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The challenges of aquaculture in protecting the aquatic ecosystems in the context of climate changes

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Abstract: The paper discusses the current prognoses of aquaculture development worldwide putting an emphasis on its effect on the environment and the issue of the protection of water reservoirs in different countries. Water consumption in diversified aquaculture systems is presented herein as well as the characteristics of the mechanical and biological water treatment methods in fish farms, with particular attention paid to the recirculating water systems. New aquaculture technologies using post-production waters are presented. The paper provides a discussion on the contribution of aquaculture to the global greenhouse gas emissions and the means of limiting this emission. The effect of climate change on aquatic ecosystems is presented in the context of the changes of the aquaculture production profile. The paper includes a brief presentation of the methods of mitigating the changes with respect to contamination of aquatic ecosystems as well as climate change. Reducing the water footprint can be achieved through selective breeding, species diversification and implementation of more technologically advanced aquaculture systems such as: integrated multi-trophic aquaculture, aquaponics and recirculation systems in aquaculture. The need for certification of fish farms with water recirculation systems is justified in the paper. The issues addressed herein are summarised and the main areas for extending the research promoting preservation of aquatic ecosystems in aquaculture are presented.

Keywords: aquaponics, freshwater and seawater ecosystems, greenhouse gases, integrated multi-trophic aquaculture, mariculture, ponds, recirculating aquaculture systems, water temperature

INTRODUCTION

Aquaculture is defined as "the cultivation of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants in natural or artificial environment" (Bouelet Ntsama *et al.*, 2018). It is one of the fastest growing branch of the food production industry worldwide. In many Asian countries, aquaculture products are the main source of animal protein in human diet (Tezzo *et al.*, 2021).

According to Food and Agriculture Organization estimates, total world fisheries and aquaculture was 214 Tg in 2020 (178 Tg of aquatic animals and 36 Tg of algae), of which aquaculture accounted for 49.2% of total production. This was due to the increase in aquaculture largely particularly in Asia (FAO, 2022). Due to the growing demand of a growing population (around 83 mln annually), fish consumption is estimated to increase to 21.4 kg per capita in 2030 (in the past background consumption was 9.0 kg per capita in 1961, 20.3 kg per capita in 2017), and global aquaculture production will reach 103 Tg, 6 Tg more than the catching sector (OECD and FAO, 2021).

PRODUCTION BY SPECIES IN WORLD AQUACULTURE

The highest increase in production is expected for tilapia (+36.9%) and shrimp (+32.0%). The increase of carp production in China is estimated to be +14% (Fig. 1).

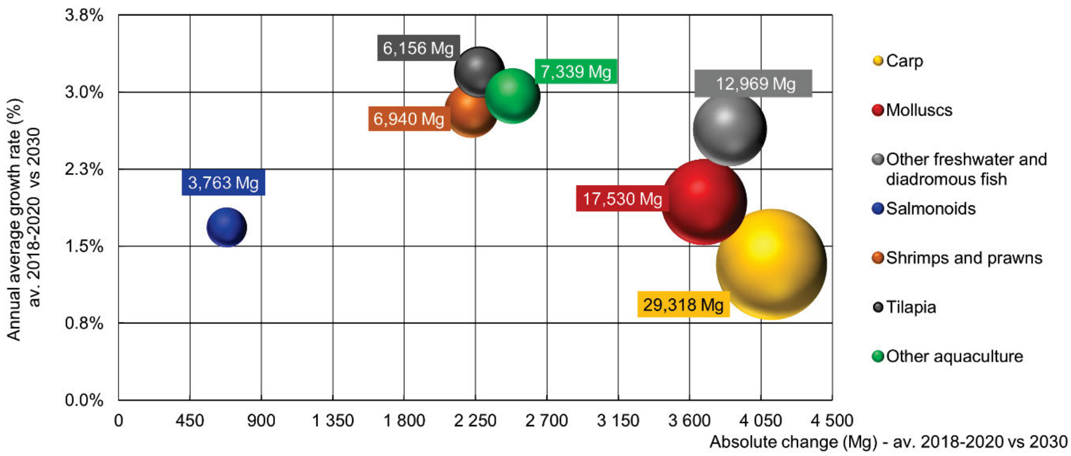

Fig. 1. Growth production by species in world aquaculture; explanations: the bubble size represents the average world total production (Mg) in 2018–2020; source: OECD and FAO (2021), modified

Crustaceans (EU: mussels, oysters and bivalves; Asia: shrimps, oysters and bivalves) and marine fish are cultivated in sea or in coastal areas. In turn, production of particular species of freshwater fish in the EU is held in systems of various intensities and water management (cultivation in fish ponds, single flow-through systems, recirculating systems with multiple water flow treated by means of mechanical, chemical and biological methods, cage farming in lakes and rivers).

Aquaculture has a strong impact on the environment, particularly on the aquatic ecosystems which undergo accelerated eutrophication (Ahmed and Turchini, 2021). Additionally, a lot of greenhouse gases are produced in the process (Cubillo *et al.*, 2021). Owing to the increased environmental control, strict regulatory provisions on wastewater disposal into water reservoirs as well as water shortages, the best practices of water management in aquaculture were developed. Reduction in the amount of wastewater and its potential effect on the environment can be achieved through intensifying and recirculating in fish farming conducted in artificial water reservoirs. Depending on the degree of aquaculture intensity (extensive and semi-intensive – e.g. ponds, intensive – e.g. cages, ponds, raceways, recirculation systems in aquaculture – RAS) the challenges of protecting the aquatic ecosystems used in aquaculture are different (Campanati *et al.*, 2021; Ahmad *et al.*, 2022).

PROTECTION OF WATER RESOURCES

Water is one of the most crucial resources on the planet as it is indispensable for all life forms. Both the number of water resources, as well as their quality, are of key importance for human health and economic sectors involved in food production. One can say with certainty that water is the factor determining the quality of life of the society. The aquatic environment is constantly at risk of being contaminated or suffering other impacts of human activities (Rana, Milke and Gałczyńska, 2021; Brysiewicz *et al.*, 2022). For the purpose of implementing the EU comprehensive water policy, the Water Framework Directive was introduced (Directive, 2000), aimed at improving surface and ground water quality observing the sustainable balance between the natural phenomena and human activities in line with the principles of sustainable development.

In the European Union, water consumption rate per capita is greatly varied. For example, in Poland in 2020 it amounted to 226 m^3 per capita (GUS, 2021), which places the country in the middle of the ratings. However, in China in 2020 water consumption rate per capita was by 80% higher (411.9 m^3 per capita) (Statista, 2022) which indicates greater access to water reservoirs and possibility of aquaculture development even using the traditional systems. The awareness of the negative environmental impact of human activities, including aquaculture, on water reservoirs is increasing worldwide. As a result of water quality deterioration, 30% of global biodiversity is lost (UN Water, 2015). The increasing global population translates into increased water consumption for food production, sanitary purposes and consumer goods production. Therefore, water contamination is estimated to increase over the next several decades and is to become a major threat to sustainable development. Till 2050, additional 80% more nitrogen and 50% more phosphorus is estimated to reach waters. Since contamination of water is correlated with population density and economic growth (Boretti and Rosa, 2019), even China, as the fastest developing country, introduces strict standards concerning water quality. The priority is assigned to monitoring the concentrations of nitrogen and phosphorus compounds as well as chemical oxygen demand (Sun *et al.*, 2021). It should be remembered that choosing the type of fish farming appropriate to the environmental conditions can help to reduce the concentration of nutrients in aquatic ecosystems (Barrett *et al.*, 2022; Jakubiak *et al.*, 2022). For example in the extensive breeding of carp, 80–95% decreases in the concentration of phosphates, nitrites and nitrates in the water flowing out of the ponds were recorded in relation to the water flowing in (Kanownik and Wiśnios, 2015). Also the experiences of bivalve and seaweed farming in Africa and Asia indicate a good impact of marine aquaculture on the environment through increase nitrogen removal from seawater mostly during harvest (Barrett *et al.*, 2022). The application of the results of scientific studies related to the presence of toxic metals in waters and their effect on aquatic organisms in trophically diverse waters will allow determination of limit values for the introduced quality standards concerning water and protective measures (Gałczyńska, 2012; Fu *et al.*, 2016).

The protection of aquatic ecosystems will become effective once the principles of circular economy are introduced to aquaculture. This means that the products, materials and resources are to remain in the economy for as long as possible, with waste production kept to a minimum (Regueiro *et al.*, 2021).

WATER CONSUMPTION IN DIVERSE AQUACULTURE SYSTEMS

Water consumption in aquaculture is connected with the production volume and worldwide structure of aquaculture. Production of each of the cultivated species of fish requires different water consumption (Fig. 2). For example, for the production of 1 Mg of carp in ponds, the water consumption is approx. 21,000 m^3, in recirculation systems the production of 1 Mg of rainbow trout requires only 10 m^3 of water, and for the production of 1 Mg of tilapia the water consumption is approx. 1000 m^3.

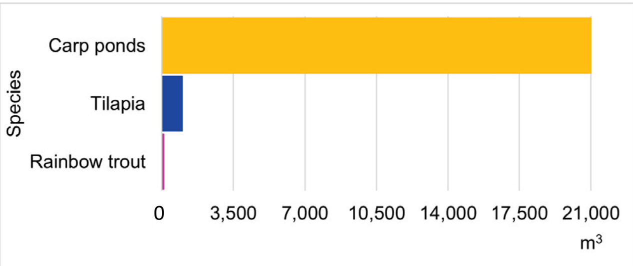

Fig. 2. Water consumption in the production 1 Mg of fish; source: own elaboration

For example, in Poland, the main aquaculture products are carp and salmonids (Fig. 3). The cultivation is held at fish farms at all intensities (carp – ponds, extensive production; salmonids – RAS, high intensity).

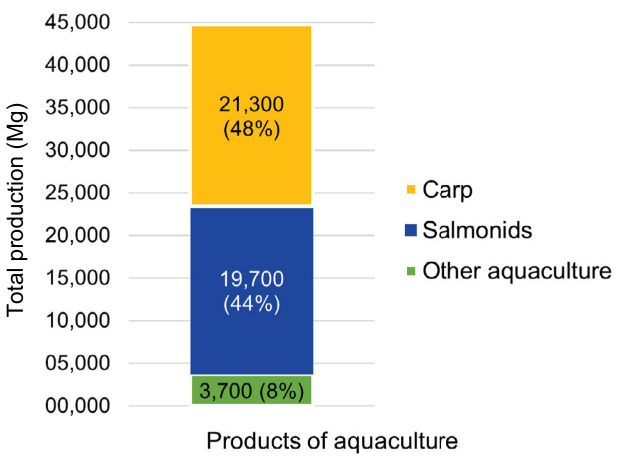

Fig. 3. Polish total production and structure of aquaculture in 2019; source: own elaboration acc. to IRŚ (2021)

Reducing the amount of water needed for production can be achieved through a change of the monoculture system to polyculture and to integrated system of fish farming (fisheries only, fisheries and poultry, fisheries and piggery, fisheries and crop farming) (Bouelet Ntsama *et al.*, 2018).

Aquaculture in Asia accounts for 91.6% of global aquaculture. The aquaculture development often took place at the expense of the environment (FAO, 2022), yet in China fish farming is conducted using the integrated systems, i.e. additionally coupled with crops and animal cultivation, particularly in the Changjiang River Basin, the Pearl River Basin and in the region of Lake Tai. This type of fish farming is considered to be a model standard as it relies on the use of local resources, waste recycling, energy conservation and maintaining ecological balance and water circulation (Mahmood *et al.*, 2016).

In the traditional flow-through systems of fish farming, water enters the farm from one side and leaves through another, thus carrying waste (fish excrement, ammonia etc.) which have a negative effect on water quality. Such systems are characterised by high water demand, preferably of consistent temperature and flow rate. Introduction of high amount of nitrogen and phosphorus compounds to the environment is an obvious disadvantage of such systems (Luo, 2022; Wang *et al.*, 2022). Additionally, there is a risk of fish escape (Bojarski *et al.*, 2022) and spreading diseases (Manoj *et al.*, 2022).

RAS with different water redistribution patterns in fish farms were developed as a response to the increasing public pressure on the classic "flow-through" fish production systems and aim to decrease water consumption as well as limit the amount of substances introduced to aquatic ecosystems. RAS make use of additional water to compensate for the water loss due to evaporation (Ahmad *et al.*, 2022).

The new importance is also assigned to systems based on aquaponics in which the recirculating aquaculture system and hydroponics are integrated for the purpose of plant production and fish farming in a closed system. The aquaponics system is a promising balanced solution which can be applied to fish farming in ponds (Diem, Konnerup and Brix, 2017). Similar solutions were suggested by Ni *et al.* (2020) in the cultivation of *Limpenaeus vanmaei* shrimp coupled with that of three vegetable species (i.e. broccoli (*Brassica oleracea*), rapeseed (*Brassica napus*), and mustard greens (*Brassica juncea*)) in ponds in Hangzhou Bay, China.

WATER TREATMENT METHODS IN FISH FARMS

The aquaculture wastewater contains solid waste and dissolved components, including biogenic compounds and residues of biocides and hormones. Depending on the water redistribution system adopted in fish farms, different methods of water treatment are used both in flow-through systems as well as in recirculation systems (Martins *et al.*, 2010; Ahmad *et al.*, 2022; Santorio *et al.*, 2022). Waste can be eliminated using integrated culture systems, aquatic wetlands, bioflok and other treatment technologies.

Given the depleting water resources and the transfer of aquaculture to land areas, recently the system with semi- or closed water circuit has been the fastest growing technology (Ahmad *et al.*, 2022).

The efficiency of RAS (Fig. 4) is to a large extent determined by the quality of the mechanical filtration (Tab. 1) of circuit water (treatment level 1).

The device which is most often used in RAS is the drum filter used for quick and effective removal of both mechanical and organic contaminants from the working fluid (biofilm particles, excrement, feed residue etc.). The water is filtered by the edges of the slowly rotating drum filter. Thanks to the special filtration

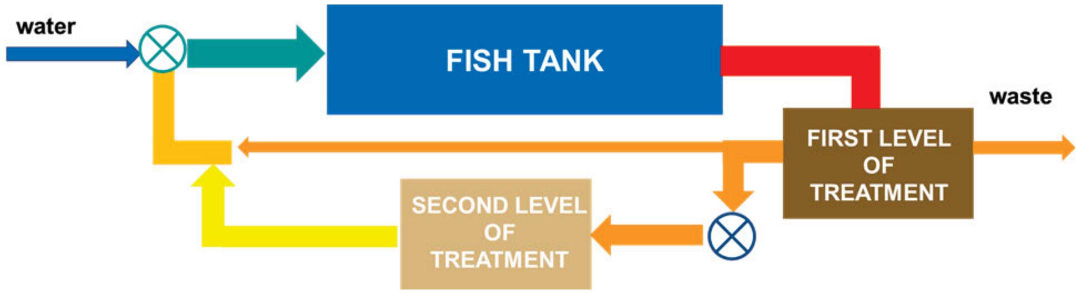

Fig. 4. A simplified diagram of a recirculation system in aquaculture; source: own elaboration

Table 1. Advantages and disadvantage of different types of mechanical filtration

Type of mechanical filtration	Advantages	Disadvantages
Equipment for the separation of solids from liquids (1–700 μm)	works better with large solids, requires little space, low cost, low water loss	not very good at removing fine particulate matter
Micro sieve drum filter (>60 μm)	widely used, requires little space, easy to maintain	pressurised water jetting requires energy and can break down particles
Parabolic screen filter (>70 μm)	simple structure, easy operation, no energy consumption and low maintenance costs	low automation, require frequent manual cleaning of the screen
Sand filter (30–75 μm)	no pollution generated during operation, low cost, simple structure, good particle removal effect	requires regular backwash under pressure, filter easy to clog
Foam fractionator (<60 μm)	used in marine aquaculture, low cost	not recommended for freshwater aquaculture, mechanical flotation devices require a lot of energy
Protein skimmer (<50 μm)	simple structure, high water treatment efficiency, better water quality control	high energy consumption causes a loss of salt and trace elements in the water

Source: own elaboration.

structure of the walls of the drum, the particles are carefully separated from the water. The solid particles are washed from the filtering material to a waste tray and then removed from the system.

Biological treatment (treatment level 2) is the core of RAS (Davidson *et al.*, 2014; Diem, Konnerup and Brix, 2017; Sikora, Nowosad and Kucharczyk, 2020; Qi *et al.*, 2022; Santorio *et al.*, 2022; Shitu *et al.*, 2022). Ammonium and nitrite nitrogen are the main metabolic wastes produced by feed residue and excrement. Biological treatment is also a process of biological removal of nitrogen that is nitrification reaction which consists in oxidation of NH_4^+-N to NO_x-N (NO_3-N or NO_2-N) under aerobic conditions by autotrophic bacteria and denitrification reaction reducing NO_x-N to N_2 under anaerobic conditions by heterotrophic bacteria. Biological aerobic or anaerobic filtration through a direct contact with microorganisms and wastewater consists in employing decomposition to absorb total ammonium nitrogen (TAN) and nitrite nitrogen for the purpose of improving water quality (Ahmad *et al.*, 2022).

The pilot studies by Nędzarek *et al.* (2022) on the possibility of employing passive activation of biological filter deposits (RK-Plast: 700 $m^2 \cdot m^{-3}$, Mutag-BioChip30: 5500 $m^2 \cdot m^{-3}$, and LevaPor: 2700 $m^2 \cdot m^{-3}$) confirmed effective nitrification for each variant of a culture medium, observing the concentrations of nitrite nitrogen and toxic forms of ammonium and nitrite nitrogen at the set level safe for fish. In the active systems, the selection of the biological culture medium and biofilm culture is important. Biological filtration is conducted in diversified technological systems individually selected to meet the requirements of a given fish culture taking into consideration their advantages as well as limitations (Tab. 2).

NEW AQUACULTURE TECHNOLOGIES MAKING USE OF POST-PRODUCTION WATERS

Maintaining good water quality is crucial for the economy of any country. Therefore, in the EU, in line with the European Parliament resolution of 12 June 2018, the Commission and the member states are called upon (P8_TA(2018)0248) to invest in research, analyses and pilot projects on innovative, future-oriented and environmentally friendly practices in the sector of aquaculture, including integrated multi-trophic aquaculture (IMTA), aquaponics and systems employing water recirculation, which reduce the effect of fish farms on habitats, wild animal populations and water quality thus contributing to the ecosystem-based approach.

The exemplary use of organic waste from commercial cage fish farming in the Mediterranean Sea is the possibility of coupling it with sea cucumber *Holothuria poli* production (Cutajar *et al.*, 2022). Khanjani, Zahedi and Mohammadi (2022) state that in IMTAs different species of finfish (e.g. *Anoplopoma fimbria*), crustaceans (e.g. *Penaeus monodon*), sea weed (e.g. *Laminaria japonica*), suspension feeder (e.g. *Scapharca brough-*

Table 2. Advantages and disadvantages of the various biological filtration devices used in aquaculture

Biological filtration devices	Advantages	Disadvantages	System of aquaculture (source)
Fluidised sand biofilters (FSBs)	they effectively reduce TAN, BOD_5, coliform bacteria; FSBs only require min. place, but provide an excellent environment for the growth of nitrifying bacteria (specific surface (SS) sand: 4,000–20,000 $m^2 \cdot m^{-3}$) at low construction costs; it can handle low or high flows up to 190 $dm^3 \cdot s^{-1}$	FSBs show hydraulic instability, do not reduce total nitrogen in used waters, remove PO_4^{3-} to a small extent	RAS (Davidson *et al.*, 2008)
Moving-bed biofilm reactors (MBBRs)	good ratio of volume to effective active surface (SS area 500–800 $m^2 \cdot m^{-3}$) and reactor volume, stable and maintenance-free operation, no need for periodic backwashing and no clogging; flexible system that can be adapted to different loads; short cleaning time with high efficiency of total COD, filtered COD, BOD_5, acetate, PO_4-P, NO_3-N	qualified service in the monitoring of water treatment	RAS (Shitu *et al.*, 2022)
Fixed-bed biofilm reactors (FBBRs)	high efficiency in total COD removal, filtered COD, BOD_5, acetate, PO_4-P, NO_3-N, higher than MBBR removal; the SS area of the medium is 200–500 $m^2 \cdot m^{-3}$	the possibility of clogging the gaps between media by bacterial membranes; the adsorbents can cause targeted water flow, lead to a lack of O_2 in some parts of the filter. FBBRs should be rinsed at least once a week to remove particles	RAS (Qi *et al.*, 2022)
Sprinkler filters	low cost, high durability, high enough porosity to avoid clogging and provide ventilation; the SS of the medium of 100–1000 $m^2 \cdot m^{-3}$ ensures high efficiency in removing impurities	it requires a large area, easy to connect, and the price of filter media is more expensive	aquaponic systems, RAS (Diem *et al.*, 2017; Sikora *et al.*, 2020)
Rotating biological contactors (RBCs)	microorganisms with high concentration, SS of the medium 400–1200 $m^2 \cdot m^{-3}$, combined nitrification and denitrification function, stable operation, full contact, wide range of applications, less sludge and easy precipitation	difficult to operate, water treatment effect is not stable	RAS (Santorio *et al.*, 2022)
Floating biofilters with beads	high SS area of the medium 1500–4000 $m^2 \cdot m^{-3}$; high processing efficiency, not easy to block	high energy consumption and high costs	RAS (Fredricks *et al.*, 2022)

Source: own elaboration.

tonii), deposit feeder (e.g. *Parastichopus californicus*) and others (e.g. *Paracentrotus lividus*) are used. The unquestionable advantage of such an activity for aquatic ecosystems resides in effective management of water resources and feed, the use of wastewater from one trophic level for the cultivation of plants, molluscs or echinoderms further in the production cycle by limiting the dependence on fish meal. The disadvantage is the risk of possible errors resulting from poorly designed biofiltration systems, as the success of the whole culture depends on the input data from several trophic levels. Moreover, extensive knowledge is necessary concerning the choice of the location of the IMTA system owing to the lack of possibility of controlling the environmental conditions. Such systems consume comparable amounts of water as the regular RAS, yet they are more environmentally friendly owing to reduced production of waste. In turn, in multitrophic recirculating aquaculture systems (MRAS), the filtration/biofiltration units are substituted with units employing extraction organisms. The systems eliminate the need for constructing ponds for waste collection (Correia *et al.*, 2020). Diem, Konnerup and Brix (2017) proved that instead of replenishing water in pond farming of tilapia, it is possible to use water from multiple recirculation of wastewater in aquaponics cultivation of *Ipomoea aquatica*, *Lactuca sativa* and *Canna glauca*. The aquaponics system is a promising balanced approach to the use of resources and protection of waters against excessive pollution.

CONTRIBUTION OF AQUACULTURE TO GLOBAL GREENHOUSE GASES EMISSION AND MEANS OF REDUCING IT

Approximately 1/4 (26%) of the global greenhouse gas emissions originates in the food industry, 30% of which stems from fishery and farming. The growth and intensification of the aquaculture sector creates climate problems (Zhang *et al.*, 2022). Based on the meta-analysis of data, it was estimated that GHG emission from fish and crustacean farms totalled, on average, to 24 kg CO_2eq per

100 g of protein (Poore and Nemecek, 2019). In aquaculture, the predominant sources of greenhouse gases are: production of feed raw materials, processing and transport of feed materials, production of compound feed in feed mills and transport to fish farms, production of cleaning agents, antibiotics and pharmaceuticals, as well as fish and crustacean farming in water.

In fish farms, GHGs are mostly generated as a result of energy consumption in production buildings and devices, such as during pond construction and maintenance works (CO_2), anaerobic decomposition of organic matter (CH_4), as a result of N_2O emission resulting from transformation of nitrogen compounds in water, animal faeces and from invertebrates or owing to refrigeration equipment failure that is the release of F-gases. For example, according to data on cultivating organisms in freshwater and saltwater in China (Xu *et al.*, 2022), GHG emissions were arranged in the following order: production of feed (52% of the total GHG emissions), N_2O (29%), energy-use (17.9%), fertiliser production within the ponds (1.1%). There is a big difference between value of aquaculture production and GHG emissions. In this country 47% of GHG emissions is connected with the highest production of cyprinids (48%). On the other hand, marine bivalves production (30%) was relatively higher than their GHG emissions (13%) because there are no emissions from feed or fertiliser. The development of non-fed aquaculture is also a good solution in reducing greenhouse gas emissions. This is confirmed by research by Roy *et al.* (2020) and Barbacariu *et al.* (2022) on fish ponds in Czech Republic and Romania. It should be noted that CO_2 emission originating from fish farms can be reduced by sequestration of the gas in pond sediments or sequestration as carbonate through invertebrates farming. But the share of non-fed aquaculture in total farmed aquatic animal production decreased from 40% to 27.8% in last twenty years. In 2020, the production of non-fed animal species was 24.3 Tg in 2020, of which 8.2 Tg were filter fish grown in inland aquaculture (mainly silver and large carp) and 16.2 Tg were aquatic invertebrates, mainly mussels (FAO, 2022).

In comparison with other branches of the meat production sector, this type of farming is characterised by low GHG emission (263 Tg CO_2eq – the level comparable to that of sheep farming). The differences stem from different physiology of the farmed animals, higher fish fertility as compared with that of land animals and lower feed conversion ratio (FCR). The latter factor is of particular importance, as in aquaculture the main GHG emissions are connected with feed (MacLeod *et al.*, 2020). Lower FCR contributes to higher productivity capacity. For example, FCR for beef ranges from 6.0 to 10.00, for pigs from 2.7 to 5.0, chickens from 1.7 to 2.0, and for farmed fish and shrimp from 1.0 to 2.4 (Fry *et al.*, 2018).

In 2017, the largest production of fish and crustaceans is held in Asia. Given the structure of the production (cyprinids 31%, bivalves 21% and shrimp 10%), cyprinids are responsible for 31% of the emission GHG, shrimps 21% and bivalves 7%. Zhang *et al.* (2022) pointed that the emissions from China's aquaculture systems were 181.66 Tg CO_2-eq·y^{-1}, offsetting approximately 7% of the country's terrestrial carbon sinks. In turn, Xu *et al.* (2022) highlights that the emission intensity parameter (2.7 Tg CO_2eq·(Tg production)$^{-1}$) in China was 1.22 times lower than the world average emission intensity (3.3). With the continued expansion and intensification of aquaculture industry in this country, the research shows its potential climate impacts and the need for monitoring and mitigation strategy.

Reduction of GHG emission from aquaculture can be achieved in the world by the use of fewer resources. The favourable changes are conditioned by technological innovations in farming and genetic selection of species, disease prevention and ongoing veterinary care, the quality of feed and nutrition as well as production systems of low environmental impact (MacLeod *et al.*, 2020). A key element in production costs and environmental impact is energy consumption in fish farms (pumping of water, illumination and vehicle power supply). The highest energy consumption, per Mg of fresh fish and crustaceans, is recorded for shrimps and prawns: 18,581 MJ·tLW^{-1}; the lowest for catfish production: 801 MJ·tLW^{-1} (Fig. 5). Optimisation of fish and crustacean nutrition seems to be crucial for resource management. Additionally, the use of renewable energy sources for technical devices power supply could decrease GHG emissions. There are studies combining knowledge on offshore wind and wave farms with aquaculture. Interesting examples of this would be multifunction offshore platforms. They allow optimisation of the use of space and limiting marine environmental impact (Abhinav *et al.*, 2020; Weiss *et al.*, 2020).

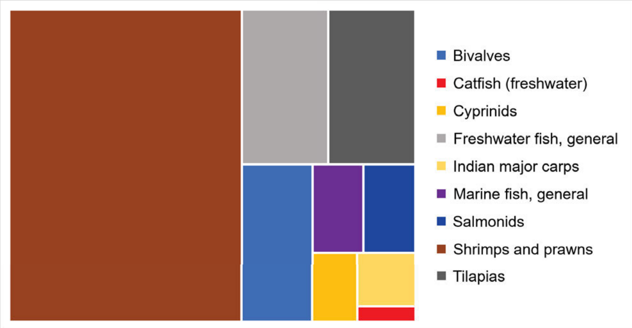

Fig. 5. Percentage share of average amount of energy (MJ·tLW^{-1}) used in fish farms by farmed species; source: own elaboration based on MacLeod *et al.* (2020), supplementary information

THE EFFECT OF CLIMATE CHANGE ON AQUATIC ECOSYSTEMS AND AQUACULTURE PRODUCTION PROFILE

The relatively small GHG emission from aquaculture does not have a significant effect on climate change. However, given that global emission of GHG in 2016, on an annual basis, amounted to around 50 billion tonnes CO_2eq (Richtie, 2020), climate change is expected not only to change marine and freshwaters ecosystems, but also to result in the need for adapting the production to new climate conditions and increased protection of the environment. The changes are of complex nature and predominantly affect the coastal and marine environment. Froehlich *et al.* (2022) point to several stressors directly as well as indirectly related to the risk of climate change and their resulting effect on the aquaculture worldwide. The most significant of them being temperature, sea level and floods. Due to regional differentiation, less important are the parameters of: ocean acidification (mainly in Asia), storms and extreme phenomena, altered precipitation patterns, droughts, changes in the occurrence of diseases (Europe), harmful algae blooms (Europe) in marine waters (Scandinavia) and freshwaters (Poland), hypoxia (North and Central America/Caribbean) and invasive species.

Water temperature is the most significant factor affecting both the physiology of fish as well as the habitat of fish and crustaceans (Teal *et al.*, 2018; Castro-Olivares *et al.*, 2022). On the one hand, depending on the geographical region, the type of farming and species, higher temperatures may result in: the lengthening of the growing season, acceleration of the growth rate and the reduction of natural winter mortality. However, on the other hand, it may cause: changes in the farming coverage due to different temperature thresholds, a decrease in the concentration of dissolved oxygen, increased biomass and species composition of algae blooms, changes in the intensity and/or frequency of storms causing damage to infrastructure, greater number of fish escapes, intensity of introgression and changes in the character and frequency of disease occurrence due to overlapping life cycles of a host and that of a pathogen (Froehlich *et al.*, 2022). Therefore, an increase in water temperature can result in changes in fishery production capacity in a given geographical region or the need to change the species of the farmed fish and crustaceans. It is difficult to assess at this time whether the farmed species show some degree of flexibility in adapting to new environmental conditions and, consequently, the effect of such changes on various aquaculture areas in Europe (Cubillo *et al.*, 2021), as well as worldwide (Froehlich *et al.*, 2022). For example, Klinger, Levin and Watson (2017) estimate that, unless there are feed shortages, the increase in temperature will translate into greater production of e.g. Atlantic salmon (*Salmo salar*) or cobia (*Rachycentron canadum*). However, given the extreme temperature, the effects could also be negative (Reid *et al.*, 2019). On the basis of modelling, in the medium (20–30 years) and long term (50–100 years), the potential effect of climate change is estimated to affect the farming of the most economically vital fish and crustacean species (80% of European production): Atlantic salmon (*Salmo salar*), bream (*Sparus aurata*), sea brass (*Dicentrarchus labrax*), Pacific oyster (*Crassostrea gigas*), mussels (*Mytilus edulis*) and Mediterranean mussels (*Mytilus galloprovincialis*) (Cubillo *et al.*, 2021). It has been found that bream farmed in marine cages in the western part of the Mediterranean Sea was exposed to the greatest risk, and the mussels suspended in sea in the south-west of Portugal showed highest resistance. In turn, the model studies by Castro-Olivares *et al.* (2022) show that future harvest of the following shellfisheries: *Ruditapes decussatus*, *Venerupis corrugate*, *Cerastoderma edule* (2025–2049) and *Ruditapes philippinarum* (2075–2099) may be lower. Additionally, the methods of crustacean harvest may need to be changed. The forecasted increase in water temperature can affect the shoals of crustaceans found in the more shallow areas of the interior part of Rías Baixas, thus reducing the production area by the end of the century.

In Africa, the effect of temperature increase and thermal shock was analysed with respect to the developmental stages of tilapia (spawn, fry, fingerling, juveniles and adults) in the ranges from 28 to 40°C (Panda *et al.*, 2022). Species acclimatisation has been achieved with a gradual increase in temperature to 34°C. Further increase in temperature accompanied by low feed intake may affect the farming of tilapia.

A significant and negative effect of changes in water temperature is recorded with respect to shrimp and fish farming in Bangladesh. The location of most hatcheries is determined by temperature variability within the range of 22.8–23.1°C and precipitation variability from 1750 to 2000 mm. Consequently, the smallest changes in the said parameters have an effect on seed production. Additionally, in natural and captive farming, the breeding stock is at risk of floods resulting in silting of rivers and deterioration of water quality. The increase in water temperature disturbs embryonic development and results in the inhibition of larval and juvenile development. In turn, in shrimp hatcheries, fluctuations in temperature, pH and salinity are responsible for the occurrence of post-larval diseases (Siddique *et al.*, 2020). In the case of Asian shrimp farming industry, the results of the studies suggest that implementing improved management strategies together with improving water quality, monitoring water exchange and/or maintaining salinity at a fixed level could reduce, for example, the incidence of the white spot disease (Hasan *et al.*, 2020). In turn, owing to the inflow of salt water to freshwater Czasopstreams, a marked decrease in the production of *Hilsa ilisha* was recorded, which brought about significant losses for the fishing industry in India and Bangladesh. Similar threat is found for the Maldives and Tuvalu (Dutta *et al.*, 2020). The farming of shrimp in the coastal area of Vietnam is determined by tropical storms accompanied by, among others, a rise in sea level and coastal erosion (Nguyen *et al.*, 2017). Similar problems are recorded in fish farms in the prawn-fish-rice ecosystems in the south-west of Bangladesh (Ahmed *et al.*, 2014).

With respect to the challenges faced by China in connection with water shortages and climate change, it has been shown that the farming of grass carp, silver carp, and silver Prussian carp would be more favourable than that of black carp, tilapia, crucian carp, sea bass or Wuchang bream. Adopting this scenario will allow decreasing the water footprint in aquaculture by as much as 22% (Song *et al.*, 2022).

METHODS OF MITIGATING CHANGES IN AQUATIC ECOSYSTEM CONTAMINATION IN THE CONTEXT OF CLIMATE CHANGE

The methods of mitigation of the aquatic ecosystems contamination by aquaculture mostly consist in limiting water consumption (Song *et al.*, 2022) and reducing the inflow of contaminants to waters (Fedorova *et al.*, 2022). With increasing production, this can be achieved first of all through the use of the most recent wastewater treatment technologies. Of particular importance is the use of well-balanced and adequately-selected feed. The introduction of the systems with semi- and complete water recirculation limits water consumption, however only efficient systems provide protection to the aquatic ecosystems (Shitu *et al.*, 2022).

Mitigating the effects of climate change in aquaculture depends on the geographical region, the type and extent of actions undertaken. Controlling climate change also concerns small-scale retention connected with ponds. Carp ponds located in the European climate zone influence the microclimate of the surrounding area by reducing summer temperatures (Jakubiak *et al.*, 2022).

An increase in water temperature which accompanies the climate change contributes to the increased solubility of numerous chemical compounds. Therefore, their concentration in waters is found to increase as well. With an increase in temperature, there is a decrease in the solubility of dissolved oxygen in water used not only for biological processes but also in decomposition of organic matter. Chemical determinants of the compounds and elements most vital to life are not easy to be met when using obsolete management technologies. Cubillo *et al.* (2021) indicate the possibility of introducing technological improvements with respect to fish cages, improved balancing of feed composition and the use of land facilities allowing more efficient monitoring of the temperature and other physico-chemical parameters of waters. In the case of crustaceans, the change of intertidal farming or farming in floating cages to that in the form of suspended lines would result in an increased resistance to changes in temperature as compared with tidal environments.

Increased frequency of floods and droughts has already resulted in developing some strategies of mitigating their effects. In Asian countries (China, Indonesia, India, Vietnam and Bangladesh) in the case of floods, the flood embankments are routinely being raised and reinforced, thus protecting the fish ponds. Changes in the dates of stocking also assist the crisis management of fish farms. In drought conditions, ground waters are used, fish cultivation is adjusted to the conditions and the rainwater is being collected (Galappaththi *et al.*, 2020).

FISH FARM CERTIFICATION IN THE RAS

The level of water reuse in fish farms shows great variability. Generally, the factor provides the basis for determining different types of recirculation systems, though it is of an arbitrary nature. Fish production in such systems still represents the smallest part of the aquaculture industry, however the application of the said system has increased in recent years (Martins *et al.*, 2010; Gyalog, Cubillos Tovar and Békef, 2022). In response to increasing consumer and social environmental awareness, Aquaculture Stewardship Council Company developed a certification programme for the production facilities of this type. A problem common for all aquaculture facilities is the effect they have on the quality of surface waters. The farms using the RAS show different energy and water consumption as well as wastewater discharge, therefore determining the necessary requirements is crucial. According to the company's guidelines, the requirements are subject to two key provisions reflecting the primary areas of the effect of RAS, i.e. minimising the negative effect on water resources, and effective and environmentally responsible use of resources (ASC, 2022). The former provision is connected with water consumption, water quality and removal of water and waste. The requirement is considered to be met when at least half of the natural flow in water reservoir is kept. Such an action is to provide adequate amount of water and allows preservation of the natural flora and fauna. Additionally, further requirements are to be observed with respect to wastewater treatment and sludge management taking into consideration the most effective technologies applicable. The latter provision relates to energy consumption, GHG emission and application of best practices for the production of a given fish species taking into consideration, for example, stocking density. Fish farms shall undertake to record energy consumption and to develop the strategies for reducing greenhouse gas emissions (ASC, 2022).

CONCLUSIONS

Rational management of depleting water resources and the application of the most effective methods of wastewater treatment are the core of reducing the negative effect of aquaculture on aquatic ecosystems. It is important to remember that feed production alone requires water consumption, therefore paying greater attention to optimisation of feed composition and its formula used for fish and crustacean farming would translate to an increased efficiency of nutrition, at the same time reducing the contamination of post-culture waters. Reduction in the water consumption for production purposes and its multiple use in recirculating system of fish farming is yet another step in the task of protection of inland and marine waters. Improved practices of recycling the nutrients as well as the application of technological solutions with respect to wastewater and by-products collection would support the task. Moreover, implementing the already developed tools for the purpose of performance assessment of the biofilters used in different operating conditions in RAS systems, would assist wastewater processing and preservation of the optimum conditions for fish farming. In terms of protection of inland waters, the increasingly more common aquaponics systems prove to be favourable since they are characterised by very low wastewater discharge, as compared with the traditional aquaculture technologies, and allow nutrient recycling for the purpose of plant growth. In order to increase the productivity of aquaculture, and at the same time to reduce the water footprint, the already developed scenarios for mitigation of climate change must be implemented in fish farming facilities. Such actions include selective breeding, species diversity and implementing the more technologically advance aquaculture systems such as IMTA, aquaponics or RAS.

The identified research needs concern such areas as food safety control in recirculation aquaculture systems and winning public acceptance for the integrated aquaculture systems, as well as gaining consumers' interest in the primary and secondary products of such aquaculture systems.

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