS outbreaks (Rozas and Enriquez 2014; Valenzuela-Aviles et al. 2022). Variability in expert ratings may reflect differences in vaccine performance across production systems, pathogen genogroups, and environmental conditions.

Substantial between-expert disagreement was observed for 23 measures (34.3%) classified as low-consensus. The low single-rater ICC (ICC (2,1) = 0.30) and the range of pairwise Spearman correlations (0.12–0.54) confirm that individual experts diverged meaningfully. Prioritization of low-consensus measures should therefore be interpreted with caution and validated through further empirical study.

The variability observed across measures and thematic sections reflects the multifactorial nature of SRS epidemiology. Notably, the high ranking and strong consensus for *Caligus rogercresseyi* control (M33) reinforces the epidemiological link between sea lice burden and SRS mortality risk previously described in field studies (Arriagada et al. 2019; Diethelm-Varela et al. 2025). This convergence between expert perception and empirical evidence highlights parasite management as a central component of SRS control strategies. Similarly, between-farm connectivity and neighbourhood effects have been identified as key drivers of SRS transmission (Bravo et al. 2020; Rees et al. 2014). These findings support the interpretation that the effectiveness of certain control measures is context-dependent and influenced by system-level interactions.

Similarly, the high ranking of smolt quality programs (M44) supports the role of early-life health status and robustness at sea entry as key determinants of disease susceptibility under production conditions. This finding is consistent with the understanding that host condition at transfer to seawater can influence subsequent disease dynamics and resilience to infection.

At a broader level, the prioritization of preventive and management-based measures is consistent with an epidemiological framework in which SRS is understood as a system-driven disease. Evidence

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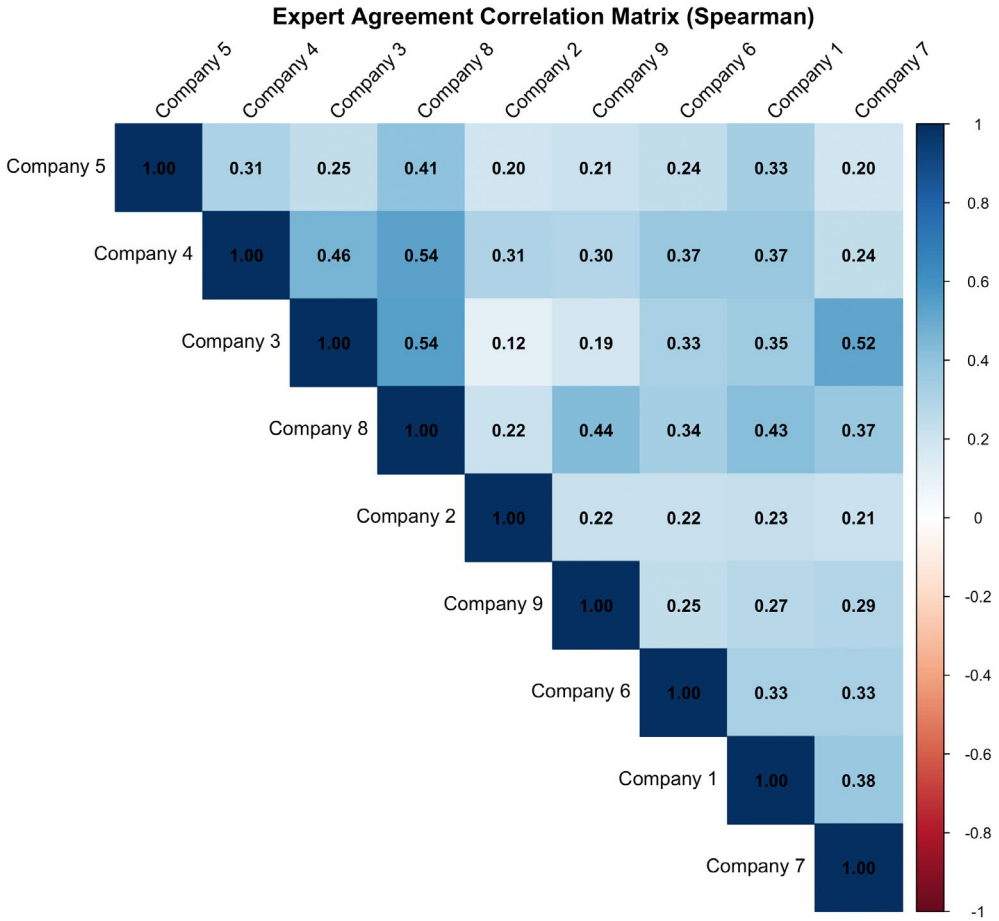

FIGURE 5 | Pairwise expert agreement based on Spearman correlation coefficients.

indicates that disease emergence and progression are shaped by interactions among host, pathogen, and environmental factors, as well as spatial connectivity between farms (Bravo et al. 2020; Diethelm-Varela et al. 2025). In this context, interventions that reduce exposure, improve early detection, and limit transmission opportunities are expected to have more consistent effects across production systems. The clustering of high-priority measures within this category suggests convergence between expert judgment and empirical epidemiological evidence.

An additional consideration emerging from the literature is the lack of standardized outcome measures to evaluate the effectiveness of SRS control strategies. Previous studies have used heterogeneous endpoints, including mortality rates, time to first outbreak, probability of treatment failure, and cumulative mortality (Jakob et al. 2014; Meyer et al. 2019; Price et al. 2020). This heterogeneity limits comparability across studies and complicates the synthesis of evidence for decision-making. The structured approach used in this study, combining effectiveness scores with consensus metrics, provides a complementary framework to address this gap by enabling relative prioritization across a broad set of interventions.

The use of a structured expert elicitation approach represents a key strength of this study, particularly in a context where empirical data remain incomplete or difficult to standardize. As demonstrated in previous applications in aquaculture epidemiology, expert judgement can serve as a formal source of evidence when uncertainty is high and data are limited (Estevez et al. 2019). In this study, the integration of effectiveness and consensus metrics allows for transparent identification of high-priority measures and areas of uncertainty. Nevertheless, expert-based assessments are inherently influenced by experience and perception and should be interpreted as complementary to empirical analyses. The variability observed across several measures highlights the need for further quantitative evaluation of intervention effectiveness under field conditions, particularly for measures with moderate effectiveness and low consensus.

Several limitations of this study should be acknowledged. First, the questionnaire was reviewed internally by the study team but did not undergo formal external pilot testing, which may have allowed ambiguities in item wording to go undetected prior to data collection. Second, no pre-specified definition of effectiveness was provided to participants; experts were therefore free to interpret the concept in terms of different outcome dimensions, including prevention of infection, delay to first outbreak, reduction in mortality, reduction in antimicrobial use, or reduction in economic losses, and this heterogeneity of interpretation is itself a plausible source of between-expert variability. Third, the questionnaire did not formally distinguish between preventive measures and those applied after clinical diagnosis, which limits the interpretability of ratings for reactive interventions. Fourth, a subset of items was not phrased neutrally and may have induced acquiescence bias by embedding an implied conclusion in the measure description; the items most affected are M33 ("Effective Caligus control to prevent

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SRS outbreaks"), M59 ("The absence of cataracts reduces the risk of SRS outbreaks"), and M60 ("The absence of skin lesions reduces the risk of SRS outbreaks"), and their ratings should be interpreted with appropriate caution. Fifth, although the coefficient of variation was used as a consensus descriptor in the original analysis, its use as a primary metric is not fully appropriate for bounded ordinal data because lower-scoring measures are mathematically predisposed to higher CV values; this has been addressed in the revised analysis by foregrounding mean-independent metrics, but readers should be aware of this constraint when interpreting CV-based comparisons in the literature. Sixth, the study consisted of a single rating round without iterative feedback or re-rating, which means that experts did not have the opportunity to revise their assessments in light of group-level results, as would occur in a full Delphi process. Finally, coho salmon was not represented among the participating companies, and the prioritization framework presented here should therefore be interpreted as most applicable to Atlantic salmon and rainbow trout production in Chile.

This study provides a structured and practice-oriented overview of SRS control strategies in Chilean salmon aquaculture. The results highlight a consistent emphasis on preventive management measures, variability in the perceived role of therapeutic and vaccination-based interventions, and the importance of integrating expert knowledge with epidemiological data to support decision-making in complex and interconnected production systems.

5 | Conclusions

This study provides a structured evaluation of SRS control measures based on expert judgment from a panel representing a substantial proportion of the Chilean salmon industry. By integrating perceived effectiveness with levels of agreement, the analysis identifies a clear prioritization of management-driven and preventive strategies over therapeutic and vaccination-based interventions. Measures related to biosecurity, mortality management, and production practices consistently emerged as high-priority and high-consensus interventions, supporting their central role in SRS control under field conditions. In contrast, greater variability in expert assessments of antimicrobial and vaccination strategies reflects the heterogeneous and context-dependent performance of these interventions. The findings reinforce an epidemiological perspective of SRS as a system-driven disease, where effective control depends on reducing exposure, improving early detection, and limiting transmission within and between farms. The structured prioritization framework presented here provides a practical tool to support decision-making and complements existing empirical and surveillance-based approaches. Future work should focus on quantifying the effectiveness of key interventions under field conditions and developing standardized metrics to enable comparison across studies. Integrating expert knowledge with epidemiological data will be essential to advance more effective, sustainable, and evidence-based strategies for SRS management.

Author Contributions

Patricio Bustos: conceptualization, methodology, funding acquisition, formal analysis, investigation, writing – review and editing, writing – original draft. **Benjamín Diethelm-Varela:** writing – review and editing, investigation, methodology, writing – original draft. **Andrés Riofrio:** methodology, investigation, project administration, writing – original draft, writing – review and editing. **Marcos Mancilla:** conceptualization, methodology, investigation, validation, funding acquisition, writing – original draft, writing – review and editing, formal analysis. **Fernando O. Mardones:** methodology, investigation, validation, formal analysis, supervision, visualization, writing – original draft, writing – review and editing.

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Ethics Statement

This study was conducted in accordance with ethical standards applicable to professional survey research. All participants were fully informed about the purpose and scope of the study and provided voluntary consent prior to data collection. No personally identifiable information was collected or disclosed. Institutional ethics review was not required, as the study involved anonymous professional opinion data and did not involve human subjects research under applicable regulations.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Raw expert ratings (0–4 scale) for the 67 candidate SRS control measures evaluated by the nine participating salmon companies (Company 1–Company 9, anonymised), organized into the 20 thematic sections described in the questionnaire (Section 2.2). Dashes ("–") denote items not rated by the corresponding company. **Table S2:** Characteristics of the nine participating salmon companies (anonymised as Company 1–Company 9), including 2025 harvested tonnes of Atlantic salmon (S. salar) and trout, the corresponding percentage of national harvested tonnage, and the gender and years of professional experience in salmon farming of the responding expert from each company. **Table S3:** Post hoc literature-support mapping conducted during manuscript revision, classifying groups of related control measures according to the strength and directness of their supporting evidence. For each control-mechanism group, the table reports the mapped measure codes (as listed in Table 1), evidence class, evidence rationale, representative reference IDs, and full bibliographic details (author/source, title, publication/source type, year, and URL) for each representative reference.

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