Chapter

New Development: High-Strength Stainless Steel as a Sustainable Material for Aquaculture

Paul Gümpel, Urs Dornbierer, Arnulf Hörtnagl and Torsten Bogatzky

Abstract

This paper presents the current state of development and selected technological challenges in the application of ecologically and economically sustainable nets for aquaculture based on ongoing development projects. These aim at the development of a new material system of high-strength stainless steel wires as net material with environmentally compatible antifouling properties for nearshore and offshore aquacultures. Current plastic netting materials will be replaced with high-strength stainless steel to provide a more environmentally friendly system that can withstand more severe mechanical stresses (waves, storms, tides and predators). A new antifouling strategy is expected to solve current challenges, such as ecological damage (e.g., due to pollution from copper-containing antifouling substances or microplastics), high maintenance costs (e.g., cleaning and repairs), and shorter service life. Approaches for the next development steps are presented based on previous experience as well as calculation models based on this experience.

Keywords: sustainability, stainless steel, high strength, redesign, predator net

1. Introduction

Of the fish consumed worldwide, the total amount since 2016 has been more than 150 million tons per year, almost half is now produced in aquacultures. While the amount of freely caught fish is stagnating or slightly declining, the amount of fish farmed in aquacultures is continuously increasing. Currently, about 150 species of fish are farmed in aquacultures, and the proportion of seawater farms is constantly increasing [1].

A crucial challenge of today's aquaculture is to protect the farmed fish but also to protect the environment and the surrounding ecosystems. The goal of sustainable aquaculture operations should therefore be to achieve as limited an impact on the environment as possible. At the same time, in the sense of economic operation, care must be taken to ensure that the fish farms are subject to as limited a maintenance and repair effort as possible. In addition, the conditions under which the fish are kept play a decisive role, so that the fish do not suffer from diseases and a sufficient exchange of water is ensured.

The massive expansion of fish farms poses major challenges for operators. Sustainable criteria for aquacultures are indispensable and it is important to avoid negative impacts on the environment in order to meet consumer confidence as well as current and future national and international requirements. The materials used for the construction of the nets play a major role. Generally, a net enclosure consists of a buoyant support system and a net that encloses the animals. There are only minor differences in the basic principles between the classic "nearshore" and the "offshore" applications that have been implemented for a few years. However, the individual installations can vary greatly in size, shape, and materials used [2, 3].

Plastics are predominantly used as the netting material. To counteract the growth of undesirable organisms on the surface of man-made structures, also better known as biofouling, these plastic nets are usually protected from fouling with anti-fouling agents. These industrially available products are currently often made of copper and zinc. It should be noted that both metals are listed by the EU under the Dangerous Substances Directive (67/548/EEC). Especially the application of copper in the field of anti-fouling has a significant impact on the fish in the fish farm as well as on the organisms in the direct environment of the fish farms [4, 5]. Thus, significantly elevated concentrations of copper in sediments can be detected in the vicinity of salmon aquaculture operations that use conventional anti-fouling strategies with copper. Individual scientific studies also indicate that the high concentrations of copper may also lead to sub-lethal effects for the fish kept in the aquacultures [4–6]. The application of copper-containing solutions to the net materials used is mainly by copper-containing dip coatings, which impregnates the nets. This results in a continuous release of copper into the environment, causing the effects listed above to occur. For example, in the OSPAR Commission reporting area, this resulted in an annual emission of at least 454 metric tons (MT) of zinc, copper, and chemical compounds based on them as early as 2009 [7]. Due to the large increase in aquaculture since 2009, a much higher number can be expected today on a global scale. These considerable amounts of valuable raw materials are consumed in this application and cannot be directly recovered by conventional recycling. The search for suitable and practical alternatives to this end has been ongoing in the field of research for several years [8]. Nevertheless, the use of anti-fouling strategies based on copper and zinc remains the state of the art.

Moreover, the polymer materials used are hardly recyclable and in turn also contribute to plastic pollution of the oceans. Plastics, and in particular the fine fibers of the nets or the ropes and braids, are also very susceptible to the biofouling already mentioned above (substance deposits on the material surfaces). They therefore require complex and costly maintenance and cleaning. In addition, the susceptibility to fouling places a burden on the fish living in the aquacultures. This in turn leads to costly treatment, which also stresses the fish and slows their growth. Omitting the substances that protect against anti-fouling leads to a considerable reduction in the cross-section of the nets within a short time due to the colonization of algae, mussels or barnacles. This fouling can adhere very well to conventional plastic nets and can only be removed with great technical effort, if at all. In addition, the fouling on the nets leads to a significant increase in the mass of the net systems. This results in a significantly higher mechanical load and, in conjunction with the other loads that occur (wave action, tides, currents), can also lead to corresponding damage to the nets [9].

Damaged nets, but also nets that can be easily bitten through by predators, do not provide sufficient protection against classical predators of fish in aquaculture. The often-used setup with two net systems (predator net to keep predators away and fish net inside the aquaculture) is also only limited suitable to keep away the highly specialized and intelligent predators. Exemplary for many other cases are seals as a challenge for salmon farms in Scotland. An adult harbor seal is an extremely efficient hunter, eating between 3 and 7 kg of fish per day, depending on species and size. In addition, continuous attacks by predators in the aquacultures lead to a significantly increased stress level of the fish, which not only inhibits their growth, but can also lead to their death. The sometimes widespread method of selectively hunting and killing corresponding predators in the environment of aquacultures is restricted by increasingly restrictive regulations at national and international level, so that there is a need here for innovative and sustainable methods to protect fish in aquacultures [10, 11].

All aspects listed here suggest that for an ecologically and economically sustainable operation of aquacultures, both “nearshore” and “offshore”, it is necessary to resort to further technological approaches and concepts. The application of high-strength metallic mesh systems represents a promising alternative technology in this respect. The state of the art, the development work carried out to date and the prospects are reported on below.

2. Material selection and mesh production

The selection and configuration of the net materials as well as their long-term behavior in seawater determine decisive parameters for aquaculture operations. As already described above, the flow of fresh water through the cages, the hygiene of the facility, the protection against external predators and, last but not least, the safety against escape of the farmed fish into the open sea are all significantly influenced by this. For all the above criteria, stainless steel is an ideal material for several reasons. The high specific strength of steel compared to polymers also makes it possible to produce larger net systems and increases the water flow. The technical challenge of producing a mesh from steel wires has now been solved very well on an industrial scale. It seems to be important that only the pure stainless steel surface is used without any coating or that no toxic substances can be used to prevent fouling of the stainless steel surface. The great advantage of stainless steel is the good and easy removal of biological fouling. To build a complete plant with stainless steel cages is in principle technologically feasible, but still represents a major challenge. In particular, the design of the plant, the connection of the nets and the associated force transmission, as well as the handling of the nets must be adapted to the properties of the stainless steel.

In order to find a fundamentally suitable material for aquaculture nets in nearshore and offshore fish farming, several development steps were carried out. The first step was to compare the properties of different stainless steels to meet both wire and net manufacturing and equipment operation requirements. The properties of different types of stainless steels were investigated and evaluated. The sometimes contradictory requirements for high strength with sufficient residual ductility for the manufacture of nets and, in particular, the corresponding corrosion resistance for use in seawater can best be met by the so-called corrosion-resistant duplex stainless steels (**Figure 1**).

Duplex stainless steels also offer the advantage of high resistance to stress corrosion cracking in seawater. In the oil and gas industry, these steels have been used in seawater for many years with very good experience.

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By using duplex stainless steels in the cold-worked condition, all requirements regarding mechanical strength and corrosion resistance can be met. Laboratory

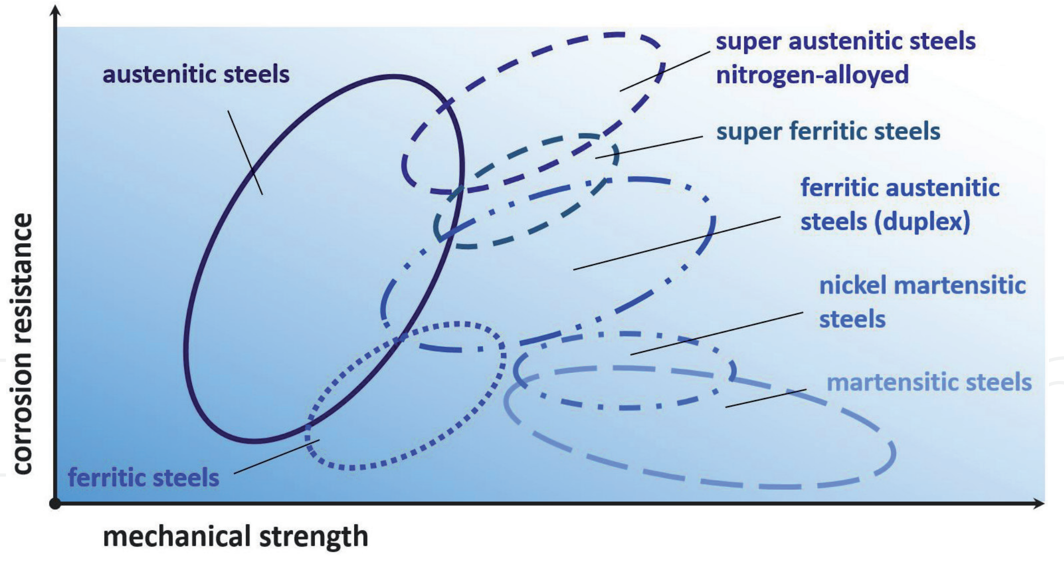

Figure 1.
Schematic overview of the relation between corrosion resistance and mechanical strength for the different types of stainless steels [12].

tests have shown that both materials A (alloy 2304 (UNS S 2304/ 1.4362)) and B (alloy 2205 (UNS S2205/1.4462)) have corrosion resistance in artificial seawater at the usual temperatures. However, the resistance of the molybdenum-containing material B is higher, resulting in greater safety against additional stress factors such as higher temperature, concentration of chloride and/or biologically influenced effects on the corrosion process. A highly specialized manufacturing process was used to produce and further process meshes made of these high-strength materials with a tensile strength of up to 2000 MPa. Therefore, the mesh system manufactured from stainless steels has much higher mechanical strength compared to the conventional plastic meshes. The use of stainless steels with the much higher strength compared to polymers results in thinner mesh bars or larger mesh sizes. The area ratio of web material to flow opening becomes more favorable and water exchange, which is so important for the quality of the plant, becomes much better compared to polymer nets. Regardless of the degree of biological growth, this improves the living conditions of the fish. This positive condition is maintained by a continuous cleaning process, which leads to a higher sustainability.

3. Practical testing

A selection of different net systems (material and antifouling strategy) represented the second step of the development carried out. For this purpose, samples were outsourced at eight locations worldwide (**Figure 2**) over a period of at least 6 months in order to investigate the individual fouling behavior in comparison to existing net systems in practical use. For this purpose, samples were outsourced in the area of fish farms or shellfish farms in order to simulate local conditions in the farm area as well (see **Figure 3**). Contamination was documented and evaluated at defined intervals using photography and light microscopy. In addition, the cleanability of different mesh systems was tested and evaluated using standardized cleaning procedures.

After several test cycles, the samples were evaluated for their corrosion and antifouling behavior. In addition to these immersion tests in natural fish farm environments, laboratory tests as well as microbiological and corrosion tests were performed to investigate and evaluate the different net systems and AF strategies.

Figure 2.
Sites for natural outsourcing in aquaculture and in artificial seawater for simulation experiments in the laboratory.

Figure 3.
Test arrangement of the outsourced samples.

The results of the laboratory tests as well as the natural deposition in seawater farms clearly showed that the development and also the growth of biofilms (**Figure 4**) is most safely hindered by the application of toxic substances, e.g. of copper as a common antifouling strategy for a limited time. In polymer nets, this is achieved by infiltration of copper. Metal nets, for example, may be made of copper alloys, or the surface of the steel may be coated with a layer of copper or copper alloys. Surface coatings of non-stick materials such as PTFE (polytetrafluoroethylene) or nanostructured materials (sharkskin effect) can reduce biofouling compared to the surface of pure steel, but fouling is only delayed but not prevented (**Figure 5**).

Another essential part of the investigations carried out was the comparison of the possibilities to clean the overgrown structures after a defined aging period. Different cleaning systems were used for these tests. The results can be described as follows: Steel/metal surfaces can be cleaned thoroughly and almost residue-free with a water jet/hydrojetting (see **Figure 6**). Cleaning with this common method is also possible in principle for polymer meshes. However, a closer examination of the surfaces showed that the cleaning result is significantly worse. In this context, biological studies have shown that considerable residues of biofilm material always remain between the individual plastic threads. Such residues of biological material accelerate re-biofouling. Thus, in these cases, a comparatively rapid re-growth of the nets is to be expected. This effect sometimes leads to a reduction in the service life of conventional plastic nets. A comparable acceleration of re-biofouling could not be determined for the steel nets used.

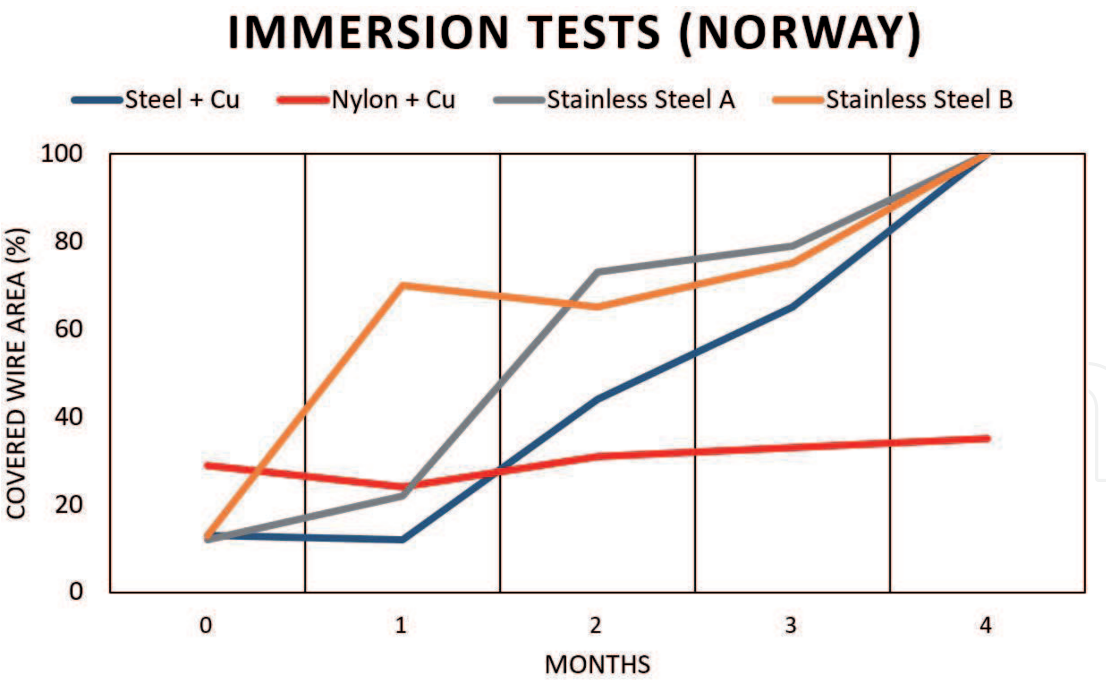

Figure 4.
Proportion of the covered area after long-term exposition in seawater (4 months).

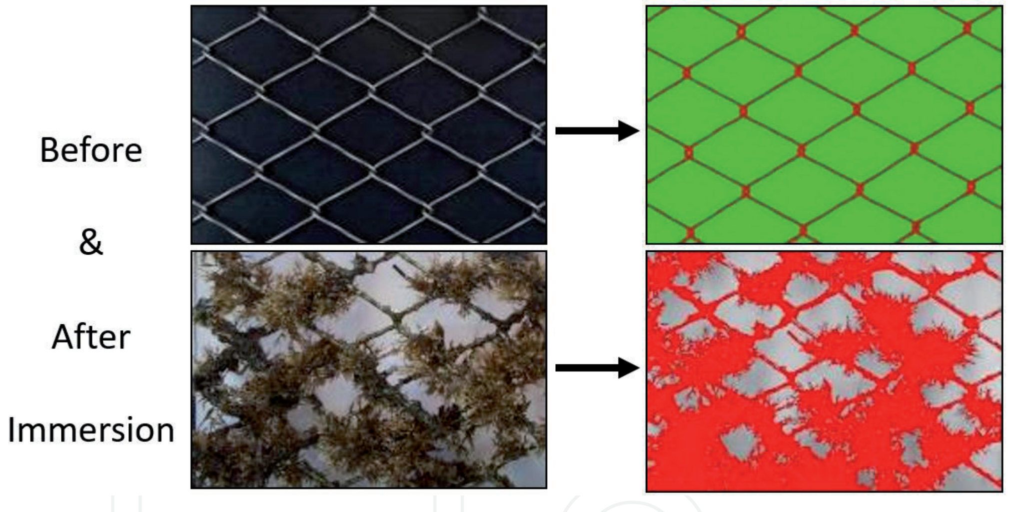

Figure 5.
Method for optical evaluation of the change in the area fraction of the biofilm on the outsourced network structures [12].

On the basis of these preliminary investigations and the material selection made, the first stainless steel nets for aquaculture could be used as predator nets. These coarse-meshed nets keep predators such as seals away from the fish nets inside. The first field trial took place in South America on the Pacific coast. **Figure 7** shows the supplied net rolls that were assembled into cages in the field. Based on the results of the previous laboratory and exposure tests, the nets were made from Material A.

Surprisingly, after only a few months of real-world application in the Pacific Ocean, corrosion attack occurred mainly at the nodes of the mesh (**Figure 8**). Some isolated corrosion attacks were caused by small, invisible defects in the surface. In general, the surface quality of the cold-drawn wires in this highly reinforced condition is a problem. These manufacturing problems were solved by the steel supplier.

The reason for the systematic failures in the node areas could be determined by fault analysis and simulation of corrosion experiments. During field operation, there is high friction at the nodes in the meshes. This friction in the nodes under

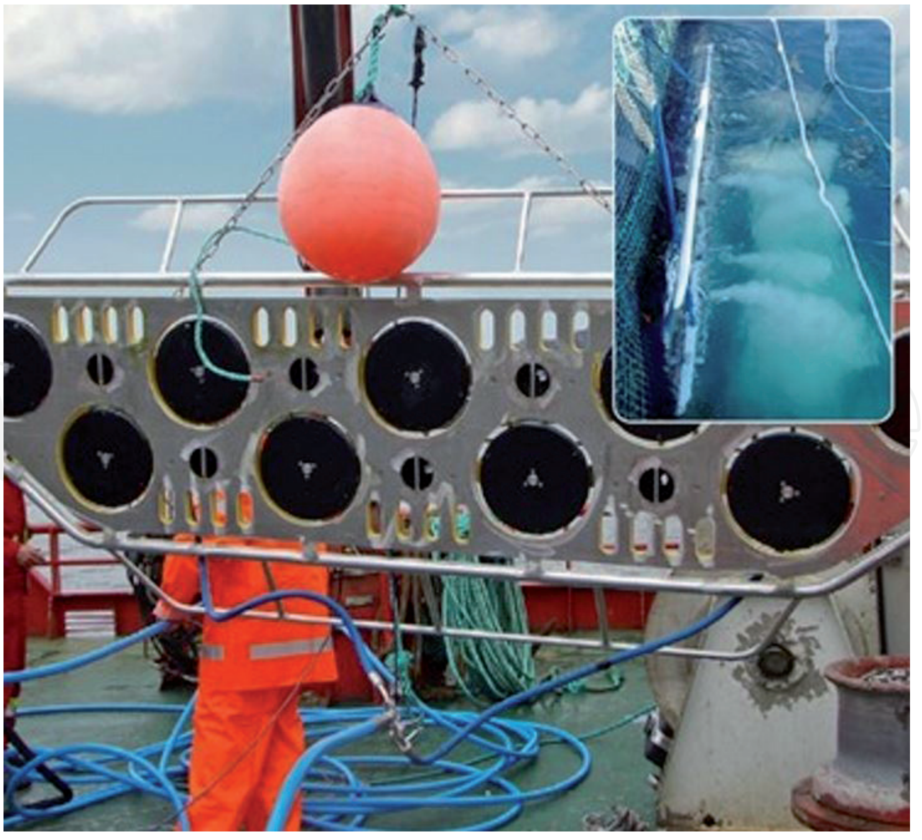

Figure 6.
Proven cleaning method to remove biofouling from surfaces.

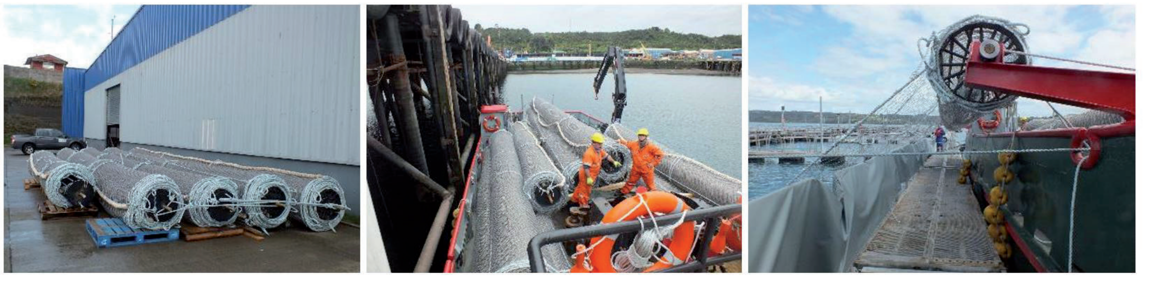

Figure 7.
Installations in South America - Total 112'000 sqm.

Figure 8.
Typical tribocorrosion in the friction area of a stainless steel net after some months in the Pacific Ocean [12].

high mechanical stress and seawater environment has led to tribocorrosion. In this particular case, the material in the friction area was activated and could not passivate again under the given conditions. Simulation tests showed the activation. The OCP breaks down during frictional loading and increases when friction stops

(**Figure 9**). A dependence on the time between activation is also evident. The tests showed very clearly that material B has a much higher resistance than material A under these test conditions (**Figure 10**). Temporary activation can occur with material B, but repassivation occurs quickly and reliably. The stainless steel with the higher alloy content and thus a higher pitting resistance value definitely has a higher tolerance to any type of corrosion [12].

The susceptibility of individual materials to the tribocorrosion that occurs led to a further and more detailed investigation of possible locations for aquacultures. Using specially developed measuring buoys, it was possible to compare the corrosivity at different locations. This clearly showed that, in addition to influencing factors such as water temperature or salt concentration, the potential shift caused by microorganisms, also better known as ennoblement, plays a decisive role in the corrosion mechanisms that occur. Since, as already explained above, a correspondingly high input of microorganisms is always to be expected in the direct environment of aquacultures, the ennoblements must always be taken into account when selecting materials. As already listed above, this is possible with the listed alloy B, which could be confirmed by laboratory tests as well as by application in aquacultures [12].

In order to better understand the advantages but also the application limits of steel nets compared to plastic nets, a consideration of specific technical properties is necessary. However, it is important that properties such as density are not considered in isolation. The density of a conventional plastic such as PA 6 (polyamide 6) is 1.1 g/cm^3, whereas the density of a stainless steel is approx. 7.8 g/cm^3. This serious difference in density is put into perspective when the achievable tensile strength of these materials is taken into account. For reconditioned PA 6 ropes, a considerable tensile strength of 110–175 N/mm^2 can be achieved. A work-hardened duplex

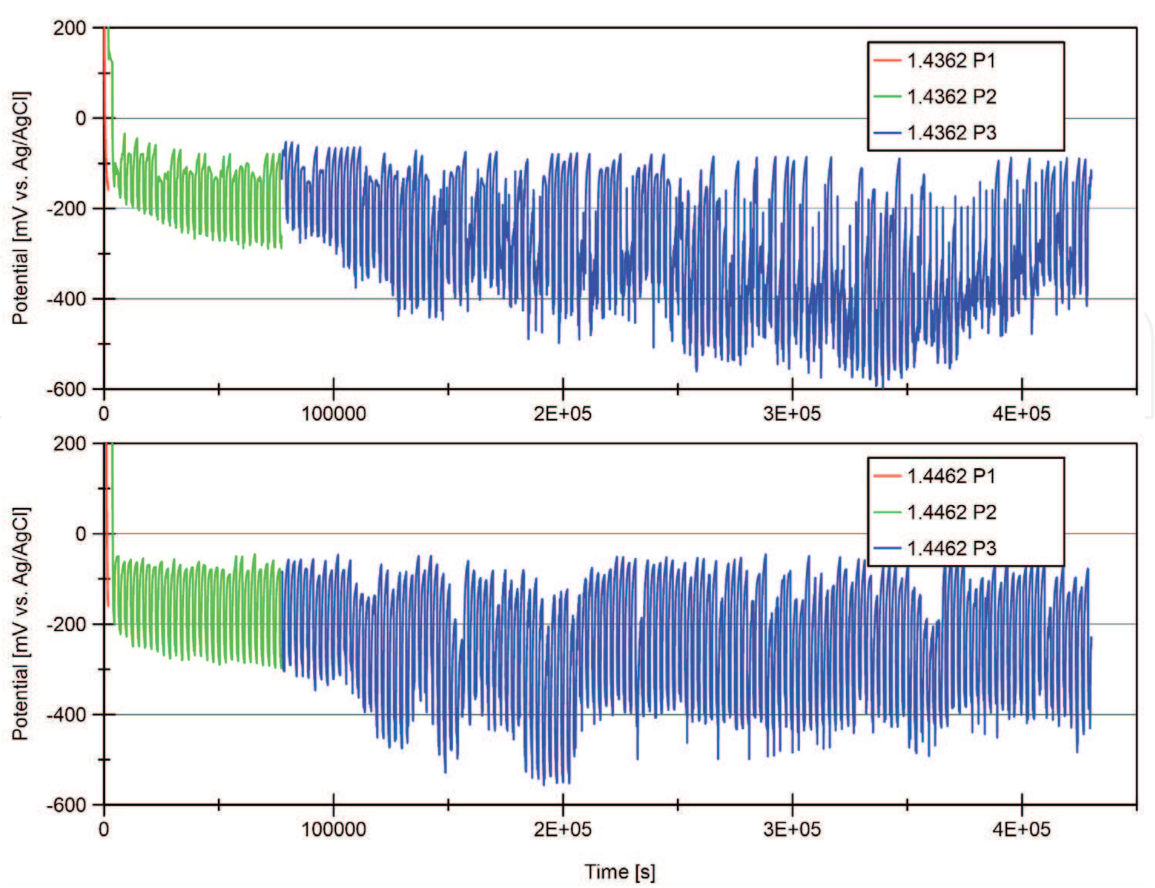

Figure 9.
Open circuit potential during friction simulation – peaks show repassivation when friction stops [12].

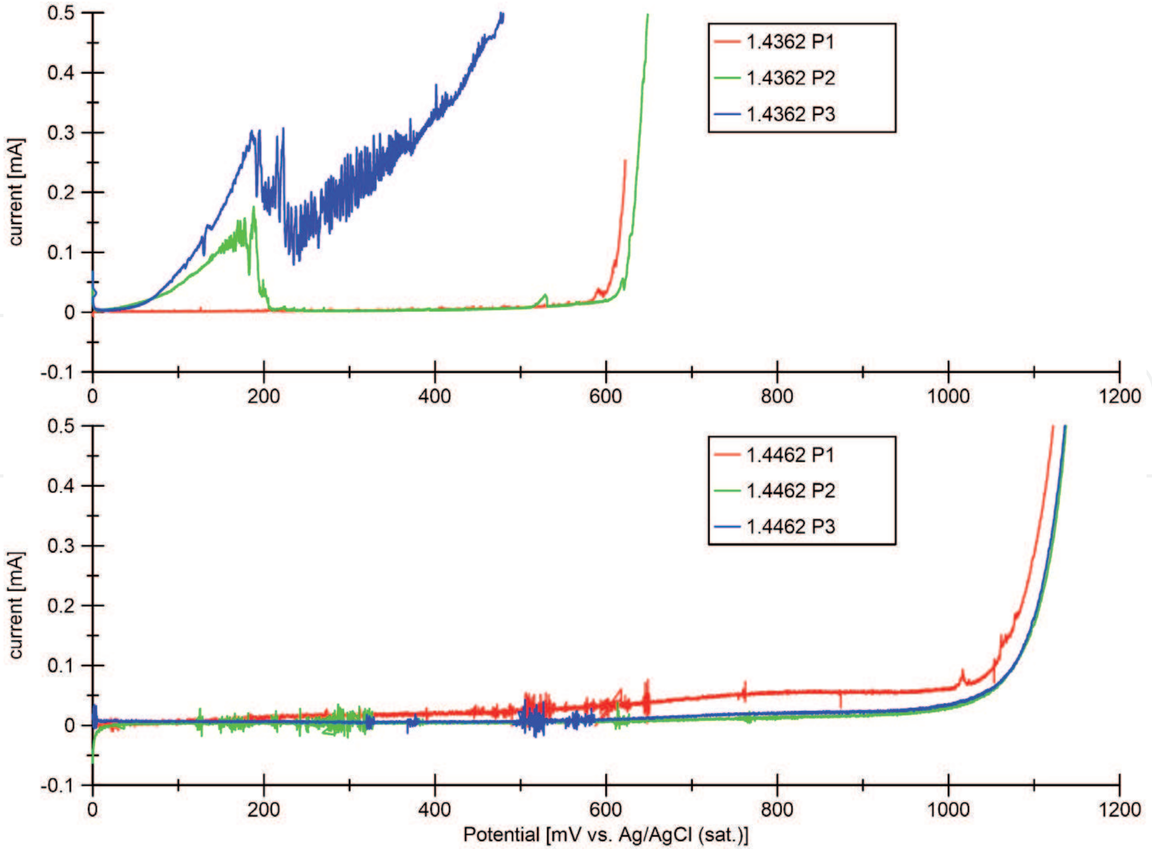

Figure 10.
Current-potential-curves after different times of friction simulation (see phases in ***Figure 9****) [12].*

stainless steel 1.4462 achieves tensile strengths of 1200–1350 N/mm^2, in the case of the highly specialized applications listed here up to 2000 N/mm^2. If these figures are put in relation to each other, the strength achieved per mass used is comparable for both steel and plastic.

Another significant difference lies in the modulus of elasticity of the materials. For the PA 6 material mentioned above as an example, this is approx. 3 GPa. For the steel 1.4462, the value is approx. 200 GPa. This difference is of particular importance, as it clearly shows that a simple substitution of plastic meshes by high-strength steel meshes can be problematic when using the same joining technology. **Figure 11** shows an example of the deformation occurring in a salmon aquaculture. It can be clearly seen that in the application, a significant deformation compared to the original prefabricated geometry occurs due to the dead weight of the mesh panels.

Subsequently, the occurring sea loads, which are composed of the external influencing factors (e.g. water current, wind and tides), result in a time dependency of the occurring forces and thus also of the occurring deformation. This can be seen from the differences in the occurring deflection recorded by measurement on three consecutive days in **Figure 12**.

While conventional plastic nets achieve high deformation even at low forces due to the comparatively low modulus of elasticity of the materials used, steel nets behave comparatively rigidly in most cases. As a result, the load distribution of plastic nets is generally more benign and stress peaks are evenly reduced, even when the mesh panels are rigidly connected to each other. If a correspondingly rigid connection is made in the case of steel nets, there is a risk of wire breaks occurring in the area of load application or at connection points between the nets. This can be the case both as a result of a one-time overload and as a result of a high cyclic load. Taking into account the corrosive environmental conditions in

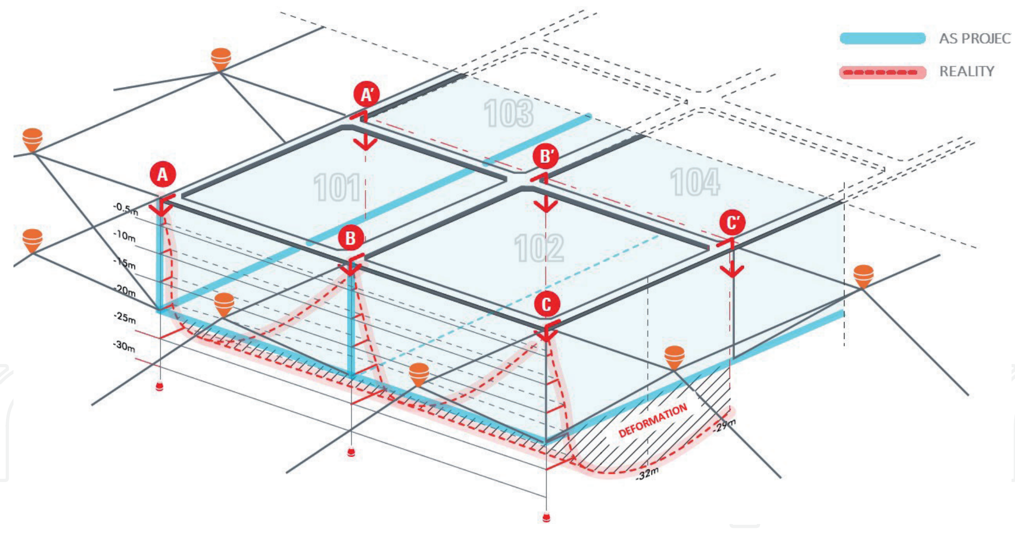

Figure 11.
Illustration of the occurring deformation of an exemplary salmon aquaculture.

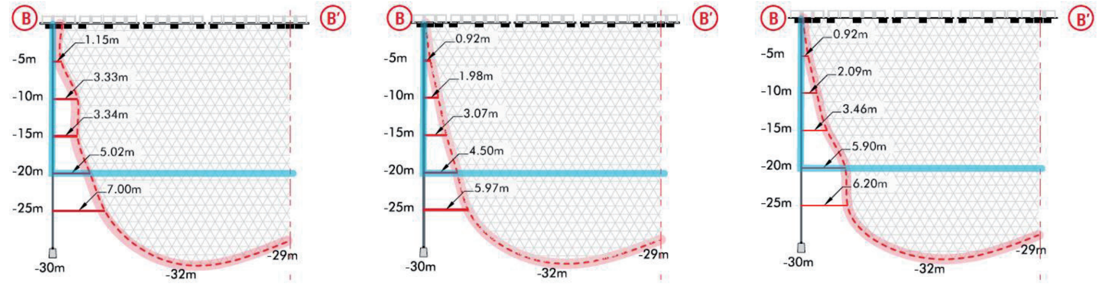

Figure 12.
Temporal variation of the occurring deformation in an aquaculture.

seawater and the tribological stress occurring at the contact points between the individual wires, the result is a highly complex system in which several damage mechanisms interact.

Before remedial measures can be defined, it is necessary to differentiate the damage patterns and the causes of damage as far as possible. As an example, the damages in **Figures 8** and **13** can be compared. Basically, both damage patterns show a reduction in cross-section in the area of the wire contact. However, tribocorrosion in the contact point, see **Figure 8**, leads to increased local corrosion of the surface, while mechanical overloading leaves a comparatively smooth contact point. The wear marks shown in **Figure 13** do not reveal any discernible corrosive attack. It should be noted that the wire breakage that occurs as a result of the load distribution is not directly present at the generated groove. Due to the geometry of the half mesh or the meshes used, the maximum stress occurs directly next to it.

More in-depth investigations on a laboratory scale and simulations based on these confirm that a simple substitution of plastic nets by steel nets in aquaculture with strong mechanical loads due to waves, wind and tides does not yet produce the fully desired increase in the targeted service life when using steel nets compared to plastic nets. As shown by the study of a wire break **Figure 14** of a net element tested for continuous load, violent bridging in the form of sliding or honeycomb fractures occurs as a result of the bending load.

However, the studies carried out and the first applications in practice also show that there is considerable potential in the technology described here. In order to do justice to this potential in the growth market of aquaculture, selected development approaches are listed in the following chapter.

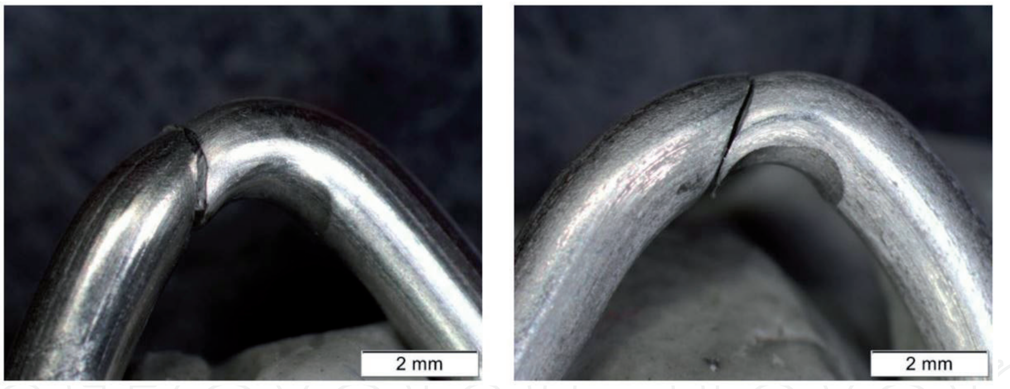

Figure 13.
Fracture pattern at a half mesh in the area of the wire contact of two different mesh patterns due to mechanical overload.

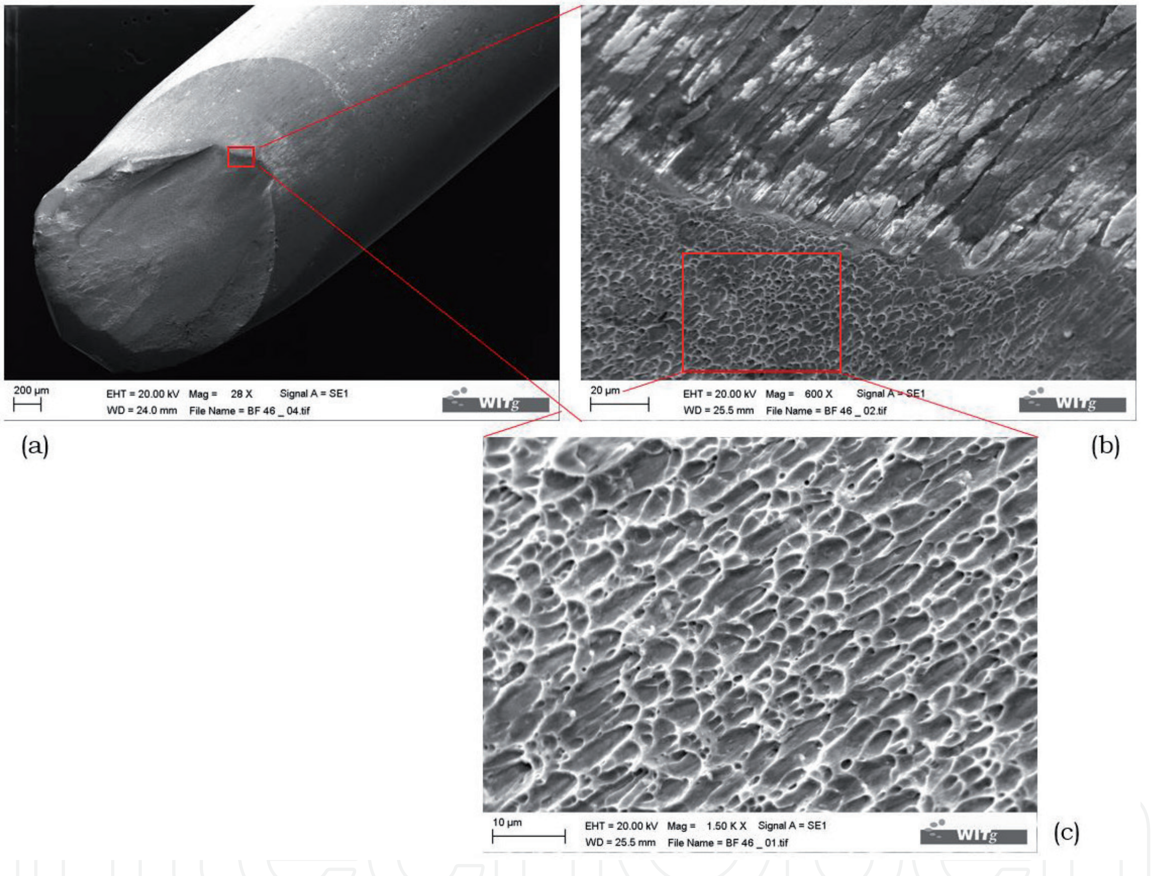

Figure 14.
SEM images of the fracture surface of a wire at different magnifications; (a) overview image showing presumed area of origin for the fracture; (b) and (c) detail images showing characteristic honeycombs of a transcrystalline honeycomb fracture.

In order to round off the comparison between plastic nets and steel nets, the input of plastic/microplastic into the waters must be taken into account in addition to the influence of the antifouling strategy applied. Similar to steel nets, the mechanical stresses that occur between the individual ropes and strands lead to wear. This wear occurs when plastic nets are used for both conventional fishing and aquaculture. It must be pointed out, however, that this input into the world's oceans is comparatively small compared with other sources. Nevertheless, from a current perspective, it is particularly important to reduce the generation of microplastics in the direct vicinity of our food sources [13]. While plastic nets must be disposed of as hazardous waste at the end of their service life due to contamination with heavy metals and biomass, steel nets can be recycled very easily as high-quality steel scrap.

4. Outlook and ongoing developments

Based on the above experience, selected changes have been made which should make a significant contribution to the possible widespread use of steel nets in aquaculture. The most significant change in the manufacture of nets is the use of the more corrosion-resistant material B, as already explained above. In addition, the structure and overall suspension of the cage were designed to minimize friction in the nodes and to have the most homogeneous load distribution possible within the net. After these modifications, no systematic signs of corrosion or tribocorrosion were observed. Another starting point is the structural adaptation of the fastening of the nets, the load application and the connection of the nets to each other. A project underway for this purpose is now in a phase in which long-term operation is being observed and a continuous improvement process is being carried out in actual use. A long-term tested, technically reliable solution for anti-predator networks should be available by mid-2022.

In parallel to the above mentioned tests, a development project for a sizing tool for farms to be equipped with stainless steel netting is ongoing. Since local influences differ greatly depending on the location of the aquacultures (prevailing currents, wave action, tidal variation and the factors listed above that affect corrosion), it is necessary to evaluate each aquaculture individually. Depending on the stress factors encountered, other design measures can then be taken. The tool will allow statements on the design of the network and its expected service life based on local conditions. This project should be completed by 2025.

Initial tests and simulation on this indicate that a successful use of high-strength stainless steels as network material for aquaculture is possible. However, due to the damage mechanisms that occur, holistic approaches must be pursued, which are aimed in particular at a possible reduction of the acting loads and their uniform distribution. The following approaches can be considered as examples.

By gradually reducing the wire diameter used in steel nets, the weight force occurring in aquaculture can be reduced as much as possible. Calculations show that the use of thinner wire diameters in the lower part of the aquaculture results in a reduction of up to 30% of the mechanical loads in the area of the upper attachment points in steel nets, without any restriction of the function.

In the case of plastic nets, whose density is only slightly higher than that of seawater even when impregnated, the use of weights and attachments to the seabed is necessary to minimize their movement due to currents and tides. These measures can and must be dispensed with wherever possible in the case of steel nets. In this way, the mechanical stress on the aquaculture can be further reduced. At the same time, the higher density of steel nets ensures less deformation of the cages.

The use of flexible connecting elements between the mesh panels allows a more even load distribution, which reduces stress peaks. These stress peaks, which can lead to fatigue failure especially with a high number of load cycles, are thus defused as critical points and a much more homogeneous load distribution is achieved. As can be seen from the example in **Figure 15**, constructive approaches can be used in the design of the network paths. Although this requires a corresponding know-how in the manufacturing and processing technology of rope systems, the simulations carried out as well as the first field tests show a significant reduction of the occurring stress peaks.

Another measure is the application of a hybrid structure of aquaculture. As already mentioned above, it must always be taken into account when selecting materials that materials from different groups in particular differ in a variety of

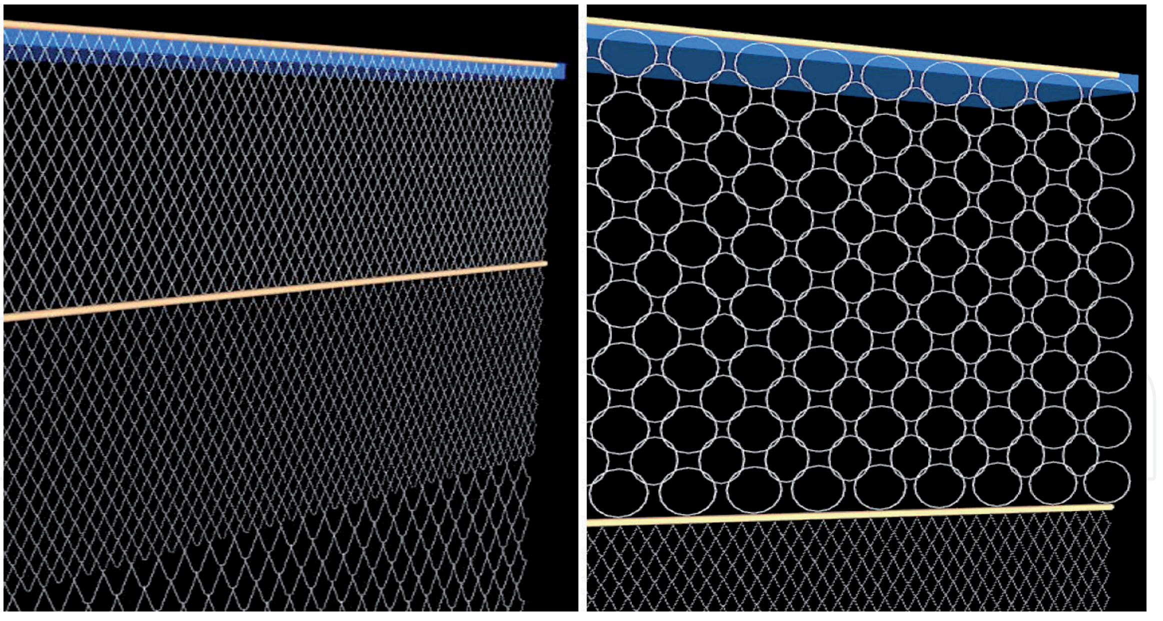

Figure 15.
Exemplary presentation of constructive design possibilities in the application of steel nets.

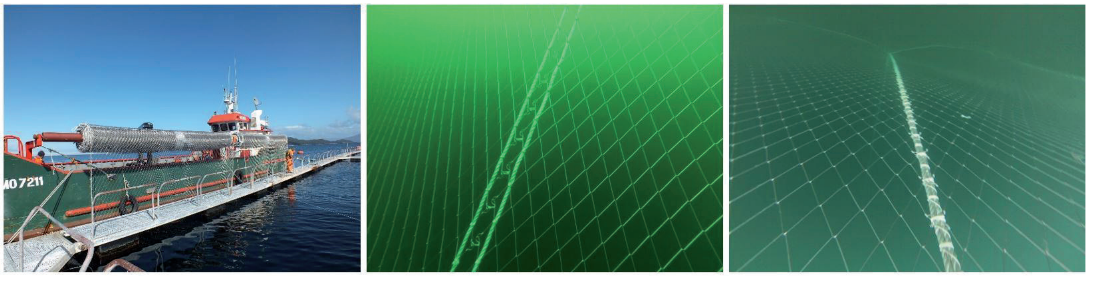

Figure 16.
Installed predator nets for salmon aquaculture in Chile.

properties. A hybrid structure provides for the use of elements made of plastic and elements made of steel. The elements made of plastic, which are used to transfer the load between the floats and the steel nets, allow the load to be distributed as evenly as possible. If the bottom of the aquaculture is also designed as a plastic net, it remains correspondingly flexible or easily deformable. If the side elements are made of steel nets, they continue to offer appropriate protection against predators and are easy to clean and do not require any further AF coating (**Figure 16**).

5. Conclusion

The use of nets made of high-strength and corrosion-resistant steel offers corresponding advantages over conventional nets made of plastic, particularly from an ecological point of view, and subsequently also from an economic point of view after a sufficient service life. The scientific studies carried out show that the challenges of corrosion and tribocorrosion in seawater, biofouling and the mechanical stresses that occur can be met by selecting a suitable stainless steel material. However, it should be remembered that the exclusive use of steel nets for large-scale conventional aquaculture is not possible at present. This challenge can be met in the future with the approaches taken for further development and adjustments in the connection and force application of the nets, according to the available data of these challenges.

Regarding the common aquacultures in the near shore area (near shore), two trends are clearly visible in the past years: off shore and on shore. It is self-evident that for most on shore aquacultures do not require a corresponding network infrastructure. For offshore aquacultures, on the other hand, new challenges and opportunities arise through the application of the high-strength steel nets presented here. The comparatively high tensile strengths of the materials used, up to 2000 MPa, make it possible to operate aquacultures safely even under comparatively harsh conditions if the overall design is adapted.

Thanks

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