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REVIEW

REVIEWS IN Aquaculture

Invisible plastics problem in intensive aquaculture: The case of polyvinylpyrrolidone

Charlotte Robison-Smith | **Jo Cable**

School of Biosciences, Cardiff University, Cardiff, UK

Correspondence
Charlotte Robison-Smith, School of Biosciences, Cardiff University, Cardiff CF10 3AX, UK.
Email: robison-smithca@cardiff.ac.uk

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Abstract

For over 70 years, aquaculture practices have relied on the same methods for biosecurity, however epidemics remain a primary limitation of global aquaculture yields with billions in revenue being lost every year due to disease. The intense nature of fish and shellfish farming necessitates the regular use of synthetic chemicals as both preventive and treatment measures, covering broodstocks to hatching and continuing through all stages of rearing. This practice, however, results in the contamination of rearing environments with persistent xenobiotics. A specific drawback in this foundational strategy for aquaculture biosecurity is highlighted in the current review: the consistent use of a water-soluble polymer polyvinylpyrrolidone (PVP) across most, if not all, stages of rearing aquacultural livestock. PVP is used intensively within aquaculture practices as it is a ubiquitous additive within commercially available germicidal, prophylactic, and therapeutic products applied to control and prevent disease outbreaks within aquacultural farms. As a polymer, PVP is synthetic and biodegradation-resistant, and has recently been described as an emerging contaminant of freshwater ecosystems. It is well documented that other persistent, synthetic polymer pollutants such as microplastics, reduce the fecundity, growth, and significantly deplete immune function in commercially important aquatic species. Despite this, intentionally added persistent soluble polymers, such as PVP, have not been considered in the context of aquaculture productivity. This review explores the potential impact of PVP on fish and shellfish highlighting the need for aquaculture to adopt sustainable chemical practices, drawing inspiration from advancements in nanotechnology applied within human medicines to address biosecurity protocol deficiencies.

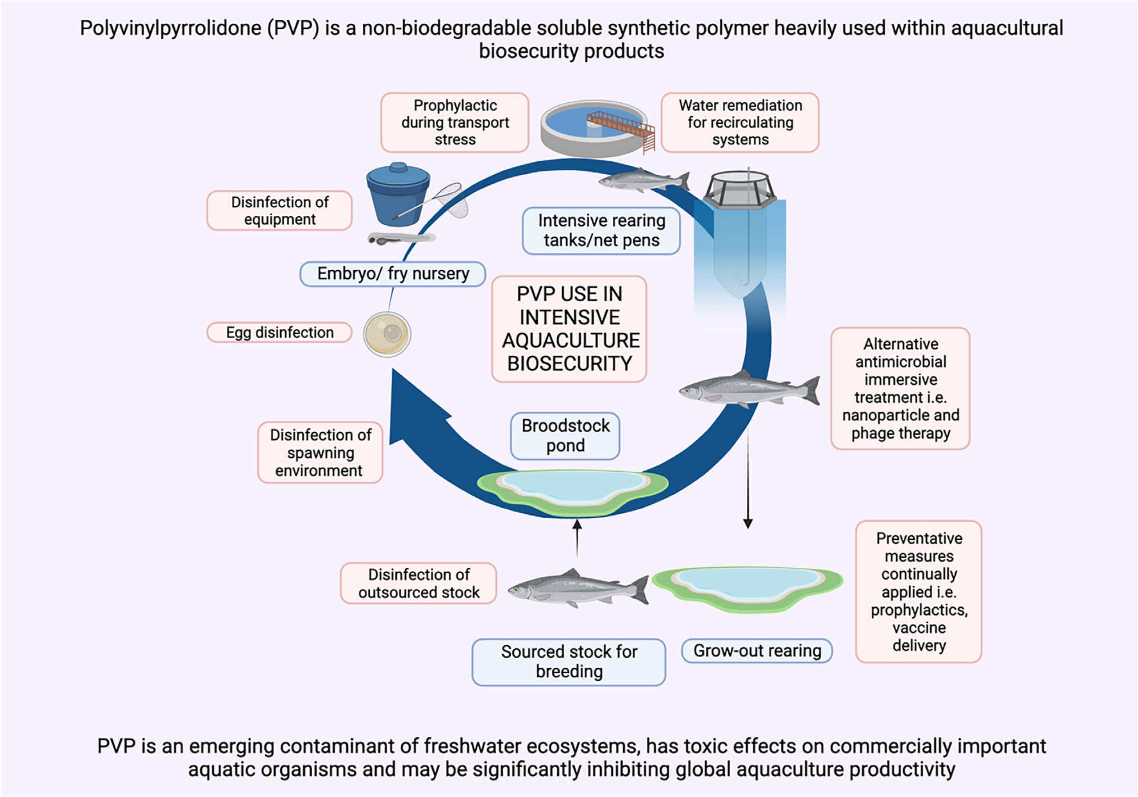
KEYWORDS
biosecurity, disease, fish/shellfish farming, povidone, sustainable chemical use, water-soluble synthetic polymers

1 | INTRODUCTION

Fish are the most efficient and sustainable source of animal protein when compared to conventional livestock, mainly due to their low food conversion ratio.[1,2] With this, a blue transformation is envisioned for the food sector to safeguard future food security amid ongoing exponential human population growth. However, despite being labelled the 'fastest growing food industry' for over 30 years, fish and seafood production is plagued by disease outbreaks, which massively constrain annual yields.[3] It is predicted that by 2050, upwards of 1 in 7 people will suffer protein deficiency.[4] Freshwater fish now account for 75% of global aquaculture stocks intended for human consumption, and although this still falls short of supplying even 20% of consumed animal protein globally,[5–7] it constitutes over 50% of the total animal protein intake in some tropical regions where it is not uncommon for aquaculture fisheries to experience 40% annual stock losses due to disease.[8–10] Intensive feeding, mass waste production and chemical treatment of stock tanks create polluted rearing environments, whilst high stocking densities facilitate rapid spread of infectious diseases. Together, pollution and disease occurrence are major limiting factors of aquaculture productivity with the two having synergistic interactive effects.[11–13] Pollution is known to enhance fish and shellfish susceptibility to disease, leaving them vulnerable to pathogenic viruses,[14] bacteria,[15] fungi,[16] micro and macroparasites,[12,17,18] resulting in mass morbidity and lethal epidemics causing billions (USD) worth of annual stock losses time and again.[19,20]

Safeguarding of livestock within intensive aquacultural rearing involves the application of immersion disinfectants and chemical water additives in preventative and therapeutic biosecurity protocols including: (i) chemical baths to reduce stress and mortalities during transport to and from farms[21] (ii) prophylactics to reduce the risk of introducing disease from imported stock[22] (iii) water conditioning and remediation for rearing/breeding stocks[23,24] (iv) treatment of fertilised eggs produced from breeding stocks[25,26] (v) intermittent or continuous prophylactic/therapeutic treatment for grow-out stocks[27] (vi) alternative antimicrobials for multi-drug resistant pathogens[28] and (vii) general surface disinfectants.[29] Chemical use is relentless in the industry and although fundamental to biosecurity, cumulative evidence suggests long-term use and bioaccumulation of these chemicals may facilitate disease occurrence.[30] One biodegradation-resistant chemical is used in all these stages of commercial stock rearing: the water-soluble synthetic polymer, polyvinylpyrrolidone (PVP).

As illustrated in Figure 1, use of biosecurity products within the fish (and shellfish) industries may mean continuous, high dosing of PVP due to its high percentage composition in some products (up to 100 g PVP complex per litre of product,[31]) and their use as prophylactics as well as therapeutic treatments implying continuous dosing into closed, semi-closed or open rearing systems. Whilst still in their infancy, detection methods for PVP in environmental samples are rapidly developing since the report of 0.18 mg/L PVP in river surface waters in Germany, as well as a peak detection of 7.1 mg/L in wastewater effluent.[32] This 2011 study applied continuous-flow off-line pyrolysis coupled with gas chromatography/mass spectrometry, determining PVP as ‘environmentally stable’ due to its high contamination levels inferring environmental persistence. More recently however, novel quantification methods are emerging; Tarring et al.[33] published a foundational method for the detection and quantification of water-soluble polymers by exhibiting the quantification of



Polyvinylpyrrolidone (PVP) is a non-biodegradable soluble synthetic polymer heavily used within aquacultural biosecurity products

PVP is an emerging contaminant of freshwater ecosystems, has toxic effects on commercially important aquatic organisms and may be significantly inhibiting global aquaculture productivity

FIGURE 1 Illustrating the stages of fish culturing (blue) and the associated biosecurity procedures (orange) indicating the extensive exposure of all rearing stages to polyvinylpyrrolidone-containing products.

polyethylene glycol (PEG) standards, using gel-permeation chromatography (GPC) coupled with matrix-assisted laser desorption/ionisation time-of-flight mass spectrometry. This method was then applied to successfully quantify PEG concentrations within a shaving gel product,[33] with further development this technique can be extended to detect PEG in wastewater and environmental samples. Moreover, it also provides a foundation for method development to enable detection of other water-soluble polymers including PVP; although method error and viability is heavily dependent on the type of water-soluble polymer and how they interact with the GPC. Further work is needed before it can be applied accurately to determine environmental/commercial water-soluble polymer contaminant levels.[33]

The race to accurately detect PVP in environmental samples arose following Antić et al.[32] work which found 'enormous' concentrations of PVP contaminating freshwater environments in the mg/L-range. Although, considerable evidence of the persistence of PVP in environmental compartments, including freshwater ecosystems, surfaced a decade before methods of environmental detection were beginning to be developed. In 2001, Trimpin et al.[34] studied the extent of aerobic biodegradation of PVP by river water determining that at low molecular weight, no oxidation and therefore no degradation of the polymer had occurred in 30 days, indicating the poor biodegradability of PVP.[34] Moreover, PVP is resistant to enzymatic biodegradation due to its affinity for sorption to enzymes and their active substances, reinforced with more reports of no degradation occurring in 4 weeks.[35–37] Together with Figure 1, these studies convey the urgency to accurately quantify PVP levels within aquaculture rearing environments, especially within closed systems, as the environmental stability of PVP implies its ability to persist and therefore accumulate in these environments rapidly, particularly given the intentional and repeated additions of PVP to aquaculture rearing practices.

2 | USES OF POLYVINYLPYRROLIDONE FOR AQUACULTURE BIOSECURITY

Water-soluble synthetic polymers (WSSPs) are invisible to the eye when in solution, once dissolved they disperse and swell in water modifying the functional properties of aqueous media.[38] They have global applications in domestic and industrial products, with a myriad of human medical uses spanning from nanotechnology, to wound dressing, to the binding and coating of pharmaceuticals.[39–41] They also have valuable applications for food security from slow-release fertilisers through to food packaging to preserve the quality and freshness of packaged goods.[42,43] Within the aquaculture industry, WSSPs are widely used within products applied for biosecurity where synthetic polymers such as PVP behave as surfactants, capping and dispersing agents at low molecular weights (Table 1).

Regarding its direct application in aquaculture, low molecular weight PVP is an additive within many antimicrobial products, such as Argovit® (12.6 ± 2.7 kDa)[44] and povidone-iodine (10–360 kDa).[45] Knowledge of the chronic toxicity of PVP is still limited but recent investigations demonstrate that at a molecular weight of 10 kDa, PVP inflicts acute toxicity to zebrafish (*Danio rerio*) embryos at concentrations of 1 μg/L and exerts chronic effects on juvenile guppy (*Poecilia reticulata*) growth and metabolism at 10 μg/L.[46–48] To the best of our knowledge these are the only studies so far to demonstrate significant detrimental effects of PVP on freshwater vertebrates. These initial studies imply fish physiology is affected by low molecular weight PVP exposure even at levels far below those regularly applied in aquaculture. Assuming farms adopt the scientifically supported biosecurity recommendations for use of the aforementioned antimicrobial products as immersion disinfectants for cultured fish and shellfish,[49–51] we estimate that PVP could be regularly dosed into closed aquaculture systems at a concentration of approximately 1000–3000 μg/L.[49–51] Whereas for egg disinfection protocols, treatments completed in accordance with manufacturer instruction, such as those for Ovadine®, would equate a 100 mg/L dose of PVP complex.[52]

Despite having similar sources and the same routes of environmental leaching as microplastics, WSSPs such as PVP remain completely unregulated.[32,53,54] Under the current European commission Annex XVII 2023 dossier concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), it is proposed that water-soluble polymers are excluded from all scopes of regulation because they do not present long-term persistence risks and in turn do not contribute to the identified risk of synthetic plastics.[55] This is despite WSSPs such as PVP being detected in rivers at levels far higher than the most prominent insoluble microplastic polymers, inferring their environmental persistence.[32,39] There is a current European Commission review on low molecular weight water-soluble polymers being included into REACH, but more evidence is required to identify what size of polymer impose significant risks for aquatic organisms.[56]

The potential impact of persistent synthetic polymers on the aquaculture industry has only been considered in the context of insoluble polymers, where it is identified that micro and nanoplastics (NPs) are unintentionally added via equipment weathering and contaminated feed.[57] Such NP exposure can increase fish disease susceptibility.[58–60] NPs are more bioavailable than larger molecules and therefore may pose greater risk to organisms as they can translocate across lipid membranes becoming internalised, accumulating within the tissues of commercial species that we consume.[61,62] Low-molecular weight PVP is used within aquaculture products due to its surfactant properties at this size (Table 1). Its use in nanodelivery of targeted drugs in human medicine implies its ability to be translocated and internalised within tissues at this size, having systemic effects.[56,63,64] Moreover, internalisation within Japanese medaka has been demonstrated for PVP coated nanoparticles as embryos immersed in solution had nanoparticles present in gill, brain, eye and heart tissues.[65] Therefore, the PVP potentially accumulating within aquaculture systems could theoretically have analogous routes of toxicity to insoluble NP polymers.[66–69] Moreover, additional effects of non-internalised polymer surfactants reside with their surface-active effects on, or in the vicinity of outer membranes, interfering directly with membrane function or indirectly by complexation with essential nutrients.[56] The intentional addition of nanosized PVP throughout the

TABLE 1 Summary of polyvinylpyrrolidone use in aquaculture practices.

Compound	Aquaculture use	References
Argovit/Argovit-4® (PVP coated silver nanoparticles)	Immunostimulant and growth enhancement in Rohu (*Labeo rohita*) challenged with bacterial pathogen *Aeromonas hydrophila*	99
	Cichlidogyrus sp.; metazoan parasitic treatment	49
	Antiprotozoal effect on pathogenic ciliates *Tetrahymena* sp. in vitro without evidence of harming pike silverside (*Chirostoma estor*) host	100
	Antiviral agent applied in shrimp farms, weekly feeding of AgNPs results in increased survival against white spot syndrome viral epidemics	50,66,93,101–103
PVP capped silver nanoparticles	Treatment of multi-drug resistant pathogenic bacterial strains *Aeromonas hydrophila* and *Aeromonas caviae*	28
	More effective than antibiotic oxytetracycline at inhibiting growth of fungal *Aphanomyces invadans* and bacterial *Aeromonus salmonicida* pathogens	92
	Antibacterial activity against antibiotic resistant bacterial pathogen of the Nile tilapia (*Oreochromis niloticus*), *Aeromonas veronii*	104
	General disinfectant: Antifungal, antiviral, antibacterial	69,105
	Antimicrobial activity via immersion increases survival of infected Rohu (*Labeo rohita*) challenged with *Edwardsiella tarda* bacterial pathogen	106
	Effective in vitro treatment of viral diseases including Spring Viraemia of Carp Virus (SVCV), European Catfish Virus (ECV), Ictalurid Herpes Virus 2 (IcHV-2)	107
	Increased survival in gilt-head bream (*Sparus auratus*) epidemics of *Vibrio alginolyticus* bacterial infection	108
PVP capped gold nanoparticles	Stimulant for purple sea urchins (*Paracentrotus lividus*) immune cells exposed to *Vibrio anguillarum* bacterial pathogen in vitro	109
PVP	Bacteriophage encapsulation; phage therapy for bacterial disease control as an alternative antimicrobial treatment	110–113
	Encapsulation of drugs/vaccines for targeted delivery	114
Copper oxide nanoparticles imbedded with PVP	Removal of pollutants from recirculating aquaculture systems (RAS) and aquaculture effluent encouraging the formation of sludge, preventing immunodeficiency of stocks and the proliferation of opportunistic pathogens	23,24
PVP-K30: PVP modified nanoscale zero valent iron	Removal of tetracycline antibiotics from aquaculture systems remediating antibiotic accumulation and evading the proliferation of multi-drug resistant pathogenic bacteria	115–118
Stress coat® with PVP	Enhance mucus layer and wound healing in cyprinid fishes as well as reduce losses from transport stress by enhancing epithelial mucus which is the first defence against invading organisms	119
	Water conditioner to promote fish health during transport	120
PVP-iodine	Improved resistance of Chinese mitten crab (*Eriocheir sinensis*) to pathogen *Aeromonas hydrophila*	121
	Disinfects pathogenic *Aeromonas liquefaciens* from brown trout (*Salmo trutta*) eggs	122
	Disinfection of Chinook salmon (*Oncorhynchus tshawytscha*) broodstocks and fertilised eggs reducing the risk of *Aeromonas salmonicida* and *Renibacterium salmoninarum* infection causing furunculosis and bacterial kidney disease outbreaks respectively	123
	Disinfection of outsourced stock before introduction via chemical bath: antifungal, antiviral, antibacterial	22,124
	Inhibits viral release and spread in salmonid farms, increasing stock survival against viral epidemics including infectious pancreatic necrosis virus (IPNV); infectious haematopoietic necrosis virus (IHNV); viral haemorrhagic septicaemia virus (VHSV)	114,125–129
	Equipment disinfectant; inactivation of spores of pathogenic parasite *Ichthyophonus hoferi*	130
Betadine® (PVP-I)	Reduces mortality rate and protects against *Aeromonas hydrophila* bacterial infection during fish transportation	131
	Egg disinfectant for pathogenic bacteria *Aeromonas salmonicida; Aeromonas liquefaciens; Vibrio anquillarum; Cytophaga psychrophia; Flavobacterium columnare; Corynebacterium* sp.; and pathogenic fungi *Phoma herbarum*	26,132–134
Ovadine® (PVP-I)	General disinfectant: Antifungal, antiviral, antibacterial	29
	Effective disinfectant against fungal *Veronaea botryosa* for cultured sturgeon (family *Acipenseridae*) aquaculture	27

aquaculture industry may be causing it to accumulate to immune-toxic thresholds, increasing disease susceptibility of stock (Table 1).

The diverse uses of products containing PVP as a substantial additive within aquaculture biosecurity (Figure 1) raises concerns regarding the concentrations of this biodegradation-resistant polymer that may be accumulating within aquacultural rearing environments, particularly closed systems, such as those commonly adopted for shrimp farming.[70] Aquatic invertebrates are acutely and chronically sensitive to PVP exposure at very low doses; far below those predicted to be present within aquacultural rearing environments. In 2019, Pimentel-Acosta et al. demonstrated that PVP alone increased the cumulative mortality of *Cichlidogyrus* monogenean.[49] A more recent study generated analogous results, where another monogenean parasite, *Gyrodactylus turnbulli*, also experienced decreased survival when chronically exposed to 1 mg/L PVP.[48] Mondellini et al.[71] reported an increase in ROS production of *Daphnia magna* and a reduced number of reproductive cycles when exposed to 5 mg/L PVP for 21 days.[71] Lacave et al.[72] assayed the acute effects of a PVP (73%): Polyethylenimine (23%) respective mixture whilst investigating the toxicity of antimicrobial silver nanoparticles (coated with the polymer mixture) on brine shrimp (*Artemia* sp.), concluding that the polymer mixture alone was non-toxic at both 24 and 48 h exposure. However, at 48 hours exposure when the experiment was terminated, survivability of brine shrimp nauplii did begin falling below 80%.[72] These studies highlight the risks of PVP exposure to aquatic invertebrates and such toxicity could be impairing industry productivity, conveying the need for more chronic exposure assessments on commercially important shellfish species, to assess the potential impairment caused by accumulating levels of this chemical and gain a comprehensive understanding of its impact on productivity in the industry.

Table 1 provides 27 references for the direct use of PVP-containing products applied specifically to promote fish health, treat and prevent disease occurrence in aquaculture. Anecdotal inferences from the literature imply the use of antimicrobial compounds in the industry is proactive as well as reactive for fish rearing, so all kinds of rearing environments (but particularly re-circulating systems) are at risk of accumulating high concentrations of environmentally stable PVP, and for fish reared in these environments, chronic exposure is probable. Studies investigating chronic exposure of PVP are beginning to emerge for freshwater vertebrates. Zebrafish (*D. rerio*) embryos displayed behavioural toxicity to PVP at concentrations at least a thousand-fold lower than those dosed into aquacultural rearing environments.[46] Fish were hypoactive even at this low exposure; where a later study investigating the underlying mechanisms behind this toxicity implied that protein modulation related to eye development was significantly affected by PVP exposure.[46,47] More recently, PVP has been demonstrated to be detrimental to another aquatic vertebrate species. Juvenile guppies were exposed to PVP at either 0.01 and 1 mg/L for 45 days, experiencing significantly inhibited growth and increased standard metabolic rate respectively.[48] Exposed guppies were then presented with an immune challenge in the form of parasitic infection with the ectoparasite, *Gyrodactylus turnbulli*. The guppy-*Gyrodactylus* host-pathogen-pollutant interaction with PVP was antagonistic, where the metazoan parasites were more sensitive to PVP than their host, as indicated by the increased mortality rate of the parasites.[48] However, parasite numbers remained the same when fish were exposed to a higher concentration of PVP implying a trade-off between depleted immune function of the host and decreased survival of the parasites when chronically exposed to 1 mg/L PVP.[48] Enhanced pathogen-specific susceptibility of hosts at 1 mg/L PVP is concerning, as it is unknown how this pollutant might impact other host-pathogen interactions and the fish holobiome. It is imperative we understand more about how PVP affects stock susceptibility to disease, as well as its impact on productivity in the form of wasted energy via inefficient metabolic rate and reduced growth.

3 | ALTERNATIVE RELEASING AGENTS FOR CHEMICAL DISINFECTANTS

Iodophors are chemical disinfectants widely used in aquaculture, consisting of iodine complexed with a water-soluble polymer that is released when in solution. The most widely used iodophor in aquaculture is polyvinylpyrrolidone-iodine, more commonly known as povidone-iodine (PVP-I), commercially available in products such as Ovadine® and Betadine® (Table 1). For over 50 years, iodophor disinfection has been applied as a standard practice on fish farms, to reduce the risk of disease spread during spawning, safeguard fish eggs during rearing, treat parasitic diseases, as an antiseptic agent and general surface disinfectant.[73–75] PVP-I antimicrobial action is attributed to the iodine; free iodine ions, like chlorine ions, kill pathogens. The ions are functionalised and maintained at a controlled equilibrium in solution by the water-soluble polymer PVP releasing agent.[76,77] The benefit of using PVP-I over other disinfectants, such as those functionalising chlorine in the same way, is that free iodine appears to be less harmful to fish than chlorine and has a shorter half-life in aqueous medium.[77] Although this heavy reliance on PVP-I chemical disinfectants within aquaculture raises the question of whether the biodegradation-resistant PVP ubiquitously pollutes aquaculture systems and exerts its own toxic effects. PVP-I has been shown to reduce the innate immunity of crayfish and alter immune function in koi carp.[78,79] However, these toxic effects are attributed to the iodine in the iodophor complex.[76,77] To date, only the antimicrobial efficacy and toxicity of chlorine versus iodine disinfectants have been compared, rather than potential effects of the polymer releasing agent.[80,81] Few have assessed iodophor and the releasing agent toxicity separately.[72,82]

Despite the adverse effects of PVP-I, alternative surfactants have merely been considered to replace PVP as a releasing agent. Altering the releasing agent can greatly alter toxicity of the therapeutic agent to aquatic vertebrates whilst maintaining excellent antimicrobial activity.[83] For example, toxicity of an alternative polymeric surfactant polyvinyl alcohol (PVA) was directly compared to PVP on juvenile guppy (*P. reticulata*) growth where, unlike PVP, it had no significant impact on growth after 45 days exposure at 10 μg/L.[48] PVA also had no significant impact on zebrafish (*D. rerio*) embryos, whereas PVP caused behavioural toxicity.[46,84] PVA is also considered to be readily biodegradable and therefore possesses less environmental and bioaccumulation risk.[85] Despite the importance of the iodophor disinfectants in both human and animal disease management, development of new, improved iodophors has not been achieved since the design of PVP-I 70 years ago.[40] However, recent assessment of the toxicity of a polyvinyl alcohol-iodine (PVA-I) complex revealed no observable effects on human cell lines or exposed mice.[40] In the knowledge that PVA appears to exert lower toxicity on organisms along with the lower accumulation potential of PVA, iodophor development incorporating PVA as a releasing agent could present less risk to cultured fish species, preventing xenobiotic pollution build up and eventual immunosuppression of commercial stocks, whilst also performing as an effective antimicrobial for the industry. Together these studies highlight the value in seeking alternative releasing agents for disinfectants regularly applied in aquaculture.

4 | ALTERNATIVE CAPPING AGENTS FOR ANTIMICROBIAL AGENTS

Another antimicrobial agent widely applied within biosecurity protocols in aquaculture includes nanoparticles, commonly in the form of PVP capped silver nanoparticle (AgNP), commercially available in products such as Argovit-4® (Table 1). Nanoparticles have an affinity for aggregation once administered in solution, hence polymer modification or 'capping' allows for bacteriostasis optimisation, which significantly improves their antimicrobial effect.[86] Nonetheless, nanoparticles are xenobiotics ubiquitously added to aquaculture systems for immersion disease control, causing accumulation to levels which have a myriad of adverse effects on commercial fish species directly impacting productivity, including behavioural toxicity,[87] reduced growth and reproductive success.[88,89] Moreover, AgNPs are known to cause immune suppression in commercial species important for food security such as the common carp (*Cyprinus carpio*),[90] Nile tilapia (*Oreochromis niloticus*)[89] and rohu (*Labeo rohita*).[91] Together these findings imply that long-term use and accumulation of AgNPs may contribute to enhanced disease susceptibility of fish stocks. Nonetheless AgNPs are effective in the treatment of fish pathogens and in some cases are more effective than antibiotic treatment.[92] Emerging research suggests that altering the polymer modifier, or capping agent, significantly affects the antimicrobial effect of nanoparticle prophylactics and in turn, alters the effect on the non-target fish/shellfish species.[83,86,93] Investigative reports on the toxicity of zinc nanoparticles capped with three different water-soluble polymers concluded that PVA highly reduced the toxic effect of nanoparticles to both embryonic and adult zebrafish (*D. rerio*) when compared with PVP and PEG polymer capping.[83] The bioavailability and uptake of zinc nanoparticles was also greatly reduced in the PVA treatment, highlighting PVA as a favourable alternative capping agent to PVP for nanoparticle use in aquaculture, due to the significantly reduced toxicity for commercial stock but maintained antimicrobial efficacy.[83] Thus, further evidence of the aquaculture industries unnecessary reliance on PVP, where future work should focus on charactering the antimicrobial efficacy and toxicity of PVA capped AgNPs on fish pathogens and commercial fish species respectively. Alternatively, differing molecular weights of water-soluble polymers have been shown to exert differing toxicities. High molecular weight (PEG; 900 kDa) polymers with ethylene oxide repeat units caused reproductive toxicity of *D. magna* at lower concentrations than the equivalent low molecular weight polymer (polyethylene oxide; 1 kDa), suggesting that toxicity of these polymers increases with increasing molecular weight.[71] Existing studies on the toxicity of PVP have only investigated a PVP standard of 10 kDa molecular weight, future studies could test the toxicity of lower molecular weight PVP surfactants.

5 | THE POTENTIAL APPLICATIONS OF BIO-NANOTECHNOLOGY FOR AQUACULTURE BIOSECURITY

Recent advances in biomaterial research have investigated the efficacy of biopolymers from natural sources, such as brown seaweeds, as delivery vessels for nanoparticles or drug therapy treatment; the effectiveness of such biopolymers in the targeted delivery of drugs have been demonstrated for aquaculture practices.[94,95] Chitosan-*N*-arginin and alginate are both biocompatible and biodegradable water-soluble polymers and establish favourable physiochemical interactions with targeted membranes once ingested by freshwater fish, enhancing the bioavailability of contained nanoparticles allowing for translocation and internalisation of encapsulated bioactive compounds.[94,95] Biopolymer encapsulation has been shown to successfully dispense the antiparasitic drug praziquantel to highly infected cory catfish (*Corydoras schwartzi*), resulting in 97% removal of intestinal trematode parasites after 14 days of oral administration.[94] Details of bio-encapsulation for the delivery of bioactive compounds acting as immunostimulants in aquaculture has been reviewed[96]; where encapsulation allows targeted deliverance of therapeutic and prophylactic agents including drugs, vaccines, prebiotics and probiotics, for disease management with low environmental impact. To date biopolymer use in iodophors has been underexplored, but recent studies have shown the antiviral and antimicrobial effectiveness of chitosan-iodine.[97] Chitosan-iodine antimicrobial and wound healing performance was also compared against PVP-iodine, where equivalent antimicrobial activity and improved healing was evident for the chitosan based iodophor qualifying it as a sustainable alternative to PVP based iodophors in vitro.[98] Biopolymers such as this represent favourable substitutions for conventional aquaculture biosecurity protocols which are classically harsh and polluting. These targeted delivery vessels remove the need for concentrated drug application and reduce the use of synthetic, degradation-resistant chemical compounds lowering the risk of persistent pollutants accumulating in aquacultural rearing environments.

6 | CONCLUSION

As capture fishery productivity becomes ever-more stagnant, the reliance on fish farming has resulted in a blue revolution for global food security, where fast and furious development of the sector has meant that for productivity, efficiency and sustainability have been increasingly neglected. This paper discusses a One Health approach to move towards sustainable growth of the aquaculture industry by proposing a long overdue re-development of biosecurity protocols for cultured fish and shellfish stocks. Here, we theorise that heavy reliance on PVP use in the industry for disease management has led to pollution and accumulation of this persistent synthetic polymer, which has the potential to inhibit growth, reproductive success and increase disease susceptibility of fish and shellfish stocks. Development and better regulation of chemical use in aquaculture practices may improve productivity of fish farms through successful and sustainable disease management. As detection methods for PVP are still in their infancy, future work should focus on detecting PVP pollution levels on aquaculture farms so the toxicity of chronic exposure to industry relevant PVP concentrations can be clarified. Furthermore, characterising the in vitro antimicrobial efficacy of biodegradable capping/releasing agents such as chitosan and polyvinyl alcohol coated iodophors and nanoparticles will elucidate whether more in vivo toxicity assessments of biopolymers would be worthwhile to avoid swapping like for like and ensure sustainable development of the aquaculture industry.

AUTHOR CONTRIBUTIONS

Charlotte Robison-Smith: Conceptualization; investigation; writing – original draft. **Jo Cable:** Supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

No new data was created during this study.

ORCID

Charlotte Robison-Smith https://orcid.org/0000-0002-3878-9217

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