Introduction of Rainbow Trout (Oncorhynchus mykiss) Aquaculture in Africa: Innovations in Breeding, Overcoming Challenges, and Future Opportunities.

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Abstract

Africa has witnessed a significant surge in the aquaculture of rainbow trout (Oncorhynchus mykiss), primarily driven by advances in breeding and the need to overcome logistical and environmental challenges. This introductory overview provides a snapshot of the current state of rainbow trout farming in Africa, highlighting the progress made as well as the obstacles that must be addressed to ensure long-term growth and financial sustainability. The introduction of rainbow trout to African aquaculture systems has created new opportunities for economic growth and food security in areas where traditional fisheries are declining. The species is a desirable choice for aquaculture due to its high market value and ability to adapt to a variety of environmental conditions. Recent selective breeding advances have produced strains that are more resistant to diseases and local climates, increasing yield and production efficiency. However, several obstacles hinder the growth of rainbow trout aquaculture in Africa. The quality and scarcity of water are major concerns, as trout thrive best in cold, well-oxygenated water. To alleviate these concerns, innovative approaches to water management, such as recirculating aquaculture systems (RAS), are being utilized. The cost and the availability of feed remain significant limitations. Efforts are being made to develop locally available and sustainable feed alternatives to reduce reliance on imported fish meal. The lack of comprehensive policies and suitable infrastructure in many African countries presents another challenge. The expansion of this industry is hindered by the absence of supportive legislation is necessary. To overcome these obstacles, funding for training, research, and development of supportive legislation is necessary. Future prospects for rainbow trout aquaculture in Africa appear promising. If the current challenge can be addressed through technical innovation, improved management techniques, and encouraging government regulations, there is a potential for substantial expansion. By integrating aquaculture with other agricultural practices, productivity and sustainability can be improved. By keeping pace with innovation and investment in this field, Africa can fully realize the potential of rainbow trout aquaculture and contribute to food security, economic growth, and environmental sustainability on the continent.

Keywords*: Rainbow trout (Oncorhynchus mykiss), aquaculture, recirculating aquaculture systems (RAS), breeding techniques, recreational fishing.*

Introduction

The rainbow trout (*Oncorhynchus Mykiss*), classified within the Oncorhynchus genus, Salmonidae Family, Salmoniformes Order, and Salmoninae Subfamily, is a species widely cultivated across the globe, with the notable exception of Antarctica (HERSHBERGER, 1992). The proliferation of non-native species, including various trout species, is increasingly acknowledged as a significant contributor to the global decline of biodiversity (Pimentel, 2011.). Freshwater fishes serve as critical indicators of the ecological impacts of the species invasions, as they represent one of the most extensively imported groups of vertebrates worldwide (Rahel, 2002); (Leprieur, 2008); (Strayer, 2010). Among these, non-native trout species, particularly those from the genera Oncorhynchus and Salmo, have become widely established in freshwater ecosystems globally (Welcomme, 1988); (Cambray, 2003); (Crawford, 2008). Research indicates that these non-native trout have formed new functional groupings within both fish-populated and fish-free environments (Strauss SY, 2006; Strayer, 2010; Simon KS, 2003). The forces of globalization have facilitated the spread of numerous species for recreational fishing, with introduced species now available for sale worldwide and capable of overcoming geographical barriers due to advancement in transportation (Cambray, 2003a). Specifically, *O. mykiss* has been introduced to nearly every continent for fishing and aquaculture purposes, with documented introductions in at least 87 countries (FAO (Food and Agriculture Organization of the United Nations), 2012); (GISD, 2012). The species' widespread cultivation can be attributed to its relative ease of production and advancement in aquaculture technologies, enabling its farming in diverse locations with sufficient supplies of cool, clean water. Notably, *O. mykiss* was introduced to South Africa in 1897 for fishing purposes, and by 1899, it had become the primary species utilized in stocking projects in the Western Cape (Cambray, 2003a). The support of anglers for these initiatives has facilitated the species' expansion into previously inaccessible regions (Clark, 2007).

The economic potential, nutritional value and adaptability of rainbow trout (*O. mykiss*) have significantly contributed to the expansion of aquaculture in Africa over the past few decades. Initially introduced for sport fishing, rainbow trout have evolved into a crucial component of the aquaculture industry in several African nations, including South Africa, Lesotho, Kenya, Egypt, Nigeria and Uganda. Notably, the region experienced a remarkable twenty-fold increase in production, escalating from 110,200 tons in 1995 to 2,196,000 tons in 2018, reflecting a compound annual growth rate (CAGR) of 15.55% (FAO., 2016); (Halwart M, 2020). In South Africa, for example, the establishment of a robust trout farming sector has fostered rural development and enhanced regional food security by capitalizing on favourable environmental conditions (Murray TS, 2015). The integration of modern aquaculture techniques, such as recirculating aquaculture systems (RAS) and advanced breeding protocols, has played a pivotal role in enhancing productivity and sustainability within the industry (FAO, 2020). However, the sector faces several challenges, including the necessity to increase production capacity, administrative roadblocks, and environmental concerns. Addressing these challenges will require further research, policy support, and international collaboration to ensure the sustainable growth of rainbow trout aquaculture in Africa, thereby potentially improving food security and promoting economic diversification across the continent (World Bank 2016). This study aims to provide a comprehensive overview of the application of improved breeding methods to enhance the productivity and resilience of rainbow trout in diverse African climates. Additionally, it investigates the primary challenges confronting the industry, such as feed shortages, water scarcity, and regulatory constraints, while evaluating the strategies and tools employed to mitigate these issues. Ultimately, this research seeks to illustrate the potential of rainbow trout aquaculture to make significant contributions to food security, economic development, and environmental sustainability throughout the African continent by analysing current practices and future prospects.

Background and Significance of Rainbow Trout Aquaculture in Africa

Rainbow trout (*O. mykiss*) is characterized by its high market value, nutritional benefits, and adaptability to controlled farming environments; positioning it as a significant player in the global aquaculture industry. Despite being a relatively recent venture in Africa, rainbow trout aquaculture has demonstrated considerable potential for growth, influenced by various ecological, dietary, and economic factors. The introduction of rainbow trout to Africa can be traced back to the early 1900s, when colonial powers primarily introduced the species for sport and recreational fishing (De Moor IJ, 1988). However, it was not until the late 20th and early 21st centuries that substantial advancements in commercial aquaculture operations were realized, largely due to an increasing awareness of the species' ability to enhance food security and stimulate economic development. For instance, commercial trout farming began in South Africa during the 1960s, leveraging the country's favourable temperature and abundant water resources (P. Britz, 2013). The aquaculture of rainbow trout has significant economic implications for African countries, serving as a vital source of income and employment in rural areas where alternative economic opportunities may be limited. According to Murray TS (2015), the trout farming industry in South Africa has played a crucial role in rural development and poverty alleviation by generating jobs in the agricultural and processing sectors. Similarly, the Kenyan government has recognized trout farming as part of a broader aquaculture development strategy, emphasizing its potential to diversify agricultural income and bolster local economies (FAO, 2018). Nutritionally, rainbow trout is an excellent source of high-quality protein, omega-3 fatty acids, vitamins, and minerals. In regions where food insecurity is prevalent, incorporating trout into the local diets can help mitigate nutritional deficiencies. Research indicates that increasing the availability and consumption of aquaculture products, such as rainbow trout, can significantly enhance dietary diversity and improve nutritional status (Beveridge, 2010). For instance, the Ugandan government has identified aquaculture, including trout farming, as a critical strategy to improve national food and nutrition security (Mwanja, 2013).

The ecological maintenance of rainbow trout aquaculture is essential to mitigate potential adverse effects on local ecosystems. Although rainbow trout are not native to Africa, Aquaculture practices have significantly reduced the risks associated with invasive species by effectively managing the introduction and spread. However, the risk of accidental farm escapes remains a concern, as these events can threaten local biodiversity and raise issues regarding competition with indigenous fish species (Ellender BR, 2014). In response to these ecological concerns, numerous countries have adopted the best management practices and established legislative frameworks designed to minimize ecological risks. For example, South Africa has strengthened its regulatory measures governing aquaculture operations to safeguard natural habitats (DEA, 2013). Furthermore, advancements in aquaculture and breeding technologies have been a pivotal in the successful cultivation of rainbow trout in Africa. Selective breeding programs have been implemented to enhance desirable traits such as growth rate, disease resistance, and feed efficiency, resulting in the production of high-quality fingerlings that thrive in African aquaculture environments. Additionally, the integration of modern aquaculture technologies, including recirculating aquaculture systems (RAS), has facilitated more efficient and sustainable production practices. RAS technology, which recycles and reuses water within the farming system, has been proven particularly advantageous in regions with limited water resources (FAO, 2020).

Through strategic initiatives and financial investments, several African nations have demonstrated considerable advancements in rainbow trout aquaculture. Africa is emerging as a leader in trout farming, having built a robust industry targeting both domestic and international markets. The Western Cape and Mpumalanga regions have evolved into prominent centers for trout production, attributed to their abundant water resources and favourable temperate climates. Support for this sector is prominently provided by South African Trout Association (SATA), which engages in research dissemination, best practice sharing, and advocacy efforts. In Kenya, the government has actively promoted rainbow trout farming as part of its strategy to diversify the aquaculture production. A significant milestone in this endeavour was the establishment of the Kiganjo Trout Hatchery and Research Center, which supplies high-quality fingerlings to farmers while enhancing extension services and research activities.

Furthermore, the integration of tourism and trout farming in the Mount Kenya region has fostered mutually beneficial synergies for both industries (Mwanja, 2013). Uganda has similarly prioritized its aquaculture sector in pursuit of food security and economic development, capacity building, and collaborative research initiatives with international partners to support the growth of trout farming. The establishment of demonstration farms and training programs has facilitated the dissemination of best practices, ultimately benefiting small -scale farmers by enhancing production efficiency and sustainability (Mwanja, 2013).

Despite notable advancements, rainbow trout aquaculture in Africa continues to contend with several significant challenges. A critical obstacle remains the access to high-quality feed and fingerlings, as many farmers depend on expensive and often unpredictable imports sources (Shoko AP, 2011). Additionally, the development of enhanced cold chain facilities and other essential infrastructure is necessary to facilitate the shipping and storage of trout products, particularly in remote areas. Prioritizing capacity building and technical training is essential to equip farmers with requisite knowledge and skills for implementing best practices. The scarcity of specialized training programs and extension services has emerged as one of the most considerable barriers in numerous regions. To effectively address these gaps, collaboration among the private sector, governments agencies, and academic institutions is imperative (World Bank 2016). Continued investment in research and development tailored to the unique challenges of trout farming in Africa is critical, encompassing the creation of locally produced and affordable feeds, disease management, and the establishment of breeding programs that reflect local conditions (FAO, 2020). Collaboration among governments, private sector stakeholders, and international organizations can stimulate innovation and leverage successful models. Public-private partnerships can enhance the overall viability of the industry by improving access to markets, facilitating information transfer, and securing funding (World Bank 2016). Moreover, the establishment of robust legal and regulatory frameworks is essential to ensure sustainable practices, DEA (2013). To effectively disseminate knowledge and best practices among farmers, it is crucial to enhance capacity-building and extension services. Comprehensive training programs should encompass all aspects of trout farming, from hatchery management to processing and marketing, to increase both output and profitability (Mwanja, 2013). Furthermore, expanding local and regional markets opportunities for trout products can significantly boost the industry's profitability. By adding value through processing and product diversity, farmers can increase their market opportunities and profitability (Mwanja, 2013.).

Research Status and Existing Problems

Current research in African rainbow trout aquaculture is emphasizing the development of breeding techniques aimed at enhancing growth rates, disease resistance, and feed efficiency. The implementation of selective breeding programs is crucial for establishing strains capable of thriving in diverse African environments. For instance, South Africa has initiated large-scale breeding initiatives focused on improving the genetic stock of rainbow trout, leveraging both local and international expertise (Murray TS, 2015). The integration of advanced aquaculture technologies, such as recirculating aquaculture systems (RAS), has led to transformative shift in the industry. These technologies significantly enhance production efficiency by enabling higher stocking densities and improved control over water quality (FAO, 2020). This successful adoption of these technological developments in African states can often be attributed to technology transfer operations facilitated by global collaborations. Notably, knowledge transfer projects incorporating modern agricultural practices and equipment have greatly benefited Kenya by increasing both overall productivity and sustainability of trout farms (World Bank 2016). For the prosperity of rainbow trout aquaculture in Africa, public-private partnerships and international collaboration prove to be indispensable. Such partnerships not only provide vital resources, including funding, expertise, and market access but also foster a conductive environment for sustainable development. For example, the collaboration between the Kenyan government and international organizations such as the Food and Agriculture Organization

(FAO) has resulted in significant advancements in infrastructure, training initiatives, and research projects aimed at optimizing trout farming techniques (FAO, 2018). Additionally, programs like the African Aquaculture Development Plan, which promote regional cooperation and knowledge exchange, enhance the growth prospects for the industry further (World Bank 2016).

One of the primary challenges confronting rainbow trout aquaculture in Africa is climate adaptability. In various regions of the continent, the lack of access to cold, oxygenated water can severely impact the viability of trout farming. Climate change-induced alterations in water temperature and quality may further exacerbate these challenges by elevating stress levels in trout populations and increasing susceptibility to disease (FAO, 2020). Additionally, the availability of resources, particularly fingerlings and high-quality fee, represents a significant obstacle. Many African countries are compelled to rely on costly imports due to their insufficient capacity to produce these essential inputs domestically. This reliance increases production costs and limits the scalability of trout farming operations (Shoko AP, 2011). For the sector to achieve sustainable growth, a consistent supply of affordable, nutritionally balanced feed is essential. Furthermore, inadequate infrastructure poses another substantial barrier to the advancement of rainbow trout aquaculture in Africa. The absence or inadequacy of critical infrastructure, including cold storage facilities, hatcheries, and advanced transportation systems, diminishes profitability and competitiveness across the entire value chain, from production to market access Murray (2007), Investment in infrastructure is thus vital for the establishment of large-scale, sustainable trout farming operations. Effective disease management is also a key component of successful rainbow trout aquaculture, as the prevalence of parasites and water-borne diseases can result in significant mortality rates and economic losses. The situation is further complicated by the fact that existing disease management practices in Africa often suffer from limited access to effective treatments, diagnostic tools, and veterinary care, exacerbating the challenges facing the industry (FAO, 2020).

Morphological Characteristics of Rainbow Trout

Fish identities are typically determined based on their observable physical characteristics. The rainbow trout (Oncorhynchus mykiss) exhibits a fusiform body shape characterized by colouration that ranges from blue to olive green, accompanied by a distinct pink stripe along its lateral line. In fresh water environments, these fish display hues of dark green, yellow-green, or brown, often featuring a prominent pink or red band that extends longitudinally along their bodies. Additionally, they are adorned with dark spots on their dorsal surface, tail, and fins. In contrast, when inhabiting brackish or salt water, O. mykiss takes on a silvery appearance, dorsal region. The body and fins are typically covered in small black spots, although the ventral surface remains unmarked (FAO (Food and Agriculture Organization of the United Nations), 2012.). Notably, the largest recorded rainbow trout reached a length of 1.22 meters and a weight of 16.3 kilograms (GISD, 2012), while the heaviest specimen caught in South Africa weighed 5.43 kilograms (Skelton, 2001).

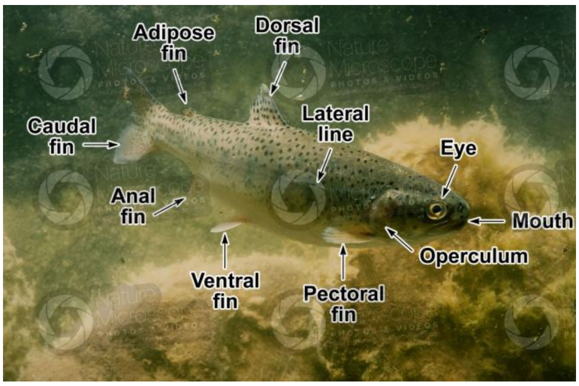

Fig.1. Rainbow trout morphology

In South Africa, the average length and weight of O. mykiss (rainbow trout) in river systems are typically reported at 0.5 meters and 1.5 kilograms, respectively, Picker (2011). This species is a cold-water fish native to North America, with its range extending from Alaska to Mexico. Predominantly a fresh water species, O. mykiss thrives in environments characterized by highly clean and well-oxygenated water. Consequently, open lakes, fast-flowing streams, and dams are common habitats for this trout (Picker, 2011). Notably, certain population of O. mykiss exhibit migratory behaviours; as anadromous fish, they spend the majority of their lives in salt water before returning to fresh water for reproductive purposes (Froese, 2011). Furthermore, rainbow trout are classified as opportunistic feeders, with a diverse diet that includes fish eggs, small fish, and various aquatic and terrestrial invertebrates.

In their natural habitats, O. mykiss primary consumes fresh water shrimp, which are rich in carotenoids, the pigments responsible for the characteristic pink colouration of the fish's flesh. To replicate this desired colouration in aquaculture settings, farmed rainbow trout are often fed diets supplemented with artificial pigments (FAO (Food and Agriculture Organization of the United Nations), 2012). It shows that the freshwater rainbow trout strain grows more slowly than the anadromous strain, gaining 4.5 kg in three years as opposed to 7–10 kg over three years (FAO (Food and Agriculture Organization of the United Nations), 2012). Under optimum conditions, rainbow trout in South Africa are reported to grow 150–180 mm in their first year and 260 mm in their second (Skelton, 2001). Growth rate is influenced by temperature and food supply. Although mature age varies widely as well, it typically reaches its peak for men at one year and for females at two years (Skelton, 2001). Only once a year, usually in South Africa between June and September, rainbow trout spawn in the wild (Skelton, 2001). In their natural habitats, spawning takes place in rocky or gravelly rivers and streams. It is thought that the lack of gravel beds in dams limits the natural range of *O. Mykiss* (Anchor Environmental Consultants, 2010). The female excavates a "red," or shallow depression in the substrate, prior to spawning. A female O. Mykiss can lay 2000 eggs for every kilogram of body weight. As a result, the yield could range from 200 to 12,000 eggs, depending on the size of the individual. A single egg's diameter ranges from 3 to 7 mm (FAO (Food and Agriculture Organization of the United Nations), 2012). The eggs are left alone until they hatch, which takes four to seven weeks. Once spawning is complete (Skelton, 2001). According to FAO (Food and Agriculture Organization of the United Nations), 2012), *O. Mykiss* can only grow and breed in colder waters (between 9 and 14°C), with 10 to 13°C being the optimal range for spawning (Piper, 1982). Despite this, the species can endure water temperatures of up to 26°C. In controlled conditions with aeration, *O. Mykiss* can tolerate temperatures as high as 30°C (Stander). Because they are anadromous, rainbow trout can withstand salinities ranging from 0 to 35% (Molony, 2001). According to Rowe (1995), *O. Mykiss* appears to be extremely sensitive to dissolved oxygen levels; a concentration of 2.5 mg/l is the minimum needed for this species. The development of two *O. Mykiss* variants can differ physically because of environmental effects. Fish that are more susceptible to opportunistic infections may develop conditioned diseases because of their stress levels rising and the environment getting worse. This was observed in Italy, where outbreaks of Lactococcus garviae in rainbow trout were brought on by warmer summer temperatures and increased pathogen concentrations (Alborali, 2006).

Fig.2. Oncorhynchus Mykiss

Artificial Breeding Technology

Assisted reproductive technology (ART), also denoted as artificial breeding technology, and encompasses a suite of innovative methodologies and protocols aimed at augmenting reproductive efficacy in both plant and animal species. The advent of ART has precipitated paradigmatic shifts in the domains of agriculture, aquaculture, and conservation biology, facilitating the enhancement of genetic diversity, circumventing inherent breeding limitations, and ensuring the preservation of species of paramount importance.

1. **Hatchery Management**

Optimal hatchery management is a crucial factor in the successful artificial propagation of rainbow trout (*O. mykiss*) in Africa. A multifaceted approach is employed in hatchery operations, incorporating a range of techniques and specialised equipment to enhance the survival and growth rates of trout from embryonic stages to fingerlings. This process commences with the deliberate selection of broodstock exhibiting superior genetic traits, including robust health, disease resistance, and growth efficiency. The broodstock are subsequently conditioned in controlled environments to optimize their reproductive health, with meticulous attention to water quality, temperature, and nutrition parameters (Gjedrem, 2012). Contemporary water recirculation systems are utilized to maintain these ideal conditions, while the strategic application of disinfectants and regular monitoring mitigate the risk of fungal infections and other disorders (FAO, 2020). The prevention and control of disease are critical components of hatchery management, with the administration of Probiotics and health-promoting nutrients, alongside regular physical examinations and vaccination schedules, serving to safeguard the health of both broodstock and fry. Moreover, rigorous biosecurity measures, including equipment sanitation protocols and quarantine procedures, are essential for preventing disease outbreaks (Mylonas, 2010). The reproductive biology of rainbow trout is well-understood, with established methodologies guiding the process. The dry fertilization method, which eliminates the need for water addition, is the most widely employed technique. Furthermore, the application of air spawning or manual eggs collection under anesthesia enables the production of cleaner, healthier eggs. This involves the gentle application of the pressure to the pelvic fins of the female fish to induce egg release, followed by removal of trapped air through lateral rubbing.

Optimization of gamete collection and fertilization is crucial in artificial propagation of rainbow trout. Up to 2000 eggs per kilogram of body weight are extracted and maintained in a dry environment to facilitate fertilization. Sperm collection from males is carried out similarly, with careful attention to prevent water and fecal contamination, using a separate dish to collect milt. The subsequent step involves combining the sperm and eggs to maximize fertilization efficiency. To mitigate the risks of inbreeding, it is recommended to pool the milt from three or four males prior to fertilization. The process of "water-hardening" involves the addition of water to stimulate sperm activation and fill the perivitelline space between the yolk and shell, resulting in an approximate 20% increase in egg diameter. Only fertilized eggs that have reached the eyed stage, characterized by visible eye structures through the shell, can be safely transferred 20 minutes post-fertilization and for a maximum of 48 hours thereafter. It is essential to avoid direct light exposure during all stages of development, as this can be lethal to the embryos. Furthermore, the application of triploidy and mono-sex culture techniques has been developed to enhance productivity. Triploidy is induced through the application of pressure or heat to the eggs, whereas mono-sex culture is achieved by fertilizing normal female eggs (XX chromosomes) with milt from sex-reversed, masculinized females (XXX chromosomes). Sex-reversed fish exhibit distinctive characteristics, including large, globular testes lacking vents. The testes excised from the abdomen and sectioned to collect the milt, which is then supplemented with an equal volume of extension fluid to render the sperm motile and competent for fertilisation of a normal egg. This approach offers the advantage that only the broodstock is subjected to sex-reversal, and the marketable fish do not receive hormonal treatment.

2. Hormonal Induction

Hormonal induction is a pivotal artificial breeding technique employed in African aquaculture to enhance the reproductive efficiency of rainbow trout (*O. mykiss*). The acceleration of final oocyte maturation is crucial for managing the broodstock in both salmonid and non-salmonid fish farms, primarily due to economic considerations. In certain salmonid species, the spawning phase of rainbow trout can extend up to six weeks, necessitating spawning control and induction, particularly in strains that ovulate at water temperatures above 14-15 ℃, which leads to rapid egg fertility loss. To mitigate this, it is essential to fertilize these fish immediately after ovulation, following synchronization, to prevent egg aging at elevated temperatures. This phenomenon is also observed in fish maintained in saltwater habitats, where ovulation is often suppressed (Breton, 1990). Various methods for spawning induction exist, including injections of pituitary extracts, human chorionic gonadotropin (HCG), gonadotropin (GtH), gonadotropin-releasing hormone (GnRH), and GnRH agonists. Notably, GnRH and its agonists are superior to GtH preparations in terms of spawning induction therapy, as they provide a more balanced stimulation of reproductive events and integrate them with other physiological functions by influencing the release of essential hormones necessary for successful final oocyte maturation and spawning (for a review, see Zohar, 2001). Broodstocks can receive GnRHa through intubation (Solar et al., 1990), injection into a vehicle, or continuous release preparations (Crim, 1997); (Peter, 1986); (Zohar, 2001), for a review). The most successful of these methods is the preparation of GnRHa for prolonged release. Numerous sustained-release approaches exist for both salmonid and non-salmonid fish (see Crim 1997; Peter, 1986; Zohar, 2001 for a summary). Sustained-release GnRHa preparations take the role of recurrent GnRHa treatments that are often necessary for a satisfactory response (for a review, see Zohar, 2001). Gonadotropins, however, control the duration of gametogenesis in salmonid species (Breton, 1983). Thus, one could propose that ovulation progression and synchronization would require a longer and more regulated stimulation of GtH secretion compared to other species (see Peter, 1986; Zohar, 2001 for a review). The African aquaculture industry has largely relied on the application of hormone induction to overcome the challenges posed by rainbow trout's regular spawning cycles, particularly in regions with suboptimal climatic conditions. The reliable production of high-quality fingerlings, enabled by this technology, has supported the expansion and sustainability of the trout aquaculture industry (FAO, 2020).

3. Feeding Regimes

Optimization of feeding regimes is crucial for enhancing feed conversion ratios, accelerating growth rates, and maintaining the overall health of rainbow trout. In recirculating aquaculture systems (RAS), precise control over feeding schedules and food composition is essential for maximizing production efficiency (FAO, 2020). Feeding protocols often involve the use of high-quality, nutritionally balanced commercial feeds specially formulated to meet the dietary requirements of rainbow trout at various life stages. These feeds are compositionally tailored to contain proteins, lipids, vitamins, and minerals that promote optimal growth and overall health. Automated feeding systems are widely employed to ensure consistent and accurate feed distribution, minimize waste, and optimize feed consumption (Murray TS, 2015). In addition to feed type and quality, strict control is also exercised over feeding schedule and frequency. The feeding strategy involves frequent, smaller feedings for juvenile trout to sustain their rapid growth, whereas adult trout benefit from fewer, larger feedings at longer intervals. This approach enhances growth performance and contributes to water quality maintenance by reducing wasted feed and organic matter (Ngugi CC and Manyala JO, 2004).

4. **Grow-out Systems**

The implementation of grow-out techniques is essential for rearing juvenile rainbow trout to market size, and innovative approaches are being employed across Africa. One of the most effective systems is the Recirculating Aquaculture System (RAS), which provides a controlled environment that significantly enhances growth rates and feed conversion efficiency. The RAS technology perpetually circulates water through mechanical and biological filters, ensuring optimal water quality and minimizing the risk of disease outbreaks (FAO, 2020). In addition to RAS, pond-based systems are also prevalent, particularly in region with adequate natural water supply. These systems capitalize on the existing environment, but they also require continuous management to prevent issues such as disease and water contamination. Furthermore, aquaponics, an integrated system that combines agriculture and fish cultivation, is gaining popularity. By utilizing the nutrient-rich wastewater from fish tanks to fertilize crops, these systems facilitate a resource-efficient and sustainable use of resources (Goddek S, 2015).

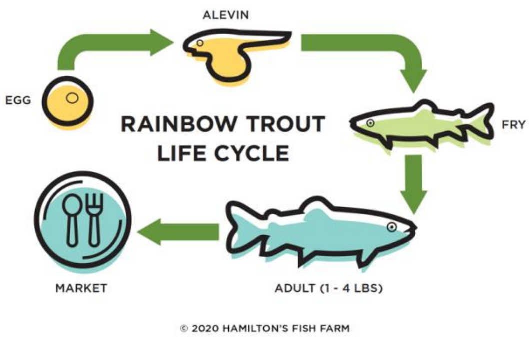

Fig.3. Life cycle of Rainbow trout

Breeding techniques

1. Selective Breeding

Selective breeding, in conjunction with improved farming techniques and nutrition, constitutes a pivotal technology for enhancing the sustainability and profitability of aquaculture production. The application of selective breeding in aquaculture is a relatively recent development, with the earliest optimized breeding programs for salmonids dating back to the 1970s (Gjedrem, 2010); (Kincaid, 1977), and those for most other species emerging in the 1990s or later (Neira, 2010); (Gjedrem T, 2018). A review of 67 studies revealed that selective breeding has been instrumental in promoting rapid development (increased body weight at a given age) in aquaculture species, although the majority of these studies were conducted over a relatively short period (averaging 2.8 generations). This technique is crucial for the development and expansion of rainbow trout (*O. mykiss*) aquaculture in Africa. By selecting broodstock with desirable traits, such as rapid growth, disease resistance, and high feed efficiency, aquaculturists can improve the overall well-being and yield of rainbow trout populations (Gjedrem, 2009). Through this process, individuals possessing superior qualities are identified and mated, and their progeny are subsequently assessed to ensure the consistent transmission of these traits to subsequent generations. Following multiple breeding cycles, selective breeding results in a population that is genetically significantly improved, rendering them more suitable to the local environment and aquaculture practices (Symonds J, 2000). Innovations such as the use of genetic markers and advanced breeding systems have further enhanced selective breeding, enabling more accurate selection and faster genetic gains (Yáñez, 2014). Ultimately, these advancements contribute to the sustainability and profitability of rainbow trout aquaculture in Africa by mitigating challenges associated with disease outbreaks, erratic growth rates, and environmental stressors.

2. Triploidization Techniques

Triploidy, a form of polyploidy is characterized by the presence of three sets of homologous chromosomes in an organism or cell. This phenomenon has been widely exploited in aquaculture and fisheries management to produce sterile fish. Triploidy induction has been successfully employed to generate numerous species of catfish, trout, and salmon for aquaculture purposes (Hussain MG, 1994); (Cassani JR, 1985). The African rainbow trout, or O. mykiss, is one of the most prominent fish species farmed in tropical; regions today. Triploid individuals, categorized as (3n), possess two sets of maternal chromosomes (2n) and one set of paternal chromosomes (1n). Triploidy induction, a method of creating individuals with three sets of chromosomes in fish, involves shocking the eggs shortly after fertilization, thereby arresting the subsequent extrusion of the second polar body and the second meiotic division (Dillon JC, 1988). The cold shock and heat shock techniques employed for triploid induction are safe and chemical-free. These processes require the maintenance of optimal treatment temperatures in large volumes to facilitate the treatment of a large number of eggs.

Triploidization, a process involving the induction of an additional set of chromosomes in fish, results in the production of infertile triploid trout. This method involves the retention of the polar body by applying chemical or physical shocks to fertilized eggs (Benfey TJ, 1999). According to Piferrer (2009), the primary advantage of triploidization lies in its ability to prevent fish from reproducing, thereby redirecting energy from gonadal development to somatic growth, which consequently enhances growth rates and feed conversion efficiency. Furthermore, triploidization serves as a sustainable aquaculture strategy by reducing the risk of genetic contamination of natural populations (Tiwary BK, 2004). In addition to promoting environmental sustainability, triploidization can aid the development of rainbow trout aquaculture in Africa by addressing challenges related to high production and rapid growth requirements. The adoption of this innovative breeding technique has contributed to the rapid and profitable expansion of the aquaculture industry on the continent.

3. Genetic Improvement Programs

Marker-assisted selection (MAS) is a prominent approach that employs genetic markers to identify and select individuals with desirable traits (Houston, 2020). Moreover, the utilization of advanced techniques such as genomic selection, which considers the entire genome of the fish, has led to more rapid and precise genetic gains (Yáñez JM, 2015). These genetic enhancement efforts not only enhance the sustainability and productivity of rainbow trout aquaculture in Africa but also facilitate the creation of strains that exhibit increased resilience to illnesses and environmental stressors unique to the region (Gjedrem, 2012). Consequently, these breeding advancements are pivotal in overcoming challenges and optimizing opportunities in the African aquaculture industry.

Breeding Process of Rainbow Trout

1. Selection of Broodstock

The breeding process for rainbow trout (*O. mykiss*) commences with the meticulous selection of broodstock to ensure that the offspring possess desirable traits. Broodstock selection is based on a range of criteria, including size, growth rate, disease resistance, and overall health (Gjedrem, 2000). Genetic selection programs have a profound impact on these traits, to enhancing fish resistance and productivity (Winkelman, 1994). Breeders commonly employ progeny testing and performance testing to maximize genetic advancements. Performance testing evaluates each fish for growth and other commercially important characteristics, whereas progeny testing assesses the performance of offspring to determine the breeding value of possible broodstock (HERSHBERGER, 1992). Modern techniques, such as molecular markers and genomic selection, are increasingly being used to accelerate genetic improvement and enhance the selection process (Houston, 2020). Artificial spawning of high-grade brood fish is typically conducted when they are fully matured, as they do not spawn naturally in aquaculture systems. The number of broodstock required is determined by the production schedule of the farm and can be adjusted based on survival rates at different life stages and female broodstock fertility. A sex ratio of one male to three females is generally considered suitable for broodstock, with males and females typically kept separate. Due to the high maintenance costs and labor requirements associated with broodstock, some farmers opt to purchase eyed eggs from external sources. These eggs must be "certified disease-free," and receive specific treatment, including gradual heating to hatchery temperature and iodine treatment (100 mg/liter for 10 min) upon arrival.

2. Controlled Breeding

The breeding of rainbow trout (*O. mykiss*) involves a series of meticulously managed stages to generate high-quality progeny with desirable traits. The initial phase of this process is the selection of broodstock, which entails choosing individuals with specific body forms, rapid growth, and disease resistance. As noted by Aitken (2016), selected broodstock are typically maintained under optimal conditions to preserve their health and reproductive efficacy. The breeding season are induced by adjusting temperature and photoperiod to create stimulate synchronous (Duan, 2008). Following this, male and female eggs, as well as milt, are carefully corrected and mixed to facilitate fertilization.

3. Incubation

Eggs are incubated in hatching jars, hatching troughs, or vertical flow incubators free from disturbance until they reach the eyed stage of development. Hatching and raising troughs typically have dimensions of 40–50 cm in width, 20 cm in depth, and a maximum length of 4 m. Water flows through the tray at a rate of 3-5 L/min, while wire baskets or screened trays (also known as California trays) are suspended 5 cm above the bottom and contain two layers of eggs. Upon hatching, which occurs within 4–14 weeks, the fry pass through the mesh to a lower trough. As an alternative, Heath incubators, often referred to as vertical flow incubators, enable the stacking of up to 16 trays, with a single water source flowing through the egg at a rate of 3–4 L/min, overflowing into the tray below, where it aerates and facilitates the hatching of a large number of eggs in a limited water volume. Sac fry can remain in trays for up to 10 to 14 days post-hatching, or until they achieve swim up. The temperature of the water significantly impacts the duration of incubation, with hatching times ranging from 100 days at 3.9 °C to 21 days at 14.4 °C, equivalent to approximately 370 degree days.

Commercially available hatching jars, or those constructed using a 40-liter drum and PVC pipe, facilitate water entry from the bottom and exit from the top, allowing for the incubation of 50,000 eggs suspended in a water flow that rolls the eggs, provide the incubator contains two-third of its volume in eggs and a flow rate that raises the eggs 50% of their static depth. In all of the aforementioned methods, dead eggs are regularly removed to minimize the risk of fungal infection. To manage fungal infections in input water, formalin, a 37 percent formaldehyde solution, can be used at a 1:600 dilution for 15 minutes daily, except within 24 hours of hatching. Once the eggs reach the eyed stage, weak and immature eggs are removed through addling, which involves dropping the eggs 40 cm. Trout, also known as alevins or yolk-sac fry, hatch with food stored in a yolk sac that lasts for 2-4 weeks. Following the hatching of the egg batch, typically within two to three days, all eggshells and any dead or deformed fry are removed. Eggs incubated separately from the rearing troughs are transferred to the latter after hatching. The fry is maintained in shallow water (8–10 cm) with a reduced flow rate in the trough until they reach the swim-up stage, at which point their yolk sacs have digested, and they begin actively searching for food; the trays are then removed.

4. Larval Rearing

Fry are typically raised in fiberglass or a concrete tank, preferably circular, although square tanks are also suitable; to ensure a consistent current or uniform fry dispersion. The tanks typically have a depth of 50–60 cm and a diameter of 2 meters or two square meters. Water is introduced into the tank via an elbow pipe or spray bar, creating a circulation pattern that facilitates even fry distribution. The drain, located at the center of the tank, is covered by a mesh screen, which enables the collection of waste for easy disposal. This design configuration generates a vortex that swirls toward the center, thereby collecting the waste. The sump or drainpipe is connected to the elbow pipe on the side of the tank, regulating the water level. Once around half of the fry have reached the swim-up stage, they are fed specially prepared to start meals using automatic feeders. Once approximately half of the fry have reached the swim-up stage, they are fed specially formulated starting meals using automatic feeders. Subsequently, feed is provided at a rate of 10% of the fish weight daily for two to three weeks, ideally using clockwork before feeders. The pellets are specifically designed to contain approximately half protein, 12-15% fat, calcium, phosphorus, sodium, vitamins A, D, and E, and a colorant to produce pink-fleshed fish. The feed pellets comprise 80% grains, fish oils, and fish meal, providing a balanced diet that promotes optimal growth and higher-quality products. By combining high-energy commercial diets with good feeding practices, feed conversion ratios (FCRs) as low as 0.8:1 can be achieved. Feeding is conducted by published tables that account for fish temperature and size when the fry is 15-25 mm in length. For a larger fish, demand feeders are typically more effective, while automatic feeders can also be useful. To avoid overfeeding, it is recommended to initiate hand feeding. As the fish grow, they are transferred to larger tanks to reduce density, and the level of dissolved oxygen is monitored to ensure optimal water quality.

5. Juvenile Development

When a fry reach a length of 8–10 cm (corresponding to a density of 250 fish/kg), they are transferred to outdoor grow-out areas. These areas can be constructed as concrete raceways, Danish ponds with flow-through elements, or cages. Individual raceways and ponds typically measure 2-3 m in width, 12-30 m in length, and 1-1.2 m in depth. The raceway design provides highly oxygenated water, and the water quality can be enhanced by increasing flow rates, however, the stock is vulnerable to the water quality issues stemming from external sources, and water temperatures have a significant impact on growth rates. The configuration of raceways or ponds in a sequence is determined by factors such as pH and land slope. For instance, a low pH (6.5–7.0) reduces unionized ammonia concentration; while aeration requires a 40 cm drop between each racetrack. A typical raceway or pond layout is illustrated below (Fig. 4). Notably, the parallel design is often preferred due to its advantages in disease control, water quality, and cleanliness, as a contamination is limited to a small area of the system. In both systems, fry are stocked at a density of 25–50 fry/m², with the potential to achieve up to 30 kg/m² of production, although higher yields can be attained with optimal nutrition and water supply. While some individuals may require more time to reach large sizes, fish typically attain a marketable size of 30 to 40 cm within 9 months. During the first year of production, the stock is typically graded four times: at 2.5 g, 10–20 g, 50–60 g, and >100 g. This grading process is conducted when density reduction is necessary to promote uniformity, ensure rapid growth, and improve feeding management. Bi-monthly fish number and size samples are taken to estimate growth rates, feed conversions, production costs, and proximity to carrying capacity, which are all essential elements for efficient farm management. An alternative approach to rearing trout is through the use of cage culture production systems, which measure 6 m by 6 m by 4-5 m deep. In these systems, up to 100,000 fish are maintained in floating cages in both freshwater and marine environments (beyond the fingerling stage), with adequate dissolved oxygen and clean water. Although this approach is technically simple, as it leverage pre-existing water bodies and is initially less expensive than flow-through systems, growth rates are temperature-dependent, and stocks are susceptible to external factors affecting water quality, and predation by birds and rats. Notably, high stocking densities (30–40 kg/m2) can be achieved, and fish housed in marine cages exhibit faster growth rates, thereby expanding their market size. In less than eighteen months, a fry weighing approximately 70 g can develop to 3 kg in weight.

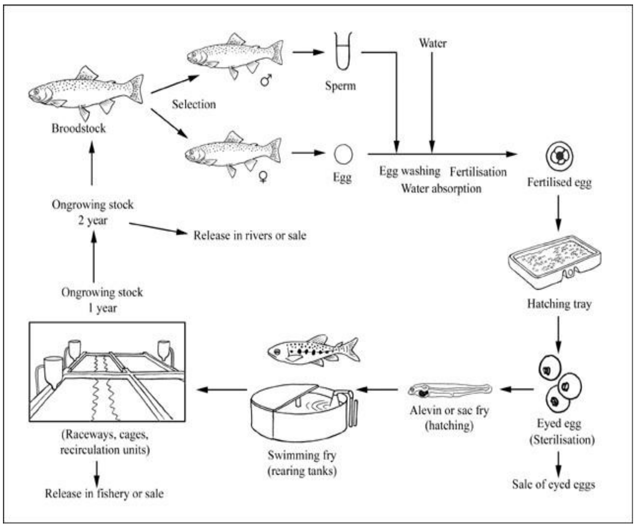

Fig.4. Breeding process of rainbow trout

Challenges in Rainbow Trout Aquaculture in Africa

1. Environmental Factors and Water Quality

The aquaculture of rainbow trout in Africa faces numerous challenges, prominently including environmental issues and water quality concerns. A primary concern is the irregularity and limited availability of suitable water sources. In many African nations, access to clean, cold water is essential for optimal rainbow trout growth, although seasonal fluctuations in water availability can compromise this access (FAO, 2018). Moreover, maintaining water quality poses a significant challenge. Untreated sewage, industrial waste, and agricultural runoff can all contribute to elevate pollution levels that degrade water quality, thereby increasing the risk of diseases and mortality in fish populations (Naylor, 2000). The maintenance of optimal water temperatures is also crucial, as rainbow trout prefer cooler water temperature. Notably, rising temperatures in certain regions of Africa may induce stress in the fish, which can be detrimental to their growth and overall health. Access to cutting-edge aquaculture equipment and technologies is limited, thereby hindering effective monitoring and regulation of water quality. The scarcity of resources constrains farmers from adopting optimal practices for maintaining ideal water conditions (FAO., 2016). Addressing these environmental and water quality challenges is a paramount to the sustained development of rainbow trout aquaculture in Africa.

2. Disease Management and Biosecurity

Disease outbreaks pose a significant threat to trout populations, resulting in substantial mortality rates and financial losses, thereby making them a critical concern. These outbreaks can be attributed to a variety of pathogen, including viruses, bacteria, or parasites. The warm temperatures prevalent in many

African regions can exacerbate health issues by stressing fish and promoting the growth of pathogens (FAO, 2020). The establishment of effective biosecurity controls is a formidable challenge. Aquaculture enterprises in Africa often lack the requisite infrastructure and resources necessary for stringent biosecurity practices, including controlled water quality management, regular health monitoring, and quarantine facilities (Ngugi CC, 2007). Furthermore, the scarcity of veterinary services and aquaculture specialists hinder prompt diagnosis and treatment of diseases (FAO, 2018). To mitigate these challenges, it is essential to develop and implement comprehensive disease control programs that incorporate the use of vaccines, improved farm management practices, and the construction of biosecurity structures. Moreover, enhancing training and capacity-building programs for local farmers and stakeholders is also crucial to preserving the sustainability and productivity of rainbow trout aquaculture in Africa.

3. Market and Economic Challenges

The absence of well-established supply chains and market infrastructures in many African countries renders it challenging for producers to effectively reach consumers (FAO., 2016). Consequently, fish producers often contend with inconsistent income and price fluctuations. Another significant financial barrier is the high costs of production. Feed, which account for a substantial portion of operating costs, is frequently imported, resulting in elevated transportation and import tax expenditures (Hecht T, 2000). The scarcity of high-quality, moderately priced local feed alternatives exacerbates this issue. Obtaining financing presents an additional challenge. Small-scale farmers may struggle to secure the capital or loans necessary to expand and enhance their operations. Financial institutions may be hesitant to engage in aquaculture due to the industry's perceived risks and lack of understanding (Kaminski, 2018). Furthermore, the absence of supportive legislation and regulation frameworks in many African countries may hinder the development of the rainbow trout aquaculture industry. In the absence of government support in the form of subsidies, training, and infrastructure development, producers may find it difficult to compete and grow (Kolding, 2019).

Future Prospects and Innovations

Genetic Improvement

The application of selective breeding methods to enhance rainbow trout growth rates, disease resistance, and feed efficiency offers a promising approach to genetic improvement, thereby promoting sustainability and productivity. The genetic gains accrued through these efforts may result in strains that are better adapted to the distinct environmental variables encountered in different African regions (Gjedrem, 2009). Furthermore, the utilization of molecular genetics and genomics techniques, such as marker-assisted selection (MAS) and genomic selection (GS), constitutes a significant advancement in the field. By leveraging these technologies, desirable genetic traits can be identified and selected with greater precision, thereby accelerating the breeding process and enhancing the overall quality of the fish population (Yáñez JM, 2015). Additionally, the incorporation of biotechnology, such as CRISPR-Cas9 gene editing techniques, may facilitate the development of strains with enhanced performance attributes. According to Hsu (2014), this could involve the improvement of feed conversion ratios, acceleration of development rates, and increased resistance to local diseases and environmental stressors. Furthermore, collaborative efforts between foreign organizations, African research institutions, and the aquaculture industry are essential for fostering innovation and facilitating the transfer of knowledge and technology. Capacity building through infrastructure development and training will be critical to supporting these advanced breeding projects and ensuring their successful implementation across the continent (FAO, 2018).

Sustainable Practices

One of the primary areas of innovation in the field of rainbow trout aquaculture is the development of advanced breeding programs that combine selective breeding and genetic improvement to enhance growth rates, disease resistance, and feed efficiency (Gjedrem, 2009). This can significantly boost output and reduce dependence on wild fish populations. A notable advancement in feed production is the development of sustainable feed alternatives. Researchers are investigating the use of insect meal and plant-based proteins as a substitute for fish meal and fish oil in trout diets (Tacon, 2008). This shift can reduce the stress on aquatic resources and encourage the adoption of more circular economy in the aquaculture sector. Another area of innovation is in water management practices, with recirculating aquaculture systems (RAS) being developed to utilize less water and produce less waste (Martin, 2010). Fish raised in these systems have access to a more controlled environment, which can promote healthier growth and reduce the risk of disease. Furthermore, initiatives focused on community-based aquaculture are gaining traction as they encourage local engagement and knowledge sharing (Beveridge, 2010). These initiatives support the development of economic opportunities and capacity building, particularly in rural areas. Finally, advancements in health management, including the use of probiotics and immunizations, are enabling improvements in disease prevention and treatment in rainbow trout aquaculture (Balcazar, 2006).

Capacity building

The advancement of rainbow trout aquaculture is contingent upon building capacity, which entails training local farmers in modern aquaculture methods and sustainable management (Munguti J and Charo-Karisa H, 2011). This involves knowledge exchange on feed production, water quality control, and region-specific disease management plans. To facilitate the sector's growth, plans are underway to establish nurseries and hatcheries equipped with cutting-edge machinery (Kamau C. N., 2018). Furthermore, collaboration between governments, educational institutions, and business leaders is essential to create a regulatory environment that supports rainbow trout aquaculture and attract capital to the continent.

Policy Support

The escalating global demand for seafood presents African countries with a prime opportunity to capitalize on their water resources and suitable climate to expand rainbow trout production (Hickling, 1962). Innovations such as recirculating aquaculture systems (RAS) and advanced breeding techniques, as noted by Kaushik G, 2017, offer viable approaches to mitigate environmental challenges and enhance output in various African locations. These developments have the potential to promote sustainable aquaculture practices by increasing feed consumption, reducing disease risk, and conserving water (WorldFish (2020) 2030, 2020). The formulation of policy frameworks that prioritize market access, research funding, and infrastructure development is essential to create an environment conductive to rainbow trout aquaculture in Africa (Beveridge, 2010). By incorporating the sector into broader agricultural plans and ensuring regulatory clarity, governments can stimulate investment and growth in aquaculture, thereby enhancing food security and economic development (FAO, 2018).

Conclusion

The introduction of rainbow trout (*O. mykiss*) aquaculture in Africa presents a significant opportunity for economic growth and food security. Advances in breeding, such as genetic improvement and selective breeding, have enhanced overall production, disease resilience, and growth rates of rainbow trout, rendering them a promising aquaculture option in numerous African locations. Technological innovations, including improved feed formulations and recirculating aquaculture systems (RAS), offer promising solutions to challenges such as water scarcity, restricted infrastructure, and disease control.

Future financing and legislative support for research and infrastructure development will be crucial for the advancement of rainbow trout aquaculture in Africa. By integrating aquaculture into their national agricultural policies and establishing a supportive regulatory framework, African countries can stimulate investment, encourage sustainable practices, and expand their aquaculture industries. Ultimately, the successful development of rainbow trout aquaculture in Africa can make a substantial contribution to food security, rural development, and economic growth.

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Competing interests

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

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Ethical Statement

All procedures were performed in accordance with the "Regulations for Review Research."

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