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Review

Lice shielding skirts through the decade: Efficiency, environmental interactions, and rearing challenges

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ABSTRACT

Lice shielding skirts are a preventative measure against salmon lice in Atlantic salmon farming. The skirt is wrapped around the top meters of the net cage to divert the current flow around the cage, and thereby keep the salmon lice out. Despite these skirts being used actively in Norwegian aquaculture for the past decade, there is no standardised way of using them, and therefore type, depth and operating procedures vary between sites. The academic literature on the lice shielding efficiency of these skirts is not extensive and reported efficiency varies across studies and sites with some reporting favourable results, while others find none. Some also report of welfare related issues, with dissolved oxygen levels being the most prevalent, but this too varies across sites and through the production cycle.

The aim of this paper is to provide a comprehensive overview and summary of relevant academic and grey literature from the last decade to identify knowledge gaps that must be filled to achieve optimal use of lice shielding skirts. This paper focuses on three main topics: lice shielding efficiency, interaction with the current flow and rearing challenges. The positive results from some sites indicate that skirts have potential as a tool against salmon lice, however, to create a best practice recommendation for skirt use, more knowledge is necessary on the interaction between skirt and the environment, and sufficient monitoring procedures and decision-making tools must be established.

1. Introduction

The parasitic salmon lice (*Lepeophtheirus salmonis*) are a naturally occurring ectoparasitic crustacean in the North Atlantic and North Pacific Oceans (Finstad et al., 2000; Thorstad et al., 2015; Misund, 2019). These lice are a potential threat for wild salmon, a welfare issue for farmed Atlantic salmon (*Salmo salar*) (Finstad et al., 2011; Thorstad et al., 2015; Forseth et al., 2017), and a significant financial burden for the aquaculture industry, costing the Norwegian aquaculture industry alone approximately 5 billion NOK in 2015 (Abolofia et al., 2017; Iversen et al., 2019; Brooker et al., 2018).

The welfare issues and the high cost in aquaculture have resulted in several different approaches for controlling the lice, which can roughly be divided into three groups: immediate, continuous, and preventative measures (Svåsand et al., 2017; Coates et al., 2021). For the past four decades, immediate chemotherapeutants have been the dominant method (Overton et al., 2019). However, the use is decreasing due to an increase in chemotherapeutants-resistant lice (Aaen et al., 2015) and unwanted environmental impacts such as harming nearby shrimp populations (Bechmann et al., 2019, 2020). As a result, there has been an increase in use of non-chemical immediate treatments such as thermal, fresh water or mechanical (Overton et al., 2019).

Thermal, fresh water and mechanical treatments require handling of the fish in the form of crowding and pumping, which are sources for injuries to the gills, skin, fins, and snout (Svåsand et al., 2017; Noble et al., 2018). Increased handling is also linked with an increased risk of salmon escapes (Thorvaldsen et al., 2015) and increased mortality rates for specific treatments (Overton et al., 2019). For instance, the high mortality rate of 15.5% in the Norwegian salmon industry in 2021 is partially attributed to an increase in the number of mechanical and thermal treatments (Sommerset et al., 2022). An alternative to the immediate treatments is continuous non-chemical treatments that do not require any handling, such as cleaner fish (Imsland et al., 2014, 2018). However, there are strong concerns regarding the welfare of cleaner fish

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(Geitung et al., 2020; Overton et al., 2020; Garcia de Leaniz et al., 2022) and others have also questioned their efficiency (Overton et al., 2020; Barrett et al., 2020a).

Given the negative aspects of the immediate and continuous measures, Barrett et al. (2020b) made an argument for a more prevention-focused louse management. Preventive measures aim to reduce the contact between lice and fish and are the preferable approach economically, environmentally and from a fish welfare perspective (Barrett et al., 2020b). The wide variety of preventive measures can be characterized as heterogenous, and include measures such as on-land production, closed cages, selective breeding, fallowing, functional feeding, geographic spatiotemporal management, manipulation of swimming depth, repellents, and host cue masking (Barrett et al., 2020b).

Included in the preventative measures are the barrier solutions, such as the lice shielding skirts and the “snorkel” cages (Dempster et al., 2009). Shielding skirts are a barrier measure that tries to keep the lice out of the cages by blocking their access to the upper layers of the water column in the cage (Fig. 1). Snorkel cages are also a barrier measure as it keeps the salmon at deeper depths by using cages with net roofs limiting the salmon’s access to the upper water column. To ensure that the salmon can refill their swim bladder, the snorkel cages have a vertical chamber at the centre of the cage, known as the snorkel, providing access to the surface. To protect the salmon from any lice when traversing this area, the snorkel is typically tarpaulin-enclosed, hence combining the two methods (Stien et al., 2016; Oppedal et al., 2017; Wright et al., 2017; Geitung et al., 2019). The use of “snorkel” cages is still quite limited with only a handful of commercially scaled cage trials (Geitung et al., 2019). Shielding skirts on the contrary are today one of the most established “barrier” technologies in Norway and is also used internationally.

Initially, impermeable tarpaulin skirts were mounted around the cage’s sides to increase efficacy of chemotherapeutants during bath treatments against salmon lice (Whyte et al., 2016; Overton et al., 2019). These semi-enclosures did not cover the bottom of the cage net, hence the exact mixture concentration and diffusion of chemotherapeutants were unknown and random due to turbulence and inflow of water, further exacerbating the issues with effectiveness and chemotherapeutant-resistant salmon lice (Volent et al., 2017). In 2011, a new regulation in Norwegian aquaculture stipulated that it should be compulsory for fish farmers to ensure full enclosure of the net-cage during in-cage delousing treatments (Norwegian Ministry of Trade, Industry and Fisheries, 2012). Almost concurrently with these stricter requirements for bath treatments, lice skirts were trialled as a preventive measure (Coates et al., 2021). According to Næs et al. (2012), the concept of using permeable skirts as a preventive measure to avoid salmon lice infestation were discussed back in 2005, approximately 6–7 years before the first trials began in 2011–12.

Shielding skirts today come in several different fabrics and design. The two main categories are impermeable and permeable skirts. Impermeable skirts are typically made of a tarpaulin cloth that block all incoming currents. Permeable skirts are made of a fine mesh fabric with a solidity of roughly 50% that in theory will allow some of the water to pass through while keeping the lice out. Most lice skirts when installed consist of either one large piece with overlap, or two pieces with an overlap on each side of the cage. To assure that the skirts maintain a vertical position in the water column, sinkers are attached to the lower parts of the skirts.

In addition to the skirts made of fabric, some newer cage designs have opted to directly implement “barrier” technology in their designs. For instance, Aquatraz (Midt-Norsk Havbruk AS) has a skirt installed along the upper 18 m of a steel cage structure (Midt-Norsk Havbruk, 2020), and Havfarm 1 (Nordlaks AS) was originally designed to have a steel skirt installed (Jenssen, 2016). There is understandably a limited amount of literature on these new production systems since they are currently under trial, hence they will not be discussed further in this paper.

How skirts are used varies widely between sites. In a small-scale qualitative study, respondents from the Norwegian aquaculture industry shared their anecdotal knowledge and experiences with lice skirts (Misund et al., 2020). The responders indicated that the use of skirts is highly dependent on the environmental conditions at the production site, and that there are different practices between sites regarding choice of skirt depth, when and how to mount, and in which period to use the skirts (Misund et al., 2020). There is as of today no best recommendation available for the use of skirts.

In the available literature surrounding barrier technology there are hardly any sources documenting the use of skirts in other salmon producing countries than Norway and Scotland, and there are no scientific publications on the subject from Scotland yet (A. Currie, personal communication, September 1, 2021). In general, the academic literature is not extensive, and a large portion of the results from full-scale trials are presented in project reports and other grey literature. The aim of this paper is to give a comprehensive overview of the literature from the last decade, both academic and grey literature. This paper is structured into six parts. Following the introductory section, Section 2 describes the design basis of lice shielding skirts on the premise of salmon lice’s biology and behavioural traits. Section 3 discusses the documented lice shielding efficiency of the skirts. Section 4 describes the interaction between skirt and current flow, including current flow reduction, changes to current flow pattern, impact of hydrographical conditions and structural implications. Section 5 describes how the interaction between the skirt and the environment influences the internal rearing environment of the cage. Finally, Section 6 emphasizes the knowledge gaps and what future work is necessary to achieve optimal use of lice shielding skirts.

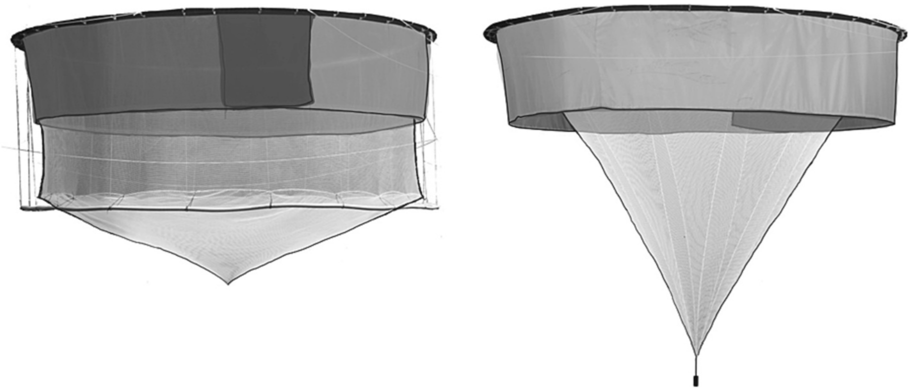

Fig. 1. Illustration of lice-shielding skirts mounted on a cylindrical (left) and conical (right) cage. The skirt on the left is installed as one long piece of fabric, with an overlap in the front.

2. Salmon lice behavioural traits and biology as a premise for barrier technology

The core concept of the lice skirt is to utilise the behavioural traits of the salmon lice to keep them out of the cage volume, specifically their vertical position in the water column. However, the lice's vertical position depends on several variables, including its development stage.

The salmon lice develop through eight life stages, starting with the planktonic non-parasitic nauplius 1 & 2 larvae, before developing into the planktonic infective copepodid stage (Hamre et al., 2013; Crosbie et al., 2020). It is during the infective stage that the lice attach itself to its host and begins to feed of the skin, mucus, and blood (Costello, 2006). The dispersion of the nauplii and copepodid stages is mainly dictated by the ocean currents as it occurs through passive transport (Costello, 2006). Their vertical position on the contrary is controlled through locomotion and sinking (Allen and Lewis, 2013; Crosbie et al., 2019), and is strongly influenced by their environmental preferences.

The vertical migration pattern of nauplii and copepodids in experimental columns has several distinctions. When a salinity step, a halocline, is present both nauplii and copepodid stages aggregate near the halocline depth (Heuch et al., 1995; Crosbie et al., 2019), but they react differently to salinity strength. The non-parasitic nauplii stages avoid salinities below 30 ppt, while the parasitic copepodids are found in water with salinities as low as 16 ppt (Heuch et al., 1995; Crosbie et al., 2019). The nauplii also prefer colder water temperatures, while the copepodids show no preference for temperature (Crosbie et al., 2020).

The two stages show different reactions to light. Early results indicated that copepodids were generally found deeper during the night than the day, while nauplii were less active and less responsive to light (Heuch et al., 1995). However, more recent studies indicate that nauplii also respond to light. When nauplii and copepodids were exposed to light ranging from 0 to 80 μmol m^{-2} s^{-1} for up to 12 h at a time, the nauplii had a stronger response to increasing light intensities, aggregating at the surface (Szetey et al., 2021). The copepodids on the other hand swam upwards independently of light intensity and duration (Szetey et al., 2021).

There is also evidence of differences between lice families. Copepodids are reactive to changes in pressure, swimming upwards towards the surface when the pressure is increased in test tubes (Coates et al., 2020). However, the response of copepodids varied between families, and results suggest that depth response of copepodids may have a genetically inherited basis (Coates et al., 2020).

The different behavioural traits of the nauplii and copepodid indicate that copepodids are motivated by host-finding, while nauplii are driven by survival and dispersal (Szetey et al., 2021). Presumably due to the stage's behavioural drivers and environmental preferences a higher abundance is found in the surface layers during the day (Heuch et al., 1995; Hevrøy et al., 2003). The concept behind "depth-based" and "barrier" technologies has therefore been to minimise host-parasite interaction, specifically by exploiting the vertical migration pattern of the copepodids and their preference for the upper water layers.

3. Lice shielding skirt efficiency

Despite widespread use of lice shielding skirts, scientific documentation of their effects on lice infestations and fish welfare are lacking. There are a few academic publications, but a large portion of available material is in the form of grey literature: project reports, reports from the manufacturers or brief reviews in annual reports from academic institutions (Stien et al., 2018).

When reviewing the literature, the results are not consistent, with some claiming near to no effect of the lice shielding skirts, while others document great results (Table 1). In the first report on the efficacy of permeable lice shielding skirts by Næs et al. (2012), 3 of the 6 cages included in the experiment were equipped with 10 m deep skirts from May until November 2011. The results were promising, with 70% less lice per fish in the shielded cages than in the unshielded (Table 1), however the infestation pressure was relatively low during this study with an average of 0.05 sessile lice during the entire period in the unshielded cages (Næs et al., 2012).

In the following report by Næs et al. (2014) permeable skirts of 6 and 10 m were installed at 6 sites. The duration of the study varied from 2 to 7 months. Five of the sites had both cages with skirts and control cages without skirt, and the last site had skirts installed on all the cages. For the farms where lice were detected, there was a decrease in both sessile and mobile lice when using skirts. Grøntvedt et al. (2018) utilised part of the dataset from Næs et al. (2014), and estimated the weekly reduction of pre-adult and adult male lice to 30% when using permeable plankton

Table 1

Overview over studies (both peer-reviewed and grey papers) that have studied the impact of skirts on lice infestation levels. All studies have used different approaches in finding lice shielding efficiency, with some comparing lice per fish in cages with and without, and others using regression analysis to determine the impact of the skirt. It is the general trend which is of most importance, but max-min reduction is included to give an indication of range of results. Studies with several sites may have different results at each site, so if there are cases of both a reduction and no effect, this is included in the table. The rows containing data from peer-reviewed studies are written in bold and are italicized. The other studies are grey-literature.

			Skirt and preventative measures			Trend lice shielding		
Study	# sites	Duration	Type	Depth [m]	Additional measures	Reduction/No effect	Comparison method	Max./Min Reduction [%]
Næs et al. (2012)	1	30 wks (2011)	Permeable	10		Reduction	With/Without same site	- / 70
Næs et al. (2014)	6	10–14 wks (2012-2013)	Permeable	6 & 10		Reduction	With/Without same site	7 / 83
Grøntvedt and Kristoffersen (2015)	17	9–33 wks (2013–2014)	Permeable	5	Cleaner fish	Reduction/ No effect	With/Without same site	6 / 28
						Reduction/ No effect	Between sites	0 / 80
Stien et al. (2018)	***1***	***15 wks (2014)***	***Permeable***	***10***		***Reduction***	***With/Without same site***	***- / 82***
Grøntvedt et al. (2018)	***5***	***11–21 wks (2012-2014)***	***Permeable***	***6 & 10***		***Reduction/ No effect***	***With/Without same site***	***30% weekly***
Midtlyng et al. (2019)	3	28–66 wks (2017–2019)	Impermeable*	5, 8 & 9	Cleaner fish,	No effect**	With/Without same site	0 / 50**
Bui et al. (2020)	***1***	***56 wks (2016–2017)***	***Permeable***	***6***	***Cleaner fish, functional and submerged feeding, submerged lights***	***Reduction***	***With/Without same site***	***- / ~40***

[*] P.J. Midtlyng, personal communication, December 8, 2021.

[**] With the exception of a short spike during the spring. See text for more info.

skirt.

Other surveys on the use of permeable skirts reported an average decrease of 18% lice infestation for cages with skirts compared to cages without on the same farm (Grøntvedt and Kristoffersen, 2015). And when inspecting the difference between neighbouring farms, where some farms used skirts and others did not, the average reduction in lice infestation was 54% (Grøntvedt and Kristoffersen, 2015). It should however be noted that there were 17 locations included in the study, and the variation of average reduction in lice infestation compared with neighbouring farms varied between 0% to 80%, meaning some farms had no effect of using lice shielding skirts compared with their neighbours (Table 1).

In the scientific study by Stien et al. (2018) a reduction of 82% during a period of 3 months was reported. From May to September in 2014 three of the farm's 10 cages had 10 m deep permeable skirts installed, like those used in Næs et al. (2014). The largest effect of the skirt was seen during the last month of deployment with an average of 0.18 (+/− 0.06) lice per fish in the cages with skirt, and 1.03 (±0.19) lice per fish in the cages without skirt.

However, Midtlyng et al. (2019) saw no effect when using skirts, as did one of the locations in Grøntvedt et al. (2018). In Midtlyng et al. (2019) four locations were mounted with skirts of different lengths for up to a year. On one of the four locations with a 5 m deep skirt a sudden peak in lice infestation indicated that the cages with skirts had a reduction of 50% of lice compared to the cages without skirt. However, the authors concluded that it was not possible to ensure that this result was due to the skirt and not the location of the cages (Midtlyng et al., 2019). As the farm was exposed to strong currents, only the four cages closest to the feeding barge had skirts installed, so the cages with and without skirts were not randomly assigned. On the other locations in the same report, there was little lice pressure throughout the year, and little difference between cages with and without skirts.

In a 13-month long study by Bui et al. (2020) the effect of combining different passive lice management strategies including lice shielding skirts were studied. The site studied had 12 cages, all with cleaner fish, 9 had in addition functional feeding, 6 had additional deep lights and feeding, and 3 of them had lice shielding skirts. The three cages which had cleaner fish, functional feeding, deep lights, and lice shielding skirts had the lowest rate of new infestations (Bui et al., 2020). Interestingly, the cleaner fish in the skirted cages were the least efficient with the smallest number of lice found in their guts (Gentry et al., 2020). It was hypothesized that this was due to reduced interaction between cleaner fish and salmon as the salmon potentially swam deeper due to the submerged lights (Gentry et al., 2020).

Apart from Midtlyng et al. (2019), all the technical reports and studies inspecting lice shielding efficiency, have used permeable skirts (Table 1). There are no studies comparing impermeable and permeable skirts at the same location, so the results with permeable skirts are not necessarily representative for cages with impermeable skirts. The difference in skirt length at the different sites also complicates comparison between studies.

It has been theorized that deeper skirts would have improved efficiency, as studies show that salmon held at 4–8 m and 8–12 m have a lower infestation rate than salmon held at 0–4 m (Hevrøy et al., 2003), and that deeper "snorkel" cages have less lice abundance (Oppedal et al., 2017). It should however be noted that in Oppedal et al. (2017), there were still lice present in "snorkel" cages of 16 m depth. In Næs et al. (2014) the results from several sites were combined and indicated an average reduction of sessile lice of 49% when using 10 m deep skirts, and 28% when using 6 m skirts. However, in Grøntvedt et al. (2018) which used part of the data set from Næs et al. (2014), it was underlined that there was only one farm which had both 6 and 10 m skirts, hence there was not sufficient data to reveal any significant shielding difference between 6 and 10 m skirts.

Although some of the studies have favourable results, it is difficult to ensure that the reduction in lice at each site was only due to the lice shielding skirt. Comparing the studies is also not possible as some studies utilised cleaner fish and deployed the skirt during different periods and durations. Not all sites began production with skirts installed, and it is not certain that the skirt remained on during the entire time in the different studies. When comparing the maximum and minimum reductions in the different documentation, it is also clear that there is a large discrepancy within each study (Table 1). This could be due to low lice pressure, as this makes it difficult to document statistically significant difference between cages with and without skirts, as highlighted by Midtlyng et al. (2019), or site variations.

The study by Bui et al. (2020) exemplifies the difficulties of studying reduction in lice infestation over a longer period, and how the environment may influence the lice shielding effect. The site of the study was near Vindsvik in western Norway, and through the 13 months study, there were periods with influx of freshwater and salinities as low as 5 ppt. This influx of freshwater may both influence the lice behaviour and preferred depth in the water column (Crosbie et al., 2019), but it could also have altered the current flow pattern at the site reducing the skirts' ability to divert the water.

4. Lice shielding skirt and current flow interaction

4.1. Current flow reduction

When the current moves through a net structure, the current speed is reduced (Løland, 1993; Patursson, 2008; Klebert et al., 2013). This reduction is influenced by the solidity of the net (Bi et al., 2013) and is found through both singular cages (Klebert et al., 2015) and entire farms (Winthereig-Rasmussen et al., 2016). A reduction in current speed has a direct impact on both the environment inside and downstream of the cage. Downstream of the cage, the reduced current speed can influence how particles and micro-organisms such as pathogens and zooplankton are dispersed (Klebert and Su, 2020). Inside the cage, the reduction in current speed can impact the dissolved oxygen levels, as the main source for fresh oxygenated water in an Atlantic salmon farm is the physical transport of water through the cage (Wildish et al., 1993; Johansson et al., 2006). A reduction in current speed through the net will force a portion of the water around the cage, rather than through, meaning that less fresh oxygenated water passes through the cage.

In full-scale trials there is a near linear reduction in current speed when measuring the current upstream, inside, and downstream of an empty cage, with 21.5% reduction inside the cage and 35% reduction downstream of the cage (Klebert et al., 2015; Table 2). This reduction is higher when fish is present, for instance in a stocked small-scale cage with a diameter of 4.6 m, the current reduction inside the cage was as high as 31% (DeCew et al., 2013). Which compares reasonably well with the results from Johansson et al. (2014) where the reduction varied between 0 and 50% when the incoming current speed was 20 cm/s (Johansson et al., 2014).

Unsurprisingly the current speed both inside and downstream of a shielded cage is further reduced, and the reduction is also influenced by present biomass. Downstream of an empty cylindrical cage with 10 m deep impermeable skirts the current speed is reduced by 61% (Klebert and Su, 2020). While downstream of a stocked conical cage with a 10 m deep permeable skirt, the current is reduced by 70.4% (Jónsdóttir et al., 2021b).

In a stocked 50 m diameter cage with and without an impermeable lice shielding skirt, the maximum current speed reduction inside the cage was 91% when the skirt was deployed, and 53% when the skirt was removed (Frank et al., 2015). The current was generally quite slow during the trial, but the largest reduction of 91% was seen when the current speed outside of the cage was 13 cm/s (Frank et al., 2015). These results compare well with a more recent study, where the same cage was studied with and without an impermeable skirt and had a maximum reduction of 78.3% when the skirt was deployed, and 44.3% when the skirt was removed (Jónsdóttir et al., 2021a).

Table 2
Overview of reduction in current speed downstream and inside cages from peer-reviewed studies. Studies written in bold and italics are performed in empty cages with no fish present. Inside cage reductions than span both Min. and Max. reduction shows the average reduction as presented in the studies.

				Downstream of cage		Inside cage	
Study	Cage diameter	Skirt type	Length	Distance	Max Reduction	Min. Reduction	Max. reduction
DeCew et al. (2013)	4.6 m	–	–	–	–	31%	
Johansson et al. (2014)	41 m	–	–	–	–	0	50%
Klebert et al. (2015)	***41 m***	–	–	***15 m***	***35%***	***21.5%***	
Frank et al. (2015)	50 m	Impermeable	5 m	–	–	32%	91%
Klebert and Su (2020)	***50 m***	***Impermeable***	***10 m***	***60 m***	***61%***	–	–
Jónsdóttir et al. (2021a)	50 m	Impermeable	6.7 m	–	–	35.5%	78%
		–	–	–	–	19.7%	44.3%
Jónsdóttir et al. (2021b)	50 m	Permeable	10 m	25 m	70.4%	60.8%	92.4%

Interestingly, the study with a permeable skirt installed on a conical cage had a higher maximum reduction of 92.4% inside the cage than downstream (Jónsdóttir et al., 2021b; Table 2). Possible explanations for this were the relatively large fish, and high density in the cage, or the conical shape of the cage. The skirt had been installed around the cage like a cylinder, so when the current increased the skirt was pushed into the cylindrical cage. This change in inclination may have reduced the skirts permeable properties, as an increase in inclination of net panels is known to reduce the flow (Bi et al., 2013).

It should be noted that the methodologies used in these studies vary greatly. Where in the cage the current was measured, for how long, size of cage, size of fish, fish density and method used to determine the reduction in current speed differ. There were also large variations in incoming current speed. In Klebert et al. (2015) the minimum current speed was 0.15 cm/s and the maximum exceeded 0.50 cm/s, while in Jónsdóttir et al. (2021b) and Frank et al. (2015) the current did not exceed 0.15 cm/s. However, all these papers conclude that there is an increased reduction in current speed downstream and insides cages with permeable and impermeable shielding skirts compared to cages without. This reduction in current speed could influence the current flow pattern around the skirt, and thereby alter its preventative efficiency.

4.2. Current flow pattern

In addition to influencing the reduction in current speed, the skirt also influences the current flow pattern within the cage. In one of the first reports on the interaction between lice shielding skirts and the current, a simulation of the current flow around a lice shielding skirt was presented (Lien and Høy, 2011). The simulation was of an impermeable skirt with a diameter of 50 m, without fish and net, and with a stable incoming current of 10 cm/s. The skirt was modelled as a rigid skirt, meaning that there was no deformation. The simulation showed that a large portion of the current was forced around the cage, which would have kept the lice out. However, a proportion of the water was also pushed down, beneath the skirt, and up into the back half of the cage, meeting the downstream area of the skirt. The current was there pushed upwards by the skirt and towards the centre of the cage as illustrated in Fig. 2 (Lien and Høy, 2011). This differed to an unshielded cage, where the current would flow straight through the cage without changing direction.

This change in flow direction within the skirt is observed in full-scale studies, with the current direction being relatively stable when no skirt was deployed but varying up to 100° when the skirt was installed (Frank et al., 2015; Jónsdóttir et al., 2021b). There was little deflection of current direction in Jónsdóttir et al. (2021a), where a shorter skirt of 6.7 m was used compared with the 10 m deep skirt in Frank et al. (2015) and Jónsdóttir et al. (2021b). In Stien et al. (2012) the shielded cage had a 3 m deep skirt and the current direction did not deflect through the cage, except for the current speed a couple of meters from the downstream area of the skirt. In this position the current pointed in the opposite direction, agreeing with the simulations presented in Lien and Høy (2011).

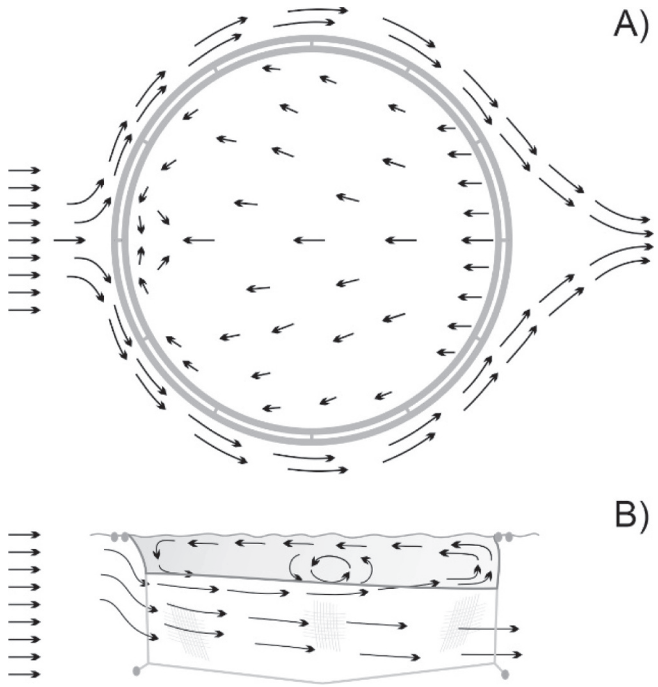

Fig. 2. Current flow pattern interaction with skirt. A) shows the horizontal view of the current flow inside the shielded area. B) shows the cross-section of the cage showing how the current flow differs within the shielded and unshielded part of the cage (Illustration: Zsolt Volent, SINTEF Ocean).

Empty full-scale cages with skirts also show indications of the simulated pattern. In two of four trials when measuring the current speed inside an empty shielded cage, the current speed at two different locations within the skirt volume flowed in the opposite direction to the current beneath the skirt depth (Klebert and Su, 2020). Assuming the current speed and direction measured beneath the skirt volume are representative for the main current direction, this indicates that the current behaved as stipulated by the simulation by Lien and Høy (2011).

To investigate if the lice shielding skirts redirected the current around the cage, full scale trials using fluorescent dye were carried out (Frank et al., 2015). Fluorescent dye was released outside a cage without skirt, outside a cage with skirt, and just inside the skirt and then monitored using an aerial camera. The skirt was 5 m deep, and the dye was released at 2.5 m depth. No blocking effect was observed when the skirt was not installed, and the dye passed through the net and into the stocked cage. After the dye had passed through the net wall it took roughly 3 min for the dye to reach the centre of the cage and was still visible inside the cage after 30 min (Frank et al., 2015).

It was theorized that the reason the dye did not simply pass through the cage was the swimming activity of the fish. Specifically, that the torus swimming pattern created a pumping effect, pushing water out at depths of high biomass, and drawing in water from above the below this point (Gansel et al., 2014; Frank et al., 2015). No indication of this pumping effect was seen in the velocity measurements done in Klebert and Su (2020) when no skirt was deployed. However, there was a weak vertical velocity component towards the surface in both stocked and empty shielded cage trials (Klebert and Su, 2020; Jónsdóttir et al., 2021a). As this effect was seen both with and without fish, it was concluded that this was an effect of the skirt, rather than the fish. It is unclear why the dye remained inside the cage in Frank et al. (2015) when the cage was unshielded.

Dye was also released in two trials outside of the cage with the skirt deployed (Frank et al., 2015). The first trial had relatively high velocity, the two-point measurements of speed outside the cage recorded 13.1 cm/s and 9.5 cm/s respectively, while in the second trial the current speed outside the cage was 4.3 cm/s and 7.6 cm/s. In the first trial there was only a small portion of dye that entered the cage, most of it being redirected around the skirt. In the second trial however, a large portion of the dye entered the cage in the upstream part of the cage before traversing the cage (Frank et al., 2015). Despite using the same cage, the results demonstrate how the current flow pattern around a shielded cage can vary from the simulated flow pattern. It is unclear why the results from the two trials differed, however one potential factor that might explain the variation are hydrographical conditions at the site.

4.3. *Salinity and density gradients affecting skirt deformation*

A temperature or salinity gradient can cause a density difference in the water column. Water with higher salinity and lower temperatures is denser and will position itself beneath water with lower salinity and higher temperatures, causing a gradient in the water column. This is typically caused by either an influx of freshwater from precipitation, nearby rivers, or ice melting, or from the surface water being heated by the sun. A pycnocline is the layer where the density of the water column changes abruptly. Once these layers are established, water moving vertically must overcome an additional buoyancy force added by the density stratification (Imberger, 2012). This can prevent vertical mixing between the layers. It will take more energy to push denser water up into the lighter water layer, hence the presence of a pycnocline will alter how the current flows around the lice shielding skirt (Fig. 3). Furthermore, the layers may behave differently from each other, interacting differently with the skirt depth.

By altering the current flow pattern, a present pycnocline could also influence the lice shielding efficiency, as mentioned in Bui et al. (2020) which observed an influx of freshwater during their study. The presence of a pycnocline is also reported to influence the internal environment conditions of a cage both for unshielded cages (Johansson et al., 2007) and shielded cages (Jónsdóttir et al., 2020), which will be discussed in more detail in Section 5.2. With regards to the study by Frank et al. (2015), it is possible that there was a gradient higher up than the skirt depth. If the dye was then released in the upper layer of the water, it would be difficult to force this lighter water into the heavier water below, forcing more of the water around the cage. However, if the water column was homogenous, more of the water may have been pressed down when reaching the skirt, forcing the dye underneath and into the skirt. Unfortunately, no measurements were done of the temperature and salinity with depth, so it is not possible to determine the cause of the difference.

There are observations of different density within and outside the skirt (Jónsdóttir et al., 2020), and there are reports of sites experiencing deformations caused by these differences. Fish farmers report of lice shielding skirts "Barrelling" or "Hour-Glassing" at farms (Fig. 4). "Barrelling" is when the skirt is forced out in all directions at a certain depth,

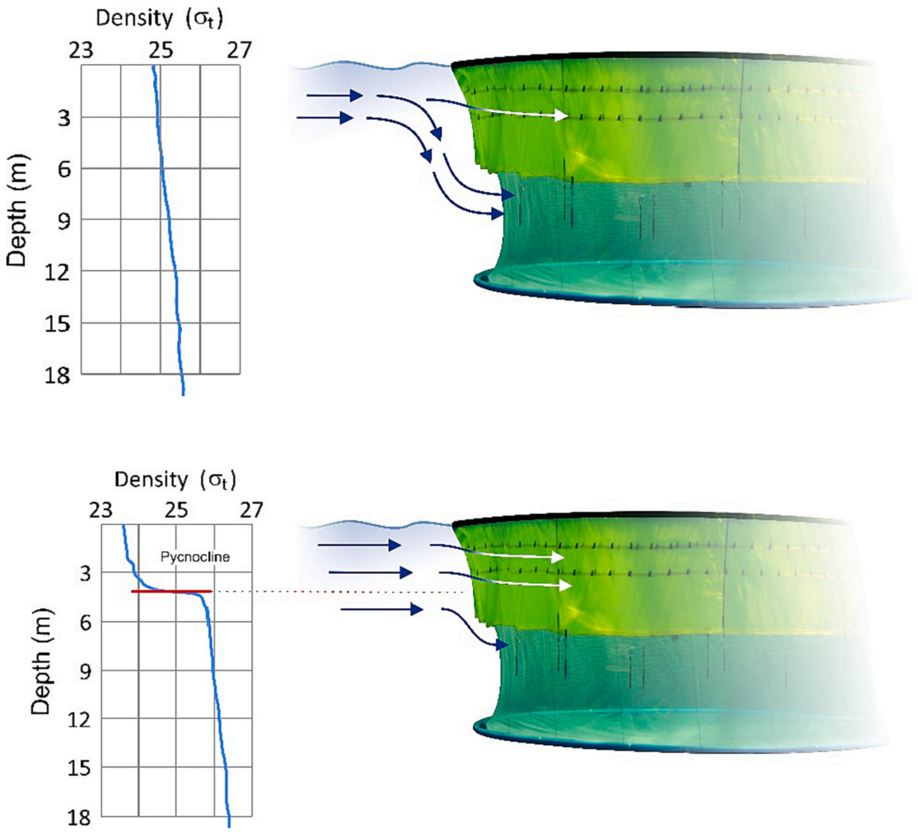

Fig. 3. Principles of how a present pycnocline can alter the current flow interaction with a lice shielding skirt. A homogenous water column will allow the water to be pressed down along and underneath the skirt, while the pycnocline may limit the waters motion by preventing the less dense water from moving down into the denser water layer.

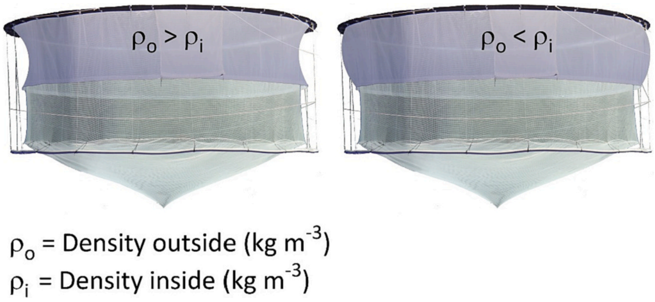

Fig. 4. Example of hour-glassing (left) and barrelling (right).

causing the skirt to take on the shape of a barrel, while "Hour-Glassing" is the opposite with the skirt being sucked in all around the skirt at a certain depth causing the skirt to take on an hourglass like shape (Misund et al., 2020). It can be theorized that barrelling is caused by higher density water inside the skirt than outside, while hour-glassing is caused by lighter water inside the skirt than outside, but this has yet to be confirmed, as there are no scientific publications on this phenomenon. Another theory has been the influence of the fish swimming in a circular pattern causing a pumping effect as previously discussed (Gansel et al., 2014; Frank et al., 2015). However, as Klebert and Su (2020) concluded with that there was no indication of a pumping effect, it is more likely that these two shapes are caused by density differences. How these deformations influence the skirt's shielding ability is also unknown.

4.4. *Structural implications of water currents: Net deformation and mooring loads*

In addition to the current potentially leading more lice into the cage during specific hydrographical conditions, ocean currents can also reduce the lice shielding efficiency by deforming the skirt. Strong currents are known to cause deformations of both cage and skirt, and increase drag forces and mooring loads, making some farms incompatible with skirt use (Lien and Volent, 2012; Lien et al., 2014; Midtlyng et al., 2019).

In the beginning of the skirt era, it was theorized that strong currents could deform the skirt and push the skirt upwards, reducing the blocking efficacy of the skirt, but early studies revealed that this deformation was most likely not an issue. When exposing model cages with tarpaulin skirts equivalent to 4.2, 6.2, and 9.2 m deep in full-scale, with a full-scale current speed of 21 cm/ s, the skirts lifted <10% towards the surface around the entire perimeter (Lien et al., 2014). Another study using the same test facilities as Lien et al. (2014), but skirts equivalent to 5 and 10 m in full-scale, observed similar lifting for 10 m skirt as the 9.2 in Lien et al. (2014) (Volent and Bekkevold, 2017). The shorter skirts in Lien et al. (2014) however were lifted higher than the 5 m skirt in Volent and Bekkevold (2017).

There was also differences in the drag forces measured in the two studies. Drag forces on cages increase with stronger current speed and the presence of a skirt. In Lien et al. (2014) the drag force on cages with skirts was 40% higher than on cages without skirts, while it was only 25% higher in Volent and Bekkevold (2017). The discrepancies between the two studies was most likely caused by different mounting of the skirt. In Lien et al. (2014) the skirts were mounted on the outside of the outer collar. In addition, the deformation of the skirt was obstructed by the chains connecting the sinker tube to the floating collar. In Volent and Bekkevold (2017) the skirts were mounted on the inside of the inner collar closer to the net which gave a smaller diameter of the skirt. It is therefore probable that the results from Volent and Bekkevold (2017) are more representative as today's practice is to mount the skirts on the inside of the floating collar.

Additional tests were carried out in Volent and Bekkevold (2017) to document how different parameters affect skirt deformation. The results showed little differences in deformation between permeable and impermeable skirts mounted on the cylindrical net. However, skirts mounted on a conical shaped net had larger deformation at low current speeds compared with the skirt mounted on a cylindrical net. This was because the skirt could freely move from its vertical position until the skirt touched the net wall (Volent and Bekkevold, 2017).

Adding weight to the bottom of the skirt had also little effect on the deformation of the skirt. Experiments with 100 kg weight mounted in one point upstream of a 10 m impermeable skirt had no effect on vertical displacement of the skirt for current up to 21 cm/ s. However, for current speeds of 41 cm/ s the weight had an opposite effect than intended on the deformation; the skirt depth in front was lifted 38% higher with the heavy weight compared to tarpaulin without weight. Similar deformation results were observed with a heavy weight downstream. The results lead to a recommendation to use 5–8 kg m^{-1} weight at perimeter at the bottom of the skirt to prevent the skirt from floating up to the surface caused by air bubbles or waves (Volent and Bekkevold, 2017).

Full-scale experiments agree well with these results. In Volent and Jónsdóttir (2019), the deformation of the skirt at three full-scale cages at different sites were compared with the lab results in Volent and Bekkevold (2017). The three sites Fornes, Josommarset and Korsneset were all equipped with pressure tags at the bottom of the skirt positioned upstream and downstream of the main current direction (Table 3). The comparison between model experiment and full-scale measurements at Fornes showed good correlation for the tags upstream of the cage, but not downstream. A possible explanation for this was the location of the skirts overlap.

Lice shielding skirts consists of either 1 or 2 parts, where the ends must either overlap with 5–10 m when mounted or be stitched together. The overlap was not stitched together and was placed downstream, which allowed more deformation than in the model experiment where the overlap was place 90° to the current direction. At Josommarset the correlation was good at the downstream side, but the skirt was lifted a little higher in front compared with the lab studies. At Korsneset both the front and rear part of the skirt was lifted higher than expected (Volent and Jónsdóttir, 2019).

Unlike the deformation by currents, waves in model-scale tests caused the skirt, independently of length and type, to be lifted equivalently to the wave height (Volent and Bekkevold, 2017). There are currently no full-scale studies on the deformation of skirts in waves. More studies are needed here to inspect the interaction between waves and skirts. The lifting of skirts caused by currents and waves upstream could cause more water to pass underneath the skirt and into the cage, reducing the shielding efficiency.

5. Shielding skirts and rearing challenges: Implications for fish welfare and production

5.1. *Challenges of the shielded internal cage environment*

Lower dissolved oxygen, poor water quality (plankton), increased

Table 3
Table shows information for each site studied in Volent and Jónsdóttir (2019), which are were compared with the results of Volent and Bekkevold (2017).

	Nordlaks – Fornes	Ellingsen – Josommarset	SalMar/ACE – Korsneset
Cage and fish	Cage perimeter 157 m	Cage perimeter 100 m	Cage perimeter 157 m
	Plankton skirt 10 m deep		Impermeable skirt 7 m
	Conical net 55 m deep	Impermeable skirt 5 m	
	Fish size 0,1 kg	Fish size 1,6 kg	Fish size and biomass not available
	Biomass 190 metric ton	Biomass 238 metric ton	

particle accumulation and deterioration of gills, poor or no effect on salmon lice infestation, perceived increase in amoebic gill disease (AGD) infestation or perceived lower feed conversion ratio (FCR) are amongst the primary reasons that certain Norwegian and Scottish companies and production sites choose not to use lice skirts (Misund et al., 2020; A. Currie, personal communication, September 1, 2021).

Many of these issues are related to the skirt's interaction with the incoming current flow, particularly how the skirt can limit the exchange of water within the cage volume. As discussed previously, the local current flow pattern can be influenced by several factors such as hydrography, deformations of the skirt and local bathymetry. Hence, the issues can be location specific or season specific. Most of the early work has focused extensively on the impact of lice shielding skirts on dissolved oxygen (DO) levels, however there is still much more research needed on the interaction between skirts and gill health.

The concerns related to perceived increase in AGD have not been extensively researched or been scientifically verified but are mentioned briefly in the Norwegian Veterinary Institutes yearly fish health report (Hjeltnes et al., 2017; Sommerset et al., 2022). Prevalence of the marine amphizoic amoeba *Paramoeba perurans* has been the cause for outbreaks of AGD in several salmon producing countries (Rodger, 2014; Oldham et al., 2016). AGD triggers the development of hyperplastic lesions on the gills of the salmon, which reduces the respiratory surface area. Because the gills are vital for oxygen uptake and ion regulation, AGD increases energy requirement and decreases hypoxia tolerance in salmon (Hvas et al., 2017; Bowden et al., 2022). Furthermore, the internal cage environment has some influence on the disease. AGD infected fish have a higher mortality after being subjected to sub-optimal oxygen levels (50% O_2 saturation) (Fisk et al., 2002), and more clinically significant AGD is observed in heavily fouled pens or those with poorer water exchange (Rodger, 2014). Mounting of skirts around the net pen and the subsequent reduction in waterflow, could contribute to the accumulation of particles, amoebas, and algae within the cage environment, and thus increasing the prevalence of AGD and gill diseases. There are currently no studies conducted which correlates the use of skirt and higher infestation of AGD. However, sites with weak to almost no current can cause low DO levels within the cage environment (Stien et al., 2012; Remen et al., 2016), and cyclic hypoxia is known to accelerate the progress of AGD (Oldham et al., 2020). Hence ensuring proper DO levels is a necessity.

5.2. *External influencing factors: Shielding skirts and dissolved oxygen*

Temperature is considered the most influential controlling factor of fish metabolism since fish are ectotherms. However, oxygen availability establishes the physiological limits, meaning that activities such as locomotion, digestion, growth and reproduction, are fuelled by energy generated through aerobic metabolism, which is dependent on the availability of oxygen in the surrounding environment (Claireaux and Chabot, 2016; Neubauer and Andersen, 2019). Oxygen consumption rate (MO_2) (or aerobic metabolic rate) of salmonids is regulated by size, feeding, stress and environmental factors, where episodes of hypoxia affect the capacity for activity and locomotion, and with smaller salmon being more afflicted (Remen et al., 2016; Oldham et al., 2019). Overall, oxygen is perhaps the most critical factor in aquaculture, as adequate (upwards from approximately >80%) DO levels are vital for several performance indicators such as growth and optimization of feed conversion ratio (FCR). Low oxygen levels can affect fish growth, induce stress responses, increase vulnerability to diseases and in extreme hypoxic cases result in death (Remen et al., 2016; Burke et al., 2021).

Physical transport of oxygenated water by tidal currents and wind driven exchange is the primary factor for oxygen renewal in sea cages (Wildish et al., 1993; Johansson et al., 2006). DO levels will therefore vary both in time and space, both horizontally and vertically within sea cages. In a study by Solstorm et al. (2018) the DO levels within an unshielded cage were generally higher at deeper depths. While horizontally, the highest DO levels were found in the upstream region of the cage, and the lowest values were recorded in the center and downstream near the cage wall (Solstorm et al., 2018). The horizontal variance was partially explained by a combination of slow ambient current speed and the presence of fish.

As the current was one of the main parameters influencing the DO levels inside unshielded cages, a physical barrier such as the lice shielding skirt is expected to influence the DO levels inside a cage as the skirt deflects the current. However, as with the shielding efficiency, although some reports and research papers note that lice shielding skirts have an adverse effect on DO levels, others see no effect over long periods (Table 4).

In a study by Stien et al. (2018) a permeable skirt was used and DO was registered daily. Initially, there was no difference in DO levels in the cages with and without skirts. However, after 2 weeks, the difference increased with average oxygen levels at 1 m depth in the cages without skirt at 104% (± 2%), and 83% (± 1%) in the cages with skirt. The levels in Stien et al. (2018) were all above 70%, hence it was concluded that the welfare of the salmon was never at risk. It should be noted that the initial biomass density at the beginning of the trial was <10 kg/m^3 for all cages, and the results may therefore not be reflective of how conditions are within cages with a higher biomass.

The results were also promising in the reports by Næs et al. (2012, 2014) where no connection was made between registered average dissolved oxygen levels and skirt presence. The median levels in Næs et al. (2012) however indicate that there was some impact of the lice shielding skirt. From measurements taken at 5 m depth in the unshielded cage, the average oxygen level was 112% and minimum recorded DO was 102%, while in the shielded cages the average DO was 102% and the minimum was 67% (Næs et al., 2012).

In contrast, in Stien et al. (2012) a 3 m impermeable skirt was installed with the intention to leave it on for 6 months, but after 7 days the experiment was aborted due to low oxygen levels. Prior to the skirt being installed, the median oxygen level inside the cage was 88%. From the moment the skirt was installed the median DO level at 1.5 m began to drop, despite the reference DO outside the cage being stable at 90–100%. During the last two days of the study, median DO cycled between 45% and 90%. After removing the skirt, DO inside the cage improved and cycled between 70 and 90% for the next two days before the experiment was terminated (Stien et al., 2012).

Similar results were obtained in Jónsdóttir et al. (2021a) where a stocked sea cage had a skirt installed for two days before it had to be removed due to a steep drop in DO. A 6.7 m deep tarpaulin skirt was installed and DO was measured at 3 m depth inside and outside the cage. During the first night of the study the DO gradually dropped to a minimum of 59% in the early morning, and the skirt had to be removed. The drop in DO when the skirt was deployed occurred over a period of 6 h. A similar drop in DO was seen the next night after the skirt had been removed, however the minimum was 69% and the DO increased gradually after reaching this point. In both situations the current speed was relatively slow and appeared to be turning. It is uncertain whether the oxygen levels would have increased naturally when the skirt was deployed. However, once removed, it only took 30 min for the DO level to increase to 81% which was the same as outside the cage (Jónsdóttir et al., 2021a).

A large sudden drop in DO was also observed in Oldham et al. (2017) where the top 6 m of an experimental research scale cage of 12x12x29 m was wrapped in tarpaulin for 60 min in four trials. DO levels dropped at all depths inside the skirt volume in all four trials, compared to a 40-min period before and after installing the skirt. The largest difference in DO when the skirt was installed and removed was close to 20%.

DO levels vary horizontally inside both unshielded (Solstorm et al., 2018) and shielded cages (Stien et al., 2012). The influence of the skirt is more apparent in the vertical plane. In Stien et al. (2012) which had a 3 m impermeable skirt, DO was recorded between 1 and 20 m depth. The DO improved nearly linearly with depth from ~49% at 1 m depth to

Table 4

Overview over studies (both peer-reviewed and grey papers) that have studied the impact of skirts on oxygen levels. Studies with several sites may have different results at each site, so if there are cases of both a reduction and no effect, this is included in the table. A reduction does not necessarily indicate a hazardous situation for the fish, only that the oxygen inside the shielded cage was reduced compared to a reference. Comparison method for impact of shielding skirt on oxygen levels are either comparing shielded cages with unshielded cages (with/without), or with itself when the skirt is removed (on/off). The rows containing data from peer-reviewed studies are written in bold and are italicized. The other studies are grey-literature.

			Skirt and preventative measures			Trend oxygen levels		
Study	# sites	Duration	Type	Depth	Oxygenation equipment	Reduction/ No effect	Comparison method	Min DO [%] With/W.O. Skirt
Næs et al. (2012)	1	30 wks (2011)	Permeable	10 m		Reduction	With/ Without	67 / 102
Stien et al. (2012)	***1***	***7 days (2011)***	***Impermeable***	***3 m***		***Reduction***	***On/Off***	***45 / 70***
Næs et al. (2014)	6	10–14 wks (2012-2013)	Permeable	6 & 10 m		Reduction/ No effect	With/ Without	76 / 75*
Oldham et al. (2017)	***1***	***11 days (2015)***	***Impermeable***	***6 m***		***Reduction***	***On/off***	***59 / 67***
Stien et al. (2018)	***1***	***15 wks (2014)***	***Permeable***	***10 m***		***Reduction***	***With/ without***	***~70 / 90***
Jónsdóttir et al. (2021a)	***1***	***3 days (2018)***	***Impermeable***	***6.7 m***		***Reduction***	***On/off***	***59 / 69***

* Not same site.

~86% at 7 m depth and stayed above 80% for the remaining depth. In Klebert and Su (2020) a 10 m deep tarpaulin skirt was used, and DO was recorded at 1, 5 and 11 m depth. During the study, DO level in all sensors dropped around every midnight, but DO at 1 and 5 m were lower than at 11 m, and the minimum of 58% was recorded at 1 m depth.

This vertical variance is also seen with permeable skirts, such as in Jónsdóttir et al. (2020), where a 10 m deep permeable skirt was wrapped around a conical cage and DO record at 3, 6, 9 and 12 m depth. The study only lasted three days, but DO levels varied greatly from 98% to 52%. The lowest DO values were found at 3 and 6 m depth. However, it was only during the first two days that the sensors at 3 and 6 m depth registered lower values than at 9 and 12 m. On the last day all DO sensors inside the cage measured similar values (Jónsdóttir et al., 2020). During the study, the current conditions were relatively similar with a clear tidal pattern, but there was a pycnocline present the first day which moved upwards and eventually broke down on the last day. There was also a difference in density inside and outside the cage on the second day. The authors therefore theorized that the variation in DO levels inside the cage were caused by the interaction between density gradients, current flow and the shielding skirts (Jónsdóttir et al., 2020).

Stratified sites have reported lower mean oxygen levels inside cages, than homogenous sites in studies with unshielded cages (Johansson et al., 2007). Given that stratification can influence the current flow, it is not surprising that stratified sites can also influence the DO levels inside shielded cages. When studying two hydrographically different locations with skirts, the DO level inside the cage at the stratified location was dependent on the strength and depth of the present pycnocline (Jónsdóttir et al., 2020). The homogenous site had a much more stable DO level throughout the 4 days the study lasted. Other studies have also commented on this interaction, for instance in Stien et al. (2012) it was hypothesized by the authors that a stratification was the cause for the low DO levels inside the cage.

The low DO levels in the top 6 m in Stien et al. (2012) could also be due to the fish congregating. Based on visuals from an underwater winch camera, it was reported that the salmon tended to gather in the top 6 m of the water column. Oldham et al. (2017) used a similar tarpaulin skirt as Stien et al. (2012), however there was a clear stratification present during trials. The depth and strength of the gradient varied, with the first trial having a thermocline and a halocline near 4 m, while trial 4 had a gradient near the skirt depth of 6 m. In Oldham et al. (2017) however, the fish was observed to avoid the top 6 m, so the low DO levels inside the skirt could not be explained by the fish congregating in this region.

The combination of low current speed, turning tide and interaction with pycnoclines could explain why some studies experience low DO levels while other do not. In Klebert and Su (2020) the lowest DO levels occurred at the sensor at 1 m depth after midnight on three consecutive days. From the echosounder data the fish appeared to gather in a denser formation in the upper layers during this period. The current was turning during midnight, and current speed was generally low. It is therefore possible that the combination of high stocking density and low currents explain the dip in DO levels, similar to that observed in Jónsdóttir et al. (2021a).

Given the difference in DO levels with depth at some of these sites, it is uncertain if the salmon were ever in an unfavourable environment. It has been theorized that salmon will actively avoid low DO levels (Johansson et al., 2007), and therefore avoid the lice skirt volume. In Oldham et al. (2017) the salmon swam beneath the lice shielding skirt and were thereby avoiding low DO levels. However, no such avoidance behaviour was seen in Jónsdóttir et al. (2021a). Avoidance behaviour for low DO levels have only been observed for extreme low levels of DO (<35%) (Stehfest et al., 2017). More moderate levels are not a primary driver of avoidance behaviour, with feeding, light and temperature being more critical drivers (Oppedal et al., 2011; Burt et al., 2012; Oldham et al., 2017; Stehfest et al., 2017). For instance, in Solstorm et al. (2018), four individual fish were tagged with oxygen sensors, and all four fish experienced suboptimal DO levels, mainly during the night. It was theorized that the low DO conditions near the surface during the night were due to the fish congregating in this area, as this was the region with the lowest DO, and salmon tend to move closer to the surface after sunset (Oppedal et al., 2011).

The varying results from the studies can be attributed to some of the different parameters such as skirt type, skirt deformation, local environmental conditions, biomass density, but also size of cage and feeding activity (Alver et al., 2022). All of these factors will influence how strong a current is necessary to replenish the water within the cage. With the increased interest in offshore sites (Bjelland et al., 2015) new cage designs are emerging which are typically much larger than the conventional cage. Much of the allure with moving to these remote location is the reduced lice infestation pressure, but any plans to use shielding structures on these large cages would require careful planning and potential oxygen enhancing equipment.

5.3. Technologies for improved skirt use: Oxygenation and water circulation

To achieve optimal growth conditions when using skirts, it is necessary to ensure good DO levels inside the cage, but which strategy that achieves this will vary depending on local current conditions, topography, fish density and stratification. To improve and control the DO levels inside a cage, systems have been developed to inject pure oxygen into the water in fish cages (Bergheim et al., 2006; Srithongouthai et al., 2006). Bergheim et al. (2006) shows a significant improvement of the DO concentration by using a network of micro-perforated hoses for oxygen distribution. Experiments with regulation of oxygen added to the water volume significantly improved DO (Bergheim et al., 2006).

Srithongouthai et al. (2006) conducted similar experiments with a microscopic bubble generator system. The water conditions in a fish farm were monitored from June to October 2004 by a vertical profiling system operated at night. The results showed improved DO levels, but bottom water with poor oxygen content occasionally appeared in the cage volume (Srithongouthai et al., 2006).

There are no scientific publications on these systems being utilised in shielded cages, but the results were promising in non-shielded cages. In addition to these two systems, there are solutions aimed specifically at shielded cages. One of the first proposed solutions was to pump water from deeper layers below the skirt, through a tube to the surface inside the skirt, thereby bringing oxygen rich water to the top layers. The intention was to distribute the deep water on the surface and press down the oxygen poor water below the skirt (Frank and Lien, 2015).

In a full-scale situation, the deeper water might have a different density than the top layer, hence experiments in scale 1:100 were performed with various relevant density differences. The water was pumped through a tube from the bottom of the tank to the surface. The results showed no distribution effect of the deep water on the surface, independently of flow rate through the tube. Instead, the water fell to the bottom of the tank sliding along the tube. The sinking speed increasing with denser water (Frank and Lien, 2015).

Other attempts at improving the water quality within lice skirt have been made with air bubble generators. The idea was to transport pressurized air into deeper parts of the cage, below the depth of the skirt. The air is then distributed in an aerator to form bubbles. The bubbles hopefully drag the deeper water upwards in to the skirt volume, replacing the oxygen low water. There are no scientific publications that verify that this principle works, however there is a report by Aquamedic AS (Midtlyng et al., 2019) which showed no significant positive biological effect when using such bubble generators.

6. Conclusion and future work

Most of the studies aimed at documenting the shielding efficiency of lice skirts report of positive results. However, due to the large discrepancies in where, when and how the studies were executed, in addition to different methods in evaluating the lice shielding efficiency, it is difficult to draw any clear conclusion regarding the general efficiency of lice shielding skirts. The additional papers and studies which indicate no effect of lice shielding skirt, further complicates this exercise. What is clear from the studies however is that there are large local variations.

Local variations in current flow patterns can influence how the current interacts with the skirt, and thereby the lice shielding efficiency. Skirts can reduce the water exchange within the skirt by deflecting the current, forcing portion of the incoming flow to diverge around the cage. However, this effect can vary with seasonal variations at the site, for instance with change in hydrographic conditions, which can change with the influx of fresh water from nearby rivers and water run-offs. The establishment of a density gradient could prevent the upper layer of the water column from moving down and underneath the skirt, thereby reducing the water exchange further. While sites with more homogenous water columns might not struggle with insufficient water exchange, as the surface water can more easily move downwards and into the skirt, which is positive with regards to water exchange, but paradoxically might reduce the lice shielding efficiency.

Statistically documenting the general lice shielding efficiency of skirts is a difficult exercise due to the many compounding variables. Even comparing a shielded cage with an unshielded cage at the same location may be inaccurate if the current conditions are different between the two cages. Comparing two cages at one site during one season may also not be representative for the other seasons, or the next year. If the goal is to document the effect of shielding skirts at a general level, it would be optimal to study several cages with and without skirts at different sites, over all seasons. In addition, the shielded cages should be installed with a form of oxygenation so that the skirt did not have to be removed during the study, and the environment would have to be monitored simultaneously to investigate the interaction between environment and skirt.

This is a complex and resource heavy task, and given the positive results of many studies, it may be of more value for the industry if future studies and projects work towards how to optimise the usage of skirts at the individual site. To develop the optimal skirt strategy for each site, better understanding of the complex interaction between cage, skirt, environment and fish welfare must be achieved, and sufficient monitoring procedures and decision support systems must be developed. It is fundamental for each site to understand their local environmental conditions and variations within their farms to obtain positive results when using skirts. An initial step could therefore be to recommend farmers to monitor the current flow and hydrographic conditions within and outside of shielded cages, while monitoring lice numbers. This could give an indication of whether the skirt is isolating the top layer, or if the site is exposed to strong mixing of the water column, rendering the skirt useless.

Despite having been used for over a decade in Norwegian aquaculture, and having spread to other salmon farming nations, the complex interaction between skirts and potential welfare risks related to blocking the incoming current are not fully documented. Most studies have focused on low DO values, which is the most prevalent issue, however with large variations between studies and locations. A newer concern, which requires attention, is how skirts may influence gill health and increase AGD incidents. This needs further investigation to document if there is an actual link here, or rather that AGD increases due to lower DO at shielded sites and increased accumulation of particles.

CRediT authorship contribution statement

Kristbjörg Edda Jónsdóttir: Conceptualization, Data curation, Writing – original draft, Writing – review & editing, Funding acquisition, Project administration. **Andreas Ugelvik Misund:** Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Leif Magne Sunde:** Writing – review & editing. **Merete Bjørgan Schrøder:** Writing – review & editing. **Zsolt Volent:** Conceptualization, Data curation, Writing – original draft, Writing – review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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