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Review article

An overview of disruptive technologies for aquaculture

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ABSTRACT

The world wild fish stocks are being depleted in an ever-increasing speed. Aquaculture is the only way to ensure sufficient seafood for the world. Conventional aquaculture can be traced back to 4000 years in China and has been very successful in the past three decades. However, aquaculture has faced serious challenges, including only a few improved species, labour-intensiveness, environmental pollution, diseases and lack of traceability of products. Aquaculture needs disruptive technologies to increase fish production. Novel and disruptive technologies, including genome editing, artificial intelligence, offshore farming, recirculating aquaculture systems, alternative proteins and oils to replace fish meals and fish oils, oral vaccination, blockchain for marketing and internet of things, may provide solutions for sustainable and profitable aquaculture. This review briefly introduces these emerging and disruptive technologies to open up a forum for an in-depth discussion on how to integrate these technologies into aquaculture to improve its sustainability and profitability.

1. Introduction

Aquaculture has a long history and contributes high-quality proteins to human beings significantly (Gui et al., 2018; Nash, 2010). In the past few decades, aquaculture is the fastest growing sector in agriculture. Since 2013, the production of aquaculture has exceeded the production of wild fisheries (FAO, 2020).

In the past 50 years, applications of science and the introduction of new technologies (Fig. 1) in aquaculture development have promoted the rapid development of aquaculture (Burnell & Allan, 2009). In terms of species, feeds, production systems, diseases, products, business structures and marketing, aquaculture is more diversified than other sectors in agriculture (FAO, 2020). Scientific and technology advances have benefited almost every aspect of aquaculture. A lot of technologies (Fig. 1) have contributed significantly to the production of aquaculture. For example, improved reproductive technologies have enabled people to close the life cycles of aquaculture species, which provides for species diversification in aquaculture (Weber & Lee, 2014, pp. 33–76). The development of the use of live feeds, including microalgae, airtimes, rotifers, brim shrimp and other copepods in hatcheries have solved the big bottleneck in culturing of some marine species (Conceição et al., 2010). Selective breeding with the help of quantitative genetics have substantially improved traits of commercial importance in over 60 aquaculture species (Gjedrem & Robinson, 2014). Sex reversal technology and DNA markers associated with sex determination have enabled the production of mono-sex tilapias (Mair et al., 1997), yellow catfish (Wang et al., 2009) and river shrimps (Levy et al., 2017). Molecular parentage has enabled intrafamily selection in mass-crosses thus reducing the danger of inbreeding (Xu et al., 2020; Yue & Xia, 2014). QTL (quantitative trait locus) mapping and marker-assisted selection (MAS) have enabled selection of traits (Yue, 2014), which are determined by single genes and a few major genes (Fuji et al., 2007; Houston et al., 2008). Improved feed formulations based on the nutritional requirements of each fish species have improved feed conversion rate (FCR) and reduced feed cost (Tacon & Metian, 2015). Technologies for disease management (Kelly & Renukdas, 2020, pp. 137–161) have reduced the occurrence of diseases in aquaculture. Although these early innovations and many others have contributed to a tremendous growth in aquaculture, to meet the ever-increasing seafood demands of the enlarging population on the earth, the challenges in aquaculture are daunting (FAO, 2020). It is essential to produce more aquaculture products. The worsening environmental conditions, reducing supply of fish meals and oils, and climate change will seriously affect our capacity in producing enough aquaculture products to meet the demand for seafood (Abdelrahman et al., 2017; Li et al., 2011; Shen et al., 2020, p. 736210).

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Further sustainable and profitable development of aquaculture is possible (FAO, 2020). More and more new technologies are being developed and entering the aquaculture industry (Ab Rahman et al., 2017). Emerging and disruptive technologies will increasingly offer novel ways to enhance the global seafood production and profitability. These technologies include genomic selection (GS) (Houston et al., 2020; Yue & Wang, 2017; Zenger et al., 2019), genome editing (GE) (Gratacap et al., 2019), information/digital technology (Hassan & Hasan, 2016), recirculating aquaculture systems (RAS) and solar energy (Aich et al., 2020), offshore farming (Froehlich et al., 2017; Hodar et al., 2020), oral vaccines (Shefat, 2018), novel marketing strategies with blockchain, and the integration of different parts of aquaculture with the internet of things (IOT) (Anderson et al., 2019) and others. This review briefly outlines and discusses these emerging and disruptive technologies, which may revolutionize the aquaculture industry, to give readers a broad view of these technologies.

2. Novel molecular technologies for genetic improvement

Genetic improvement through breeding has been key to the boom of the world aquaculture. Conventional breeding programmes have played a critical role and will continue to drive the global aquaculture industry forward (Gjedrem & Robinson, 2014). The combination of molecular technologies into existing breeding programs has significantly accelerated the genetic improvement of some aquaculture species (Yue, 2014). Marker-assisted selection (MAS) has already been applied to improve disease resistance, including resistance to IPN in salmon (Houston et al., 2008), lymphocystis in Japanese flounder (Fuji et al., 2007) and to produce all males in tilapia (Chen et al., 2019). Other biotechnologies, including sex control, polyploidization, gynogenesis and androgenesis (Fig. 1), have played an important role in improving aquaculture productivity (Zhou & Gui, 2018).

Genomic selection (GS) (Meuwissen et al., 2001) is a novel approach of molecular breeding. GS uses many markers as predictors of performance and consequently delivers more accurate predictions of breeding values (Fig. 2). With the continuous advances in sequencing and bioinformatic technologies, and the decrease in cost of SNP (single-nucleotide polymorphism) genotyping, GS using SNPs covering the whole genome and/or using selected SNPs associated with traits is increasingly being applied across the broad range of aquaculture species to optimize selective breeding and accelerate genetic improvement (Shen & Yue, 2019). Details about GS can be found in previous reviews (Houston et al., 2020; Zenger et al., 2019).

Genome editing (GE) using CRISPR/Cas is able to speed up genetic improvement of aquaculture species (Gratacap et al., 2019) when the genes to be edited are known (Fig. 2). GE allows for rapid introduction of favourable alleles to the genome, to increase the frequency of desired alleles at the loci determining important traits, to generate new alleles, and/or introducing favourable alleles from other species (Shen & Yue, 2019). Aquaculture species is especially suitable for GE due to their high fecundity and external fertilization, which enables genome editing for many individuals simultaneously. Readers may find detailed approaches of GE and potential challenges in published reviews (Gratacap et al., 2019) and books (Luo, 2019). One important issue in GE in aquaculture species is to find the right genes, which can be edited to rapidly change traits. Knowledge of gene functions in model organisms, livestock, humans and popular aquaculture species may supply useful information for selecting the right genes for editing.

Advances in GS and GE are poised to dramatically reshape the aquaculture industry by helping improve the economically important traits of many aquaculture species. In the future, combining GS and GE with advanced conventional breeding strategies and matured biotechnologies will substantially accelerate genetic improvement in aquaculture. Hopefully, consumers will understand benefit and risks of GE, and accept these emerging technologies for the genetic improvement in the aquaculture industry. Certainly, it is essential to enact regulatory criteria to assess if organisms resulting from GE can be released for commercial production.

3. Information/digital technologies

Although, in the past 50 years, the development of aquaculture is very fast, there is still much to be done to improve its profitability and sustainability (FAO, 2020). The following information/digital technologies (Fig. 3) may possess the power to revolutionize the aquaculture industry.

3.1. Robotics to carry out laborious work

Aquaculture production is a complicated process. Many steps,

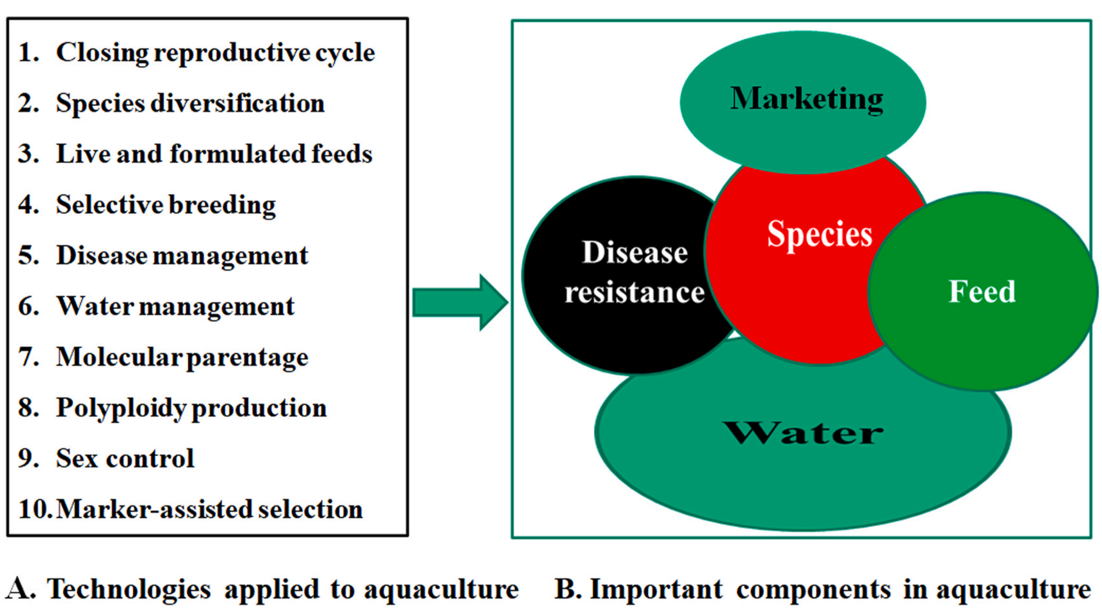


Fig. 1. Technologies applied in aquacuture leading to the rapid increase of aquaculture production in the past 50 years (A) Many technologues (e.g. 1–10). have been applied in different parts (B) of aquaculture to improve aquaculture production.

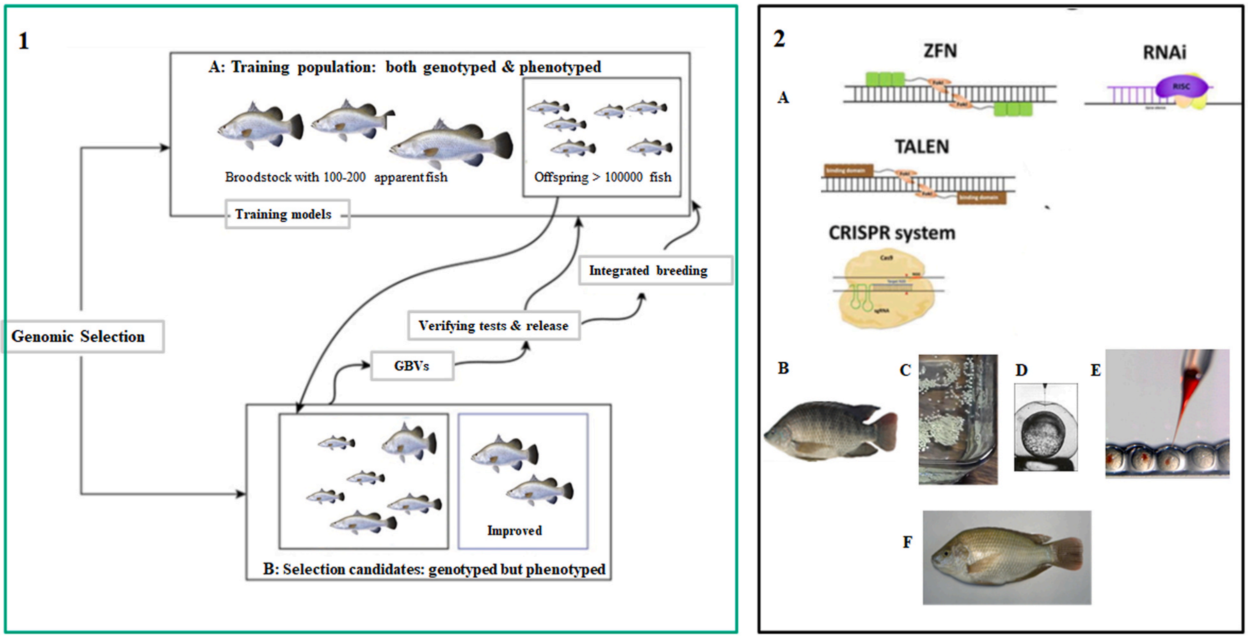


Fig. 2. Genomic selection (GS) and genome editing (GE) eable to rapaidly improve economic traits of aquaculture species. 1. Genomic selection. (1-A): The training population is the population, which is phenotyped and genotyped. The broodstock with 100–200 parents used to produce the offspring by crossing selected parents. Offspring are used as a validation set to train the model against the training sets in the training population. (1-B): Selection candidates in breeding populations are only genotyped but not phenotyped. The breeding candidates with highest genomic estimated breeding values (GEBVs) are selected and will be used to produce next generation. 2. Genome editing (GE). There are basically four different approches for GE, including ZFN, RNAi, TALEN and Crispr/Cas-9. (A). In fish, GE is conducted by microinjection of gRNA and Cas protein into single-cell fertilized eggs. (B): Original fish; C & D: Single cell eggs, E: microinjection and F: gene-edited fish.

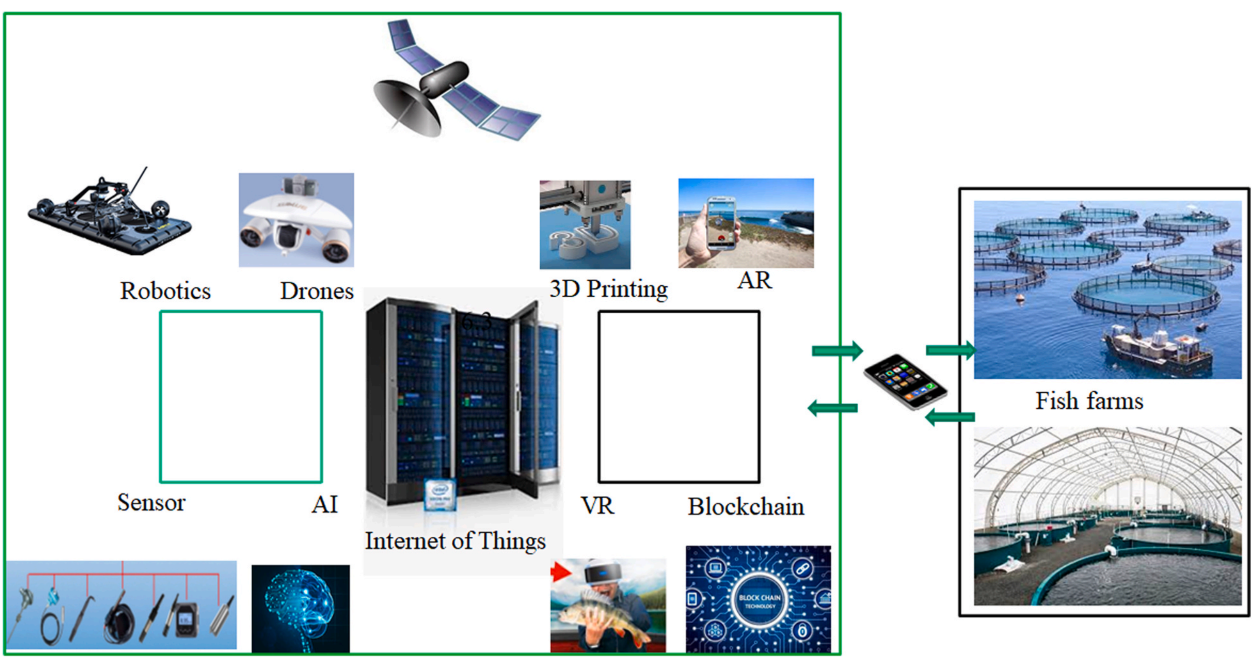


Fig. 3. Emerging and disruptive information/digital technologies applicable to futher increase aquaculture production. Information/digital technologies include robotics, drones, sensors, artificial intelligence (AI), 3D pringting, argumented reality (AR), visual reality (VR) and blockchain. These technologies are connected with farms through satellines, internat of things (IoT) and mobile phones.

including feeding, cleaning ponds and nets, monitoring behaviours and removing sick fish, are labour-intensive and costly (Lucas et al., 2019), which can be difficult without the use of machines. In addition, in the aquaculture industry, there are few customized systems, which can work universally for all aquaculture species and culture systems (Kruusmaa et al., 2020) due to the high diversity of aquaculture species and systems. From a technological perspective, the solutions for these complicated tasks in aquaculture exist. Robots can be applied in feeding, cleaning ponds and nets (Osaka et al., 2010), injecting vaccines (Lee et al., 2013) and removing sick fish (Antonucci & Costa, 2020; Sun et al., 2020). Therefore, they have the potential to conduct some laborious and risky tasks in aquaculture. For example, automated underwater robots have already been used in inspection and cleaning of the status of nets in the salmon industry, which led to fewer human operations (Paspalakis et al., 2020). Robots have also been used to survey the fish's health, monitor and prevent escapes of farmed fish (Ohrem et al., 2020). In fact, robots can make aquaculture more profitable because robots are able to work continuously without interruption under bad environmental conditions and without a need for human assistance. Fish behaviours can be monitored in real time (Kruusmaa et al., 2020). Many research institutes and companies, including Robotfish (http://www.qdlbf.com/), Cermaq (https://www.cermaq.com/), Innovasea (https://www.innovasea.com/), SINTEF (https://www.sintef.no/en/), SeaVax (https://www.theexplorer.no/), Sublue (https://store.sublue.com/) and Massachusetts Institute of Technology (MIT)'s AUV lab (https://seagrant.mit.edu/auv-lab/) have developed and are developing various types of robots for aquaculture. Some types have been tested and proved to be effective. Despite all these exciting robotic products, it is important to note that fully automated aquaculture is still currently impossible, and may not materialize in the short term (e.g. 5–10 years). However, it is certain that the next 5–10 years will bring substantial changes in how fish are cultured with assistance of robots. It should also be noted that any automation using robotics must consider the specificity of each species, culture systems and various environments.

3.2. Drones for data collection

Like robots mentioned above, drones can do a lot of work above and below the water for the aquaculture industry. Drones are able to monitor fish farms on land and in sea, especially offshore aquaculture sites. Many works, including the checking of holes and damages in cages, can be carried out by drones (Sousa et al., 2019). Many research institutions and companies, including, Subblue (https://www.sublue.com/), Qifai (https://qifeizn2020.en.made-in-china.com/), Apium Swarm Robotics (http://apium.com/), Blueye Pioneer (https://www.avetics.com/), SeaDrone (https://seadronepro.com/) and many others are developing and producing drones for aquaculture. More importantly, drones can collect novel information, which are difficult to be obtained by humans. This information can be used to generate algorithms for further developing technologies to improve the efficiency of aquaculture production (Yoo et al., 2020). For example, Saildrone (https://www.saildrone.com/) collected farm data, analysed fish stock and tracked environmental conditions. These data could easily be applied to aquaculture. Drones in combination with artificial intelligence (AI) and cloud computing will cut costs and improve operations for the aquaculture industry (Chen et al., 2020). It is estimated that drone market in agriculture and aquaculture is worth US$5.19 Billion by 2025 (Meticulous Market Research Pvt. Lt).

3.3. Sensors to measure water parameters and monitor feeding and health status

Sensors can be used in collecting water parameters, including dissolved oxygen (DO) levels, pH values, salinity, turbidity and pollutant concentration (Su et al., 2020; Xing et al., 2019). In fact, many of the above-mentioned robots and drones use sensors to obtain data in real time in water. In the aquaculture industry, biosensors have been developed and applied to analyse DO levels, water salinity and temperature (Antonucci & Costa, 2020; Su et al., 2020). In the salmon industry, the heart rate and metabolism of individuals can be monitored and recorded (Svendsen et al., 2020). Using underwater sensors connected to the internet, the hunger status of cultured fish in cages, ponds and rivers can be monitored, and thus feeding can be conducted accordingly (Zhou et al., 2019). Proper feeding according to the hunger status can substantially increase feed usage and reduce the wastage of feeds, thus reducing total production costs (Li et al., 2020, p. 735508; Su et al., 2020). In Europe, a consortium, including marine scientists, aquaculture companies, fish farmers and research engineers, is working to develop an automated and integrated platform to detect and monitor chemical contaminants, harmful algae blooms, pathogens and toxins (Johnston, 2018). Norwegian AKVA Group (https://www.akvagroup.com) has built a huge cage for offshore aquaculture with sensors and cameras. China has developed several deep-sea cages with many sensors to monitor water quality, hunger status of fish, net status and fish movement (Chu et al., 2020).

Sensors in water in combination with cloud management and mobile connectivity will maintain the ideal environment for fish and supply optimal feeding for growth and feed conversion for the aquaculture industry. In the future, it is essential to develop real-time sensors to measure the stress level of individual fish and to detect pathogens in water. These sensors should be easily inserted into live fish or put in water and be able to deliver strong signals, which could be detected by devices on land, boats or satellites. Inspirations can be gained from the studies conducted by Stanford researchers in developing cortisol-detecting wearables to measure stress and overall health in humans (Parlak et al., 2018).

3.4. AI empowers rapid and precise decisions

Although robots, drones and sensors enable rapid and real-time data collection, it is still very hard to make correct decisions using the collected data due to the large amount of data (Evensen, 2020; Jothiswaran et al., 2020). Nowadays, several research institutes and aquaculture technology start-ups are studying and applying artificial intelligence (AI) to make better and faster decisions (Evensen, 2020; Razman et al.). Through AI, the aquaculture production can be rapidly increased within a short period as it makes aquaculture a less labour-intensive field. It can take the form of any labour at work. For example, feeders, water quality control, harvesting and processing (Jothiswaran et al., 2020). In aquaculture, wastage of inputs can be managed through AI and costs can be reduced by up to 30% (Jothiswaran et al., 2020). Thus, AI provides complete control over the fish producing systems with less maintenance and reduced input cost. However, AI still has limits due to the limited data available. Dataset is becoming increasingly important. Therefore, fish farms and big aquaculture companies should share their data in aquaculture production and marketing. Only with sufficient data in aquaculture production of each species under different culture conditions, and the establishment of databases in public domains, will researchers and farmers be able to use a broader variety of sample data to develop improved algorithms to make more precise and better decisions.

3.5. Augmented reality (AR) improves production efficiency and enhance aquaculture education

AR is an interactive experience in the environment of a real-world. The objects locating in the real world are strengthened with assistance of computer-generated perceptual information (Jung, 2019). In AR, objects produced by a computer are used to improve the impression of real-world experiences by adding clarity and data. Aquaculture activities are highly variable, unforeseeable, laborious and dependent upon the species, location and aquaculture systems (FAO, 2020). AR is able to decrease cost, spare time and facilitate underwater drone and robot operations, including monitoring fish behaviour, net holes and dead fish (Stene, 2019). With the assistance of AR, farmers may gain a better overview in production places, and complete operations more effectively and with zero risk. AR has been used in the aquaculture industry to increase the efficiency of field production, monitor and analyse mortalities, health status and measure many water parameters (Xi et al., 2019). Recently, an AR plus cloud system was designed to improve in-situ water quality data collection and query (Xi et al., 2019). Another application of AR in the aquaculture industry is in teaching and education. The Norwegian University of Science and Technology (NUST) has developed and applied AR and virtual reality (VR) in teaching students about fish welfare, disease prevention, escaping fish and dangerous working conditions (Stene, 2019). It is certain that AR is also able to contribute significantly to the optimal management of fish farms, including water quality management, remote collaboration and boardroom discussion. However, affordability of such systems is always a critical issue in using this technology for small fish farms. Also, development of simple and cost-effective software to enable AR is important for the aquaculture industry.

3.6. Virtual reality (VR) for training and consulting

Virtual reality (VR) is able to convert the environmental situations into a digital interface by putting virtual objects in real-time and the real world (Ferreira et al., 2012). VR is able to be watched through many experiences, which enables users to locate life-size 3D models in their environment and/or show contextual information (Psotka, 1995). In the aquaculture industry, there are several potential applications of VR, including in teaching and education. For example, VR has been applied to stimulate the interest in aquaculture of young people in Norway (Prasolova-Førland et al., 2019). NUST has developed a VR system, which enables students to see real activities and situations of a fish farm (Boe & Prasolova-Forland, 2015). In China, Dalian Ocean University has also developed/constructed a virtual simulation platform, which can rely on VR, multimedia and human-computer interaction for the high-risk environment, high cost, high consumption and condition of traditional college experiment teaching (Chen & ZHANG, 2017). It is certain that VR could also be used for consulting purposes in the aquaculture industry. The combination of VR with internet of things (IOT) (Gubbi et al., 2013) will broaden the applications of VR in teaching, education and consulting.

3.7. 3D printing technologies to produce tools for aquaculture

3D printing enables the production of a 3D solid object from a digital file. The end product of 3D printing is an object, which is printed with additive processes. In the printing procedure, the object is generated by laying down several layers of materials, until the object is completed (Mostafaei et al., 2020). With development of digital and printing technologies, 3D printers are becoming more affordable (Awad et al., 2020). In aquaculture, the application of 3D printing is just in its infancy. 3D printing has been used in printing hydroponic systems (Takeuchi, 2019) and fish robots (Clark et al., 2012). Recently, prototypes of 3-dimensional (3-D) vitrification devices were printed using the 3D printing technology for sperm vitrification of aquatic species (Tiersch et al., 2020). These systems enable quick and cost-effective preservation of sperms, and thus they are suitable for small-scale freezing for research purposes on small aquatic species with tiny testis and fieldwork at remote locations. A 3D printed water sensor system to detect water parameters, including temperature, oxygen level, and PH are being tested (Banna et al., 2017).

There are several challenges to adapt 3D Printing in aquaculture, including equipment cost, manufacturing cost, post-processing requirements and limited materials, which can be used in water and other places (Yeh & Chen, 2018). To tackle these challenges, aquaculture scientists, fish farmers, engineers and software developers must work together to make the 3D printing technology fit products and business models, and to develop cost-effective products for the aquaculture industry.

3.8. Blockchain as a trustworthy traceability tool

Blockchain was introduced in 2008 by Nakamoto as the data management mechanism in the system of Bitcoin cryptocurrency (Nakamoto, 2008). In blockchain, data are decentralized, in which no individual, no corporation or no government owns or controls these data while they are shared by everyone. Its major advantages are that the data in the chain formed by blocks of data are secured and are tamper-proofed (Drescher, 2017). For example, blockchain-based applications are developed and applied to support data sharing, payment processing, money transfers, distributed cloud storage systems and digital identity protection (Bodkhe et al., 2020). The aquaculture industry has generated and collected huge data in different companies and farmers. However, these data are usually not shared by different players. Therefore, these data have been used effectively. With the blockchain technology, the supply chain in the aquaculture industry can go digital, which enables full traceability from farm to consumers and will connect global stakeholders together. The blockchain technology is able to safely and effectively collect, share and analyse huge data sets from different parts of the aquaculture industry (Fig. 4). This technology could greatly benefit the aquaculture industry by addressing issues related to food traceability costs, food fraud, food waste and food-related diseases (Altoukhov, 2020). Blockchain in aquaculture is able to reduce transaction processing time, enhance the relationships of reliability and trust among the producers, retailers, consumers, governments and certification bodies. Digital traceability is a critical step to ensure food safety. Blockchain-based tools are being developed and applied in the aquaculture industry (Altoukhov, 2020).

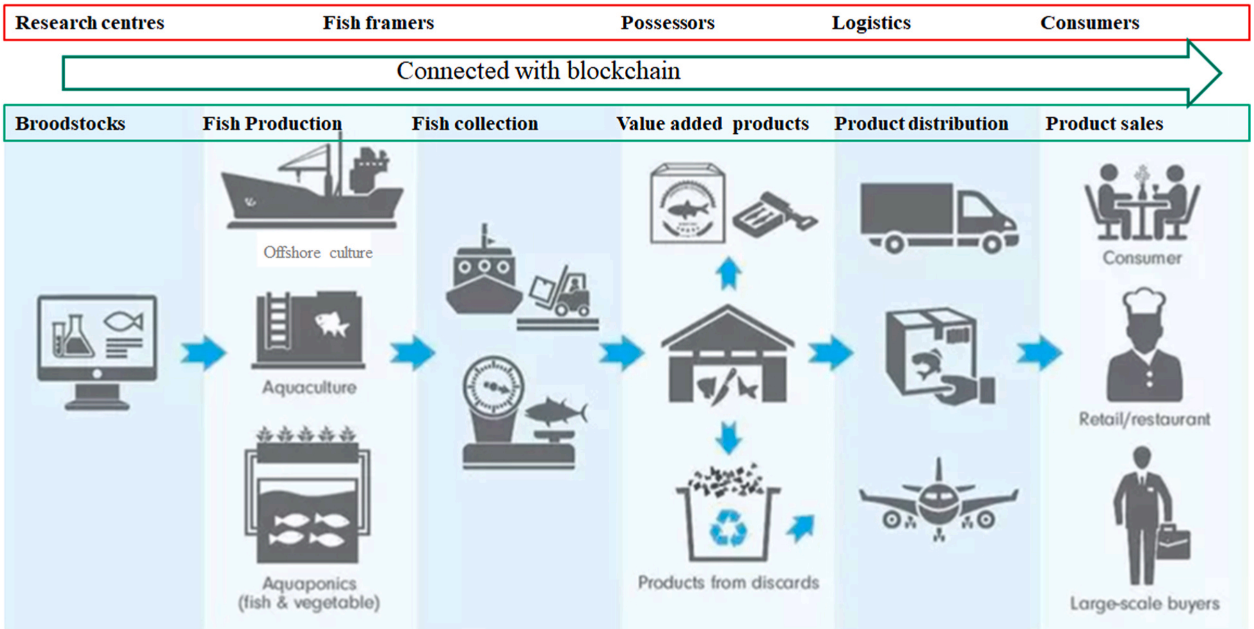
To enjoy the benefits of blockchain tomorrow, it is essential now to invest this emerging technology for farmers, processors, shippers, distributors and retailers in the aquaculture industry. Those costs can be variable in different parts of the aquaculture industry. Application of a blockchain solution for the aquaculture industry is basically similar to a major software development project, requiring everything from a software backbone to hardware sensors, to processing power and more. All of these could easily cost millions of dollars.

3.9. Internet of things connects different parts of the aquaculture industry

The internet of things (IoT) is playing an important role in many industries (Gubbi et al., 2013). IoT is relatively new in aquaculture (Jothiswaran et al., 2020). It is able to connect big data (i.e. massive amount of streaming data) across the entire aquaculture industry (Fig. 4). This technology brings new opportunities to the industry (Kamaruidzaman & Rahmat, 2020). Besides data from farms, production places and food processing factories, big data from social media is also becoming important for the industry (Dupont et al., 2018). There are several benefits of applying the IoT technology in the aquaculture industry. (1). The environmental conditions in aquaculture sites can be effectively monitored in real-time and with higher coverage by incorporating many underwater cameras and sensors across multiple cages. (2). It allows for better environmental management by monitoring the effects of fish farms on the surrounding environment continuously and on time. (3). IoT in combination with machine learning with data acquired over time can be applied to generate predictive models. These predictive models will result in making better and precise decisions, which enables timely alerts for potential risks. IoT with big data solutions is able to revolutionize the aquaculture industry by making it more productive, sustainable and profitable, safer and easier to manage risks. Therefore, it makes processing systems and supply chains much more interconnected. However, application of IoT technologies in remote marine aquaculture sites is still a practical challenge, where information acquired from sensors remote to the main fish farm are required to be sent elsewhere globally.

4. Offshore farming

Offshore aquaculture, also called as open ocean aquaculture, is an emerging approach to culture marine foodfish (Chu et al., 2020) (Fig. 5). Offshore aquaculture is increasingly regarded as one of the important means to ensure a sufficient and stable supply of seafood where it is believed to minimize the negative effects of conventional marine aquaculture on the environment of oceans (Froehlich et al., 2017). In addition, offshore sites, provide sufficient sea space for the culturing of fish, and water quality is usually good enough for aquaculture (Gentry,



Figue 4. Brockchain for auquacture production and markerting. Blockchain is commercially available to combat fraud, document long and complex production cycles for aquaculture products and track critical chain of custody.

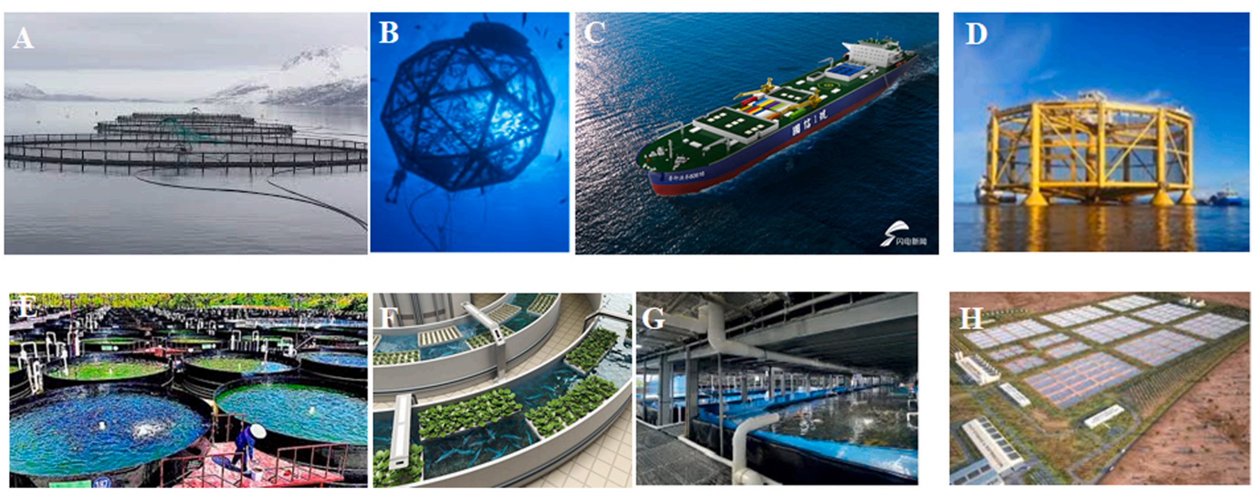


Fig. 5. Offshore aqauaculture and land-based recirculating aquaculture system (RAS). There are many offsore aquaculture systems, including cage aquaculture (A), submersible Cages (B), vessel aquacultue (C) and fish farm permanently moored in deep water (D). There are also many recirculating aquaculture systems (RAS), such as tanks based (E), vertical aquaponics (F), multistory vertical tanks (G), and tanks in desert (H).

Froehlich, et al., 2017). More and more big aquaculture companies are planning to initiate offshore aquaculture (Froehlich et al., 2017). For example, in Norway, one company marked the world's largest offshore fish pen (110 m wide), which can hold 1.5 million fish, and equipped with 22,000 sensors to monitoring environment and behaviour of fish (Stokstad, 2020). For offshore aquaculture, it is essential to consider the following factors: location, cage types, vessel types and species (Chu et al., 2020). Co-location with other maritime industries, including shipping and fishing, tourism, is possible for future offshore fish farms (Gentry, Lester, et al., 2017). China started to build the world's first 100, 000-tonne intelligent fish farming ship in Qingdao. The ship is 250 m long and 45 m wide. Its designed speed is 10 knots. The vessel is able to avoid typhoons, red tides and other severe weather and disasters, conducting aquaculture operations in seas around the world. The vessel is expected to produce 4000 tons of high-value marine products each year (Huaxia, 2020). Offshore aquaculture is still an industry in its infancy. Offshore aquaculture needs reliable technologies, including AR, which can conduct remote operations and surveillance (Stene, 2019). It seems that there is not enough research on the effects and consequences of offshore aquaculture on seafood security and marine environments (Gentry, Lester, et al., 2017). The understanding of the social dimensions and effects of offshore aquaculture is yet incomplete. It is to note that offshore marine aquaculture set-ups require large investments. Therefore, how to reduce the cost of offshore farming is a critical issue in ensuring the sustainability and profitability of this endeavour. It is also to note that there is an opinion that farming fish in the sea will not nourish the world (Belton et al., 2020). Offshore finfish aquaculture might face economic, biophysical, and technological challenges that prevent its growth and hinder it from contributing significantly to global seafood and nutrition security (Belton et al., 2020). The aquaculture industry needs to consider many factors, including cost, environment, affordability and sustainability, before entering offshore aquaculture.

Certainly, with the rapid development of novel technologies, offshore finfish aquaculture is promising and worth trying.

5. Recirculating aquaculture systems (RAS) and renewable energy

RAS are tank-based aquaculture systems (Fig. 5), where fish are farmed under controlled conditions (Badiola et al., 2018; Ebeling & Timmons, 2012). The major advantages of RAS include the use of less water, biosecurity and high yield. There are several types of RAS for aquaculture, which are running for culturing of salmon, Asian seabass and flatfish (Fig. 5). However, there are a few major challenges, including insufficient knowledge about the technology high energy requirement, high initial investment and difficulties in removing pathogens once entered the RAS (Badiola et al., 2018; Xiao et al., 2019). Researches have been carried out to improve recirculating loop and waste treatments, and to reduce of energy cost by using renewable energy (Badiola et al., 2018). Some RAS farms are using renewable energy, including solar and wind energy (He et al., 2017). However, the existing solar collector system in aquaculture has problems of high initial investment and slow cost recovery (He et al., 2017). Low-cost solar collector systems for supplying hot water for an aquaculture system were developed. Experiment results showed that the average daily collector efficiency of the system could reach 49.6% (He et al., 2017). In addition, wind energy may also be used in offshore RAS on vessels (Zheng et al., 2020). Advances in renewable energy production reduce RAS operating costs (Belton et al., 2020). However, with the current knowledge and technologies of RAS, it is highly possible that on RAS farms, only the culture of high value product species can make profit. To reduce the cost of RAS, it is essential for fish farmers, fish scientists and engineers to work together to design every part of the RAS stems effectively. It is certain that with more knowledge on RAS and understanding of the interaction between its components through research and field tests, RAS will revolutionize the aquaculture industry, especially for big cities and countries with limited water space for traditional aquaculture.

6. Alternative proteins and fish oil

In the aquaculture industry, especially in marine aquaculture of finfish, including salmon, most feeds rely heavily on fish meal and fish oil (Han et al., 2018). Fishmeal and fish oil are by-products of smaller forage fish including herring, krill and other fish caught from oceans. Fish meal contains high percentage of protein (Hodar et al., 2020). The rapid growth of the aquaculture industry and the increasing demand of farmed marine finfish have resulted in a rise in the amount and the price of fishmeal and fish oils over the last few years (Cao et al., 2015). However, fish meals and fish oil relay heavily on wild-caught marine fish (Cao et al., 2015). Overfishing has already put serious pressure on wild stocks of fish. At the current increased rate of the aquaculture production, supplies of fish meals are not able to meet the demands of the aquaculture industry (Hodar et al., 2020). To replace fish meals, alternative proteins have been extensively sought after and studied. Plant-based proteins, including soybean protein (Fig. 6), have been studied for many years and obtained promising results (Hodar et al., 2020). Micro- and macro-algae have been included in fish feeds as replacements of fish meals. Currently, high-quality algae feed is still expensive, but shows promising results (Han et al., 2019). Many aquafeed producing companies are working on improving algae feed and increasing accessibility. Another replacement option of fish meal is insect-based proteins. Black soldier fly and crickets (Rumbos et al., 2019) are the promising candidates for insect-based proteins (Mousavi et al., 2020). Culture protocols using food wastes for these insects have been established (Wang & Shelomi, 2017). Several companies have started to produce these insects and scaled up production to reduce cost.

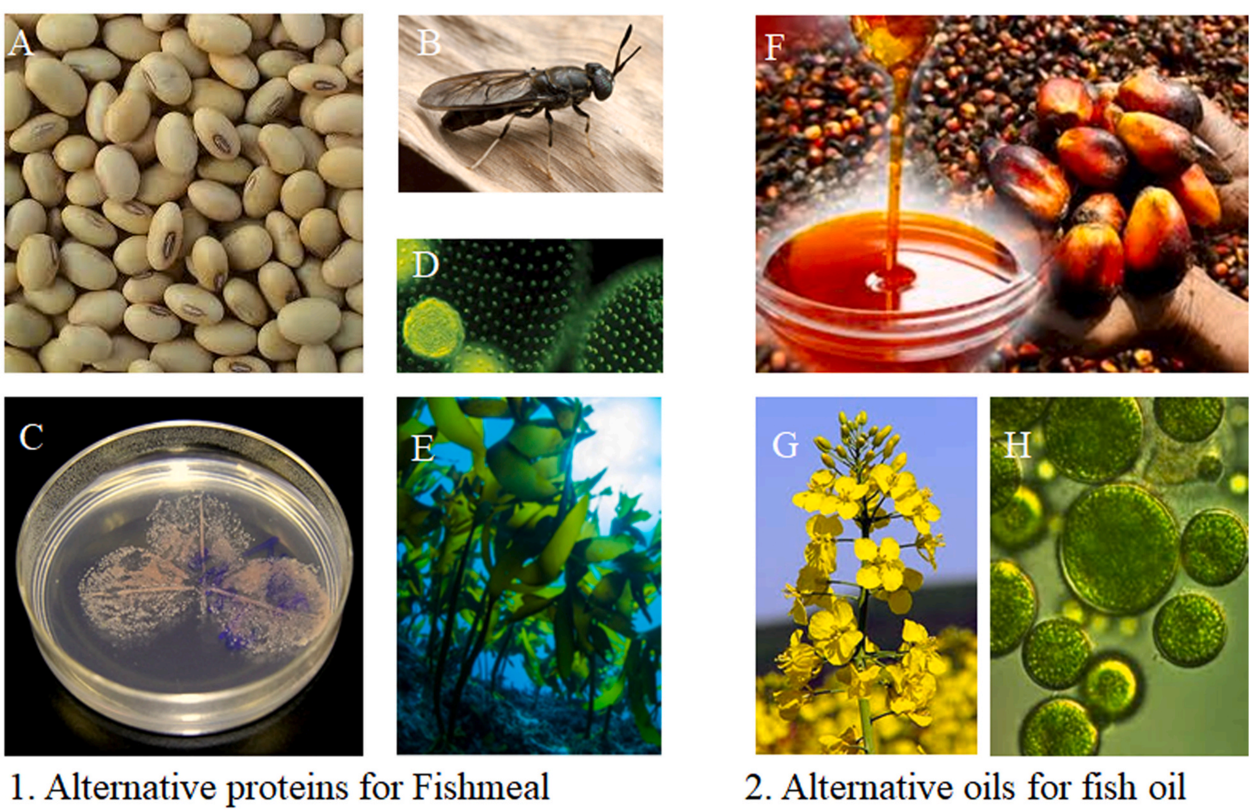


Fig. 6. Potential sources for replacing fishmeal and fish oils in fish feeds. Ptotential sources for replacing fishmeal include plant-based protein (e.g. A. soyabean), insect proteins (e.g. B. black soldier fly), single cell proteins (C), microalgae (D), and seaweeds (E). Ptotential sources for replacing fish oils are palm oil (F), rapseed oil (G) and oils from microalgae (H).

The third type of alternative protein is single-cell proteins (SCPs) (Jones et al., 2020). SCPs are produced by fungi, bacteria and algae (Sharif et al., 2020). SCPs have the potential to fulfil the protein needs in the aquafeed industry. Feeding trials revealed that in Atlantic salmon, rainbow trout, and white-leg shrimp, SCPs are able to replace fish meals (Jones et al., 2020). Therefore, the SCPs are a promising candidate to replace fishmeal. In the past decades, significant breakthroughs in the replacement of fish oil with plant oils in formulated fish feeds have been made (Nasopoulou & Zabetakis, 2012). Plant oils such as palm oil and rapeseed oil appear to be promising candidates for replacing fish oil.

Although alternative proteins and oils are promising in replacing fish meals, there are several critical issues which must be considered. These issues include the cost, production capacity and consistency of supply. Only with sufficient and content supply, the industry of alternative proteins and oils for fishmeal and fish oils can sustain.

7. Oral vaccines against diseases

Diseases are a major challenge for the aquaculture industry. Each year, the economic loss caused by diseases in the aquaculture industry is estimated at 6 billion USD (Kelly & Renukdas, 2020, pp. 137–161). Immunization of aquaculture fish has started for over 50 years. Vaccination is an effective means to prevent bacterial and viral diseases (Gudding & Van Muiswinkel, 2013; Ma et al., 2019). Vaccination also contributes to environmental, social, and economic sustainability of the aquaculture industry (Ma et al., 2019). Unfortunately, vaccine development in the aquaculture industry lags far behind the livestock industry. Only a few vaccines have been registered and applied in the industry (Erkinharju et al., 2020; Gudding & Van Muiswinkel, 2013). Furthermore, vaccination in fish is a labour-intensive process, where individual fish is manually injected with a dose of a vaccine (Gudding & Van Muiswinkel, 2013). Oral vaccines are an alternative to labour-intensive traditional vaccination with hand injection (Gudding & Van Muiswinkel, 2013). Oral vaccination minimize handling and damage to fish thus reducing mortality rates during the vaccination (Adams, 2019). Micro-encapsulation, in which antigen from pathogens are incorporated might be a technology to deliver oral vaccines to fish (Masoomi Dezfooli et al., 2019). There are ways to develop ground breaking vaccines for oral delivery systems (Lee et al., 2020). However, it seems that there is currently no effective oral vaccine available in the aquaculture industry.

Although oral vaccines are promising, oral delivery is still very challenging for fish in water. It is eventual to find ways to keep the vaccine active in water for a certain time, overcome harsh gastrointestinal environment to achieve effective protection. Therefore, the development of effective oral vaccines needs to carefully design delivery systems and to incorporate molecules, which can enhance their effect to bring out strong immune responses. Certainly, alternative and emerging approaches should be explored to develop effective and cheap oral vaccination for the aquaculture industry.

8. Conclusion

Aquaculture has played an important role in supplying high quality proteins and has been the fastest growing sector in food production for over 20 years. Due to the ever-increasing population on earth and improvement of incomes of people, the requirement of seafood will substantially increase in the coming decades. The expansion of aquaculture requires novel and disruptive technologies. Fortunately, several emerging and disruptive technologies have the potential to revolutionize the aquaculture industry. These technologies include robotics, information/digital technologies, offshore farming, RAS, replacement of fish meal and oils with alternative proteins and fish oil, and oral vaccines. Although the aquaculture sector is among the slowest to adopt new technologies, people in the field realized that recent advances of technologies can offer opportunity for sustainable and profitable aquaculture. All these technologies have been approved (in relatively small scale) to be able to revolutionize some parts of aquaculture. However, there are great gaps between the availability of novel and disruptive technologies and their real applications in the aquaculture industry. Integration of various technologies into different aquaculture systems is a complicated process. It requires a combination of different types and quantities of aquaculture equipment, including oxygen enrichment facilities, feeding equipment, different types of sensors and water treatment equipment. These facilities need similar working voltage, communication interfaces, transmission mode and other parameters of various equipment. Therefore, integration of various equipment requires establishment of a uniform standard for the parameter design of aquatic facilities, selection of equipment according to this standard. The layout of the facilities in the integrated aquaculture system should be optimized to maximize their efficiency. Then, all types of equipment will be connected to the IoT platform for monitoring and control. All these factors make it highly impossible for a single farmer or aquaculture company to accomplish this complicated task. Therefore, fish farmers, fish scientist, engineers, software developers and economists should work together to effectively integrate these technologies into each part of the aquaculture industry to make the industry more sustainable and profitable. Government agencies may supply research funds on multidisciplinary projects on this front while aquaculture extension stations, venture capital and investors may support novel start-ups for integrating disruptive technologies into the aquaculture industry. It is certain that emerging and disruptive technologies will substantially make the aquaculture industry more resource and energy-efficient. These technologies will also generate opportunities for businesses and jobs, including opportunities for women and younger people. On the other hand, it is to note that some emerging and disruptive technologies may generate barriers for small/family-based fish farmers, which don't have financial resources to adopt them. It is essential to ensure that effective management is in place so that emerging technologies are used to improve rather than undermine the sustainability of aquaculture (FAO, 2020).

Authors' contributions

KNY and YBS conceived and designed the study; KNY collected papers in web of sciences and google scholars; KNY and YBS contributed data analysis tools; KNY wrote the draft of this manuscript. KNY and YBS finalised the paper.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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