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Exploiting the "gold of the ocean": Can live storage solve the paradox of the purse seine fishery for Atlantic bluefin tuna in Norway?

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ABSTRACT

The Norwegian quota for Atlantic bluefin tuna (ABT) (*Thunnus thynnus*) is not completely caught every year. This is paradoxical because Norway is a leading fishing nation. The fishery is currently executed by rod-and-reel and purse seine, with ~ 80 % of the quota being allocated to the latter. Purse seine is therefore the main determinant for the overall success of the fishery and vessels aim to take catches that are manageable for their size (typical LOA < 40 m). These vessels are not designed to target ABT, so they tend to have variable capture efficiency, inadequate catch control technology and often produce inconsistent product quality of relatively low value. Furthermore, participation in more profitable fisheries with better shore-based infrastructure and marketing channels is prioritised over ABT fishing. The storage of purse seine caught ABT in cages is currently practiced worldwide but not in Norway. Storage allows on-demand supply to the market and can improve quality by allowing physiological recovery after capture. There is therefore great interest from Norwegian policymakers and industry in developing a live storage fishery. This manuscript investigates aspects related to ABT live storage in Norway. Findings are presented from sea trials exploring the feasibility of these procedures. Challenges that will determine the future perspective of Norwegian live storage are discussed, and the potential of alternatives such as longlines, traps and rod-and-reel is examined. Any future success in developing the Norwegian ABT fishery will serve as an example for other fisheries around the world facing similar challenges.

1. Introduction

Modern industrialised fishing is driven primarily by the potential for economic profit [1]. Most global fish stocks are either fully- or over-utilised, and those that are under-utilised (e.g. mesopelagic fish) cannot generally be harvested in an economically sustainable way using current fishing technology [2,3]. It is therefore rare to find examples of developed nations with potentially economically valuable but under-utilised fishing resources within their 200-mile exclusive economic zone.

Atlantic bluefin tuna (ABT) (*Thunnus thynnus*) is the largest of all tuna species, with individuals reaching > 300 cm in length and 700 kg in weight [4]. On a per kilogram basis, they are amongst the most valuable global seafood products [5,6]. Their high value has led to labels such as "the gold of the ocean" [7]. The highly migratory nature of ABT necessitates a complex management structure involving many different stakeholders [5,8]. The International Commission for the Conservation of Atlantic Tunas (ICCAT) was created in 1966 to manage the exploitation of tuna (including ABT) and other tuna-like species in the Atlantic Ocean and adjacent seas. ICCAT is responsible for setting quotas, providing management advice, and coordinating international research and stock assessment. There are two main stocks of ABT; a western stock

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that spawns mainly in the Gulf of Mexico, and an eastern stock which spawns in the Mediterranean Sea. The former spawns in April–June [9], while the latter spawns during May–July [10]. Some of this eastern stock migrates north during late summer/autumn to the coast of Norway to feed on small pelagic fish (e.g. mackerel [*Scomber scombrus*]) [11].

Norwegian tuna fishing has a long and varied history [12,13]. In the 1950s and -60s, Norway had one of the world's largest ABT purse seine fishing fleets with nearly 500 vessels operating nationally [14]. There was minimal quota, vessel or management regulation at the time. The fishery supplied high volumes (~ 15,000 tonnes [t] was caught at its peak) of product to the European market, primarily for canning [14,15]. Due to overfishing throughout its range and other potential factors that led to an apparent population ageing at the time, the stock decreased during the 1970s and collapsed in the early-1980s [16,17]. Thereafter, ABT observations in the Northeast Atlantic became rare and the Norwegian fishery ceased. An ICCAT managed recovery plan implemented severe quota, catch and effort restrictions [8]. This has contributed to a substantial increase in spawning stock biomass over the past 30 years [18]. ABT began to re-appear with regularity in Norwegian waters from 2012 [11]. In 2014, the Norwegian fishery was reopened with an ICCAT mandated quota of 31 t. This has increased to 383 t in 2023 (Fig. 1).

The Norwegian authorities divide the available quota between research, recreational and commercial fishing. Commercial fishing allows for both targeted fishing (either by rod-and-reel or purse seine) and for bycatch in other fisheries. Most ABT in ICCAT fisheries is captured by purse seine [20]. Historically, tuna fishing in Norway also used this gear type. As a result, the majority (~ 80 %) of the present Norwegian quota is allocated medium-sized coastal purse seiners (typical LOA < 40 m). Activity with this gear type is therefore the main determinant for the overall success of the local ABT fishery.

Aggregations of ABT are now commonplace throughout the Skagerrak, the North Sea and southern part of the Norwegian Sea during August to October. The fish are typically large, often have excellent physical condition (Fulton's Condition Factor [K] > 1.5, especially later in the season) and can be found relatively close (< 10 nm) to shore [11]. There is consequently great interest amongst fishers and the wider industry in developing a modern national fishery. Despite this, ABT fishing by the purse seine fleet has been limited and irregular. Between 2018 and 2023, only 11–62 % of the total available quota was landed (Fig. 1). This represents a paradoxical situation, because fisheries are socio-economically important in Norway and the fleet is modern and diverse [21]. With respect to the wild capture of marine species, Norway was the 9th most productive nation with ~ 3 % (2.5 Mt) of the global catch in 2020 [22].

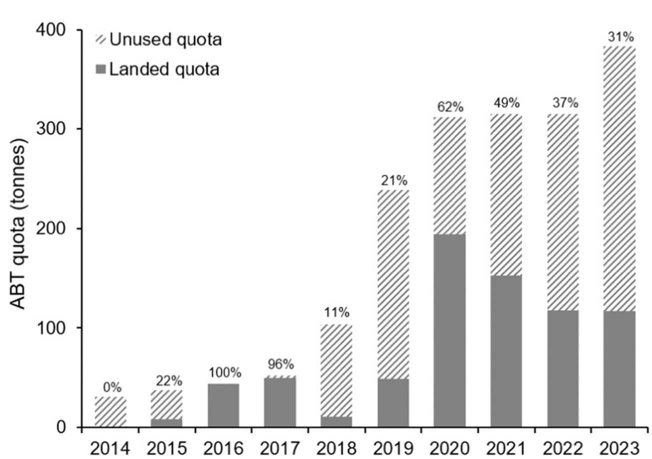

Fig. 1. Utilisation of the total Atlantic bluefin tuna (ABT) quota allocated to Norway by the International Commission for the Conservation of Atlantic Tunas (ICCAT). The percentage of the total quota which is landed each year is indicated. Source [19].

The primary quality consideration in the historical Norwegian fishery was to produce products suitable for canning [23]. The global commodification of ABT as a raw premium product (e.g. sushi) in the intervening years has resulted in different market requirements [24,25]. Quality is now determined individually and in terms of fat content, freshness, colour and shape [26]. Fish of high quality achieve a considerable price premium [26]. There is also now a greater awareness of animal welfare related issues in food production systems [27]. Any modern purse seine fishery in Norway must align itself with these new market and societal expectations.

Live capture and storage (hereafter: live storage) is the commercial practice of capturing wild animals alive so that they can be retained and later utilised for consumption [28]. Live storage of purse seine caught tuna is an established and profitable industry in the USA [29], Japan [30], Mexico [31], Australia [32] and many Mediterranean countries [25]. There is, however, currently no live storage industry for ABT in Norwegian waters. The management authorities and the fishing industry have identified live storage as a promising approach for harvesting Norwegian caught ABT because it can enable recovery from capture stress potentially yielding better product quality and prices, as well as stabilise the supply to the market. Purse seine has initially been prioritised over other gears because historically that was the preferred capture method for ABT in this region.

In this article, we examine the following questions:

1) Why is the purse seine fleet in Norway not fully utilising its ABT quota?
2) Could live storage improve the exploitation of the resource?
3) How feasible is ABT live storage in Norway?
4) Are there alternatives to purse seine capture and live storage that could improve the exploitation of the resource in Norway?

Section 2 outlines challenges faced by Norwegian purse seiners that may explain the current under-utilisation, i.e., the whole quota is not being caught. Section 3 details the potential advantages of live storage and the particular circumstances in Norway that will dictate how it takes shape. Section 4 presents findings from sea trials examining the feasibility of Norwegian live storage. Section 5 discusses remaining challenges facing the live storage fishery. Section 6 examines the potential of capture methods other than purse seine and live storage.

2. Current challenges in the Norwegian purse seine fishery

2.1. Sub-optimal vessel characteristics

In 2023, seven coastal purse seiners with LOA ranging between 26 and 41 m were licenced to fish for ABT. Successful purse seine capture of ABT is reliant on rapid encirclement with a fast-sinking net due to their exceptionally fast swimming speed [33]. However, Norwegian coastal purse seiners operating in the fishery are designed to harvest small pelagic species such as mackerel and herring (*Clupea harengus*) and so cannot achieve encirclement speeds over 8–9 knots. Moreover, unlike specialised tuna vessels, Norwegian purse seiners generally do not deploy a skiff; i.e. a small, auxiliary boat used to pull the purse seine in the opposite direction to the main vessel. Therefore, when trying to encircle fast-moving tuna, especially without a skiff, their operational encirclement speeds are somewhat limiting.

The large size of ABT requires adequate deck space for safe and efficient handling. Most of the deck in Norwegian purse seiners is occupied by equipment (e.g. suctioning pump and tubes) necessary to handle small pelagic fish, limiting tuna processing speed and manoeuvrability. Thus, these vessels are not well suited to efficient ABT fishing or processing.

2.2. High opportunity costs

Coastal purse seine vessels in Norway usually hold quota for several species, with their main source of income coming from herring and mackerel fishing. Most mackerel are caught in the autumn, with the peak occurring in September/October. This coincides directly with the ABT season (Fig. 2). Vessels therefore face an important opportunity cost, as ABT fishing may come at the expense of participating in a more established and profitable fishery for which the vessel is better suited and the crew have more experience. An analogous situation is seen in the developing Norwegian *Calanus finmarchicus* fishery. Although several vessels hold permits, quota utilisation is low because they prioritise other fisheries that occur at the same time [34]. The requirement to have an independent ICCAT observer onboard also adds a financial cost and a logistical challenge when participating in ABT fishing.

Historically, Norwegian purse seiners had reliable access to British waters to continue catching good quality, high price mackerel after they migrate westwards out of local waters in the late autumn. This effectively extended the season and alleviated concerns about revenue loss from incomplete quotas. However, the ongoing situation regarding post-Brexit bilateral fisheries agreements means the extent of future access is less certain [35]. In the 2021 and 2022 seasons, the Norwegian mackerel fleet was not permitted to operate in UK waters at all [36]. In 2023, 60 % of the quota was allowed to be taken in UK waters. Such scenarios add additional incentives for vessels to prioritise mackerel fishing over ABT.

2.3. Variable capture efficiency

The behaviour of ABT in Norwegian waters varies throughout the fishing season in a way that impacts upon catchability and catch efficiency. During August, schools are relatively small and display migratory-like behaviour with steady, uni-directional swimming that rarely breaks the surface [37]. Fishers rely on ABT surfacing or detection by sonar to locate schools. Together with the small number of vessels active in the fishery, this means finding schools can be difficult. Extensive time spent searching leads to high fuel costs. Later in the season, larger feeding aggregations form, displaying fast and unpredictable swimming that often breaks the surface [11,37]. Whilst more easily located, such behaviour results in increased probability of unsuccessful (empty) casts or undesirably large catches. Large catches increase the likelihood of fish becoming tangled in the seine netting, leading to a long and potentially dangerous retrieval process as hauling must be repeatedly stopped to disentangle animals. Such scenarios can have serious consequences for animal welfare, fish quality and crew safety. Large catches may exceed the vessels quota or processing capacity, both onboard and at shore-based fish factories. Late season ABT fishing in Norway is also often complicated by relatively short daylight hours and challenging autumn weather conditions.

2.4. Lack of information available to fishers before and during capture

Norwegian coastal purse seiners are typically equipped with omni sonars to determine school volume and size when fishing for small pelagic species. ABT fishing, however, requires accurate detection and quantification to avoid catches that are too large. Consequently, fishers lack the necessary information to make informed decisions regarding whether a particular school should be targeted, or whether the whole catch should be taken onboard or partially released. Early release of unwanted catch is desirable to avoid poor welfare and associated mortality [38].

2.5. Reduced product quality resulting from onboard practices

Current practice in the fleet involves crowding captured ABT by reducing net volume. Individual animals can then be lifted onboard by the tail using a crane. However, the crowding process can be stressful and cause severe behavioural and physiological disturbance [38]. In particular, ABT rely on ram ventilation [39], so restricting swimming by crowding means they likely die due to asphyxiation, which is highly stressful in fish [40]. Acute stress responses during capture and slaughter can induce a cascade of physiological changes in the fishes' muscle tissues (e.g. elevated catecholamine, cortisol and lactate concentrations, reduced pH and depleted ATP inducing early onset and strengthened *rigor mortis*) that can detrimentally affect the quality and shelf life of seafood products [41]. As ABT are highly oxyphilic with a large anaerobic and thermoregulatory capacity, they are particularly susceptible to stress induced quality reductions [42]. For example, tuna species are prone to burnt tuna syndrome (a.k.a "*yake niku*" in Japanese), which is a pronounced denaturisation of muscle tissues, likely due to elevated *post-mortem* muscle temperature and reduced pH [43] and/or calcium-activated neutral protease activity catalysed by elevated catecholamine concentrations [42].

A key principle in the preservation of tuna quality is rapid cooling following death [44]. However, dead tuna often remain inside the seine at ambient seawater temperature for extended periods of time (particularly for large catches) because it takes considerable time to

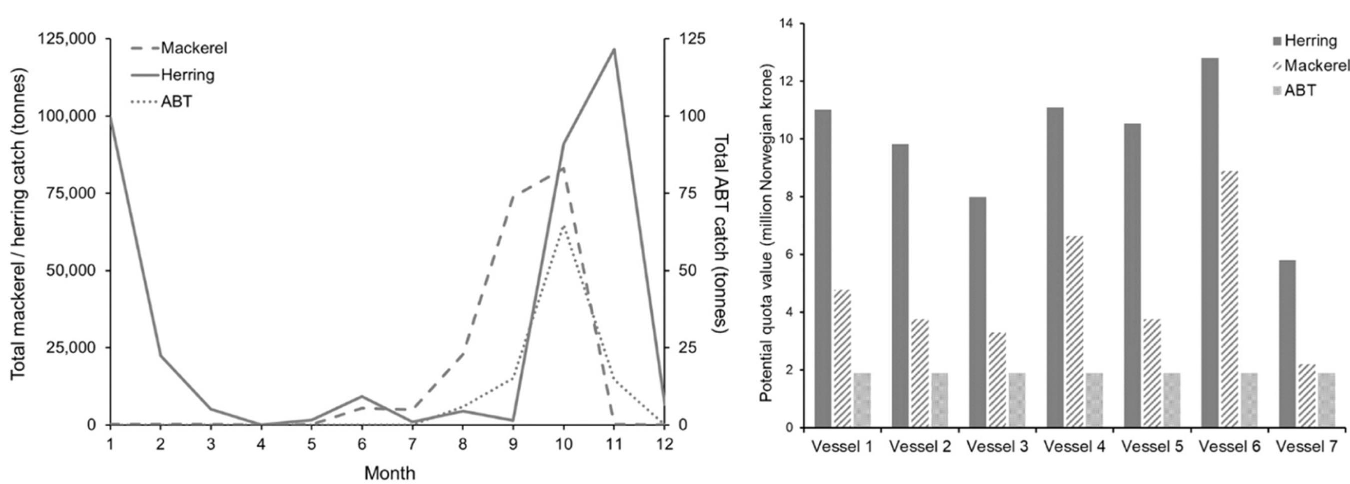

Fig. 2. : Opportunity costs associated with Atlantic bluefin tuna (ABT) fishing in Norway. **Left**: total catches of herring (left axis), mackerel (left axis) and ABT (right axis) by all Norwegian purse seine vessels throughout 2023. Note the different y-axis scales. **Right**: the potential value of herring, mackerel and ABT quotas for the seven purse seiners permitted to fish for ABT in 2023. Herring catches/quota combines separate quotas for North Sea and Norwegian Spring Spawning herring. Potential values are derived from average first-hand sale price achieved by all Norwegian vessels in 2022. Source [19].

individually lift, bleed and process each of them. Norwegian purse seiners are typically equipped with refrigerated seawater (RSW) tanks for storing catches onboard. However, quality can deteriorate in RSW tanks if the catch is large and fish rub against one another or the tank walls. Such factors have contributed to Norwegian purse seine caught ABT not complying with international quality standards in a market with high quality demands [45].

2.6. Under-developed infrastructure and market channels

Deterioration of tuna quality during storage can be reduced by freezing at ultra-low temperatures (< − 55 °C, [46]). However, the Norwegian industry has not invested in such infrastructure. This is mainly due to the currently low total quota [19], the unpredictability of landings in space and time, and the uncertain future perspective of the fishery relative to the cost of developing such capacity. Consequently, catches are typically ice stored and sold fresh on the international market.

The purse seine mode of capture means that several fresh fish tend to be delivered at the same time. There is often high availability of fresh ABT on the international market during the Norwegian season because it collides with the peak USA/Canadian rod-and-reel fishing season [47]. Furthermore, there has been a three-fold increase in global ABT landings in the last decade [48]. Together with the variable product quality (see Section 2.5), these factors have led to unstable and low-profit trading conditions that make Norwegian ABT an unattractive proposition for fishers and buyers. Norwegian tuna is also new to the market and does not therefore have an established reputation or sale channels. Variable and relatively poor market prices are therefore a common occurrence. The average first-hand sale price per kg for all fishing gears since 2013 is 57 ± 32 Norwegian krone (mean ± SD, [19]). This lack of profitability contributes significantly to the under-utilisation of the resource.

3. Live capture and storage of bluefin tuna

Live storage of ABT offers advantages over how the purse seine fishery is conducted today because it: i) allows the product to be supplied to the market on demand; and ii) optimises product quality by allowing fish to recover physiologically from capture related stress (i.e. reverting muscle catecholamine, cortisol, lactate, pH, temperature and ATP to return to non-detrimental levels). This is of particular relevance for the Norwegian fishery because the current quality of fish (i.e. those dying in the seine without physiological recovery) is too low to exploit the preservation benefits of ultra-low freezing. This is the primarily reason why the development of live storage procedures has been identified by industry and policy makers as essential for the development of a profitable Norwegian purse seine fishery. A substantial research quota to develop these procedures has been allocated by local authorities in recent years. ICCAT Resolution 22-07 [49] also authorised a pilot project to investigate the feasibility of short-term live storage of ABT in Norway.

During existing live storage operations, tuna are first captured by a purse seine vessel. The seine is attached to a floating towing cage by divers. Fish are then stimulated to swim into the cage by reducing the volume of the seine and by the activity of the divers. The cage is towed towards land at slow speeds by a separate towing vessel. Upon arrival near-shore, it is attached by divers to a static holding cage into which the fish are transferred [50]. For ICCAT managed fisheries, there is an obligation to determine by video camera the number and weight of fish being transferred. Video recording is undertaken by divers. Often, fish are fed and fattened during storage to maximise their market value. Slaughter of large tuna is typically conducted by divers.

The circumstances of Norwegian tuna purse seine fishing are distinct from other existing live storage operations around the world. The national and respective vessel quotas are small [19]. As such, dedicated tuna vessels would be uneconomical. Instead, it is envisaged that coastal based, medium-sized purse seines will also execute the live storage fishery. Mediterranean ICCAT managed fisheries target large spawning aggregations, whereas smaller, more disperse feeding schools made up of large post-spawning individuals occur in Norwegian waters [11]. These differences could affect transfer and storage processes. In existing fisheries, transfers are facilitated and verified using divers. Local legislation, as well as practical and financial considerations onboard, mean that divers are not currently feasible in Norway. The country does, however, have extensive live storage experience with small species like Atlantic cod (*Gadus morhua*), mackerel and saithe (*Pollachius virens*) [51, 52]. These operations use a net channel to transfer fish without using divers. The intention is to develop these practices for ABT. Clearly, new cost-effective technology and knowledge suited to local conditions is needed if a functional and profitable live storage industry is to be realised.

4. Potential implementation of live storage in Norway

Trials at sea were carried out to determine whether capture, transfer and caging of tuna in Norway is feasible, as these phases are the first premise to successfully implement live storage (Fig. 3). Other important aspects such as the storage phase conditions and duration period, as well as the potential recovery from capture and handling stress and associated gain in product quality need to be determined in future scientific trials.

4.1. Overview of sea trial methodology

A series of 5–13-day sea trials were conducted each autumn between 2020 and 2023 (Table 1). The purse seine fishing trials were conducted ≤ 20 nautical miles from the coast, between Bergen (60° 23’ N, 5° 19’ E) and Fosnavåg (62° 20’ N, 5° 38’ E). The chartered vessels were two medium-sized, coastal purse seiners, who are mainly active in the herring and mackerel fisheries. MS Vestbris (Fig. 4, LOA = 35 m) was equipped with two sonars, a high-frequency Furuno FSV 75 (180 kHz) and a low frequency Simrad SU90 (20–30 kHz). MS Sjarmør II (LOA = 35 m) was equipped with a Simrad SH90 high frequency (114 kHz) sonar. Both vessels used RSW tanks to store catches.

Once fish were captured (Fig. 3, Phase c), the trials aimed to attach a towing cage to the seine using a transfer channel. The channel would be attached to the seine gavel using a ring-to-ring coupling system. This operation would be carried out onboard; not underwater using divers as is done in other live storage fisheries. This technique has been used earlier for other species in Norway (see [53] for an example with mackerel), but never for ABT. The towing cage was 65 m long, 17 m wide and 11 m deep, with 52 mm nominal mesh size. The front part was V-shaped and constructed with a 156 mm mesh size to facilitate towing and waterflow. The channel was 6 m wide, 6 m long and 4 m deep with a 200 mm mesh size. Both were designed to be stored onboard the catching vessel. Transporting the towing cage onboard the catching vessel reduces the duration of the capture phase (Fig. 3). This offers welfare and efficiency advantages over other existing live storage operations, where it can take several hours for a towing vessel to arrive at the capture site with a cage [24,50].

By reducing the volume of the seine, the trials aimed to stimulate the tuna to swim through the channel and into the cage (Fig. 3, Phase d). In existing ICCAT live storage fisheries, diver operated cameras are used to monitor the number and size of fish transferred. As divers are not feasible in Norway (see Section 3), the trials tested the following alternatives: i) a portable multibeam high frequency sonar (Kongsberg M3, frequency = 500 kHz; Fig. 5a); and ii) a stationary stereo-camera system mounted on a steel frame [54–56] (Fig. 5b). High frequency sonars can discern individual fish [37,57], which would allow assessment of numbers during either transfer or earlier in the capture process. Determining if and how many ABT are present within the seine is of particular importance for determining whether the towing cage and transfer

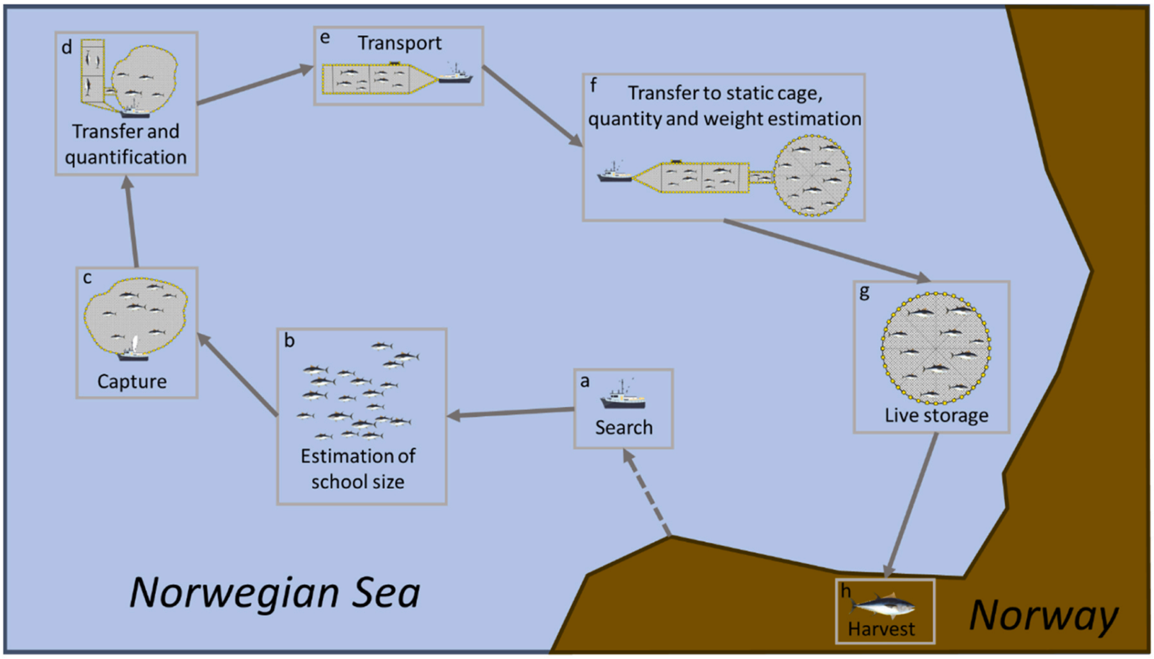

Fig. 3. The different phases required for successful Norwegian Atlantic bluefin tuna live storage: **a**: fish location using a coastal based purse seiner; **b**: pre-capture acoustic estimation of fish numbers; **c**: capture by purse seine; **d**: transfer and quantification of fish into a towing cage via a transfer channel. The channel and cage are stored onboard the catching vessel prior to deployment; **e**: transport of the towing cage inshore by the catching vessel; **f:** transfer of fish to a static holding cage via a transfer channel. **g**: fish stored in an inshore holding cage and slaughtered at a later date; and **h**: slaughtered fish are harvested for sale. No divers are used at any phase.

Table 1
Details of sea trials investigating the feasibility of Atlantic bluefin tuna (ABT) purse seine live storage in Norway. Following a successful cast (i.e. one in which fish were caught), ABT were to be transferred from the purse seine into a towing cage and subsequently into an inshore holding cage.

Year	Vessel	Start date	End date	No. of successful casts	Total no. of ABT caught	Mean weight (kg)	Total no. of ABT transferred
2020	MS Vestbris	27th September	2nd October	1/4	152	250.3	51
2021	MS Vestbris	28th September	7th October	1/4	1	285.0	0
2022	MS Sjarmør II	26th September	4th October	0/2	0	-	0
2023	MS Vestbris	14th August	27th August	3/3	28	242.7	26 (3*)

* Transferred to a static holding cage.

Fig. 4. A typical medium sized, coastal Norwegian purse seine vessel. The vessel shown (MS Vestbris) was used in sea trials to investigate Atlantic bluefin tuna live storage feasibility. MS Sjarmør II (the other vessel used in the trials) was similarly designed.

channel should be deployed at all. Once transferred to the towing cage, the fish would be towed inshore (Fig. 3, Phase e) and transferred again (Fig. 3, Phase f) to a static holding cage for live storage (Fig. 3, Phase g).

4.2. The 2020 trial – the first transfer of fish

The main aim was to determine if it was possible to transfer ABT from the purse seine into a towing cage using a transfer channel. Only one cast was successful at capturing fish (Table 1). The catch size (152 individuals) was much larger than indicated by the vessel sonar prior to

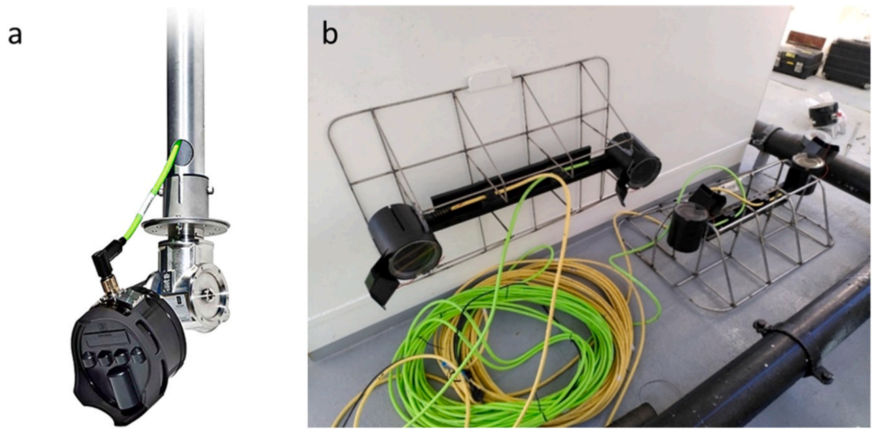

Fig. 5. : Technology tested during Norwegian sea trials to assess the feasibility of quantifying Atlantic bluefin tuna catches during purse seine live storage procedures: **a**: a portable multibeam high frequency sonar (Kongsberg M3); **b**: a stereo camera.

net setting. The portable high-frequency sonar was not available for this trial. Several fish became entangled in the purse seine netting prior to transfer. The camera was attached to the channel netting wall closest to the vessel, at ~ 2 m depth and ~ 2 m from the entrance to the seine. Fifty-one individuals were successfully transferred into the towing cage. Transfer could not be reliably observed on camera because of poor light conditions and backwash disturbance from the vessel's thrusters. Deploying the towing cage was complex and it was concluded that a lighter and more manoeuvrable design would be required.

4.3. *The 2021 trial – low capture efficiency*

The primary aim was to test material improvements to the towing cage design and to improve the reliability of images gathered by the stereo-camera system. The portable high-frequency sonar was not available for this trial either. Practice deployments (i.e. not capturing

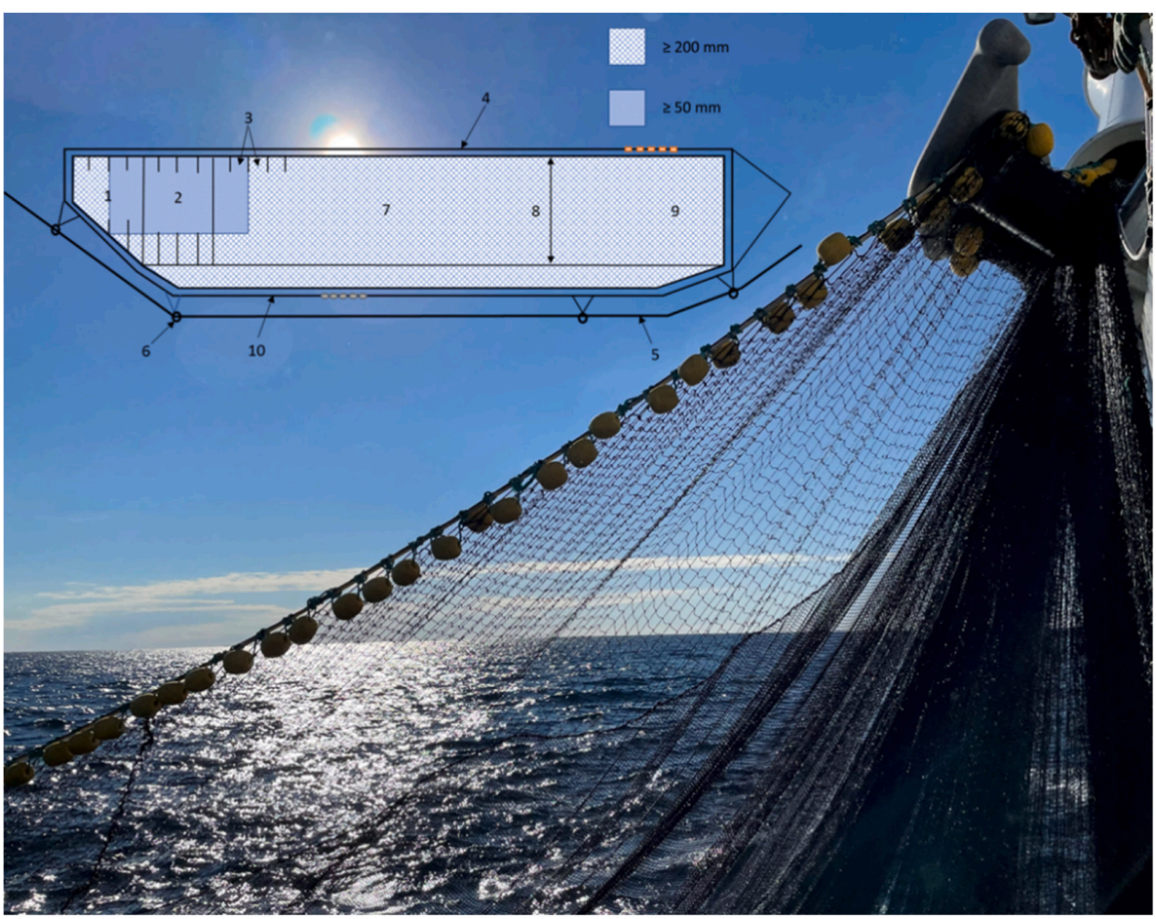

Fig. 6. A small mesh panel tested during sea trials in Norway assessing the feasibility of live storage of purse seine captured Atlantic bluefin tuna. The panel (50 mm mesh size) was designed to reduce fish entanglement. It covered the upper parts of the bunt, shoulder and main body of the net. The inset diagram shows the different elements of a purse seine net and the position of the small mesh panel (dark blue): **1:** bunt; **2:** shoulder; **3:** netting sections; **4:** headrope; **5:** purse wire; **6:** purse rings; **7:** main body; **8:** netting joining; **9:** wing; **10:** footrope.

fish) demonstrated the new cage had improved handleability relative to the 2020 design, and that thruster disturbance to the camera could be reduced by attaching it to the channel wall furthest away from the vessel.

Despite high availability of ABT in the fishing area, only four casts were undertaken (Table 1). This was primarily due to the behaviour of the fish (high swimming speed, unpredictable direction, close to the surface). Sonar tracking and capture were difficult in such circumstances. Only one cast of the four resulted in capture; a single individual that was tangled in the purse seine netting. Consequently, no attempt at transfer was made.

4.4. The 2022 trial – further capture efficiency difficulties

The findings of the 2020 and 2021 trials demonstrated that net entanglement and accurate pre- and during-capture fish quantification were major issues. A small mesh (50 mm mesh size) netting panel was incorporated into the upper parts of the bunt, shoulder and main body of the purse seine (Fig. 6) to attempt to avoid fish entanglement. Testing this solution, as well as a new stereo-camera (Fig. 5b) and the portable high frequency sonar (Fig. 5a), was the focus of the 2022 trial.

Although observations of ABT were abundant, weather conditions and unpredictable fish behaviour meant all casts failed to catch fish. However, there were no operational issues with the use of the small mesh panel and the sonar mounted on an auxiliary skiff proved able to make clear observation inside the seine. It was concluded that it would likely be suitable for quantifying the number of animals inside the net during a successful capture event.

4.5. The 2023 trial – successful capture, transfer and caging

The aim was to further develop and test the solutions implemented in earlier trials. Three casts were performed, all resulting in catches and transfers of fish (Table 1). No entanglement in the small mesh panel occurred. The portable high frequency sonar was able to discriminate individual fish targets both inside the seine and the towing cage (Fig. 7a), but quantification was not reliable. Neither could reliable quantification during transfer be achieved using the stereo-camera. This was mainly because of deformations in the shape of transfer channel meant the camera field-of-view was not stable. Accurate estimates of fish length (plus weight derived from a length-weight relationship) were however gathered using the camera inside the towing cage (Fig. 7b) [55]. The towing cage functioned satisfactorily and allowed tuna to exhibit loose shoaling behaviour during transport (Fig. 7c).

For the first two casts, fish were prepared for slaughter by crowding them in the towing cage. Three fish from the final cast were transported inshore, and successfully transferred to a 15 m diameter and 14 m deep holding cage using a transfer channel identical to that used at sea (Fig. 7d). Fish quantification in the channel failed because the camera view was not stable. Behaviour and environmental conditions inside the holding cage were consistent with good welfare throughout the 10-day holding period. Fish were then crowded and slaughtered. Blood analysis indicated that the crowding and slaughter procedure can induce severe physiological disturbance with negative quality implications (e.g. poor blood exsanguination and burnt tuna syndrome). Upon sale, the fish were noted to have undesirably low fat content.

5. Future perspectives for live storage in Norway

The sea trials detailed in Section 4 demonstrate that transfer and holding of purse seine caught ABT is feasible in Norway without the need for divers. However, challenges currently exist at practically all stages of the operation. The future success of a Norwegian live storage industry relies on addressing these challenges.

The high opportunity cost for purse seiners to participate in ABT fishing is a major contributing factor in the current under-utilisation of the resource. Developing live storage procedures will not necessarily overcome this. It may be that dedicated tuna vessels (i.e. vessels not holding quota for other concurrent fisheries) are required. For such an investment to be viable, revenue potential from the fishery would need to be substantially larger through increased quota allocation to Norway from ICCAT and/or value added from caging fish. Any added value will ultimately depend on how the market responds to a new product such as live stored Norwegian ABT. Contributions from publicly or privately funded marketing organisations may have an important role to play in making live storage a profitable success.

Improving capture efficiency would help establish a robust profit base for live storage, especially during times of high fuel costs. Therefore, in addition to vessels better suited to tuna fishing, finer-scale information of ABT distribution within Norwegian waters is required so that schools can be efficiently located. Vessel-operated aerial drones can rapidly locate schools in a cost-effective manner [58]. However, current

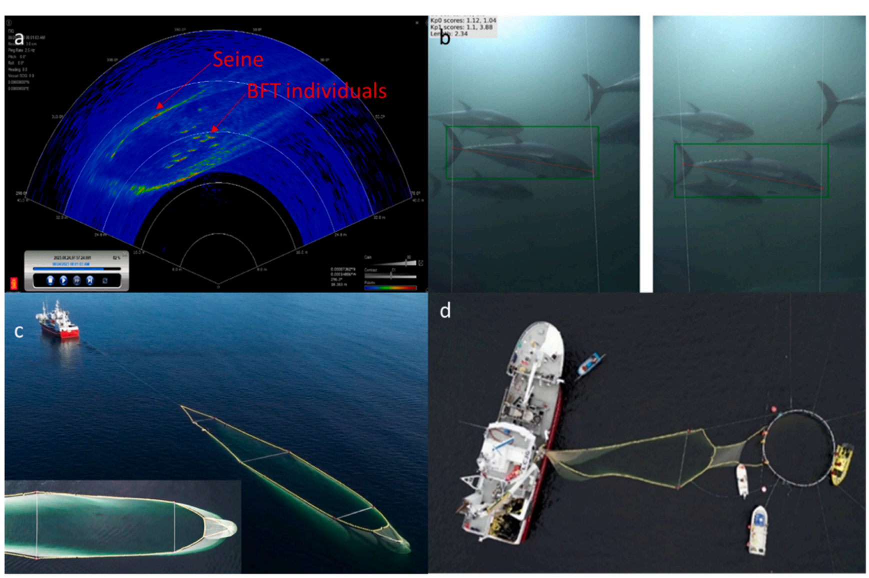

Fig. 7. Outcomes from a 2023 sea trial assessing the feasibility of ABT live storage in Norway: **a**: multibeam high frequency sonar image from inside the purse seine during capture; **b**: stereoscopic images from a stereo camera to quantify and measure ABT; **c**: towing a cage with ABT inside (inset: overhead view); and **d**: transferring ABT from the towing cage to an inshore holding cage.

ICCAT regulations prevent searching for ABT by aerial means [59]. Capture-related fish behaviour and fishing gear design must also be better aligned to capture schools more readily. One widespread method is to feed small pelagic fish, from small auxiliary boats, to tuna schools to induce a feeding frenzy and thus slow them down. This has not been tested in Norway but given the abundancy of naturally available prey during the fishing season this technique may not be as effective as in other regions. Gathering such information will require close collaboration and research with the industry, in Norway and elsewhere.

Only the 2023 trial produced reliable catches that were small enough to handle in an effective way. This trial was conducted earlier in the season relative to the other years (Table 1). It is likely that smaller school size and more predictable fish behaviour during this time contributed to the success. A better understanding of the drivers of this behaviour is therefore needed. Fish caught in August, however, have had little opportunity to feed and recover their condition after spawning in May–July [10,11]. This is consistent with the relatively low-fat content of fish caught during the 2023 trial. High market prices for ABT tuna rely on adequate fat content [25]. This implies that early season capture in Norway may not be profitable.

The animal welfare and quality impacts of caging ABT in Norwegian conditions is still largely unknown. The migratory behaviour of the species suggests it cannot tolerate temperatures < 10 to 11 °C for sustained periods without severe metabolic costs [60]. Seawater temperature well below this threshold can be expected during the autumn and into the winter in Norwegian coastal waters. Prolonged caging will require fish to be fed to maintain their condition. Potential inter-relationships of this with local environmental conditions and product quality outcomes are unknown. Furthermore, live storage of ABT must be adapted to comply with Norwegian legislation and ICCAT requirements. The duration of the storage phase and the food to be provided during storage will have to be investigated, because it will have implications with regards to adherence to current Norwegian and ICCAT regulations. According to ICCAT, *short-term live storage* means keeping bluefin tuna in a storage cage up to a maximum of three months, without fattening them or increasing their total biomass [49], whereas *fattening* or *farming* means caging of bluefin tuna in farms and subsequent feeding aiming to fatten and increase their total biomass [59]. New research is required to determine which processes are viable in Norway and, consequently, which legislation is relevant.

The limited trials to date suggest the addition of the small mesh panel helps reduce the incidence rate of entangling. This is promising from an animal welfare perspective. However, the technology for fish quantification and measurement must be improved. Although the high-resolution sonar was able to identify individuals during- and post-capture, quantification lacked accuracy. A sonar with a wider beam angle may address this, as may optical observations using cameras from remotely operated vehicles. Improving stereo-camera observations so that the number and weight of transferred fish can be reliably measured is more difficult but could be achieved increasing the number of stereo cameras used or in combination with acoustic cameras. Increasing the size of the transfer channel would increase the field of view of the camera and therefore the likelihood of fish being captured on film. A larger channel would also facilitate easier passage of the fish. However, the channel itself does not provide a stable platform from which to film. A further challenge is that ICCAT requires the transfer procedure be filmed without interruption, including the opening and closing of the channel [59]. Either a technological solution must be found or ICCAT regulations altered to accommodate transfers that are not filmed by divers. The current practical and financial limitations associated with divers primarily applies to operating them from a fishing vessel. It is more feasible to use divers to film caging operations once inshore.

There may be a further necessity for shore-based divers for Norwegian live storage operations. The crowding of fish for slaughter (as was conducted in the 2023 trial) effectively negates any physiological recovery achieved during the caging period and can result in poor quality. The future perspective for the Norwegian fishery therefore relies on finding a slaughter method consistent with good animal welfare. In other existing tuna live storage operations, fish are slaughtered individually in a stress-free manner using diver operated devices (e.g. a *lupara* [61]).

If a live storage industry is to be realised, decisions must be made on what form it will take. It may be more efficient to use separate vessels to transport towing cages inshore while the purse seine fleet continues to operate on the fishing grounds (as is done in Mediterranean fisheries). Efficiency may also be optimised by having several holding cages situated along the coastline at convenient locations, to reduce the distance fish must be towed. The suitability of such solutions with logistics further down the value-chain, as well as their profitability implications, must be determined. Formal cooperation between companies may help to improve catch efficiency, reduce individual risk in future investments and stabilise prices by better controlling the supply of fish to the market.

6. Alternatives to purse seine capture and live storage

Developing an efficient and profitable Norwegian ABT purse seine fishery is clearly challenging. It is therefore questionable whether allocating most of the quota to this gear type is the most rational and economically profitable option for the exploitation of the resource. Consequently, it is appropriate to consider the feasibility of alternative capture methods for ABT in Norway.

Behind purse seine, longlines are the next most productive gear type in terms of landings of eastern ABT in ICCAT fisheries [48]. However, due to low capture efficiency in recent trials and a national ban on using live bait, the Norwegian fishing industry does not currently consider longlining to be a viable alternative. Opportunity costs that limit longline participation, like those currently experienced by Norwegian purse seiners, may still arise. However, considering the success of this gear type in other locations [48,62], and its market reputation for supplying high quality product [63], further work and potential knowledge recruitment from countries with successful longline fisheries (e.g. Japan, Italy or Spain) is needed to fully explore its potential.

Traps land similar amounts of eastern ABT as longlines [48], and ~ 50 % of landings outside of the Mediterranean Sea were caught by this gear type [48]. The method involves herding tuna into cages using guiding nets situated close to shore [64]. This is similar to traditional Atlantic salmon (*Salmo salar*) traps used inside Norwegian fjords [65], although the logistics around tuna traps may be more complex. Fjord catches of tuna using purse seine were abundant during the 1950s and 1960s [14]. If the ABT stock continues to increase and they re-occupy their previous inshore niches, trap capture for some of the quota may become an alternative. The passive nature of traps would at least avoid vessel opportunity costs, whilst still allowing for potential value creation via live storage. On the other hand, tuna exhibits mostly migratory and feeding behaviour in Norway, which is different to the spawning behaviour observed for ABT in regions where traps are successful, questioning the potential efficiency for this type of gear in Norwegian waters.

Tuna fishing with rod-and-reel is an important fishing activity in many countries [66]. In the western Atlantic, it accounted for 58 % of total western ABT landings in 2022 [48]. Commercial and recreational rod-and-reel fishing for ABT in Norway is currently a small (~ 10 % of the 2023 quota) but rapidly growing sector. In the commercial fishery, small (< 15 m LOA) coastal-based power boats are used. The opportunity cost for such vessels is lower than for purse seiners. Rod-and-reel may pose animal welfare and quality issues but, because the fish are individually caught and handled, this provides good opportunities for controlled research to develop and implement practical solutions [e.g. [67]]. Targeting tuna in this way is also considered by many recreational anglers to be the ultimate sport fishing experience, and they are consequently willing to spend substantial quantities of money in its pursuit [68]. This allows value-creation in the form of tourism that commercial fishing alone cannot provide. Taken together, these characteristics mean that rod-and-reel is likely to become increasingly important for Norwegian ABT fishing in future years. In the western ABT fishery, landings by handline or rod-and-reel increased from 804 t to 1521 t between 1994 and 2022, while purse seine catches declined from 301 t to zero [48].

In some regions, like the Bay of Biscay, pelagic otter trawls are successfully used to catch ABT [69]. However, pelagic trawl has not been, nor will likely be, considered to directly target ABT in Norway. Although ABT is caught by pelagic trawlers in Norway, it is only as incidental catch while targeting mackerel. More importantly, a key objective for the fishery is to improve the quality and welfare of the captured fish compared to those caught by purse seiners today. This would not be achieved with pelagic trawls as they are currently operated.

Independent of how the ABT fishery evolves, Norway will still require some level of management policy in the future. As the number of fish in local waters continues to increase [11], unwanted interactions with existing industries are becoming increasingly prevalent. Between 2020 and 2023, over 15 t of ABT was recorded as bycatch [19,70], which is most likely an underestimation. Over a third of cases were ABT swimming into Atlantic salmon aquaculture cages, which are common along the Norwegian coast. Such interactions cause substantial equipment damage, add additional labour cost and can have environmental consequences if farmed fish escape. The remaining bycatch was taken during commercial fishing using trawl, drift net or purse seine. The bycatch of charismatic marine megafauna such as ABT can also affect the perception of a fishery with both managers and the public.

7. Final remarks

The current population growth of ABT makes it likely that the increase in the number of tuna observations experienced in Norwegian waters during recent years will continue. Considering the potential ecological, economic and societal impacts of this, it is probable that commercial, recreational, research and policy activity around the species will continue to increase. It is difficult, however, to predict whether or when the paradox that currently exists for the Norwegian ABT purse seine fishery will be resolved. Live storage has the potential to address several of the existing challenges, but will require close collaborative efforts from researchers, industry and legislators to properly determine its viability. Much will also depend on the magnitude of increase in ICCAT quota allocations for ABT to Norway in the near future, and whether opportunity costs continue to dictate participation. The potential of other capture methods such as rod-and-reel as an alternative to purse seine must therefore also be fully considered. Which sector of the fishing fleet is to be prioritised by management authorities will undoubtedly play an important role. Substantial investment in shore-based infrastructure and establishing market channels will be required for all sectors.

Considering the experiences and trends presented in this study, the implementation of the following policies in Norway may be beneficial for the ABT fishery:

- Diversify the gears used to improve the temporal and special opportunities to utilise the annual ABT quota;
- Limit purse seine licenses for ABT to vessels that specialise in the fishery and can guarantee participation as well as predictable high quality product delivery; and
- Develop the rod-and-reel fishery for ABT to increase the general interest and revenue, including from tourism, without competing directly with the purse seine fishery.

The comeback of ABT to the sub-arctic waters of Norway has provided new possibilities for exploitation and research of this remarkable species. Considering the huge changes in market demands and fishing technology since the ending of the historical fishery in the 1980's, the challenges outlined in this article are understandable. Norwegian fishers and industry have essentially had to re-learn the fundamentals of ABT fishing and marketing. The fishery has now been in operation for nearly a decade despite these challenges. Given the context, this is a considerable achievement. Continued successful collaboration between industry, research and management in the coming years can be expected to further catalyse development. Any future success of the Norwegian ABT fishery will serve as an important example for other under-utilised fisheries facing similar challenges around the world.

CRediT authorship contribution statement

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Data availability

Data will be made available on request.

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