



Promoting sustainable aquaculture through selective breeding:

Assessing progress and identifying gaps of knowledge

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Promoting Sustainable aquaculture through selective breeding: Assessing progress and identifying gaps of knowledge.

Att främja hållbart vattenbruket/akvakultur genom selektiv avel: identifiera framsteg och kunskapsluckor i forskningen.

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Abstract

In this review the goal was to assess progress in the field of aquaculture selective breeding. It was done through an extensive literature review. Since aquaculture is the fastest growing category of food production, sustainability is of high relevance. Overall, selective breeding in aquaculture species is lagging compared to terrestrial livestock, not only in technological development but also, and most importantly, in the basic knowledge of the different species that we farm, which is delaying sustainability in several ways. One of the key differences between aquatic and terrestrial livestock species is clearly the fecundity, where aquaculture species produce spawn at a completely different level than the mammals we keep in production e.g. which gives selective breeding a very different outcome and possibility. Furthermore, data recordings are more challenging in aquaculture production systems with technological advancements being of high relevance. In this review we will dive deep into aquaculture breeding, explore and compare different methods and technologies and evaluate sustainability in the production.

Keywords: Aquaculture, Breeding, Selective breeding, Sustainability, Breeding technologies

Sammanfattning

I denna omfattande litteraturstudie var målet att se över framstegen inom selektiv avel i akvakulturen. Eftersom akvakultur är den snabbast växande grenen inom livsmedelsproduktion är vikten av hållbarhet mycket stor. Domesticering och selektiv avel inom akvakulturen ligger långt bakom den gällande landlevande produktionsdjur, inte bara när det gäller teknologiska aspekter men även och kanske mest anmärkningsvärt: i den grundläggande kunskapen inom arterna som halls och odlas. Några av de stora skillnaderna mellan vatten och landlevande produktionsdjur är den höga fruktsamheten hos fisk som ger en helt annan möjlighet inom selektiv avel. Något av problemen med att odla akvatiska arter är hantering, där det istället krävs en helt ny nivå av teknologiska hjälpmedel för produktionsmiljön. I denna studie dyker vi ner i akvakulturens avel, jämför och utforskar olika metoder och teknologiska aspekter bakom avelsprogrammen samt hållbarhet inom produktionen.

Nyckelord: Akvakultur, Avel, Selektiv avel, Hållbarhet, Avelsmetoder

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Abbreviations

| Abbreviation | Description |
|--------------|---|
| FCR | Feed Conversion Ratio |
| GS | Genomic selection |
| GBLUP | Genomic Best Linear Unbiased Prediction |
| GWAS | Genome Wide Association Study |
| MAS | Marker assisted selection |
| PIT-tags | Passive integrated transponder |
| QTL | Quantitative Trait Loci |
| SLU | Swedish University of Agricultural Sciences |
| WGS | Whole genome sequencing |

1. Introduction

Global aquaculture production is mainly seen in Asia where approximately 90 % of the world's consumption of aquaculture species is produced. Among the most common species we farm in the world are Salmonids, Carps, Cichlids, Crustaceans and Bivalves. Salmonids occupy a special place amongst the farmed species including some of the most economically important ones in the whole industry, like Atlantic salmon (*Salmo salar*). Aquaculture is undoubtedly the fastest growing food producing industry worldwide but it is still far behind in the domestication process especially in terms of selective breeding compared to terrestrial livestock (Gjedrem et al. 2012b; Lind et al. 2012; Sonesson et al. 2023). As the world's population is growing rapidly, the demand for healthy and sustainable food, and foremost protein, is increasing (Gjedrem et al. 2012a). Aquaculture is considered to have potential of being a regenerative farming method, because of the ending land and freshwater resources currently used in the agricultural industry, when using marine and brackish water resources (Azra et al. 2022). Aquatic species differ in many ways from terrestrial ones. Remarkable genetic gains of 10% per generation or more have been often reported far surpassing ones from terrestrial animals (Huston et al. 2020). Nevertheless, major challenges exist. Currently, selective breeding efforts have been focused on only a handful of species with most of the aquaculture production still relying on unselected stocks. Furthermore, data collection is more challenging compared to livestock, even though many methods are developing rapidly and are showing great promise for the future research and development of the industry.

1.1 Background

The purpose of this review is to assess progress in the field of aquaculture selective breeding and try to identify how the use of resources can be more effective. The main breeding technologies that are currently used in aquaculture systems, and show potential, are described and evaluated. Overall, selective breeding is useful for many different aspects, not only to get a higher production output but also to improve important traits other than growth, like disease resistance and feed efficiency which makes a great difference in the economic and environmental sustainability of production. The overall goal for most of the breeding companies in the field is to improve production related traits as well as animal welfare. Through further domestication we learn a lot about the animals we are keeping and with it comes knowledge of genetics and heritable traits for each species (Abdelrahman et al. 2017b).

Current breeding goals are mainly directed to faster growth, resistance to disease, robustness, sex determination, late sexual maturation, and filet quality. These traits are influenced by several different genes as well as by the environment the animals live in, which makes it difficult in general to select the right individuals. In a changing climate, it is more important than ever to direct the breeding towards robustness in different temperatures, water quality, and towards disease and viral resistance. As the animals become more tolerant with better breeding programs, they also grow better and have better feed conversion ratio (FCR) as they tend to use the energy derived from feeding more efficiently. There are several ways that aquaculture breeding techniques are considered contributing to ecosystem services and sustainability when it comes to food production and this review is partly investigating those areas of possibilities (Azra et al. 2022).

Overall, aquaculture breeding had a slow start due to the inherent difficulties of keeping track of animals that live in an aquatic environment. Keeping track of relationships is critical in selective breeding. Therefore, it is important to know which individuals are which, when recording traits and collecting data. One important welfare aspect of farming fish is the problem that handling of the fish causes. Handling creates stress and can lead to issues e.g. when recording traits because of handling of the fish itself will affect the recorded traits. Researchers are using an aid called “PIT-tags” to keep track of the fish to avoid extensive handling, both for the sake of the fish but also for the sake of the data. “PIT” stands for passive integrated transponder and are very small microchips that the fish are tagged with. The PIT-tags works as identification for individuals but they also measure growth and help keeping track of families when used in selective breeding programs (Abdelrahman et al. 2017a; Sonesson et al. 2023).

The number of active breeding programs, traits and other information can be seen in Tables 1-3. Some of the major species, Atlantic salmon (*Salmo salar*) and Common carp (*Cyprinus carpio*), have been domesticated and bred longer than others and therefore we know more about them in general. Selective breeding differs between terrestrial and aquatic livestock species mainly because of the extreme fecundity in the aquatic species. Although there are many benefits of breeding aquatic species, there are also difficulties, like the problem with recording individual traits and data, handling, environmental effects and the lack of knowledge regarding many physiological and nutritional requirements of the farmed species. Furthermore, as those species are farmed in different environments under widely varying environmental conditions accounting for genotype by environment (G x E) interactions can be challenging (Sonesson et al. 2023).

2. Materials and method

Databases used to research for content included the Web of Science (20 results), the SLU library search engine Primo (2181 results) and Google scholar. Literature from the period 1990 – 2026, including studies that assessed the topic of aquaculture breeding and sustainability or selective breeding and methods of breeding technology in the aquaculture food production systems, articles were chosen from impact, peer review and topics. Search words used were “QTL Aquaculture” “selective breeding for sustainable aquaculture”, “breeding programs in aquaculture”, “selective breeding AND/ OR aquaculture”, “Selective breeding AND/OR fish”, “Aquaculture AND/OR breeding”, “genetic gain AND/OR heritability” “disease resistance AND/OR sexual maturation AND/OR growth rate”, “salmonids”, “cichlids”, “carps”. Studies behind paywalls and with too unspecific or too specific content were excluded. Specific articles were searched for, to find accurate numbers of the heritability, genetic gain and production total for Tables 1, 2 and 3. 1 article for each subject and species group was used. 29 articles were selected in total by the number of citations, if they were peer-reviewed and from the content after abstract screening. The literature was first viewed by title/abstract screening and then viewed in full text. The analysis used was a thematical analysis. All the information above can be overview in table 4 below,

No AI was used during the research process or during the compilation.

Table 4. Search words, databases and articles found/used

| Database | Search words | Results | Articles used |
|----------------|---|---------|---------------|
| Google scholar | QTL Aquaculture | 297 | 2 |
| Primo SLU | Selective breeding for sustainable aquaculture. Breeding programs in aquaculture. Selective breeding AND/ OR aquaculture. Selective breeding AND/OR fish. Aquaculture AND/OR breeding. “genetic gain AND/OR heritability” “disease resistance AND/OR sexual maturation AND/OR growth rate”, “salmonids”, “cichlids”, “carps”. | 2181 | 23 |
| Web of science | Selective breeding for sustainable aquaculture. Breeding programs in aquaculture. Selective breeding AND/ OR aquaculture. Selective breeding AND/OR fish. Aquaculture AND/OR breeding. | 20 | 4 |

3. Selective breeding/Breeding methods

Pedigree based selectionThe first ever family-based selection program was started in Norway by AKVAFOSK, 1975, for Atlantic salmon. The program was based on selection for body weight, but later more traits were added like disease resistance, age for sexual maturation and fillet quality parameters (Gjedrem 2010).

After some early research mainly in rainbow trout (*Oncorhynchus mykiss*), the obtained genetic gain suggested breeding programs such as the ones used in terrestrial livestock could be implied in fish farming as well, with the main difference that one could replace progeny testing with sibling testing due to the high fecundity of aquaculture species (Gjedrem 2010).

Notably, the economics in salmon breeding back then was not at all how it is today, but rather comparable to how it looks in developing countries. Economic support had to come from non-government organizations and investors.

In general, selective breeding results in genetic gain, that is permanent and can be passed down to the next generation. Individual selection is considered the most cost-effective method because of its simplicity, where the individual's phenotype is the base for selection. Nevertheless, this approach runs the risk of accumulating inbreeding rapidly posing problems in the long-term viability of farming. A more elaborate approach is the so-called family breeding where separate families are kept in separate systems or tanks. This technique is to prefer when deciding what role the environmental effect plays on different members of the same family (Lind et al. 2012). Using large number of families with many offspring each allows for accurate estimation of genetic parameters and for applying higher selection intensity (Migaud et al. 2013).

Because of the high fecundity of aquatic species, it is easy to apply selective breeding and get astonishing results, but with it comes a higher risk for inbreeding and lower fitness if not handled with care (Saura et al. 2017).

Selective breeding requires a higher understanding of quantitative genetics, which requires staff with higher education but also physical management of genetic variation which complicates logistics around housing of the fish in the breeding facilities to avoid inbreeding. This is a bit more costly and requires more logistic work and trained staff that manage the animals, science traceability is a very important aspect..

3.1 Genomic technologies for selection

3.1.1 Genetic markers

To make further advances in aquaculture breeding, genomic selection technologies are very important. Genomic selection can result in a higher profitability as it provides information about the genetic factors that could control the targeted trait(s). This makes it easier to reach breeding goals based on the specific traits which will increase income in both production and breeding programs. Genomic technologies can assist in understanding the underlying genetic architecture controlling traits of interest. As such, genomic technologies can be used to improve animal health and welfare, as salinity tolerance, heat tolerance, feed efficiency, disease resistance and many other traits (Abdelrahman et al. 2017a). Genomic selection also has shown a larger benefit for the traits of interest which cannot be measured directly on the candidates of breeding but rather on e.g. siblings like disease resistance traits (Dagnachew & Meuwissen 2019).

There are different genomic technologies to use in breeding programs, some of the most common ones are listed in this section.

Mapping of quantitative trait loci; (QTL) is not a method per se but rather a useful description of specific genome regions that control complex traits. To identify QTL's, it is necessary to find specific genetic markers commonly used as proxies to locate the QTLs on the genome. The most used genetic markers are the single nucleotide polymorphisms (SNPs), due to their high abundance SNP's and ease to screen in high throughput formats. The latter is critical as in selective breeding it is common to process large amounts of biological or genetic samples. (Abdelrahman et al. 2017a). The infectious pancreatic necrosis (IPN) resistance in Atlantic salmon is one of the most important QTL findings in high value species (Abdelrahman et al. 2017a; Yáñez et al. 2023). Usually, a large number of markers in the magnitude of thousands is required to identify QTLs . (Abdelrahman et al. 2017a).

Genome-wide association studies (GWAS) refer to methodologies where genetic markers (usually SNPs) are used to identify QTLs. GWAS is a well-established method in aquaculture breeding (Abdelrahman et al. 2017a). GWAS have been used to identify markers associated with traits like environmental tolerance, growth or disease resistance in various aquaculture species (Zhu et al. 2026a).

Genetic markers are usually identified using whole genome sequencing (WGS) and genotyping by sequencing (GBS). A critical piece of information for identifying genetic markers is the availability of reference genome. Reference

genomes are somewhat mainly available for the high value species since the process is costly.

Genetic markers are usually applied in breeding programs through either marker assisted selection (MAS) or genomic selection (GS) to improve breeding programs. Both approaches has been used for research in high value, key species, for example Atlantic salmon (*Salmo salar*), Arctic Charr (*Salvelinus alpinus*), different catfish species, Common carp (*Cyprinus carpio*), Pacific oyster (*Crassostrea gigas*) and Giant tiger prawn (*Penaeus monodo*), where traits as growth, sexual maturation, disease resistance, salinity tolerance, sex determination and heat stress was identified.

The difference between MAS and GS mainly lies in the required number of markers. MAS requires only a handful of markers, while GS uses information from several thousands of markers. In general MAS is suitable in cases where the target traits are controlled by QTLs of large or moderate effects. However, in most cases the trait(s) under selection are polygenic and controlled by many genes of small effect each. As such GS is generally more applicable. However, the requirements of GS to use information from thousands of markers make it far more expensive than MAS. MAS is useful in aquaculture breeding because many species is still unselected, compared to terrestrial livestock where it's rarely seen. As mentioned above, costs of GS are directly proportional to the sample size. Larger sample size means a higher cost, which again comes back to large groups of individuals in aquaculture systems (Abdelrahman et al. 2017a; Yáñez et al. 2023; Zhu et al. 2026b).

3.2 Gene editing

CRISPR/Cas9 is a gene editing technology called the gene scissors that uses guiding RNA and offers an effective and precise way to modify genetic materials by "cutting" it and matching it back up again with the help of the RNA-guide. CRISPR/Cas9 is often referred to as a genetic engineering tool that speeds up the breeding process because of its immediate improvement in phenotype, but this technique often faces doubt from the public and legislations because of it being a GMO-strategy (Abdelrahman et al. 2017a).

This method is best use when a better understanding and more data is collected on the species that are keep in our production systems so that the risks become lower and when it is known exactly what will happen to the genomics when edited (Abdelrahman et al. 2017a).

4. Progress

The genetic gain and progress in the key species are not very far from each other if viewed as stated in the tables below. The main differences have to do with the individual traits that are selected for. For example, the general genetic gain of growth lies between 10-14%, FCR is around 5% and disease resistance approximately 12% for all key species gathered here.

Table 2. Breeding in salmonids

| Global production | | | | | |
|---|---------------|--------------------------|-----------------------------------|---|------------|
| 4 243 (FAO 2024) | | | | | |
| Active breeding programs | | | | | |
| 32 | | | | | |
| Trait | Growth | Sexual maturation | Harvest weight/Body weight | Disease resistance/survival rate | FCR |
| Heritability (h ²) | 0,2-0,4 | Correlated to growth | 0,2-0,4 | 0,1-0,3 | 0,1-0,3 |
| Genetic gain | 13% | 10-13% | >60% by 4 gen | >12% | 5% |
| Sources | | | | | |
| (Gjedrem et al. 2012b), (Kause et al. 2005), (Kashyap et al. 2024), (Vandeputte 2023), (Gjedrem & Robinson 2014), (Guy et al. 2009), (Thodesen et al. 2001), (<i>Aquaculture production</i> n.d.a) | | | | | |

Table 3. Breeding in cichlids

| Global production | | | | | |
|--|---------------|--------------------------|-----------------------------------|---|------------|
| 6549 (FAO 2024) | | | | | |
| Active breeding programs | | | | | |
| 27 | | | | | |
| Traits: | Growth | Sexual maturation | Harvest weight/Body weight | Disease resistance/survival rate | FCR |
| Heritability | 0,2-0,4 | Correlated to growth | 0,2-0,4 | 0,1-0,3 | 0,32-0,11 |
| Genetic gain | 10-14% | No data | 14 % | >12 % | 4,6 % |
| sources | | | | | |
| (Gjedrem et al. 2012b), (Kashyap et al. 2024), (<i>Aquaculture production</i> n.d.b), (Gjedrem & Robinson 2014), (Guy et al. 2009), (de Verdal et al. 2018) | | | | | |

Table 4. Breeding in carps

| Global production | | | | | |
|--|---------------|--------------------------|-----------------------------------|---|------------|
| 31 788 (FAO 2024) | | | | | |
| Active breeding programs | | | | | |
| 9 | | | | | |
| Trait | Growth | Sexual maturation | Harvest weight/Body weight | Disease resistance/Survival rate | FCR |
| Heritability | 0,2-0,4 | Correlated to growth | 0,2-0,4 | 0,1-0,3 | No data |
| Genetic gain | 12% | No data | 7% | 12,5% | 5% |
| Sources | | | | | |
| (Gjedrem et al. 2012b), (<i>Aquaculture production</i> n.d.b), (Prchal et al. 2023), (Gjedrem & Robinson 2014), (Guy et al. 2009) | | | | | |

5. Gaps of knowledge

5.1 Areas where further research is needed

Mainly the areas concerning breeding methods in aquaculture, where more research is needed, are identifying traits and genes with positive connection to what we want to see in the industry and managing negative genetic correlations that appear. Naturally, the above needs to take place in a cost-effective way. Overall, significant gaps of knowledge still exist when it comes to the different aquatic species genetics, even less knowledge exists about those who are not high value species, where investment in the application of genomic technologies for the breeding programs is lacking (Gjedrem et al. 2012b; Abdelrahman et al. 2017a; Sonesson et al. 2023).

Further research is needed in the areas of the different genomic technologies for the different species. To achieve further progress in breeding programs, knowledge of reproduction physiology together with aspects of sex determination, seed harvest (and supply) and sexual maturation, is required. Furthermore the usage of various production systems and rearing across different environmental aspects creates challenges as G x E might negative affect selection (Sonesson et al. 2023). Additionally, only a few companies have the staff with the correct skills to handle and analyse large amounts of genomic data and gene mapping, and very few hire consultants to help (Sonesson et al. 2023).

5.2 Gaps of knowledge in different high and low value species

The majority of GWAS has been performed on Atlantic salmon and Rainbow trout with focus on disease resistance, using dense SNPs genotyping platforms (Abdelrahman et al. 2017a). Therefore, there seems to be a large potential in performing GWAS in other aquaculture species as well. In the last few years, we witnessed the development of genotyping tools, e.g. SNP arrays for other aquaculture species as well, which is particularly positive.

When it comes to recordable traits, a better understanding of the basic genetics of the species we farm is of essence and will be helpful when it comes to interpret results of selective breeding in most species where selective breeding programs are applied (Azra et al. 2022). For example, the shrimp genome has proven to be the hardest of all aquatic species because of its active DNase and large number of chromosomes (Abdelrahman et al. 2017a). The low value species in the small sector industry are in general not using selective breeding as a tool for progress, which for sure would have led to increased production and income. This is often

because of lacking finances to start breeding programs in the first place (Sonesson et al. 2023).

5.3 Gaps of knowledge in the field of gene editing

5.3.1 CRISPR/Cas9

Since we do not have particularly much information about the implications of gene editing several questions about its applicability in aquaculture species remain. Gene editing requires understanding on what will happen with the genome, what changes will be heritable, and which will not, negative and positive correlations in traits and much, much more. That is still information that we don't have in the majority of the species we keep and breed. (Abdelrahman et al. 2017). One aspect of great discussion lies in the relatively high risk of escapees from aquaculture rearing systems, where individuals escape e.g through holes or jumping out of the facility and risk mating with wild individuals from the same species and therefore spreading the edited genes to wild populations with consequences we yet don't know anything about (Sonesson et al. 2023). Furthermore, genome editing technologies have a very low acceptance in the consumers eye, even though it can help improve species in aquaculture and other food producing industries, as it can result in direct improvement in a phenotype in only one generation. Last but not least relevant costs during its application in practice still remain substantial (Abdelrahman et al. 2017b)

5.3.2 Risks to assess in the breeding methods of aquaculture

When breeding aquatic species, where the knowledge of the general genome is low, it is important to assess that the traits of interest can be unfavorably genetically correlated. For example, growth/disease resistance can correlate and when you reach your goal of fast growth, you may also gain a lower tolerance for disease resistance. Many factors that play a big role in the animal's welfare and health can be unfavorably correlated by other breeding factors that are higher on the priority list, like heat stress, salinity tolerance or other environmental factors. In the end they all play a big role in the economic sustainability of aquatic species and aquaculture breeding.

Individual selection, as mentioned before, can come with a risk of inbreeding because of the slim selection base from a few parents that produce the best juveniles (Lind et al. 2012). Within family selection, a big issue is that tagging juveniles is impossible, which leads to the separate raising of families in family tanks, this method will lead to "the tank effect" which means that the same family has been exposed to the same environmental factors which can lead to a lower response to selection (Saura et al. 2017).

6. Future development

In general, there is a lack of knowledge on the phenotypes and genomics behind desirable traits for the aquaculture industry. Today's greatest area of development is by far the automation of data collection often communicated under the umbrella term of precision farming (Kashyap et al. 2024). The more progress we make in the technological aspect of recording traits, behavior, animal welfare and general physiological parameters, the higher precision breeding programs the industry can have and the better output we will get from them (Sonesson et al. 2023; Kashyap et al. 2024).

For example, interesting developments can be witnessed in bivalve farming when it comes to integrated multi-trophic aquaculture (IMTA), where environmental aspects are taken more seriously, where producers try to develop production systems that can keep many different species and be more resource efficient. One major aspect of bivalve aquaculture (which is a big area in the field of aquaculture, approximately 19 000 tons a year) is seed supply, which works a bit differently from our terrestrial livestock. Seeds from natural spawning events in the wild are collected, and the grow out devices are placed where seeds float by and attach to the ropes/platforms/nets that are being used, and they are then cultured for human consumption. This method is in direct competition with the wild populations. Another way of collecting seeds for bivalves is by culturing them in a captive environment but this is, as of today, usually costly and demands specific technology. Technological development may make it more user friendly in the future.

When it comes to fish, the general collection of seeds is made by letting them spawn naturally in captivity in different breeding populations or by "milking" female and male fish and fertilizing the eggs in a controlled grow out environment, where the different stages of fish are being bred until they are ready for harvest or move to a last grow out system. Examples of seed-supply systems using eDNA markers and pooled DNA markers have been suggested where a gene bank, on national or regional level, could be put to use to help producers get good quality seed that is fit for their production environment and will give a good harvest, as well as it gives the fish the best possibility of a healthy and stress free life (Sonesson et al. 2023). In breeding fish, one very important factor is the survival rate amongst spawns and studies have shown that the feed provided to broodstock is of great importance. This needs to be kept in mind when the future of more vegetable feed ingredients enters the market. The feed should be combined with different fatty acids to provide for the different aquaculture species needs in terms of nutritional value. (Migaud et al. 2013).

Today one of the areas with potential in precision fish farming is echo sounders that describe the distribution of fish in the system. Automatic recording of animals becomes increasingly important to the aquaculture industry. The use of AI could play a big role here as well. This area could advance fast if the use of other marine businesses with more advanced equipment got to the industry, like hydrophones. Passive hydrophones have been used to study animal behavior through the sounds the fish make in the system. Acoustic telemetry can be used to monitor the fish's physiological parameters while camera and sonar are limited to measuring behavior parameters and parasite-count, used in salmon farming where sea-lice is being counted on individuals to measure the total infestation (Føre et al. 2018). There are none or only a few regulations regarding introduction of new technologies on the fish farming market, which can be used as an advantage in the early stages of developing those technologies but needs to be handled with responsibility (Føre et al. 2018). Machine learning can be a potential diagnostic tool for e.g identifying females who will lay bad eggs, determining gender or reproductive state for the animals (Abdelrahman et al. 2017a). Therefore, recording more data about various phenotypes of interest using AI technologies can empower selective breeding and eventually lead to higher genetic gains.

Gene editing is also a field of future interest that holds substantial potential. It is, as of now, an area that needs a lot more research to be considered safe and ethical in the eyes of consumers (Abdelrahman et al. 2017a). Gene editing is suggested not only in animal breeding but also in agriculture and other smaller and more obscure research fields of human genetics. Many are concerned about how this will turn out if not handled with care as well as many researchers find the possibilities exciting.

Speculations of how CRISPR/Cas9 can be used to protect endangered species, eradicate invasive species is to be found in research and some studies have been made on these topics, e.g eradicating the white-nose syndrome in bats (Ansori et al. 2023).

6.1 Future development in pedigree based- and genomic selection

Since the start of the genomic research in aquaculture species, we have been relying on phenotypes and pedigrees and even if we still need a lot more phenotypes it is leaning more towards genome technologies for some of the high value, well studied key species. Whole genome sequencing is available for several aquaculture species but needs further development to be available for all. GWAS, and GS should be used more frequent as they can boost the efficiency of breeding programs (Abdelrahman et al. 2017a).

7. Discussion and Conclusion

To feed the expanding world population, aquaculture must grow so that it can provide healthy food and work for people, especially in developing countries. However, it is imperative that this growth takes place in a sustainable way and does not endanger wild populations and aquatic ecosystems.

Since bivalve production is completely dependent on wild populations for broodstocks or seeds, it is of great importance that this resource's value is appreciated for what it is, going into the future, the industry will learn to rely on breeding instead of wild captured seeds, which will make the industry more efficient. It is also crucial for the industry to learn how to control sexual maturation, spawning and production of high quality seed (Migaud et al. 2013). Initiatives of selective breeding are missing in general for bivalves and this is a factor that rapidly could increase the sustainability of aquaculture production. As a vegetable-based feed is better for the planet it is important that the fish also is bred to tolerate/like/eat this type of feeds and maybe there is a greater need to look in to domesticating more herbivore species instead of carnivores (Gjedrem et al. 2012a). Selective breeding has contributed to this in many ways and will continue to do so, one major factor is the FCR that is the best among any livestock bred to feed humans (Gjedrem et al. 2012c).

Because selective breeding is man made, where we decide what individuals that should produce spawn, the field is very open for whatever technologic aspects we can apply to it if we know the basics of the tech or method that is used. Today generational gain is implied, and the time it takes to see results of the breeding differs between terrestrial livestock and aquaculture species, based on the fecundity but also the design of the breeding programs with progeny/sibling testing; the result shows faster in aquaculture species than in terrestrial livestock. Developing the different methods is one part of the future improvement of the breeding programs that is important but will need both time and money, educating scientists and farmers. With further development of e.g AI technologies together with different underwater equipment, a lot more accurate data can be collected and analyzed, this will provide cost effective and secure material for the breeding programs in both research facilities as well as on farms. More specifically, with AI-camera supervision of the fish schools we could recognize individuals who are most fit to be used as breeders. Other features as a better knowledge of the overall animal welfare and behavior in the systems will also be better elucidated by such technologies. These are factors that present great promise for the development of sustainable food production.

When it comes to genomics, different sequencing technologies can be used in the field based on either short or long reads. Currently most research is based on the former as long read sequencing is currently substantially more expensive

(Abdelrahman et al. 2017a). Therefore, future developments in sequencing technologies could benefit aquaculture breeding programs

Putting together tables 2, 3 and 4, depicting genetic gain in key species, a general gap of knowledge was discovered when reviewing data for the different sub species regarding genetic gain, where much important data is missing and focus has been on growth for most of the species. Data might be available, but it is not documented in a viewer friendly format, if all data could be collected in one database with easy access it would help future research a lot, this is also a field for computer sciences and AI developers to assess.

In conclusion, aquaculture has a great potential to provide nutritious and sustainable food for a growing population, even though there are areas that need a lot more research as it is today, for example developing breeding methods and collecting data and phenotyping of the animals will make a great difference for the future aquaculture industry.

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Popular science summary

In the aquaculture industry, many opportunities lie ahead. It's of great importance that science and producers as well as governments, investors and consumers work together so that we can have a sustainable future in the production of "seafood", or aquaculture. The focus of live animal production has been mainly weighted on the terrestrial animals because they have been domesticated by man for a much longer period. We've also collected a far better understanding of how to process and refine the products from those animals. In general, seafood has a piece of history in all cultures, mostly as fisheries or small scale farming, like the Asian concept "fish and rice" but as the earth population grows and the question about how we produce food in a better, more sustainable way rises, the need for more research in the field of aquaculture has come of day. This review aims to gather information from the field of aquaculture breeding to make it easier to access and over wive. In aquaculture breeding programs, there is a large difference from terrestrial breeding programs, presented as the extremely high fecundity of aquaculture species, compared to e.g dairy cows that produce one, maybe two calf's a year, the fish species in the industry produces thousands of offspring in one mating which opens up for many opportunities when it comes to selection on family basis, and not offspring selection as we've seen in the terrestrial livestock breeding programs. With this opportunity comes a lot of responsibility, to be aware of the risks and to know what methods fit the different species and breeding schemes best, therefore there is a collected review of both pedigree selection and the more technological advanced methods like Crisps/CAS9 in this paper.

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