Formaldehyde Use in Scottish Salmon Farms

A Report by Fidra

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About Fidra and our Best Fishes project

This report is published by Fidra as part our Best Fishes project. Fidra is an environmental charity working to reduce chemical and plastic pollution in our seas, on our beaches and in the wider environment. Fidra shines a light on environmental issues, working with the public, industry and governments to deliver solutions which support sustainable societies and healthy ecosystems. We use the best available science to identify and understand environmental issues, developing pragmatic solutions through inclusive dialogue. Find out more at www.fidra.org.uk .

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Executive Summary

Scottish salmon farming is the third largest source of farmed Atlantic salmon globally and the main component of Scottish aquaculture, estimated to be worth over £1.8 billion annually. Parasites and disease inflict a significant financial burden on the industry, despite advances in medicine and vaccination. Chemical parasiticides are frequently used to protect against costly disease outbreaks and to ensure the health and wellbeing of fish stock.

Formalin, an aqueous solution of formaldehyde, is one of the most commonly used parasiticides in aquaculture. Although it degrades rapidly in water, concerns remain over its impacts on both target species and the wider environment, with publicly available data on formalin-use limited. In Scotland it is used in freshwater farms to treat fungal infections, with the main target not saltwater tolerant. There are a small number of marine finfish farms with very old permits that still include formalin, which are progressively being identified and the permission for using formalin removed.

A statement made in a 2014 Aquaculture Science & Research Strategy refers to the 'planned removal of formalin for use during freshwater phase of salmon and trout'. **From 1st January 2016, formaldehyde has no longer had a UK marketing authorisation for use as an animal medicine**, however it is still used in Scottish aquaculture and its use controlled by several bodies. The Veterinary Medicines Directorate issues a special import certificate which allows operators to import a product authorised in another country and use it to treat fish under the veterinary cascade system. The Health and Safety Executive has a role in relation to the health and safety of the workforce using formalin. Discharges to the water environment require prior authorisation by the Scottish Environment Protection Agency (SEPA), with discharge limits calculated to meet the Environmental Quality Standard (EQS) published for formaldehyde. **The EQS for formaldehyde only applies to freshwater environments and is classified as non-statutory, and so is not believed to be monitored or enforced.**

Research suggests the potential impacts of formaldehyde exposure on fish species being treated to be highly variable, with the **most commonly reported adverse effects to be damage to fish gills and changes to mucous cells**. Differences in the recorded impacts are thought largely to be the result of varying environmental conditions, as well as fish age, species and prior health, emphasising the importance of individual site conditions in determining appropriate treatment levels. **As the margin between concentrations needed to kill target organisms and those which might harm fish stocks can be small, it is repeatedly advised for formalin to be administered only in essential circumstances.**

Formalin can reduce dissolved oxygen levels within a given waterbody. Oxygen deficiency in turn can inflict severe stress on fish and other aquatic species, and in severe cases result in changes to entire ecosystem structures and function. **As rising global temperatures threaten an increased frequency and intensity of anoxic conditions in aquatic environments, the additional pressure inflicted by use of formalin treatments is cause for concern.**

Multiple treatment methods are available to remove residual formalin from effluent before discharge to natural waterbodies, however it is unclear if any are used by the

industry. Alternatives to formalin are also available. Peracetic acid (PAA) is currently preferred, due to increased potency which requires reduced concentrations, and with rapid decay into harmless breakdown products in the natural environment. Further research is needed to optimize PAA treatments and ensure safe use for both target and non-target species.

To minimise the potential risk of chemicals treatment in aquaculture pose to the environment, Fidra are calling for greater transparency between the salmon farming industry and the public, stringent statutory requirements and increased emphasis on following best practice, using alternatives and mitigation measures.

Fidra makes the following recommendations:

1) Information on all chemicals used in both marine and freshwater aquaculture, including quantities, frequency of use and methods of regulation and enforcement should be published in a publicly accessible and comprehensive database, or ‘sustainability dashboard’;

2) Statutory EQS values need to be established for formaldehyde, methanol (a common stabilising agent of formalin) and hydrogen peroxide (an alternative treatment);

3) Best practice for these chemicals, including limitations, should be clearly defined, with further research completed into the wider ecological implications of their use and potential impacts of rising water temperatures due to climate change;

4) Investigation and implementation of safer alternatives should remain a top priority, with incentives towards alternative treatments or mitigation actions. Mitigation could include ensuring farms are in suitable sites that are not in protected areas and can support the discharges from open net pens, and if sites are unsuitable taking actions such as installing semi-closed or closed containment, or closing farms, and/or moving to a more suitable site.

1. Scottish Salmon Industry

1.1 Economic Value

The Scottish salmon farming industry has grown steadily since the 1970s and now represents the third largest source of farmed Atlantic salmon in the world, after Norway and Chile. At present, it constitutes the main part of Scottish aquaculture as a whole, which is worth over £1.8 billion annually. As a significant contributor to the Scottish economy, the Scottish Government is supporting the industry's plans to double in production by 2030, resulting in a total net worth of around £3 billion[1].

According to the Scottish Salmon Producers' Organisation (SSPO) official HMRC figures from February 2021 show that the global Covid-19 pandemic resulted in export sales reduced by £168 million in 2020 from 2019. Exports to the EU have become more important, increasing in volume and value by approximately 50%. SSPO figures claim that by the end of February 2021 losses of at least £11 million had been made as a direct result of changes due to Brexit[2].

While playing an important economic role in rural areas, the industry has a range of environmental impacts that give cause for concern, from discharges of chemical treatments to escapes of domesticated salmon into wild populations. In some settings a reduction in visual amenity and loss of wilderness values can have additional social impacts[3].

1.2 Farming Practices

Intensive fish farming can be conducted using numerous enclosure types. These include enclosures reliant upon recirculated or reused water systems (closed or semi-closed circuits), as well as open water enclosures (Figure 1).

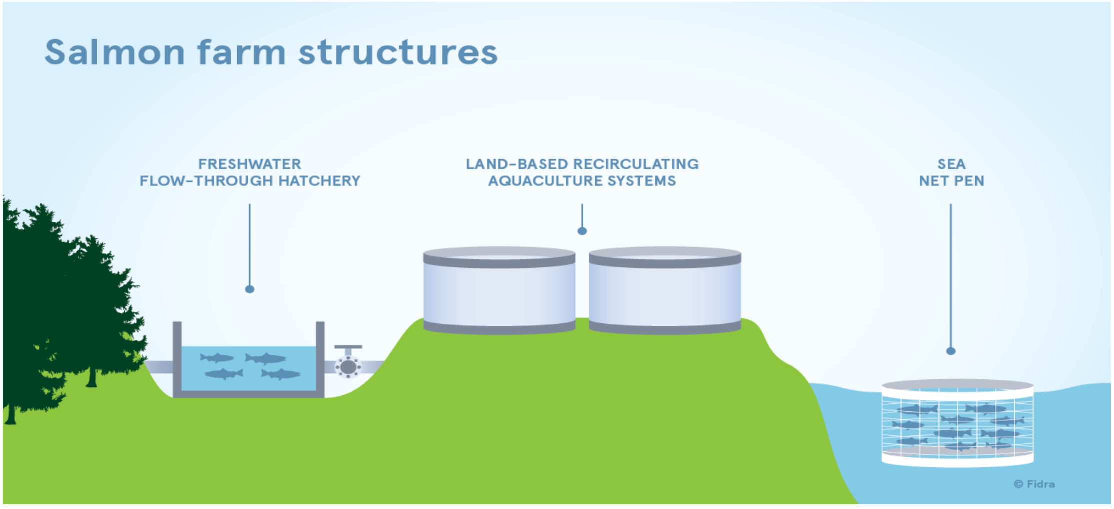

Figure 1. *The three main production systems for Atlantic salmon © Fidra.*

As salmon are anadromous, in the wild migrating from the sea to spawn in freshwater, stock is reared in both freshwater and marine environments and may be moved across multiple enclosure types throughout their lifecycle (Figure 2). Fertilised Atlantic salmon eggs are typically imported into Scotland and reared in hatcheries. Fry are then grown either in tanks using freshwater flow-through (semi-closed system) or land-based recirculating systems (closed system). Once at the parr stage they may be moved to open net farms in freshwater lochs (open systems). Parr undergo smoltification to the seawater stage and the smolt are then transferred to seawater open net farms in coastal areas or sea lochs to reach harvest size.

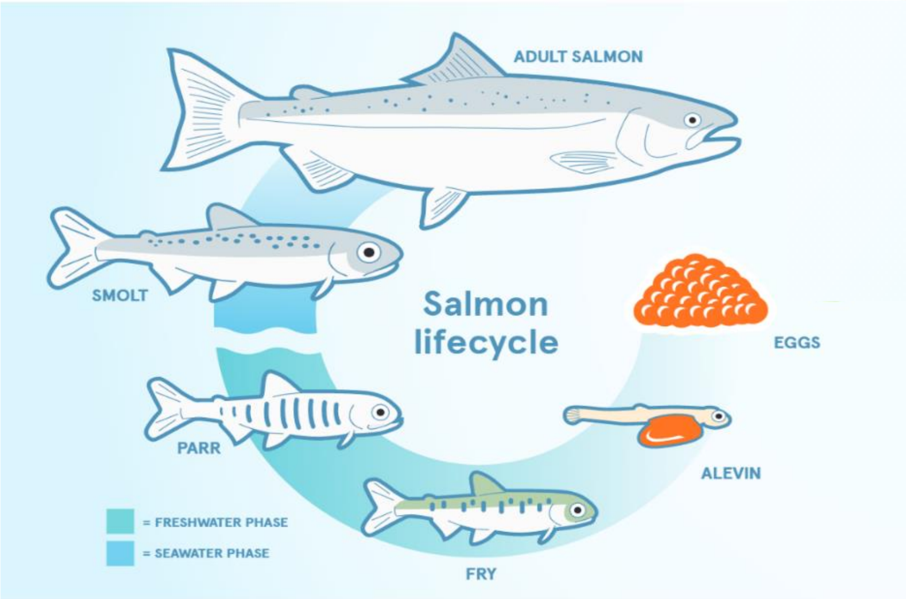

Figure 2. *The salmon lifecycle © Fidra.*

1.3 Parasites and Disease

Despite considerable advances in medicine and increased vaccination, the occurrence of parasites and disease continues to be a significant issue for aquaculture[4]. Depending on the variant, parasites and disease can cause anything from mild skin irritation of a small number of fish, to outbreaks and heavy losses across the entire stock[5]. As well as a welfare concern, these are a major financial burden for the industry, through direct loss of fish stock as well as ongoing management and treatment costs[6].

Examples of this in practice are shown by the parasite *Desmozoon lepeophtherii* which resulted in a loss of 8.7% of Scottish Atlantic salmon during 2009-2010, with a further 10-20% loss in 2011 due to the parasite *Paramoeba perurans*[6]. Combined, the mortality of stock in these two examples was estimated to result in a loss of US $81 million. Overall, the total cost of aquatic parasites on global finfish production is estimated to be up to US $9.6 billion annually.

There are also increasing concerns for the environmental impacts of disease occurrence in fish farms, with some studies finding evidence for potential disease interactions between farmed and wild fish populations[4 7]. However, due to the challenges in sampling diseased wild fish, the significance of such risk remains unclear [4].

2. Formaldehyde Use in Scottish Salmon Farms

2.1 Formalin Treatments

Formaldehyde is a simple and extremely reactive chemical compound with a wide range of modern-day applications (Figure 3). It is used in the production of resins, adhesives, plastics, paints and glues[8,9], as well as for use as a biological preservative, embalming fluid and antiseptic treatment in medicine[10]. It is also produced naturally by most living organisms as a result of normal metabolic processes[11].

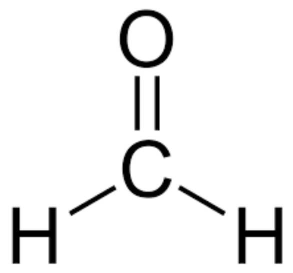

Figure 3. *Formaldehyde chemical formula*

Formalin is an aqueous solution of formaldehyde, and one of the most used parasiticides in aquaculture[12]. It is effective against most protozoans, monogeneans and oomycetes[a]. It can be used to kill parasites on fish gills, skin, fins and eggs, although cannot be used to treat internal infections[13].

Box 1. Scottish Salmon Case Study – *Saprolegnia*

The fungus *Saprolegnia* is thought to be responsible for at least 10% of annual mortalities in most salmon hatcheries and freshwater sites, ranking as one of the most important pathogens to Atlantic salmon[14]. Also known as winter fungus, it usually occurs in waters below 15ºC. Fish suffering with saprolegniosis display cotton-like growths on their gills and skins. If left to progress, this can extend to the muscle tissue, causing the fish to die slowly over time[15,16].

Cases of saprolegniosis have been increasing in freshwater Scottish salmon farms, resulting in a £1.1 million research project being launched in 2017 to better understand causes for the outbreaks: Risk Factors for Escalating Saprolegniosis Outbreaks in Salmon Farms (RIFE-SOS). The project involves collaboration of 12 partners from industry and academia across the UK and is said to underpin “the scale of the issue and the size of the opportunity both for the sector and global food security”[17].

A leading treatment for saprolegniosis in freshwater aquaculture, malachite green, was banned in 2002 following research demonstrating its toxicity in numerous animal species and potential risk to human health[18,19]. Formalin is now one of most common treatments[4,19,20]. Another medicine, bronopol (2-bromo-2-nitropopane-1,3-diol), is the active ingredient in Pyceze®, which has full UK marketing authorisation and can also be used as a treatment. Issues with the supply of Pyceze® has resulted in SEPA issuing an interim position statement in December 2020 to allow the use of Cress, a bronopol product licensed for use in Chile, at sites where Pyceze® is already authorised[21].

[a]Protozoan: relating to any of a diverse group of single-celled organisms. Monogenean: a class of parasitic flatworms. Oomycete: aquatic and terrestrial fungi-like organisms. *Saprolegnia* spp. are classed as oomycetes.

The commercial formulation of formalin usually contains 37- 40% formaldehyde and is stabilized with 10-15% methanol to prevent formation of paraformaldehyde, a white precipitate known to be highly toxic to fish[12]. Formalin treatments must also be kept in darkness and at temperatures above 4°C to prevent paraformaldehyde formation whilst in storage[12 13].

Formalin is administered to fish stock as a 'bath treatment'. The frequency of treatments is a matter for the prescribing veterinarian and may be a prolonged exposure bath or a short-term bath, usually between 30-60 minutes. For prolonged exposure, treatments normally range between 15 and 25mg/L for around 12 hours[12]. Fish farm operators must comply with discharge limits specified in their permits and calculated to ensure environmental standards are met. The discharge limits depend on the capacity of the receiving waters to assimilate discharge without breaching environmental standards and are therefore site specific.

Taking an example of a farm with 36 cages each of size 48m^2, with a net depth of 3m for a bath treatment, it is estimated that the resulting treatment volume of 5,184m^3 would require between 77,760g and 129,600g for prolonged exposure treatment as described.

When used in flow-through systems, it is recommended for the water flow to be turned off to ensure sufficient exposure of the parasite to the treatment. In such cases, water quality, including pH, nitrite and dissolved oxygen levels, should all be checked in advance. For short-term baths, a treatment of 250mg/L formalin solution for up to 1 hour is most common. Short-term treatments are only recommended for use in systems where fish may be exposed to formalin-free water immediately after treatment and where fish are of sufficient health to tolerate higher formalin concentrations. For fish that may be moved for treatment, potential transport of pathogens across sites must be considered[12 13].

Fish hatcheries may also be treated with short-term formalin baths. This usually involves concentrations of between 1000-2000mg/L for 15 minutes[13].

As formalin can significantly reduce dissolved oxygen levels, water must be heavily aerated during treatments. Formalin is also an algicide which further reduces dissolved oxygen levels by inhibiting that produced through photosynthesis. Consequently, formalin is not recommended for use in pond aquaculture[13].

The margin between concentrations needed to kill target organisms and those which might harm fish stocks can be small and vary with changing external conditions, such as water flow rates, temperature and quality.

Formalin must therefore be administered with the greatest of care and is advised only to be used in essential circumstances, with close attention paid to fish behaviour throughout the duration of treatments[12 13].

Box 2. Scottish Salmon Case Study – levels of formaldehyde use in Scotland

Incidences of formalin use on finfish farms in Scotland are recorded and published by the Fish Health Inspectorate (FHI), without specifying the dosage used. The monthly quantity of formaldehyde used on individual farms is available from SEPA through Freedom of Information (FOI) requests. Current information available in this form covers use of formalin from 2017-2019[b]. A total of 12 farms recorded the use of formaldehyde, with 4 recording use for all 3 years (Figure 4) and the remainder only in 2019.

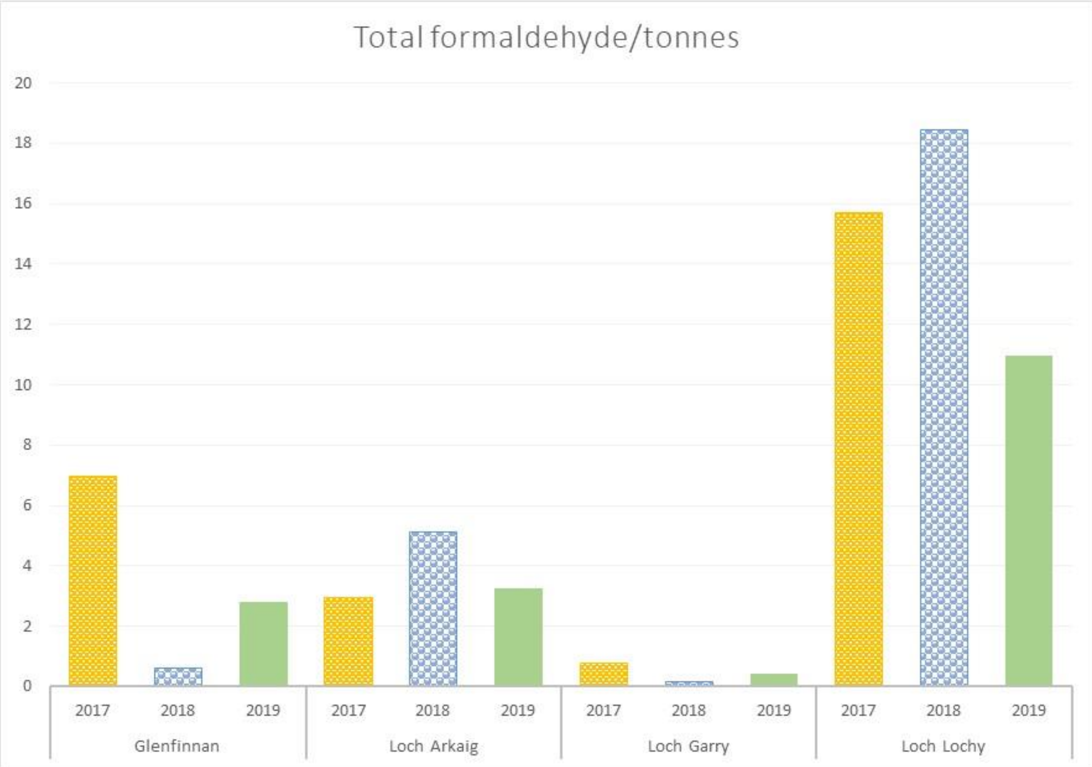

Figure 4*. Formaldehyde use in 4 Scottish finfish farms*, *2017-2019*.

Between the years of 2017 and 2019 the amount of formaldehyde used in a single month by an individual farm ranged from 18.75 kg to 4.44 tonnes, at Loch Arkaig and Loch Lochy respectively. No more detail is given in the FOIs. The FHI reports detail the reason for use, usually as 'fungus'. The Scotland Aquaculture website entries show the number of cages on the farms but not their size and have no details of treatments or disease. The rate at which formaldehyde is entering the aquatic environment surrounding the farms, and therefore the potential impact it is having, cannot be gauged from any publicly available information.

2.2 Regulations for Use

The SEPA website states that the 'medicines and products used on fish farms are approved and regulated through chemicals legislation or veterinary medicines regulations'[22]. This relates to the Health and Safety Executive (HSE), focused on

[b] https://www2.sepa.org.uk/disclosurelog/# Ref Numbers F0191629, F0191202, F0190713, F0190275.

managing risks in the workplace, and the Veterinary Medicines Directorate (VMD) respectively.

According to the HSE, biocides are covered under GB Biocidal Products Regulations and therefore require approval before being used in the UK. This includes pest controls, such as molluscicides, insecticides and general repellents, as well as disinfectants and algaecides but in this case, only those not intended for direct application to humans or animals[23].

The 2014 Aquaculture Science & Research Strategy, produced by Marine Scotland, makes specific reference to formalin as a priority for the industry to phase out in order to achieve its 2020 sustainable production targets. In the report, development of alternate therapeutants, especially for *Saprolegnia* (see Box 1), is listed as medium to high priority. The report states that, '**due to planned removal of formalin for use during freshwater phase of salmon and trout**, the industry is vulnerable to a *Saprolegnia* epidemic' [24].

While veterinary medicines legislation and biocide legislation cross over, products are only on one or the other and not both. From 1st January 2016, formaldehyde (formalin) has no longer had a UK marketing authorisation for use as an animal medicine[25] and so is not on the VMD under current authorised products[26] . However it can still be imported under a special import certificate issued by the VMD, which applies where a product has approval for a relevant medicinal use in another country. The process is outlined by the British Veterinary Association guidance on the use of formaldehyde in aquaculture[27] .

Recently, SEPA stated that the 'application process for applying pesticides to fish farms is strictly regulated, with operators requiring authorisation before using formaldehyde'[28]. It is understood that this refers to the CAR licence application process under the Water Environment (Controlled Activities) (Scotland) Regulations 2011, which may impose conditions for use on certain chemical treatments[29].

It is unclear what, if any, conditions for use may apply to formaldehyde. It is stated that 'in the case of some products, SEPA sets controls or limits on the quantities that are allowed to be used and discharged so that environmental standards are met'[13]. This is based on the relative risk a product imposes on the environment. Products that are determined to 'pose no or low environmental risk' are added to the Permitted Substances List. Anything classified above this threshold is listed as 'permit with conditions controlling use'[13]. Formaldehyde is not listed under SEPA's 'permitted substances working plan' document[30]. As discharges to the water environment from any site require prior authorisation from SEPA, it could therefore be assumed that SEPA set conditions to control the use of formaldehyde, however the details of such are not available. As the frequency of treatments is a matter for the prescribing veterinary surgeon, it is further assumed that these are calculated while taking account of any conditions set by SEPA.

2.3 Environmental Quality Standards

The greatest environment concentration at which a chemical is deemed to be tolerable is set by an Environmental Quality Standard (EQS). The EU Water Framework's Directive (WFD) requires EQS for polluting substances. If these standards are exceeded, they could result in adverse effects to ecosystems.

A value for an EQS is typically based on laboratory experiments to find maximum concentrations that have no effects on test subjects. Results from laboratory experiments allow the derivation of Lowest Observed Effect Concentration (LOEC) and no observed effect concentration (NOEC). Based on these values obtained in the laboratory for a range of species, the predicted no effect concentration (PNEC) can be derived, which is established to ensure protection of non-target species and the wider environment. The PNEC is derived by applying a factor of 10, 100 or 1000 to the obtained values in the laboratory, depending on the data available, the degree of precaution required and the likelihood that the test organisms are more robust than most in nature. Protocols for the derivation of EQS values are well-established, although the results can be controversial, especially when extrapolating to effects on interdependent communities of organisms[31].

The EQS values based on laboratory toxicity testing are updated when necessary. SEPA is required to take account of both statutory and non-statutory substances. The environmental pressure from a chemical resulting from salmon farming is deemed to be significant if concentrations exceed a relevant EQS on an appropriate spatial scale.

Box 3. Formaldehyde EQS

The EQS values set for formaldehyde relate to freshwater only and are classified as 'non-statutory'. They include a Maximum Allowable Concentration (MAC) value of 50ug/L and an Annual Average (AA) value of 5ug/L[32]. As non-statutory EQS, it is understood that they are not set out in legislation or actively monitored.

2.4 Certification Schemes

The Aquaculture Stewardship Council (ASC) certification scheme notes records of formalin use, including proof of veterinary instructions and sign off, during routine surveillance audits, as well as within their certification reports[33]. Certification reports also require proof of the reason for use, amount of treatment used and treatment supplier, although these details are not quoted within the report or published in the publicly available audit online. Of the 12 finfish farms on which formaldehyde use from 2017-2019 was shown by FOIs (see Box 2), 5 are ASC certified; Glenfinnan, Loch Arkaig, Loch Garry, Loch Lochy and Loch Ness. The publication of the ASC audits online enables more information on the farms to be accessed, such as cage size, water quality and other certifications held by the farm.

Loch Arkaig and Loch Garry farms are also certified as Organic by the Soil Association. The Organic Standard requires farms to have an aquaculture management plan with details of diseases, treatments and methods of application including date and length of treatment[34]. Allopathic drug treatments may be used for a maximum of two treatments a year with the exception of vaccines, and parasite treatments may be used to a maximum of twice per year with prior approval. Formaldehyde use was recorded 4 times in 2018 and 3 times in 2019 at Loch Arkaig, however there is no publicly accessible information through the Soil Association on certified farms, apart from an online register, so it is unknown if the use affected the Organic status.

Publicly accessible data on freshwater finfish farms is extremely limited, including those certified by the ASC and Soil Association. The details of how use and environmental levels of formaldehyde are monitored and ultimately regulated within Scottish aquaculture therefore remain unclear.

3. Risks Associated with Formaldehyde Use in Aquaculture

3.1 Personnel Safety

Exposure to formaldehyde has been associated with numerous human health conditions, ranging from mild irritation of the eyes and nose to nervous system, kidney and liver damage, and multiple forms of cancer[35 36]. To prevent damage from exogenous formaldehyde, organisms rely on the enzyme alcohol dehydrogenase 5 (AHD5) converting formaldehyde into formate, a less reactive molecule used for nucleotide biosynthesis. A repair system, known as the Fanconi Anemia pathway, is also used to provide additional protection and alleviate any DNA damage caused by formaldehyde exposure[11].

Human exposure to anthropogenic sources of formaldehyde can take place through inhalation, ingestion and dermal absorption[36 37]. Inhalation often occurs in occupational settings that use or produce formaldehyde, vapour release from formaldehyde-containing products in indoor environments, or through outdoor air pollution, such as from industrial emissions and car exhaust fumes[38]. For indoor air, the World Health Organisation (WHO) provides a guideline of a 0.1mg/m^3 formaldehyde concentration to ensure no observed adverse effects[37].

As most living organisms produce formaldehyde, consumption of products such as fruits, vegetables, meats, fish and dairy also results in increased exposure. Levels vary greatly across food products, with recorded values of 0.1-0.3mg/kg in milk, to over 200mg/kg in some fish species[39]. Formaldehyde is also used as a treatment for some animal feeds, although such contributions have been found to be negligible to overall human oral exposure. According to the European Food Safety Authority (EFSA), daily oral exposure of formaldehyde from consumption of animal or plant-based food is believed not to exceed 100mg/kg per day.

Given the aforementioned human health risks associated with exposure to formaldehyde, knowledge of suitable precautionary methods, including use of appropriate personal protective equipment (PPE), is essential to ensure the safety of workers who regularly handle formalin. Formalin solutions must also be stored in sealed containers and in well ventilated areas to reduce exposure to formaldehyde fumes and subsequent irritation of the nose, eyes and lungs.

Individuals may develop a sensitivity to formaldehyde following repeated exposure, in which case they are to refrain any further handling of the chemical[13]. HSE has a role in relation to the health and safety of the workforce and has established workplace exposure limits for formaldehyde[40].

3.2 Risks to Fish Stock

3.2.1 Formalin Treatments

A 2018 review of current literature concluded the potential impacts of formaldehyde exposure on target fish species to be highly variable, with the **most commonly reported adverse effects to be damage to fish gills and changes to mucous cells**[12]. A 2004 study observing the impacts of formalin exposure on rainbow trout fry recorded proliferation of mucous cells after a limited exposure to formalin treatment (50mg/L, 1hr). Higher concentrations (200-300mg/L, 1hr) or reduced concentrations over a longer time period (24hrs), resulted in decreased mucous cell density. Blebbing[c] of epithelial cell membranes was also observed, as well as dilated openings of mucous cells, indicating increased mucus release[41].

Some studies have also recorded toxic impacts such as low blood chloride ions (Hypochloremia), reduced blood pH, increased blood haemoglobin and increased plasma protein concentrations[42]. Other studies have found there to be limited to no significant effects, for example a 1988 study exposing common carp fry to formalin at 25, 50 and 75mg/L for 8 weeks continuously, observed no histological changes in gills, liver, spleen, kidney, intestine, skin or muscle[43]. However, their results did indicate a reduction in the average growth of carp fry by the end of the study. They concluded formalin concentrations of between 25-50mg/L to be safe for use unless exposure exceeded 4 weeks.

The 2018 review concludes **differences in experimental conditions to be a significant factor in the variation of results, re-emphasising the importance of individual site conditions in determining appropriate treatment levels**[12]. Misuse of formalin has been shown to have devastating consequences. In October 2017 the Fish Health Inspectorate (FHI) recorded that an accidental overdose of formalin at Mowi's Glenfinnan salmon farm in Loch Shiel caused 1,343 mortalities in a pen containing 75,000[44]. The reported cause was due to 'human error (dosing pump not working correctly)'.

Box 4. Potential impacts of formaldehyde on target fish[12 41 42 43 44] .

Potential impact of formaldehyde on target fish include:

- Damage to fish gills;
- Changes to mucous cells: dilated openings, increased mucous release;
- Blebbing[c] of epithelia cell membranes;
- Low blood chloride ions;
- Reduced blood pH;
- Increased blood haemoglobin;
- Increased plasma protein concentrations;
- Reduction in average growth of fry;
- Mortality.

[c] The bulging out of a part of a cell below the plasma membrane or expansion of air-filled tissue.

3.2.2 Methanol Toxicity

The stabilising agent used in formalin treatments, methanol, has been shown to have numerous toxic impacts on both fish and crustaceans, which gives additional cause for concern.

Researchers have found that a reduction in growth and fecundity[d] of fish occurs in ninety-day chronic toxicity tests at 47.49mg/L or higher concentrations of methanol[45]. Between the lower concentrations of 15.4g/L to 29.4g/L, the ninety-six-hour LC_{50} values for fish were found to vary[e]. A further study reported relatively high sensitivity of the crustacea, *Moina micrura*, to methanol[46]. Ninety-six-hour acute toxicity tests determined the LC_{50} for *Moina micrura* to be 4.82g/L, significantly lower than that determined for other species. The study authors therefore suggested **impacts on food chains and community function of aquatic ecosystems could be observed at relatively low concentrations of methanol exposure.**

Although methanol is quickly degraded in the environment by photo-oxidation and biodegradation processes, concern remains for the long-term impacts and recovery of an ecosystem following lethal or sub-lethal exposure[12 46].

There appears to be no data available on any potential impacts of methanol exposure relating to formalin use in aquaculture.

There is also no Environmental Quality Standard (EQS) for methanol determined by SEPA in Scottish water bodies[32].

In response to the numerous risks associated with formalin use on fish stock, it is repeatedly advised that:

- treatments be carefully calculated in relation to the specific conditions of the site in question;
- fish behaviour be monitored throughout the entirety of bathing periods;
- treatments be only used when absolutely necessary[12 13].

3.3. Impacts on Water Quality

The impact of formalin on water quality can be considered in two separate instances; the impact on water used within aquaculture systems, and the impact of formalin-treated effluent on water bodies in the natural environment. Each are discussed below.

3.3.1 During Treatments

Formalin can directly reduce dissolved oxygen levels within a given waterbody[12 47]. For every 5mg/L of formalin added to an aquatic waterbody, 1mg/L of dissolved oxygen is removed[13]. When it is considered that standard oxygen solubility[f] in freshwater is only 8.3mg/L and even lower in seawater, adequate aeration during formalin treatments is therefore essential to ensure stable oxygen levels are maintained[12]. Oxygen deficient water can inflict severe stress on fish, usually displayed by gatherings at the surface or at water inlets to avoid suffocation[48].

[d] The ability to produce an abundance of offspring.

[e] LC_{50} relates to the concentration able to kill 50% of exposed organisms.

[f] At 25°C, in equilibrium with air at atmospheric pressure.

3.3.2 Reused and Recirculated Water

Semi-closed and closed circuits such as Recirculating Aquaculture Systems (RAS) rely partially on the recirculation of used water. In such cases, water must first be treated to remove harmful biological waste, such as urea, ammonia and nitrites before re-entering the system. This is in-part achieved through biofiltration[12].

Biofilters are structures used to house aerobic, nitrifying bacteria. These bacteria facilitate the conversion of ammonia and nitrite into nitrate, a compound considered to be safer for exposure to fish within reasonable levels[47]. Formalin however has been found to interrupt this process in some cases[49].

As the nitrifying bacteria involved in biofiltration are aerobic, formalin can inhibit the conversion of ammonia and nitrites to nitrates by reducing the availability of oxygen. Studies have found low dissolved oxygen levels to greatly impede the oxidation of nitrites to nitrates, although the effects appear less for the oxidation of ammonia[50 51]. Formalin also acts as a bactericide and so can impact the microbial activity of the biofilters, similarly obstructing nitrification. Bath treatments of formalin at varying concentrations and exposure lengths do not affect ammonia oxidation but greatly reduce nitrite oxidation rates in treated versus untreated water, with nitrite concentrations increasing in water exposed to formaldehyde for 1 hour at concentrations of 40mg/L or more[47]. In the presence of ammonia, formalin can also react to produce imines ($HN{=}CH_2$) and hexamethylenetetramine [$(CH_2)6N_4$] as alternative end products[12]. Both of these products are believed not to cause harm to fish, however data in this area is limited[11 52].

3.3.3 Effluent Release into Natural Environment

Formalin breaks down quickly in the natural environment. It readily reacts with oxygen to produce formic acid, which in turn is broken down into carbon dioxide and water, through oxidation, as shown:

$$2H_2C{=}O + O_2 \; > \; 2HCOOH$$
$$HCOOH + O_2 \; > \; CO_2 + H_2O$$

This lack of persistence means formalin is not associated with bioaccumulation. Most research has therefore been focused on first generation impacts[12] (see section 3.2). This breakdown process of formalin, however, also results in a depletion of dissolved oxygen levels[12 53]. Combined with formalin's function as an algaecide, meaning less oxygen can be replenished through photosynthesis, this raises concern over its potential impacts on the surrounding ecosystem function (see section 3.3.1). Therefore it is repeatedly advised for formalin not to be used in pond aquaculture, where water volumes are low and flow rates are slow, and for sites that do use formalin to be well aerated[12 13].

Low dissolved oxygen levels can result in changes to entire ecosystem structures and function. Depending on severity, more mobile species may abandon sites with low dissolved oxygen levels, whilst benthic invertebrates begin to display abnormal behavioural traits and in extreme cases, may undergo mass die-offs. This can ultimately lead to a reduction in species diversity and potential dominance of a site by only a few well adapted species[54].

It is well understood that aquacultural practices in themselves have a propensity to reduce dissolved oxygen levels due to the biodegradation of associated waste material[55, 56]. It is also predicted that **rising global temperatures may result in an increased frequency and severity of anoxic conditions in aquatic environments[54, 57] . The additional pressure inflicted on ecological communities by formalin treatments should therefore be given serious consideration.**

The direct impacts of formalin, and methanol, residue give cause for concern as described in sections 3.2.1 and 3.2.2. SEPA provide Environmental Quality Standards (EQS) for formaldehyde in freshwater only, which are classified as non-statutory[32] (see section 2.3). No guidance is provided for formaldehyde levels in marine sites, or methanol levels at both freshwater and marine sites and so these are similarly understood not to be monitored. Formaldehyde and methanol are also not listed under Environmental Quality Standards or the List of Priority Substances under the EU Water Framework Directive[58].

It is understood that formalin is predominantly used in freshwater farms to treat fungal infections, the main type of which is not saltwater tolerant. There are a small number of marine fish farms with old permits that still include formalin. These are progressively being identified and formalin being removed from permits.

4. Formaldehyde Removal and Alternative Treatments

4.1 Formaldehyde Removal Treatments

Some estimates suggest the half-life of formaldehyde under natural environmental conditions to be 36 hours[59, 60]. However, it is noted that the surrounding parameters, such as temperature, oxygen availability and microbial activity, can lead to significant variations in degradation rates[11]. Formalin removal treatments can therefore be employed to help reduce formaldehyde levels in water effluent before being released into the environment. A desired formalin removal process should be effective, low cost and cause no detrimental impact to aquaculture practices or the wider environment. While such processes are not stipulated as mandatory, any producers are required to meet the discharge limit specified as a condition of their permit, therefore may need to use a formalin removal treatment. Common formalin removal treatments are aeration, biodegradation and biofiltration.

Aeration is a physical process where levels of oxygen in the water are increased to promote oxidation of formaldehyde into CO_2 and water. A study to assess the impact of aeration on formaldehyde-treated seawater found that for seawater containing 25-200mg/L of formalin it reduced the time to reach minimum detection limits (0.05mg/L) from within 8-19 days to within 6-10 days[61].

Biodegradation of formaldehyde may occur naturally in aquatic environments and can be promoted through use of settlement tanks, which allow the water to rest for a period of time before being released. **The rate at which natural degradation of formalin occurs is influenced by temperature and oxygen availability**, as well as further reduction through oxidation reactions. At 20^{o}C, the half-life of formaldehyde under anaerobic conditions was found to be twice that under aerobic conditions, with complete degradation occurring within 30 hours under aerobic conditions[62]. Under anaerobic conditions at 8^{o}C, formaldehyde levels remained for 3 days, before gradually reducing and being completely lost over the subsequent 3 days.

Biofiltration can reduce concentrations of formalin through the reaction processes previously described (see 3.3.2). The increased degradation rates with increased temperature have been found to lead to complete removal of formaldehyde through use of a biofilter within 32-35 hours at 15°C, with the result that accurate calculations of degradation rates from biofilters can be made to ensure sufficient formaldehyde removal in effluent water[63]. Research on biofiltration in recirculation aquaculture systems has found that regular doses of formalin at low concentrations significantly increased removal rates[64]. Therefore a **higher frequency of treatment with lower concentrations of formalin is preferable to a lower frequency of the treatment at higher concentrations**.

Other treatments of formalin removal include chemical neutralization and Advanced Oxidation Processes (AOPs).

Chemical neutralization can be simple and effective, although expensive and in some cases requires follow-up pH treatments. In addition neutralized solutions may be more harmful to some aquatic species than formalin-treated effluent[65].

AOP generally refers to a set of procedures designed to remove organic waste from water through reactions with hydroxyl radicals (·OH). These usually involve use of ozone (O_3), hydrogen peroxide (H_2O_2) and/or UV light, and are generally targeted at formaldehyde concentrations higher than the 100-10,000mg/L expected from aquaculture effluent[12]. The AOPs with the greatest degradation rates have reduced the highest concentrations of formaldehyde (1,200-12,000mg/L) by 98% [66].

It is worth noting that methanol, used as a stabilising agent in formalin solutions, can act as an inhibitor by competing with formalin for hydroxyl radicals and may therefore impact treatment outcomes[12].

4.2 Alternatives to Formalin

With concern over the human health risks and potential environmental harm associated with formaldehyde use, numerous alternatives have been investigated. Hydrogen peroxide and peracetic acid are amongst those most referenced in current literature and are discussed below.

Scottish regulations on the use of authorised chemicals have been designed to comply with the EU Water Framework Directive and the Dangerous Substances Directive. The latter mandates a requirement to impose standards and safety factors on all chemicals discharged into the marine environment and should be in place regardless of how rapidly a chemical is deemed to degrade in the environment. As far as possible, a precautionary approach should be taken and use of chemical treatments minimised. **Where treatments are repeatedly required, the contributing factors to their use should be examined, in particular whether the siting of the farm has a role in disease or parasite outbreaks.**

As well as chemical disinfectants, best practice methods for managing aquaculture sites can help to reduce the frequency of outbreaks, and therefore the need to use formalin. These include routine sanitation and biosecurity measures such as regular deep cleaning of a site and its equipment, limiting access for visitors and non-essential vehicles, and ensuring adequate PPE for all staff and visitors[67].

4.2.1 Hydrogen Peroxide

Hydrogen peroxide (H_2O_2) is already used in Scottish salmon farms as an immersion bath treatment, similar to formaldehyde. It can be used to treat numerous common bacteria, fungi and parasites, including sea lice and *Saprolegnia*[68]. As with formaldehyde, hydrogen peroxide is highly reactive and readily breaks down into water and oxygen[g].

An environmental risk assessment for its use in US aquaculture determined it to constitute 'no significant threat to the environment, the populations of organisms residing therein, or public health and safety when present at or less than 0.7mg/L in receiving waters' [69]. In the UK, hydrogen peroxide is similarly considered to be low environmental risk and has not been assigned an EQS[4 32]. There is also currently no data publicly available on its use in Scottish salmon farms or synthesis of annual usage, per farm or collectively as a country[4].

Despite its lack of persistence, some concern over the impacts of hydrogen peroxide to both target and non-target species remains. Research has shown **hydrogen peroxide efficacy and toxicity vary depending on fish species, age and size, as well as with differences in environmental parameters**[70]. Correlation between toxicity of hydrogen peroxide and lifecycle stages of rainbow trout indicates larger fish to be more sensitive, and the general **toxicity of hydrogen peroxide increases with increasing water temperature**[71]. Salmon observed harmful effects from hydrogen peroxide treatments on the mucosal barriers of the gills, skin and gut health of the fish studied[72].

Recent research shows that sublethal concentrations of hydrogen peroxide could increase the risk of predation on a non-target species by impairing its response to predation, and prolonged (one hour) exposure to 10% of recommended treatment levels (170mg/L) was lethal[73]. Therefore **the current 'safe' values determined for hydrogen peroxide underestimate the potential impact on non-target species**.

4.2.2 Peracetic Acid

Peracetic acid (PAA) is considered an alternative to formalin treatments in aquaculture. It has been found to effectively control common parasites and fungal outbreaks, including white spot disease and *Saprolegnia*, at very low concentrations, and breaks down quickly in the environment.

PAA is far more potent than hydrogen peroxide as both an antimicrobial and an antifungal[74]. Consequently, the necessary PAA concentrations for an effective treatment are significantly less than that of hydrogen peroxide; often between 0.3-1.5mg/L[75]. This, combined with an estimated half-life of less than 30 minutes for both freshwater and marine environments[h], results in any residual PAA being very low, to non-existent[75 76 77]. When in water, PAA degrades into hydrogen peroxide and acetic acid, which then break down into water, oxygen and carbon dioxide[78]. PAA is therefore deemed to be an ideal, environmentally neutral treatment option.

However, the rapid breakdown of PAA can make effective treatments difficult to achieve. Currently two treatment options are suggested; a continual low dose exposure or regular repeated exposure, referred to as 'pulse' treatments[74]. In both treatments, extremely low PAA concentrations were found to induce mild oxidative

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[g] Estimated to degrade by 67% after 7 days at 15°C[3]

[h] Approximate half-life of PAA in freshwater at concentrations of 2mg/L

stress to fish[79]. With continuous treatments the lack of recovery period experienced was thought to result in a significant reduction of antiprotease activity in serum, implying a potential risk of chronic inflammation. There is also some concern over the use of hydrogen peroxide as a common stabilising agent in commercial PAA, given its slower degradation rate and potential toxicity (see 4.2.1)[80].

Although it is recognised that further research is still needed to optimize PAA treatments and ensure safe use for both target and non-target species[74 75 80], **the low concentration requirements and rapid decay of PAA make it a potentially promising formalin alternative**.

5. Recommendations and Concluding Remarks

Aquaculture makes a significant contribution to the Scottish economy and so it is understood that measures are required to protect the industry from costly disease outbreaks, as well as to ensure the health and wellbeing of its stock. However, Fidra believes there should be greater transparency between the industry and the public.

Information on all chemicals used in fish farming, including quantities, frequency of use and methods of regulation and enforcement, should be made easily accessible. Due to the potential risks from the chemical treatment discussed in this report, Fidra believes that statutory EQS values should be provided for formaldehyde, methanol and hydrogen peroxide, with further research completed into the wider ecological implications of their use and potential impacts of rising water temperatures. Best practice for these chemicals, including limits to their use, should be clearly defined, with investigation and implementation of alternatives that have lower environmental impact and are safer to users remaining a top priority.

One of Fidra's main recommendations is the development of an accessible 'sustainability dashboard' on which data already collected for regulatory purposes and published on the Scotland Aquaculture website[81] and by the Fish Health Inspectorate[82] is presented in a comprehensive manner that can be accessed at individual farm level. However, most of the data presently published in turn focusses on the marine environment around the net pens, with very little detail accessible for the farms in freshwater lochs. A much-publicised mitigation for the impacts of open net farms in marine waters is to grow the smolts to a larger size in freshwater where they will not suffer from sea lice, and then transfer them to marine net pens for a shorter spell[83]. Originally devised for smolt raised in land-based recirculating aquaculture systems (RAS), this is intended to minimise the environmental impact of farming salmon in open net pens. However, Scotland's salmon farming industry predominantly uses open net pens in freshwater lochs for rearing smolt. A longer freshwater residence time would increase the risk of disease which may then require the use of chemical treatments such as formaldehyde.

It is imperative that increased transparency and accessibility of salmon farm data applies to freshwater as well as marine sites, for example through a 'sustainability dashboard'.

In the absence of a 'sustainability dashboard' on which data on all aquaculture sites is accessible to farm level and comprehensive, the only way to access such data is through Freedom of Information (FOI) requests, or if the site is Aquaculture Stewardship Council (ASC) Certified through the audits published on the ASC website. In both cases the information remains limited.

Alongside greater transparency **there is a need for the legislation, regulation and enforcement around chemical treatments to be revised, to ultimately deliver statutory EQS values for formaldehyde**, as well as for methanol and hydrogen peroxide.

The use of chemicals in open net pen farms is inherently problematic to monitor due to the lack of a point source such as a pipe outlet. By comparison, Denmark has established statutory EQS for formaldehyde and hydrogen peroxide[84], for which effective monitoring is possible due to more than half of Danish freshwater Atlantic salmon aquaculture occurring in RAS. It should be noted that even with statutory EQS in place, the cumulative impact of several farms discharging into the same water body needs to be taken into consideration.

A precautionary approach should be taken and use of chemical treatments minimised, while those that are used should have established statutory EQS.

If regular use of chemical treatments is occurring at some sites and not at others, the suitability of those sites should be examined and monitored with the potential to close or relocate the farm. In relation to farm siting, the potential impacts of discharges on protected areas should also be taken into consideration. In the example of the farms in Figure 4, each of Glenfinnan, Loch Garry and Loch Lochy is situated within or close to one or more of the following; Site of Special Scientific Interest, Special Area of Conservation, Special Protection Area or National Scenic Area[85].

Based on this report, Fidra makes 4 recommendations on the use of chemicals and formaldehyde in particular, in both marine and freshwater aquaculture sites (Box 5).

Box 5. Recommendations on chemical use in marine and freshwater aquaculture:

1) Information on all chemicals used in both marine and freshwater aquaculture, including quantities, frequency of use and methods of regulation and enforcement should be published in a publicly accessible and comprehensive database, or 'sustainability dashboard';

2) Statutory EQS values need to be established for formaldehyde, methanol (a common stabilising agent of formalin) and hydrogen peroxide (an alternative treatment);

3) Best practice for these chemicals, including limitations, should be clearly defined, with further research completed into the wider ecological implications of their use and potential impacts of rising water temperatures;

4) Investigation and implementation of safer alternatives should remain a top priority, with incentives towards alternative treatments or mitigation actions, such as ensuring farms are in suitable sites that are not in protected areas and can support the discharges from open net pens, and if sites are unsuitable taking actions such as installing semi-closed or closed containment, or closing farms and/or moving to a more suitable site.

References

[1] Scotland Food and Drink. https://aquaculture.scot/. *Aquaculture 2030.* Retrieved from https://aquaculture.scot/.
[2] SSPO (2021) Post-Brexit export problems cost Scotland's salmon farmers £11 million. *SSPO Press Release*, https://www.scottishsalmon.co.uk/news/press-release/post-brexit-export-problems-cost-scotlands-salmon-farmers-ps11-million.
[3] Black, K. & Hughes, A. (2017) *Future of the Sea: Trends in Aquaculture*. Foresight, Government Office for Science. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/635209/Future_of_the_sea_-_trends_in_aquaculture_FINAL_NEW.pdf
[4] SAMS Research Services Ltd. (2018) *Review Of The Environmental Impacts Of Salmon Farming In Scotland.* 02468_0001, Issue 01, 24\01\2018.
[5] Shepherd, C.J. and Bromage, N.R. (1988) *Intensive fish farming.* Blackwell Scientific Publications Ltd.
[6] Shinn, A.J., Pratoomyot, J., Bron, J., Paladini, G., Brooker, E. and Brooker, A. (2015) Economic impacts of aquatic parasites on global finfish production. *Global Aquaculture Advocate*, **9**, 58-61
[7] Wallace, I. S., P. McKay, and A. G. Murray (2017) A historical review of the key bacterial and viral pathogens of Scottish wild fish. *Journal of Fish Diseases*, **40**, 1741-1756.
[8] Biological Dictionary (2017) Formaldehyde. *Biological Dictionary.* Retrieved from https://biologydictionary.net/formaldehyde/.
[9] Chemical Safety Facts (2021) Formaldehyde. *Chemical Safety Facts.* Retrieved from https://www.chemicalsafetyfacts.org/formaldehyde/.
[10] Aronson, J.K. (2015) *Meyler's side effects of drugs: the international encyclopaedia of adverse drug reactions and interactions.* Amsterdam, Netherlands: Elsevier.
[11] Reingruber, H. & Pontel, L.B. (2018) Formaldehyde metabolism and its impact on human health. *Current Opinion in Toxicology*, **9**, 28-34. https://doi.org/10.1016/j.cotox.2018.07.001
[12] Leal, J.F., Neves, M.G.P., Santos, E.B. and Esteves, V.I. (2018) Use of formalin in intensive aquaculture: properties, application and effects on fish and water quality, *Reviews in Aquaculture*, **10**, 281-295.
[13] Francis-Floyd, R. (1996) *Use of formalin to control fish parasites*. Cooperative Extension Service, Institute of Food and Agriculture Sciences, University of Florida.
[14] University of Aberdeen (2021) Risk factors for escalating saprolegniosis outbreaks in salmon farms (RIFE-SOS). *UK Research and Innovation .* Retrieved from https://gtr.ukri.org/projects?ref=BB%2FP020224%2F1.
[15] El-Sayed, A-F. M. (2020) Chapter 9 - Stress and diseases. In Editor, El-Sayed, A-F. M. (ed.), *Tilapia Culture (Second Edition)*. Academic Press, pp 205-243. https://doi.org/10.1016/B978-0-12-816509-6.00009-4.
[16] Durborow, R.M., Wise, D.J. and Terhune, J.S. (2003) *Saprolegniasis (winter fungus) and branchiomycosis of commercially cultured channel catfish.* Southern Regional Aquaculture Center. SRAC Publication No. 4700.
[17] Benchmark (2017) Cross-sector collaboration to boost Scottish salmon. *Benchmark plc.* Retrieved from https://www.benchmarkplc.com/news/cross-sector-collaboration-to-boost-scottish-salmon/.
[18] Just Food UK (2002) Use of malachite green banned in fish farming. *Just Food .* Retrieved from https://www.just-food.com/news/use-of-malachite-green-banned-in-fish-farming_id71140.aspx#:~:text=The%20use%20of%20a%20common,the%20product%20with%20immediate%20effect.
[19] Tedesco, P., Fioravanti, M.L. and Galuppi, R. (2019) In vitro activity of chemicals and commercial products against *Saprolegnia parasitica* and *Saprolegnia delica* strains. *Journal of fish diseases*, **42**, 237-248. DOI: 10.1111/jfd.12923
[20] SSPO (2020) What is formalin. *Scottish Salmon Producers Organisation .* Retrieved from https://www.scottishsalmon.co.uk/facts/faqs/fish-health-welfare/what-is-formalin#:~:text=Formaldehyde%20is%20used%20to%20protect,in%20almost%20all%20freshwater%20environments.

[21] SEPA (2020) *SEPA Position Statement: Cress (50% bronopol) use in finfish aquaculture.* Retrieved from: https://www.sepa.org.uk/media/433428/baseline-survey-and-monitoring-plan-design.pdf.
[22] SEPA (2021) Medicines and chemicals. *SEPA.* Retrieved from. https://www.sepa.org.uk/regulations/water/aquaculture/medicines-and-chemicals/
[23] Health & Safety Executive (2021) Biocides: The basics. *Health & Safety Executive.* Retrieved from. https://www.hse.gov.uk/biocides/basics.htm.
[24] Marine Scotland (2014) *Aquaculture Science & Research Strategy.* Retrieved from https://www.gov.scot/publications/mgsa-science-research-working-group-aquaculture-science-research-strategy/pages/32/
[25] DEFRA (2015) Changes to Formaldehyde (Formalin) rules. *Changes to Formaldehyde (Formalin) rules.* Retrieved from https://www.gov.uk/government/news/changes-to-formaldehyde-formalin-rules.
[26] VMD (2021) Product Information Database. Retrieved from https://www.vmd.defra.gov.uk/productinformationdatabase/.
[27] British Veterinary Association (2021) *Guidance on the use of formaldehyde in aquaculture.* Retrieved from https://www.bva.co.uk/media/4036/guidance-on-the-use-of-formaldehyde-in-aquaculture-2021.pdf.
[28] ENDS Report (2020) Formaldehyde use in Scottish fish farms raises pollution concerns. *Formaldehyde use in Scottish fish farms raises pollution concerns.* Retrieved from https://www.endsreport.com/article/1684367/formaldehyde-use-scottish-fish-farms-raises-pollution-concerns.
[29] Scottish Government (2020) Field trials of Imidacloprid (Ectosan/BMK08) by the salmon farming industry: EIR release. Retrieved from https://www.gov.scot/publications/foi-202000038615-2/.
[30] SEPA (2021) Permitted Substances Working Plan. Retrieved from https://www.sepa.org.uk/media/115683/fish-farm-manual-permitted-substances-working-plan.pdf.
[31] ECHA (2008) Guidance on information requirements and chemical safety assessment. Retrieved from https://echa.europa.eu/documents/10162/13632/information_requirements_r10_en.pdf.
[32] SEPA (2020) *Supporting Guidance (WAT-SG-53) Environmental Quality Standards and Standards for Discharges to Surface Waters.*
[33] Aquaculture Stewardship Council (2021) Find a Farm. Retrieved from https://www.asc-aqua.org/find-a-farm/.
[34] Soil Association (2020) Soil Association Standards Aquaculture. Retrieved from. https://www.soilassociation.org/media/18614/aquaculture-standards.pdf.
[35] Nowshad, F., Islam, M.N. & Khan, M.S. (2018) Concentration and formation behavior of naturally occurring formaldehyde in foods, *Agriculture & Food Security*, **7,** 17.
[36] National Toxicology Program, NTP (2016) *Report on Carcinogens*, 14th Edition; Research Triangle Park, NC: US Department of Health and Human Services, Public Health Service. Retrieved from https://ntp.niehs.nih.gov/go/roc14
[37] World Health Organization. Regional Office for Europe. (2010). *WHO guidelines for indoor air quality: selected pollutants*. World Health Organization, Regional Office for Europe. https://apps.who.int/iris/handle/10665/260127
[38] World Health Organization (2002) *Concise International Chemical Assessment Document 40. Formaldehyde.* World Health Organization, Geneva. Retrieved from https://www.who.int/ipcs/publications/cicad/en/cicad40.pdf
[39] European Food Safety Authority (2014) Endogenous formaldehyde turnover in humans compared with exogenous contribution from food sources, *EFSA Journal*, **12,** 3550.
[40] HSE (2020) EH40/2005 Workplace exposure limits. TSO, London, 61 pp. https://www.hse.gov.uk/pUbns/priced/eh40.pdf
[41] Buchmann, K., Bresciani, J. and Jappe, C. (2004) Effects of formalin treatment on epithelial structure and mucous cell densities in rainbow trout, Oncorhynchus mykiss (Walbaum), skin, *Journal of Fish Diseases*, **27**, 99-104.

[42] World Health Organization (1989) *International Program on Chemical Safety, Environmental Health Criteria 89: Formaldehyde.* World Health Organisation, Geneva. Retrieved from http://www.inchem.org/documents/ehc/ehc/ehc89.htm

[43] Chinabut, S., Limsuwan, C., Tonguthai, K. and Pungkachonboon, T. (1988) Toxic and sublethal effect of formalin on freshwater fishes. *NACA/WP/88/73, Network of Aquaculture Centres in Asia-Pacific (NACA)*, Bangkok, Thailand.

[44] Fish Health Inspectorate, FHI (2017) Case No 2017-0494 Report . Retrieved from https://www.webarchive.org.uk/wayback/archive/20180517182138/http://www.gov.scot/Topics/marine/Fish-Shellfish/FHI/CaseInformation/caseinfo2017/octdec/20170461-20170512.

[45] Poirier, S.H., Knuth, M.L., Anderson-Buchou, C.D., Brooke, L.T., Lima, A.R. and Shubat, P.J. (1986) Comparative toxicity of methanol and N, N-dimethylformamide to freshwater fish and invertebrates, *Bulletin of environmental contamination and toxicology*, **37**, 615-621.

[46] Kaviraj, A., F. Bhunia, and N. C. Saha. (2004)Toxicity of methanol to fish, crustacean, oligochaete worm, and aquatic ecosystem, *International journal of toxicology*, **23**, 55-63.

[47] Keck, N. and Blanc, G. (2002) Effects of formalin chemotherapeutic treatments on biofilter efficiency in a marine recirculating fish farming system, *Aquatic Living Resources*, **15**, 361-370.

[48] Brown, L.(Ed) (1993) *Aquaculture for Veterinarians: Fish husbandry and medicine*. Pergamon Press Ltd., Oxford, 447 pp.

[49] Yanong R.P.E. (2003) *Fish Health Management Considerations in Recirculating Aquaculture Systems. Part 2: Pathogens*. In Circular 121, Department of Fisheries and Aquatic Sciences, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, 1-8.

[50] Eiroa, M., Kennes, C. and Veiga, M.C., (2004) Formaldehyde biodegradation and its inhibitory effect on nitrification, *Journal of Chemical Technology & Biotechnology: International Research in Process, Environmental & Clean Technology*, **79**, 499-504.

[51] Hanaki, K., Wantawin, C. and Ohgaki, S. (1990) Nitrification at low levels of dissolved oxygen with and without organic loading in a suspended-growth reactor, *Water research*, **24**, 297-302.

[52] MERCK (2021) Hexamethylenetetramine. *MERCK .* Retrieved from. https://www.sigmaaldrich.com/catalog/product/sial/398160?lang=en&region=GB.

[53] Muir, J.F. and Roberts, R.J. (2012) *Recent Advances in Aquaculture: Volume 3.* Portland : Springer.

[54] Friedrich, J., Janssen, F., Aleynik, D., Bange, H.W., Boltacheva, N.A., Çağatay, M.N., Dale, A.W., Etiope, G., Erdem, Z., Geraga, M. and Gilli, A. (2014) Investigating hypoxia in aquatic environments: diverse approaches to addressing a complex phenomenon, *Biogeosciences*, **11**, 1215-1259.

[55] The Scottish Government (2002) Review and synthesis of the environmental impacts of aquaculture. Chapter two the discharge of waste nutrients and their interaction in the wider marine environment. *The Scottish Government. UK Web Archive.* Retrieved from. https://www.webarchive.org.uk/wayback/archive/20150220013202/http://www.gov.scot/Publications/2002/08/15170/9408.

[56] Yakushev, E.V., Wallhead, P., Renaud, P.E., Ilinskaya, A., Protsenko, E., Yakubov, S., Pakhomova, S., Sweetman, A.K., Dunlop, K., Berezina, A. and Bellerby, R.G. (2020) Understanding the Biogeochemical Impacts of Fish Farms Using a Benthic-Pelagic Model, *Water*, **12**, 2384.

[57] European Commission (2015) In situ monitoring of oxygen depletion in hypoxic ecosystems of coastal and open seas, and land-locked water bodies. *European Commission.* Retrieved from. https://cordis.europa.eu/article/id/90958-oxygen-depletion-in-aquatic-ecosystems.

[58] European Commission (2008) Directive on Environmental Quality Standards (Directive 2008/105/EC). *European Commission - Environment .* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0105&from=EN.

[59] Food and Drug Agency, FDA (1995) Environmental Impact Assessment for the Use of Formalin in the Control of External Parasites on Fish*.* W-02-01/Sec#3.10.2.7. Washington. Retrieved from https://animaldrugsatfda.fda.gov/adafda/app/search/public/document/downloadEA/115

[60] Masters, A.L. (2004) A review of methods for detoxification and neutralization of formalin in water, *North American Journal of Aquaculture*, **66**, 325-333.
[61] Jung, S.H., Kim, J.W., Jeon, I.G. and Lee, Y.H. (2001) Formaldehyde residues in formalin-treated olive flounder (*Paralichthys olivaceus*), black rockfish (*Sebastes schlegeli*), and seawater, *Aquaculture*, **194**, 253-262.
[62] Kamata, E. (1966) Aldehydes in lake and sea waters, *Bulletin of the Chemical Society of Japan*, **39**, 1227-1229.
[63] Pedersen, L.F., Pedersen, P.B. and Sortkjær, O. (2007) Temperature-dependent and surface specific formaldehyde degradation in submerged biofilters, *Aquacultural Engineering*, **36**, 127-136.
[64] Pedersen, L.F., Pedersen, P.B., Nielsen, J.L. and Nielsen, P.H. (2010) Long term/low dose formalin exposure to small-scale recirculation aquaculture systems, *Aquacultural Engineering*, **42**, 1-7.
[65] Gearheart, J.M., Masters, A.L. and Bebak-Williams, J. (2006) Application of methods for the detoxification and neutralization of formalin in fish hatchery effluents, *North American Journal of Aquaculture*, **68**, 256-263.
[66] Guimarães, J.R., Farah, C.R.T., Maniero, M.G. and Fadini, P.S. (2012) Degradation of formaldehyde by advanced oxidation processes, *Journal of Environmental Management*, **107**, 96-101.
[67] Hill, B. J., Berthe, F., Lightner, D. V. and Sais, R. E. (2013) Methods for disinfection of aquaculture establishments. *Manual of Diagnostic Tests for Aquatic Animals*, pp.28-39.
[68] Scottish Salmon Producers Organisation (2020) Why is hydrogen peroxide used by salmon farmers? *Scottish Salmon Producers Organisation.* Retrieved from https://www.scottishsalmon.co.uk/facts/faqs/fish-health-welfare/why-is-hydrogen-peroxide-used-by-salmon-farmers#:~:text=Why%20is%20hydrogen%20peroxide%20used%20in%20salmon%20farming%3F,form%20pure%20water%20and%20oxygen.
[69] Schmidt, L.J., Gaikowski, M.P. and Gingerich, W.H. (2006) *Environmental assessment for the use of hydrogen peroxide in aquaculture for treating external fungal and bacterial diseases of cultured fish and fish eggs.* USGS Report.
[70] Yanong, R. (2009) Use of Hydrogen Peroxide in Finfish Aquaculture. *EDIS* 2009 (1). https://journals.flvc.org/edis/article/view/117661.
[71] Rach, J.J., Schreier, T.M., Howe, G.E. and Redman, S.D. (1997) Effect of species, life stage, and water temperature on the toxicity of hydrogen peroxide to fish, *The Progressive Fish-Culturist.*, pp. 41-46.
[72] Braden, L. (2016) H_2O_2 treatment concerns. *Fish Farming Expert .* Retrieved from https://www.fishfarmingexpert.com/article/h2o2-treatment-concerns/.
[73] Escobar-Lux, R.H., Fields, D.M., Browman, H.I., Shema, S.D., Bjelland, R.M., Agnalt, A.L., Skiftesvik, A.B., Samuelsen, O.B. and Durif, C.M., (2019).The effects of hydrogen peroxide on mortality, escape response, and oxygen consumption of *Calanus* spp*. FACETS*, pp. 626-637.
[74] Straus, D.L., Meinelt, T., Liu, D. and Pedersen, L.F. (2018) Toxicity of peracetic acid to fish: variation among species and impact of water chemistry. *Journal of the World Aquaculture Society*, pp. 715-724.
[75] Pedersen, L.F., Jokumsen, A., Larsen, V.J. and Henriksen, N.H. (2014) Promising water treatment practices with peracetic acid products. *D5.1 Technical Note, RobustFish*; Organic RDD 2 programme coordinated by International Centre for Research in Organic Food Systems (ICROFS).
[76] EnviroTech. (2020) Frequently Asked Questions. *Envirotech .* Retrieved from https://envirotech.com/faq/#:~:text=PAA%20is%20highly%20unstable%20in,life%20of%2012%2D%2030%20minutes.
[77] Pedersen, L.F., Meinelt,T. and Straus, D.L.. (2013) Peracetic acid degradation in freshwater aquaculture systems and possible practical implications. *Aquacultural Engineering*, pp. 65-71.
[78] LENNTECH (2021) Disinfectants Peracetic acid. *LENNTECH.* Retrieved from https://www.lenntech.com/processes/disinfection/chemical/disinfectants-peracetic-acid.htm#ixzz6k1GTK6eX.
[79] Liu, D. (2017) *Effect of peracetic acid at low concentrations on fish health and water quality*. Dissertation zur Erlangung des akademischen Grades doctor rerum agriculturarum

(Dr.rer.agr.) eingereicht an der Lebenswissenschaftlichen Fakultät der Humboldt Universität zu Berlin.96 pp.

[80] Chhetri, R.K., Di Gaetano, S., Turolla, A., Antonelli, M. and Andersen, H.R. (2020) Ecotoxicity evaluation of pure peracetic acid (PAA) after eliminating hydrogen peroxide from commercial PAA*. International journal of environmental research and public health*, p. 5031.

[81] http://aquaculture.scotland.gov.uk/default.aspx

[82] Scottish Government (2017) Topics: Marine and Fisheries: Aquaculture: Fish Health Inspectorate (FHI): Publication of Case Information. Retrieved from - https://www.webarchive.org.uk/wayback/archive/20180514154148/http://www.gov.scot/Topics/marine/Fish-Shellfish/FHI/CaseInformation

[83] Bjorndal, T. & Tusvik, A. (2020) Economic analysis of on-growing of salmon post-smolts. *Aquaculture Economics & Management,* **24**, 355-386. https://doi.org/10.1080/13657305.2020.1737272

[84] Miljø- og Fødevareministeriet (2017) Bekendtgørelse om fastlæggelse af miljømål for vandløb, søer, overgangsvande, kystvande og grundvand, BEK nr 1625 af 19/12/2017. https://www.retsinformation.dk/eli/lta/2017/1625

[85] https://sitelink.nature.scot/map