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RESEARCH PAPER

Identifying the Capacities, Production Figures and Marketing Patterns that Affect Cost-Effectiveness of the Aquaculture Sector in Egypt: 1- Fish Hatcheries

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Abstract

The aquaculture industry in Egypt has witnessed rapid development as a result of the Egyptian government's plans over the past years to encourage increased investment from the private sector. However, the future development of the aquaculture industry in Egypt depends to a large extent on addressing water quality issues representing, amongst other, one of the most important limitations for increasing production. In the present study, market research was conducted aiming at identifying the willingness to adopt novel technologies in addition to identifying the main constraints and problems affecting the fish seed hatcheries sector in Egypt. The results were collected via surveys and field interviews on 20 fish hatcheries in the top 12 largest fish producing governorates in Egypt. Our results indicated that water source and quality were the most prominent contributing factors on seed hatcheries production losses. Furthermore, at present, most of the tasks related to fish seed production, including monitoring water quality parameters are done manually. Overall, our results indicated that 85% of interviewed hatcheries consider that new technological media such as, e.g. automated water monitoring and control systems, could have a positive impact in productivity while 90% is aware of the potential of new technologies to decrease the environmental impact of the sector. In conclusion, the fish hatcheries sector in Egypt perceives new technologies as suitable means to face currently existing challenges and to contribute to its sustainable expansion.

Introduction

Aquaculture has become the fastest-growing food production sector globally, with finfish dominating production at 54.3 million tonnes in 2018, followed by molluscs (17.7 million tonnes) and crustaceans (9.4 million tonnes), contributing to a total of 82.1 million tonnes that year. The global fisheries and aquaculture production rose significantly to 223.2 million tonnes in 2022—a 4.4% increase from 2020—comprising 185.4 million tonnes of aquatic animals and 37.8 million tonnes of algae, reflecting the sector's expanding role in meeting global food demand (SOFIA 2024).

Outside China, several major producing countries (Bangladesh, Chile, Egypt, India, Indonesia, Norway and Viet Nam) have consolidated their shares in world aquaculture production to varying degrees over the past two decades (FAO 2020a). African coastal waters contain some of the richest fisheries in the world and have great potential for aquaculture development, as demonstrated by the spectacular aquaculture growth in Egypt.

Egypt is the largest aquaculture producer in Africa and the 6th largest globally. Egyptian fish production sector plays a central role in the country's economy, producing over 1.6 million tons of fish. In 2020 the aquaculture production was about 1 591.9 t (FAO, 2022). Despite that there is a problem with the sustainable use of water resources and eutrophication in the Middle East, including Egypt. ''The biggest reasons in the Egypt are seen as excessive-illegal fishing and eutrophication. For this reason, the government needs to reconsider issues such as supporting sustainable aquaculture, regulating net mesh sizes, fisheries of freshwater resources, use of appropriate fishing gear and equipment, and improvement of fishing laws.'' (Günay et al., 2018; Mohammed and Mehanna 2016 & Saygi et al., 2018).

The aquaculture sector is a rapidly growing sector and contributes significantly to income, job creation and food security. Fish consumption in Egypt rose from 0.008 to 0.022 t /person /year between 1996 and 2021 (LFRPDA, 2024). The value chain of fish culture in Egypt depends mainly on the production of tilapia, while mullet is the second most important species in fish farms, along with some other types of fish such as carp and catfish (Macfadyen et al., 2011).

The total Egyptian fisheries production provides about 21.27% of the total national fish production, while the aquaculture industry provides about 78.73% of the total national fish production where production reached a record of 1,576,189 t in 2021, tripling the total amount recorded in 2007 (476,000 t) i.e., total market value of $ 2.9 billion (USD 3.11 billion, LFRPDA, 2024).

This increase was attributed to the shift from extensive and semi-intensive towards intensive aquaculture systems. Nowadays, the demand for fish and aquaculture production is increasing as the per capita consumption of local fish increased by 45.48% between 2007 and 2018; from 0.013 to more than 0.019 t / year. Fish currently provides approximately 38% of the animal protein needs of the Egyptian population (FAO, 2020a), and is an affordable source of micronutrients essential for good health highlighting the growing importance of fish in local diets.

A new Egyptian strategy for Sustainable Agricultural Development (SADS) towards 2030 was developed to: achieve comprehensive economic and social development on the basis of a dynamic agricultural sector capable of sustained and rapid growth, with special attention given to assisting disadvantaged social groups and reducing rural poverty".

The mission of SADS 2030 is to modernize Egyptian agriculture on the basis of achieving food security and improving the livelihood of the rural population, through the effective use of development resources, and the utilization of geopolitical and environmental advantages, and comparative advantages of the different Agro-ecological regions (ICARDA & FAO 2013)

Increasing per capita consumption of animal protein by 4 g / day by 2030 is one of the main intentions of developing animal, poultry and fish production. To achieve these goals, the strategy was based on achieving, amongst other, the following objectives: (i) sustainable development of lake fisheries production; (ii) extending fishing in the Mediterranean Sea to the exclusive economic zone extending up to 200 nautical miles and (iii) expanding aquaculture activities to increase production to 3.0 million tonnes by 2030.

The (SADS 2030) also included complementary objectives such as (i) applying modern information and communication technologies, modern techniques and practices in monitoring, analysing and forecasting natural and marketing risks and developing risk mitigation measures and (ii) optimizing production to market chain links aim at increasing competitiveness of agricultural products in local and foreign markets.

The Egyptian fish hatchery sector began in 1980 with freshwater spawning (carp and tilapia fish) (Nasrallah, et al., 2014). The number of hatcheries (mostly private sector) increased from 7 by 1996 to more than 500 licensed hatcheries and an unknown number of unlicensed hatcheries by 2018 (GAFRD, 2018). A limited number of studies have been conducted to shed light on the technical characteristics and economic performance of the various commercial fish hatchery systems in Egypt.

The aims of the present study are to: i) understand and describe the Egyptian hatcheries sector by identifying the main constraints and problems they face; ii) define the requirements of a potential automated monitoring and control system (AMCS); iii) describe the marketing of fish seed and the factors that affect their availability; iv) suggest ways to overcome required production, quality and safety limitations. Thus, to attain such targets, a market research study was conducted on 20 fish hatcheries in the top 12 largest fish producing governorates in Egypt.

Materials and Methods

Methodology for Data Collection

A detailed questionnaire covering qualitative and quantitative issues of fish hatcheries was drafted during the first quarter of 2021. Prior to the analysis, the data were checked for quality, then slight changes in the questionnaires were made during the interviews depending on the stakeholder insight. One-on-one focus interview discussions were held with fish hatchery operators, which aimed at providing introductory comments to the aim of the study, discussing the main characteristics of the fish feed production sector including key stakeholder problems and potential solutions. Electronic versions of the questionnaires were also sent via on line forms.

Hatcheries Selection

The selection of the individual hatcheries was based on accessibility, willingness and cooperation of the hatchery operator to be interviewed and provide the information requested on the questionnaire. Twenty individual fish hatcheries were examined. The sample included one governmental hatchery, while the rest was from the private sector, which constitutes about 98% of the fish production sector hatcheries in Egypt according to LFRPDA (2024). The number of interviews for each governorate was determined on a stratified basis, according to available statistics on the number of fish hatcheries in the targeted governorates. The geographical distribution of hatcheries approached in this study (governorate location) is shown in Figure 1.

A total of 25 questionnaires were completed out which 18 were filled in via field interviews. 5 questionnaires conducted through the internet were excluded due to unreliable or incomplete data. The remaining 20 questionnaires (2 of them from on line forms) had adequate data quality and were included in the main analyses. Table 1 describes the number of individual questionnaires completed in each governorate.

Contents of the Questionnaire

The questionnaire was designed to cover a range information presented on the following topics derived from the number of individual questionnaires completed in each governorate. See the SI for the final version of the questionnaire used.

Location

General business data aspects collected: (i) location of the business; (ii) date when the business was started; (iii) land regime; (iv) total business size; (v) utilities available; (vi) type of business; (vii) type of aquaculture system; (viii) species spawned; (ix) type of spawning units; (x) source of water used and (xi) type of fish feeds.

Production Figures and Values

Information related to production figures and economic value comprised: (i) annual production in relation to the last production season (average price, annual production mass, annual sales value); (ii) estimated main causes of production losses in relation to water quality (different options were provided including: drastic changes in water parameters as temperature, poor dissolved oxygen (DO) levels…etc

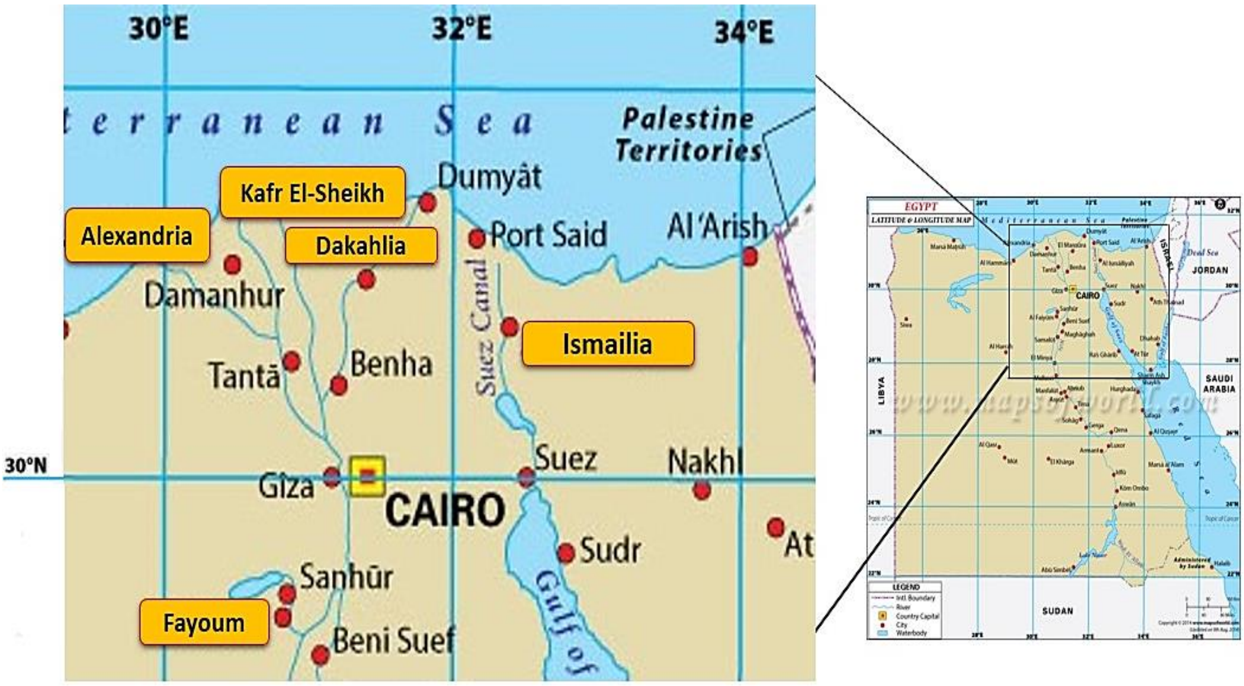


Figure 1. Geographical distribution of study areas.

Table 1. Number of hatcheries selected in the study

Governorate	Fish hatchery
Kafr El-Sheikh	12
Fayoum	5
Alexandria	1
Dakahlia	1
Ismailia	1
Total	20

and organic pollutants from agriculture origin (e.g. plant protection products, fertilizers), diseases and parasitic infections; (iii) estimated production losses associated to water quality in the last production period (both in terms of quantity and economic value).

Water Quality

Data collected in relation to: i) water quality parameters monitored in the facility; (ii) estimated costs associated to water quality monitoring actions during the last production season, number of automated sensors for water quality monitoring installed in aquaculture unit; (iii) availability of means to condition water parameters (artificial aeration in fish ponds, automated dosage of fish feed, replenishing fish pond water, heating, cooling or no technological interventions available).

AMCS Requirements

Regarding the AMCS requirements, required data collected as follows: (i) water quality parameters of interest different options were provided; (ii) number of sensors required; (iii) availability / possible access to SIM Card with 3G Network; (iv) range of EC values (µS/cm); (v) possible limitations in terms of weight and size and (vi) preferred system for sensor data collection visualization. Finally, from economic perspective, data on the willingness to pay (WTP).

Future Projections

Data were also collected from a qualitative perspective in terms of (i) forecast future production figures, annual sales value; (ii) planned investments, (iii) internal and/or external factors positively or negatively affecting hatcher's production capacities and (iv) degree of farmer's agreement on a series of statements.

Data Management and Analysis

Data collected in Arabic form were translated to English and summarised. Quantitative data were entered into a Microsoft Excel spreadsheet and used to define a number of key indicators. The indicators were calculated separately by averaging the data provided within the sample frame as a whole.

Statistical Analyses

Statistical analyses were conducted using IBM SPSS Statistics for Windows, Version 16.0. Armonk, NY: IBM Corp. The Kruskal-Wallis test was used to assess the distribution of key dependent variables, confirming that they met the assumption of homogeneity of variances across groups ($P \geq 0.05$) before proceeding with ANOVA. A univariate binary logistic regression model was used, with yes/no outcomes as responses after excluding ''don't know'' was used for comparing knowledge, attitude and practices of farmer in hatcheries.

Results

General Business Data Collection

Hatcheries Characteristics and Management Systems in Egypt

According to LFRPDA (2024) the total Egyptian fish production values (million fingerlings) reached 900.28 (million). The total seed production from carp and Nile tilapia, recorded 34.41 and 157.75 (million) respectively, while the remaining were catfish, shrimp, sea bass and seabream.

Table 2 shows the Egyptian hatchery production of fish fingerlings by fish group million unit in 2021 LFRPDA (2024). According to our results, Nile tilapia (90%) is the main fish species spawned in the hatcheries selected for the present study (Figure 2). When we mention the results of freshwater hatcheries, we specifically mean tilapia hatcheries, unless otherwise stated.

The questionnaire results show that 70% of hatcheries use outdoor (hapa- based- earthen ponds), 20% use greenhouse-concrete pond-based hatcheries and 10% of the total hatcheries use greenhouse-fibreglass tanks-based hatcheries for production tilapia fry. The type of hatchery units including the average number, average size (m^3) and total size (m^3) of concrete tanks, hapa- based- earthen ponds and concrete pond-based hatcheries either freshwater or marine hatchery used in each hatchery systems summarized in Table 3.

Table 2. Egyptian hatchery production of fish fingerlings by aquatic animal groups in 2021 (millions) LFRPDA (2024)

Fish Name	Private Hatcheries		Governmental Hatcheries		Total
	Marine water	Freshwater	Marine water	Freshwater	
Common carp (*Cyprinus carpio*)	-	-	-	5.475	5.475
Silver carp (*Hypophthalmichthys molitrix*)	-	-	-	23.060	23.06
Grass carp (*Ctenopharyngodon idella*)	-	-	-	5.872	5.872
Tilapia (*Oreochromis niloticus*)	-	74.000	-	83.748	157.748
Gilhead seabream (*Sparus aurata*)	5.000	-	1.409	-	6.409
European seabass (*Dicentrarchus labrax*)	1.000	-	3.352	-	4.352
Shrimps	35.000	-	654.039	-	689.039
Red tilapia (*Orechromis* spp.)	-	-	8.320	-	8.320
Total	41.000	74.000	667.120	118.155	272.02

The highest percentage of total hatchery size recorded for hatcheries group area >1000 m^3 (80%) compared to 20% for groups of 500-1000 m^3. The highest percentage of interviews in the hatcheries were conducted by a person acting as both the hatchery owner and manager (50%) followed by owner only (30%) and manger (20%), indicating that management by owner is common. Most of hatcheries (95%) pertain to the private sector, while the remaining (5%) are Governmental hatcheries.

Regarding the degree of education of those responsible for operating the hatchery, the results indicated that uneducated or primary, secondary school (diploma) and higher education or later represented 15%, 35% and 50%, respectively. Regarding utilities available in the hatcheries, the main source of energy in hatcheries is electricity, household water availability and internet connection representing 90%, 65%, and 25% from the selected sample, respectively.

No renewable energy system and no sharing of owner equipment with neighboring hatcheries (95%) was reported for any hatcheries. The average percentage of either fish farm or integrated fish system associated with the fish hatchery representing 30% and 5%, respectively, and the key water source used in interviewed hatcheries is freshwater (70%) followed by brackish (20%) and marine (10%) water.

The results indicated that 58% of the hatcheries use agricultural drainage water as a source of water, while the hatcheries using ground water (or well water), surface water (from rivers, lakes, springs or reservoirs) and sea water represent 11%, 23% and 8%, respectively.

For the type of feeds, the surveyed hatchery operators reported the use of floating fish feeds (70%), followed by sinking pellet (30%) relying on commercial fry feed produced by local companies. In 30% of the interviewed hatcheries, the hatchery manager formulates the high feed protein powder on-farm (average 45.4% crude protein (CP) for feeding newly hatched tilapia fry (during first 21-days).

Production Figures and Values

Most of freshwater hatcheries use outdoor hapa-based hatcheries compared to fiberglass tank or earthen pond in marine hatcheries. The average stocking rate for parents (male and female, 1:2) in freshwater hatcheries is 0.82 /m^3, which is higher than the rate of earthen pond in marine hatchery (0.44 fish /m^3). The average annual seed (fry and fingerling) production rate per freshwater hatchery (mainly Nile tilapia) is 7.28 million/ year/ hatchery compared to 6.50 million/year in marine hatchery (Table 4).

Our results showed that hatcheries with more control over water temperatures, especially at the end of winter, could have the highest number of spawning cycles per year. An average of 6.65± 1.66 spawning cycles per year is reported by freshwater hatcheries in

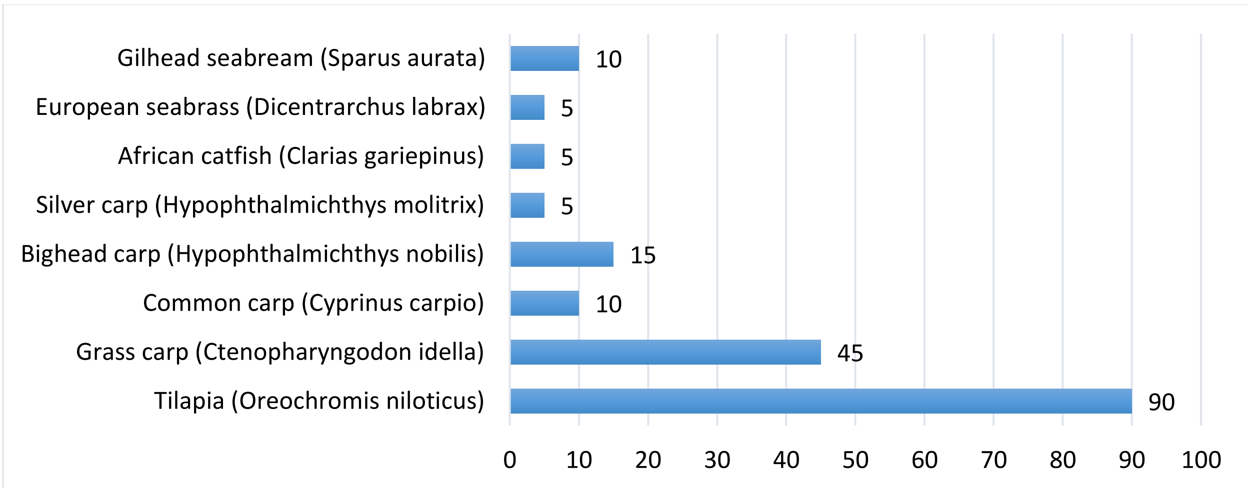


Figure 2. Percentage of major fish species that are spawned in hatcheries. Calculated as a percentage of each individual fish frequency rate in the hatcheries' sample.

Table 3. Types of hatching units and average dimensions (SD±).

	Freshwater Hatchery			Marine Hatchery		
	Number	Average size (m^3)	Total size (m^3)	Number	Average size (m^3)	Total size (m^3)
Concrete Tank (Intensive)	44.0±13.61	23.17±2.56	1019.5±24.41	27.0±4.2	40±0.0	907±41.44
Fiberglass Tanks (Intensive)	10.0±1.50	51.5±6.65	1030±15.45	25±1.8	37.5±1.77	550±1.07
Hapa	109.57±8.67	22.86±1.78	2282.86±17.92	-	-	-
Earthen pond	3±1.50	3587.5±31.40	10762.50±126.47	1±0.0	4200±0.0	4200±0.0
Greenhouse	2.25±1.5	640±21.2	1340±13.63	2±0.0	520±0.0	1040±0.0

contrast to 3.00±1.01 spawning cycles reported by marine fish hatcheries (Table 4). The average fry production in freshwater hatcheries corresponds to 2206.28±23.36 fry/female/year with reported ranges between 119 and 331.77 fry/female/cycle.

These figures suggest that fry production variation was due to differing female weights, time of hatching, hatchery management systems, and use of water aeration equipment, which allowed to safely hold higher numbers of fry and average price of 1000 fry. Regarding the key causes of production losses in hatcheries in respect to water quality, the results showed that high level of ammonia (NH_3) poor dissolved oxygen (DO) levels, temperature and pH and viral diseases are the major water quality-related factors contributing to production losses of fry in either freshwater or marine hatcheries (Figure 3).

Generally, average total capital (TC) of the hatchery were noticeably lower in freshwater hatcheries, compared to marine hatcheries, this may be due to higher and different costs of the production process. Accordingly, the results confirmed that the return on investment (RI) was higher in marine hatcheries representing 61.82% from the TC of the hatchery (Figure 4), than in freshwater hatcheries representing 21.18% from the TC.

In terms of Economic loss data showed that high associated to water-quality parameters (calculated as a ratio of the TC and RI; %) recorded 10.77% and 50.84%, respectively in freshwater hatcheries compared to 38.64% and 61.82% in marine hatcheries (Figure 4).

Regarding water quality parameters the results indicated that temperature, DO levels, NH_3 and pH are the main water quality parameters currently monitored in fish hatcheries. Water salinity level measurement is essential in marine hatcheries. Taking into account hatcheries in which the water quality parameters were monitored only, a 52% of the studied sample indicated a daily frequency for monitoring actions, followed by 23% and 19% for weekly and hourly frequency, respectively whereas, 5% perform monthly monitoring actions.

Table 4. Average annual seed production rate per freshwater hatchery compared to marine hatchery (Last production season) *

	Freshwater Hatchery	Marine Hatchery
Average hatchery area (m^3)	3968.88±29.60 ^{b}	13120±13.13^a
Average number of (Hapa) pond	98.88±6.99 ^{a}	52±2.54 ^{b}
Average number of spawning cycles	6.65± 1.66 ^{a}	3.00±1.01 ^{b}
Average number of brooders (parents)	4900±7.26 ^{a}	825±5.77 ^{b}
No. of Female / hatchery	3299.67±18.18 ^{a}	550.00±9.28 ^{b}
Average stocking rate of Female/ m^3	0.82±0.35 ^{a}	0.44±0.14 ^{b}
Average annual production mass (Million fry/ hatchery)	7.28±3.76 ^{a}	6.5±2.12 ^{b}
Average annual production mass (Million fry/ hatchery) #	0.77±0.43	2.81±0.21
Average No. of fry production / Female	2206.28±23.36 ^{a}	1136.54±20.44 ^{b}
Average fry production/ Female/ cycle	331.77±13.54^b	378.85±3.16 ^{a}
Average price of 1000 fry ($)	6.21±0.11 ^{b}	82.85±1.03 ^{a}

* 1 USD = 48.28 EGP (Egyptian pound) in 2024, # According to last official production data available (LFRPDA, 2024).

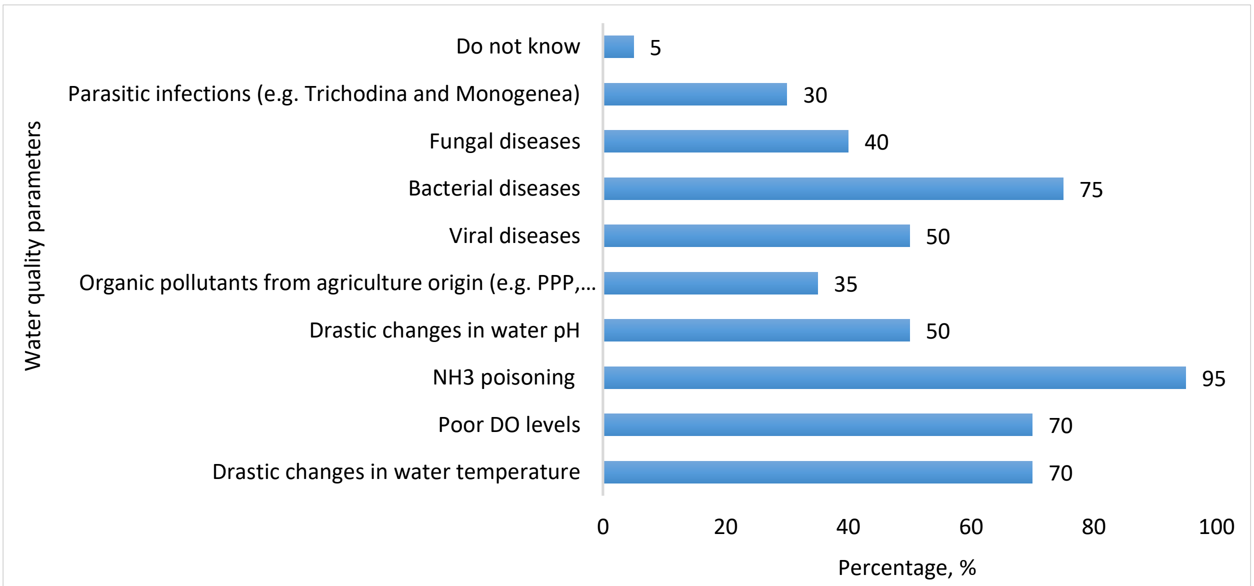


Figure 3. Main causes of production losses in both freshwater and marine water hatcheries attributed to water quality parameters in the last production period. Calculated as a frequency rate of each identified parameter.

Regarding the costs associated with water quality monitoring actions in hatcheries, most of the hatcheries (75%) did not spend any direct money for water quality monitoring actions. As for the rest of the hatcheries monitoring water quality (25%), the total annual cost recorded was 103.55 USD (1 USD = 48.28 EGP). In this context, 100% of the interviewed hatcheries confirmed their willingness to use automatic sensors to monitor water parameters. However, most of the companies providing sensors for monitoring water quality parameters and/or related products in Egypt are not well known.

The partially automatic method of industrial aeration was observed in fish ponds (75%) and replenishment of fish pond water (70%). While the non-automa tic methods heating (or cooling in marine hatchery) and filtration were used in freshwater hatcheries (95%) compared to the partially automatic methods used in marine hatcheries.

Automated Monitoring and Control System (AMCS) Requirements

In the present section the requirements of a potential newly developed AMCS are described.

Technical & Information Requirements– Hardware Components -Parameter(s) of Interest

The important water quality parameters, technical and informational requirements of the proposed hardware components in hatchery operators explained that DO levels, water temperature, NH_3 and water pH are the major water quality parameters needed to be monitored either in freshwater or marine fish hatcheries. In addition, water salinity is essential in marine hatcheries. The importance of other parameters in 55% of the studied hatcheries, confirmed that water turbidity (55%), either nitrites (NO_2^-, 40%) or nitrate (NO_3^-, 40%) and electrical conductivity (EC, 35%) are critical parameters to be monitored in their hatcheries.

The results regarding the anticipation of the tendency to use the sensor to measure relevant water quality parameters in the near future and depending on hatchery area indicated that apparently 65% of hatcheries prefer to have 5 sensors, followed by 35% preferring 5-10 sensors for the bigger hatchery area. In addition, 65% of the interviewed hatcheries required the possibility to obtain a customized frequency for sensor's readings compared to 35% who required a 60-second reading interval.

Moreover, regarding the availability and possible access to SIM Card with 2 or 3G Network, the results of the questionnaire got a 100% approval answer. According to the information provided by the hatchery operators, 95% of examined sample seems to prefer a specific mobile application system for the visualization of the data collected by the monitoring sensors compared to a web-based system (5%).

The 60% of examined sample of hatcheries seems to prefer average values of sensor's readings for different periods (e.g. every five minutes interval or hourly). No limitations or specific restrictions regarding the weight and size of the ACMS were indicated, but 40% of the interviewed sample indicated that it is preferred to get the least weight and the smallest size. Moreover, 65%, 25% and 10% of the examined sample indicated that they prefer 5, 1 and 10 years, respectively as an average life expectancy of the hardware components.

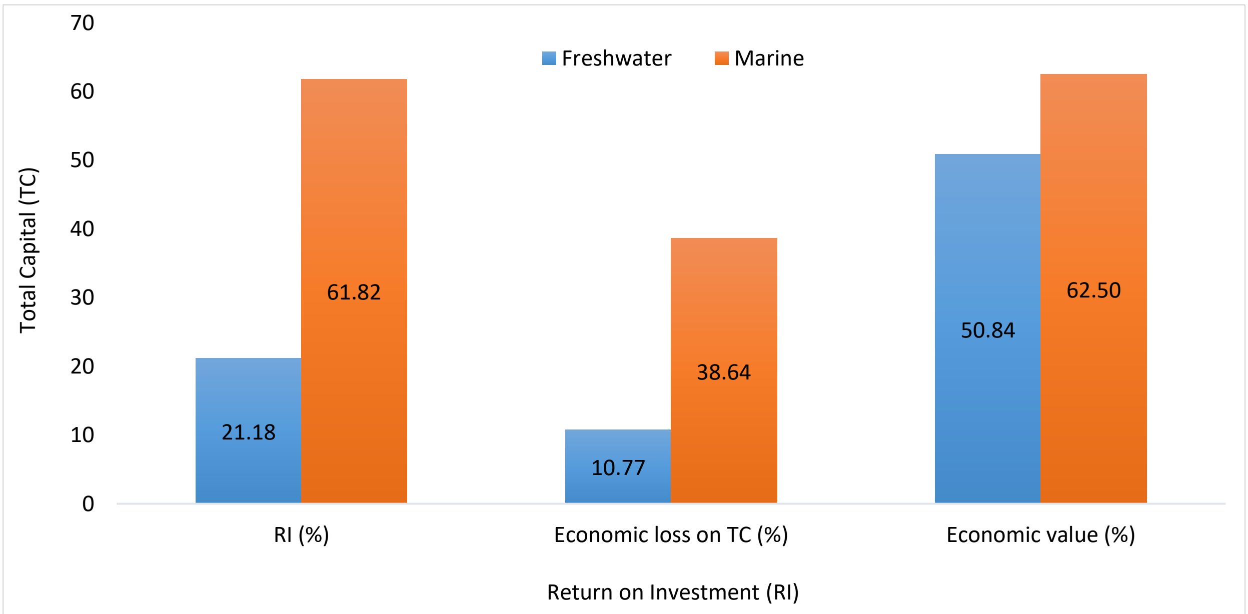


Figure 4. Estimated economic losses percentage from hatcheries, total capital (TC) and return on investment (RI) associated with water quality parameters.

The present results revealed that 60, 50, 45 and 35% of the examined sample (Table 5) indicated that they prefer floating system, prediction of abnormal situations and required actions, database describing optimal parameters for different aquaculture species and analytics of the collected data, respectively compared to 20, 35, 45 and 50%, that didn't manifest interest in complementary system services.

The results in relation to commercialization approach for the software component of a newly developed ACMS indicated that 95% of the hatcheries' sample preferred a subscription fee (software license paid with a monthly periodicity) compared to 5% only preferring one payment for 3 years use in addition to yearly updates for the software license. For indicative price our results indicated that interviewed hatchery operators and managers are willing to pay an indicative price ranging from 21-104 USD (30%) compared to 25% either 311-2050 or 311-410 USD. The lowest indicative price (20%) was recorded for 104 USD.

Future Projections and Qualitative Assessment

Projected Figures -Forecast Yearly Production Figures

Figures 5-7 summarize the forecasts of annual production figures and planned investments in freshwater and marine hatcheries during the period from 2021 to 2025. The data showed that the most common size for selling tilapia seeds was 0.2-0.5 g (21-days, after the sexual inversion). Average price 1000 fry USD, is relatively lower ranging from 6.06 to 6.50 USD (Figure 5) compared to marine hatcheries (82.85 to 151.52 USD, Figure 6).

Average total production (million fry) of the freshwater hatchery is ranged from 685.19 to 737.53 fry thousand from, 2021 to 2024 and will expect to reach to 770.72 thousand fries in 2025, compared to marine hatcheries (from 2.69 to 2.81million, Figure 6). While the expected total production of freshwater hatcheries (Million fry, considering 984 hatchery according to LFRPDA (2024) ranged from 674.22 Million fry in 2021-2022 and expected to reach to 758.39 million fry in 2024-2025 (Fig. 5) according to the current study results. In contrast, the expected total production of marine hatcheries (Million fry) ranged from 11.22 million fry in 2024-2025 from 10.75 million fry in 2021-2022 (Figure 6, The production of the National Company hatchery was not included due to the lack of data)

The estimation of the average annual sales per hatchery (2021-2024 period) ranges from 4.15 to 4.30 (thousand, USD) in freshwater hatcheries and expected to reach to 3.79 thousand, USD in 2024-2025 compared to 407.61 - 232.47 (thousand, USD) in marine hatcheries (Figure 7). Whereas the expected annual sales 984 freshwater hatcheries values ($) (2021-2024 period) ranges from 4.9 $ to 4.72 (million USD) and expected to reach to 4.71 million USD in 2024-2025 compared to 1.63 to 0.93 (million USD) in total 4 marine hatcheries.

Likewise, the investments planned during 2021 - 2025 in terms of work force and infrastructure are steady in value, either in freshwater hatcheries or marine hatcheries, due to price fluctuations as a result of the financial and economic reform program undertaken by the government since 2016 until now, a result of being affected by pandemic Covid-19 in 2022 (Table 6) and sharp fall in the currency price compared to the USD throughout the period of 2022-2024.

Currently, there are no more than 4 hatcheries producing marine fish fry in Egypt. Taking their figures together, there are about 11.17 million fry of seabass, gilthead seabream, and without including marine shrimp hatching production in the study's statistics (National Company), which has reached a production of more than 600 million larvae in 2024, in order to maintain the clarity of marine fish production.

Referring to the internal factors that negatively or positively affect the production capacities of interviewed hatcheries, our results indicated that the introduction of technology-based production techniques represent the highest expected effect (75%) compared to 55% for diversification of approaches (production methods) while no effect was shown for both factors (5% and 30%, respectively) of the interviewed sample (Table 6).

Similarly, external factors related to changes in the prices of inputs required for fish farming (75%), changes in the prices of fish farming products (75%), and the COVID-19 pandemic (70%) were observed in the highest expected incidence of external influences compared to 45% and 25% for changes in the international regulatory landscape and the Egyptian regulatory landscape, respectively. The percentages were recorded at 60%, 35%, 15%, 10% and 0%, in descending order for the expected impact associated to changes in the Egyptian regulatory landscape, the international regulatory landscape, the COVID-19, changes in the prices of fish farming products and prices of inputs required for fish farming in interviewed hatcheries (Table 6).

Table 5. Manifested interest in relation with complementary services to a potential water AMCS

	No interest (%)	Low interest (%)	Medium interest (%)	High interest (%)
Floating system	20	5	15	60
Database describing optimal parameters for different aquaculture species.	45	0	10	45
Analytics of the collected data	50	5	10	35
Prediction of abnormal situations and required actions	35	0	15	50

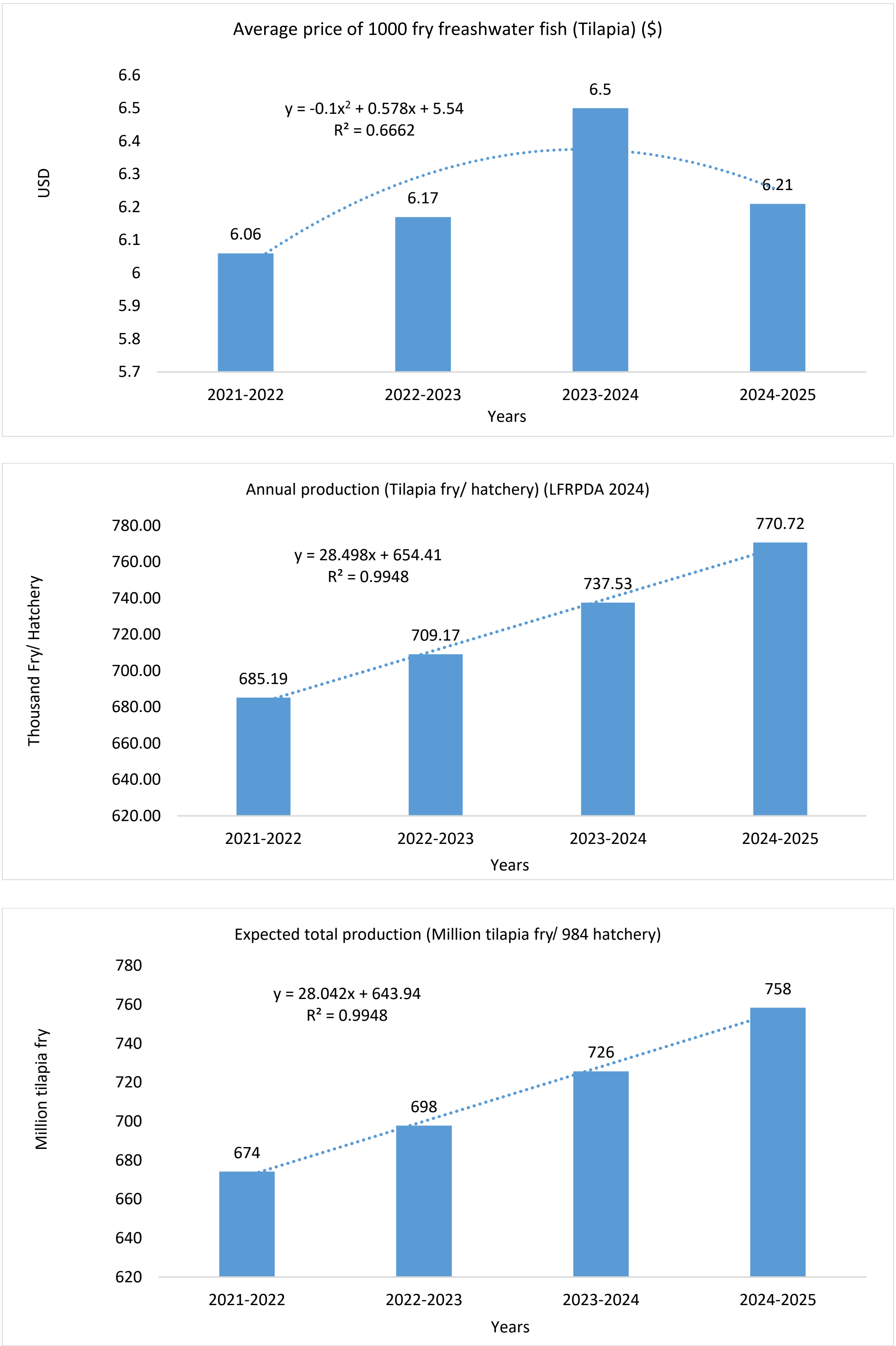
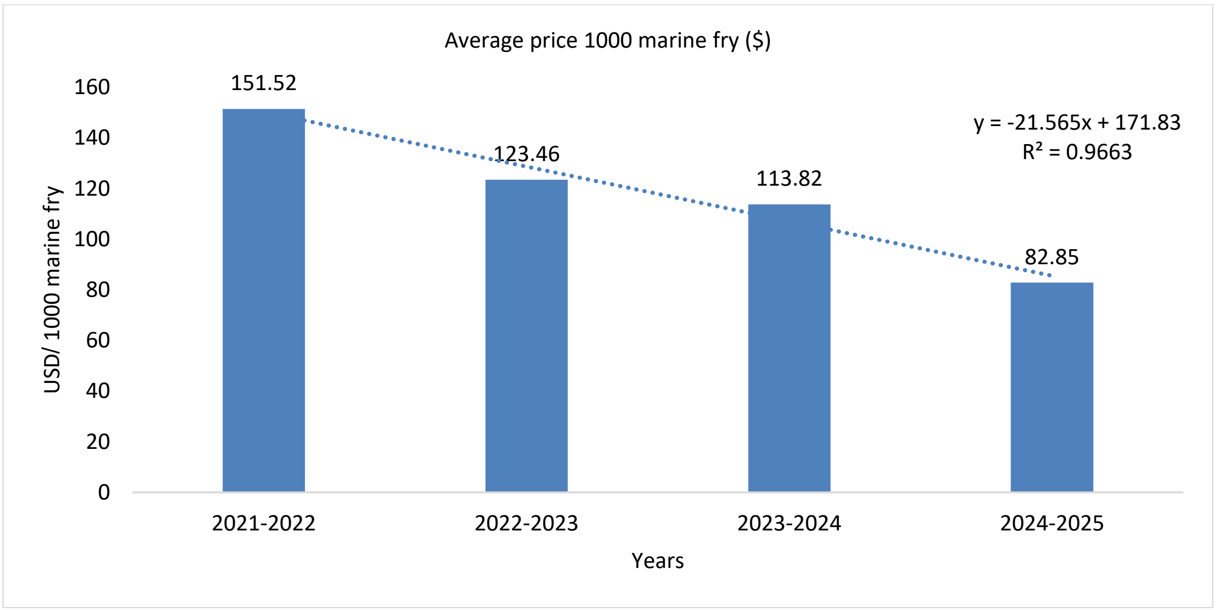
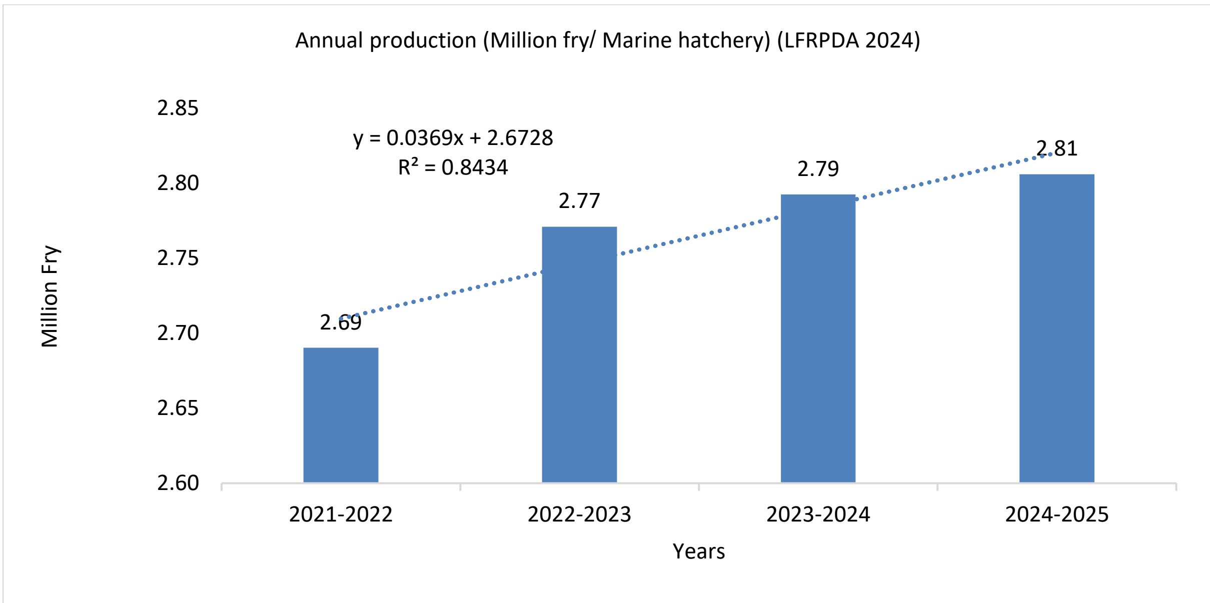


Figure 5. Forecasts of annual production figures during 2021-2025 for freshwater hatcheries (1 USD = 16.5 EGP in 2021-2022; 1 USD = 24.30 EGP in 2022-2023; 1 USD = 30.75 EGP in 2023-2024; and 1 USD = 48.28 EGP in 2024-2025.





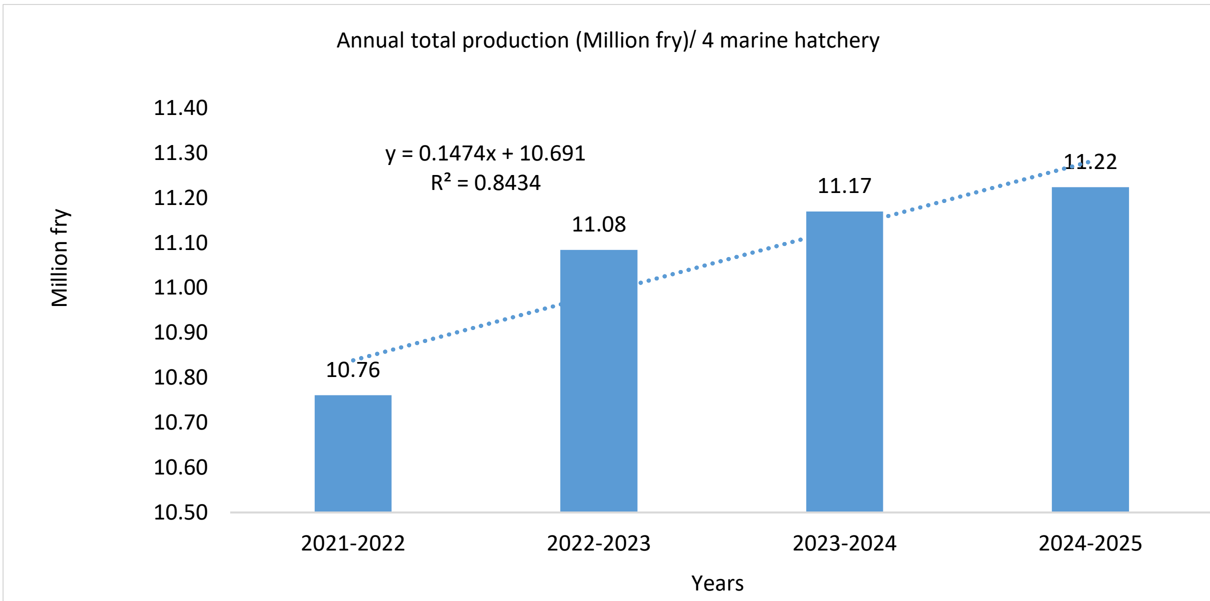


Figure 6. Forecasts of annual production figures during 2021-2025 marine hatcheries (1 USD = 16.5 EGP in 2021-2022; 1 USD =

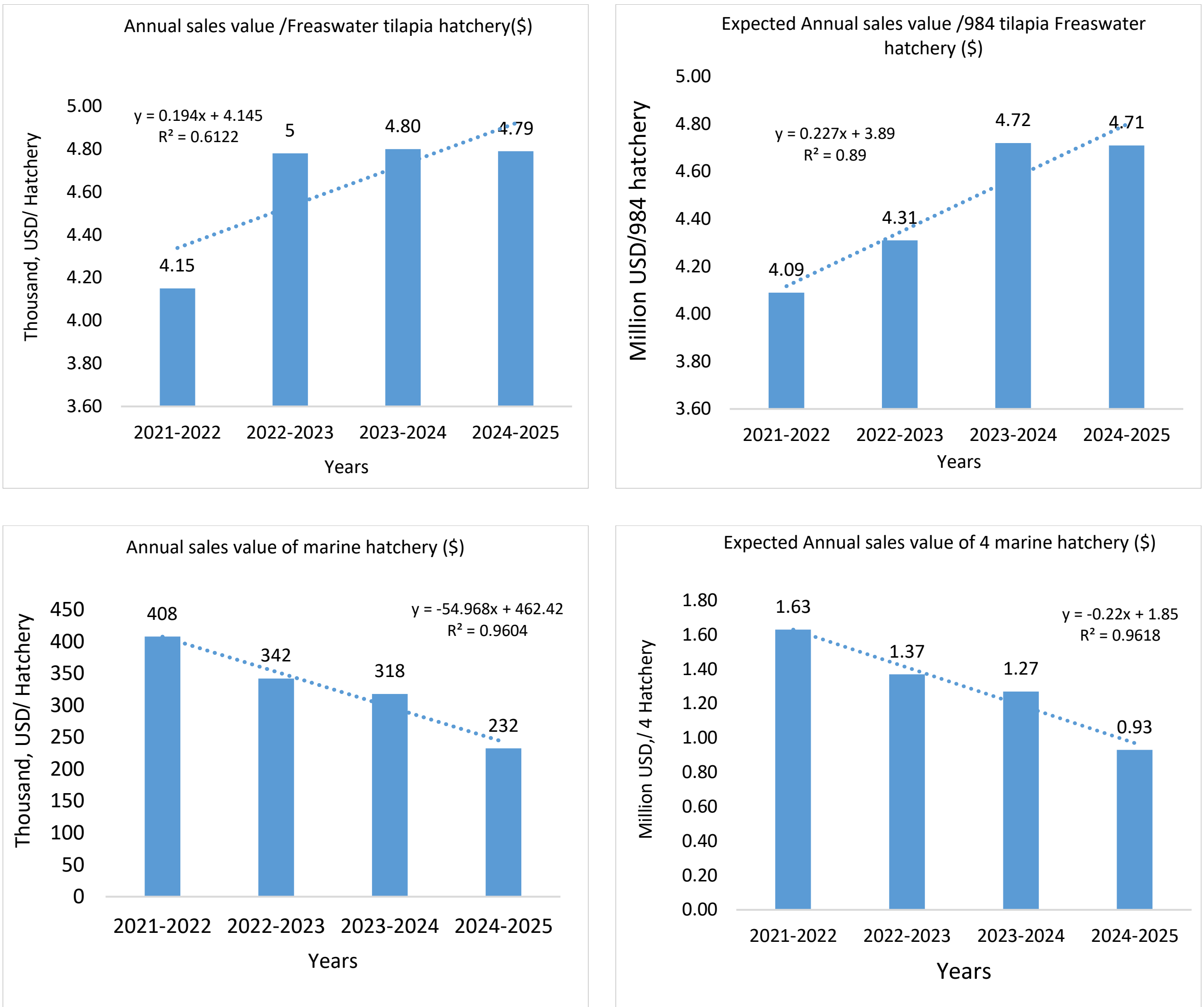


Figure 7. Average of annual sales per hatchery during 2021-2025 for freshwater and marine hatcheries (1 USD = 16.5 EGP in 2021-2022; 1 USD = 24.30 EGP in 2022-2023; 1 USD = 30.75 EGP in 2023-2024; and 1 USD = 48.28 EGP in 2024-2025.

Table 6. Manifested perceptions of the impact associated to internal and external factors positively or negatively affecting the production capacities in Egyptian freshwater and marine water hatcheries

	No impact foreseen (%)	Low impact foreseen (%)	Medium impact foreseen (%)	High impact foreseen (%)
I Internal factors				
Introduction of technology based production techniques	5	5	15	75
Diversification of production approaches (new species farming e.g. in aquaponics, complement freshwater with marine water production)	30	5	10	55
II External factors				
COVID	15	0	15	70
Changes in the Egyptian regulatory landscape	60	5	10	25
Changes in international regulatory landscape	35	10	10	45
Changes in prices of inputs required for fish farming (feeds, energy, fuel, land costs…)	0	0	25	75
Changes in prices of fish farming products	10	5	10	75

General Interest

The perception of the potential of new technologies (i) to reduce the environmental impact, (ii) to foster an improved quality of life including the development of new high added value jobs for current and future generations and (iii) to increase productivity of the fish feed production sector were in complete agreement 90%, 90% and 85%, respectively. Our results confirm that Egyptian aquaculture needs to incorporate new technological media (Table 7).

Discussion

Predicting Uptake of Aquaculture Technologies among Smallholder Fish Farmers and Hatcheries in Egypt

Aquaculture provides considerable scope for technical innovation to increase the supply of animal protein and resource efficiency (Waite et al., 2014). In the past two decades, technological developments in the global aquaculture system and management practices have helped the growth of the aquaculture sector (Kumar and Engle 2016; Joffre et al., 2017). Therefore, investments in new production systems, management practices and new products lead to significant benefits for producers and consumers (Kumar and Engle 2016; Kumar et al., 2018).

As the development of new technologies and innovations aims to ensure market supply and consistent high quality of farmed fish and therefore is an urgent need for a clear understanding of the impact of technological change on aquaculture development. Meijer et al. (2015) reported that traditionally, decision-making processes was potentially affected by external variables classified in three categories: farm's characteristics, the characteristics of the external environment, and the characteristics of the innovation.

Kumar et al. (2018), selected five broad categories of the factors driving the adoption of aquaculture technology: source of information, the characteristics of the technology, economic factors, the characteristics of the farm and social, demographic and institutional factors. Moreover, there are still relatively few attempts to make predictions about, attitudes and behaviour (Olaoye et al. 2016) analysed. Therefore, in the present study, we have applied an analytical framework, which demonstrates the linkages and interactions between internal and external variables in the decision-making process regarding the adoption of new technologies by the Egyptian hatchery sector.

Smart aquaculture is a smart production mode. It can be controlled in a distance and automation by applying of IoT, big data, artificial intelligence, 5G, cloud computing, and robotics. On the other hand, smart aquaculture can be controlled by robot which can manage facilities, equipment, machineries to operate whole systems to achieve successful production (Kassem et al., 2021). There are several aspects related to smart aquaculture including collecting information through variety of temperature, dissolved oxygen, humidity, light, pH sensors for management of the water quality parameters in aquaculture system; transmitting the collected data by communication nodes to the control center; analyzing data and decision-making stored in cloud platforms; feedback of decision to each execution equipment, and the intelligence to operate a system automatically in order to develop aquaculture in a sustainable and efficient way, friendly to the environment (Vo et al.,2021).

Socio-demographic Characteristics of Hatcheries Affecting the Uptake of Novel Technologies

Half of the interviewed hatchery operators (50%) reported a higher education or beyond compared to 35% and 15% for secondary school (diploma) and non-educated, respectively.

On the contrary, un-educated or primary, middle school and secondary school (diploma) the interviewed hatchery managers represented 62.50% (17.5%, 1.25% and 43.75%, respectively compared to 37.50% for higher education or later, indicating that management by un-educated, basic and non-advanced education is common. This could be a reason for not using new technologies of production and still using traditional methods on fish hatcheries.

Education is closely linked to the adoption of technology and positive aquaculture (Läpple et al., 2015; Ngoc et al., 2016). Well-educated gives farmers the ability to perceive, interpret and respond to new information much faster than their less educated

Table 7. Manifested perceptions in relation to the impact of new technologies on the future development of hatcheries

To what extent to you agree on the following statements	Not agree at all (%)	Low agreement (%)	Medium agreement (%)	Completely agree (%)
Egyptian aquaculture needs new technological media to increase productivity	0	5	10	85
Egyptian aquaculture needs new technological media to decrease its environmental impact	0	0	10	90
Egyptian aquaculture needs new technological media to foster an improved life quality of its citizens including the development of new high added value jobs for current and future generations	0	0	10	90

counterparts (Uaiene et al., 2009). Furthermore, the availability of a limited number of experienced hatchery technicians, lack of technological development for freshwater and marine hatcheries to produce the required seed may due to a lack of knowledge, awareness and best management practices, which is one of the most serious constraints identified in the fish feed production in Egypt.

More than half of hatchery producers (80%) reported to have a hatchery size of >1000 m^3. Hatchery size is often suggested as important in hatcher-based decisions on technology adoption and other aquaculture-related activities (Kumar et al., 2018). Often it is suggested that farmers who own larger hatcheries are more likely to innovate and adopt improved aquacultural technologies than those who have small hatcheries (Wetengere 2011; Bosma et al., 2012).

Hatchery Production and Economic Characteristics

The information on estimated production losses in freshwater and marine hatcheries associated with water quality confirmed that the return on investment was higher in marine hatcheries (61.82%) than freshwater hatchery (21.18%) as the total capital (TC) of the hatchery. Moreover, the results observed that the percent values of economic loss as a ratio of the TC and return on investment (RI) corresponded to 10.77% and 50.84%, respectively in freshwater hatcheries compared to 38.64% and 61.82% in marine hatcheries, this may be due to higher and different costs of the production process.

Several authors (Munguti et al. 2017; Obwanga and Lewo 2017; Obiero et al. 2019) have argued that the cause of production decline observed in hatcheries is mainly due to (i) the high cost of inputs, (ii) inadequate supply of quality and affordable parents fish and feed, (iii) limited financial and credit facilities, (iv) lack of skilled workforce, (v) water scarcity, and (vi) complex and expensive technologies, which are consistent with previous studies.

Water sources are inadequate especially between winter and summer are considered as one of the most important constraints. There is a problem faced by the hatcheries, which is the presence of sanitary level in drainage source which used as the water source in some hatcheries, and with the increase in the temperature in the summer, this leads to an increase in NH_3, causing a large death of the produced larvae, which reduces production and increases losses.

Source of energy lower availability and higher price for energy (fuel and electric power), especially since 2014 for tractors, water pumps and other vehicles represent another significant challenge. Alternative sources of energy such as electricity and / or solar energy need to be explored.

In addition, decrease of fish seed prices is another challenge due to an increase in oversupply of the seed demand, shortages of good quality brood fish. Nasr-Allah et al. (2014) stated that oversupply means that the hatcheries may not get paid for 8 months, with associated cash flow implications. Fry prices also fluctuate through the year peaking at the start of the year but gradually declining through the season. Therefore, producers today are interested in new methods that enable them to produce fish with high quality and safety indicators through the development and selection of simple aquaculture technologies that increase production, productivity and hatcheries' income.

Also, the present study indicated that the main technologies and innovations associated with increased incomes and profits include use of commercial pellet feeds, either sinking or floating pellet. With regard to seed production, one of the most important techniques used mainly in Egypt is hormonal sex reversal to produce mono sex male tilapia to control reproduction and improve productivity and marketing of Nile tilapia (Nasr-Allah et al., 2020; Ali et al., 2020). At this regard, a significant proportion of the feed used in hatcheries (30%) with sex reversal purposes is produced on-farm using fish meal, protein concentrate and soybean meal.

The Impacts of the Adoption of Aquaculture Techniques on Hatcheries Livelihoods

Our results have shown the perceived benefit as a key indicator in determining technology adoption among smallholder hatchery farmers. Across the technology adoption process, interviewed hatcheries are aware of the need to adopt new technological media to (i) increase productivity (85%) and (ii) decrease the environmental impact (90%) of the Egyptian fish feed production sector. Most hatchery operators have decided to try new technological innovations, but the adoption of modern culture systems, e.g., aquaponic, is still extremely low.

Limited human presence also means that decision-making processes need to be at least partially automated. Although there are no automated decision-making or decision support systems (DSS) operating in the Egyptian aquaculture industry, advances in AI and information technology have led to the development of DSS. DSS is defined as a computer tool that combines inputs (e.g. data collected by sensors or mathematical models) and historical user experiences (that is, from similar situations or previously faced problems) in a specific case or problem between inputs into composite output values (Føre, et al., 2019).

There are examples of the successful application of various electronic methods (e.g. mathematical modelling, sensor technology, automated and robotic control) to automated control of feeding, growth and spawning of aquatic animals, where the ability to control essential aspects of the environment factors (such as temperature, oxygen and flow) ponds (Føre, et al., 2019).

Additional Challenges Faced by Egyptian Fish Hatcheries

Egyptian fish hatcheries productivity is hindered by several obstacles. Many facilities rely on outdated methods, lacking advanced breeding, larval rearing, and water management technologies. Obtaining pure selected strains of broodstock and impairment of larval survival during the rearing stage is also challenging due to common fish disease problems (bacterial, fungal and parasitic infections). Inadequate filtration and aeration systems compromise water quality, increasing fry and fingerling mortality. Weak biosecurity measures also make disease outbreaks frequent, further diminishing yields.

Another challenge is the high cost of imported feed, while low-quality local alternatives stunt growth and survival rates. Genetic degradation from unimproved broodstock results in weaker fish strains, exacerbated by inbreeding. Aging infrastructure, energy-intensive operations, and financial constraints such as limited credit access hinder modernization efforts.

The price fluctuation of seed is due to the availability and accumulation of seed from natural sources especially for marine fish compared to freshwater may due weak marketing programs and channels. Furthermore, reducing the time need for sex reversal conveys poor seed quality. Market inefficiencies, including poor producer-buyer linkages, inconsistent fingerling quality, and regulatory bureaucracy, add to the difficulties. Therefore, determination of the best time for periodical harvesting to obtain fingerlings that are closely uniform in size is recommended. To overcome the challenge of high feed prices, provide high quality feed with high feed conversion efficiency and while maintaining proper water quality. Finally, due to the current challenges faced by hatcheries, there is a potential risk of leaving aquaculture activities to other businesses.

Environmental threats like water scarcity and pollution from agricultural and industrial runoff further jeopardize sustainability. Addressing these issues requires adopting advanced systems like Recirculating Aquaculture Systems (RAS), enhancing broodstock management, and developing affordable local feed. Government support, training programs, and better policies could improve productivity.

To optimize output, hatcheries should determine ideal harvesting times to ensure uniform fingerling sizes. Reducing feed costs while maintaining quality and water conditions is essential. Without these improvements, there is a growing risk of aquaculture being abandoned in favor of more profitable ventures.

Effect of Covid-19 on a Future Pandemic-like Hatcheries Situation

Recently, one of the main external factors related to changes in fish prices (lower fish selling prices) and the cost of production inputs required for fish farming (high input prices) was the COVID-19 pandemic. COVID-19 currently represents the highest expected rate of external impacts on hatchery activities (70%) and is expected to continue until 2022 (World Bank 2020).

Jamwal and Phulia (2021) reported that the negative impacts of the COVID-19 pandemic on the aquaculture sector are evident due to reduced availability of labour and raw materials, seeds, feed, chemicals, and medicines for fish production and post-harvest processing (FAO, 2020b; ILO, 2020).

Therefore, as the situation due to COVID-19 continues to evolve, the aquaculture sector needs to leverage the technology to its advantage. For example, automatic feeders or water quality sensors can help reduce reliance on manual monitoring (Zhou et al., 2018). AI can manage farm activities to reduce labour costs and improve the use of feed, water and energy to reduce stress and disease in brood fish (Lee, 2000). Technological improvements and education are also required as a goal to preserve profits and biodiversity while using multidisciplinary knowledge (UNCTAD, 2020).

At the conclusion of 2023 and beginning of 2024, the USD average cost exchange rate was 30.9 EGP, up from 15.68 pounds in 2021-2022 (Central Bank, 2022). According to Khaled (2023), the USD-EGP exchange rate increased by over 96% throughout this period. Despite the expansion of aquaculture facilities and increased production between 2016 and 2024, fish prices have doubled since pre-2020 levels. This is due to an increase in fish consumption by Egyptians looking for a low-cost source of animal protein to replace meat and poultry, both of which have been adversely affected by the Egyptian pound's appreciation and inflationary pressures. This is evidenced by a decrease in marine hatchery production (Figure 6), as well as Egyptians' reluctance to consume expensive marine fish in favor of popular tilapia. Furthermore, the current state of uncertainty has kept private sector investment in the aquaculture sector (hatcheries and fish farms) at a low level, resulting in the stabilization of infrastructure investment value from 2021 to 2024.

Conclusion

Within the present study we have analysed the factors that influence perceptions, trends and behaviours of hatcheries towards the adoption of innovative, technology-based tools for water quality monitoring supporting aquaculture production in Egypt by means of a market research study on 20 fish hatcheries.

Work practices in the Egyptian hatcheries producing freshwater and marine water fish seed including current production figures and future projections have been described. We have also identified the desired characteristics of a potential new automated water monitoring and control system (AMCS) and its perceived benefits to overcome the identified issues related to poor water-quality. Overall, the Egyptian fish seed production sector perceives that new technologies hold the potential to reduce its environmental impact, improve its quality of life and increase current production figures.

Ethical Statement

The NIOF Committee approved all the experimental protocols for Institutional Care of Aquatic Organisms and Experimental Animals.

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Author Contribution

Ashraf M.S-A. Goda : Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. . Nevine M. Aboushabana: Writing – review & editing, Writing – original draft. Ahmed M. Aboseif: Conceptualization Writing – review & editing, Writing – original draft, Methodology, Ehab El-Haroun: review & editing, Sherine R. Ahmed: review & editing, Ahmed M. Kotit: Methodology, Nora Ibañez: review & editing. María Blázquez Sánchez: review & editing.

Conflict of Interest

The author(s) declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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