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The impact of water quality on health and performance of farmed fish and shrimp, Part 1: dissolved oxygen and carbon dioxide

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Despite a general consensus on the importance of water quality, many farmers still underestimate the negative impacts of marginal water conditions on aquaculture outcomes

Dissolved oxygen (DO) and carbon dioxide (CO2) are key parameters for water quality in aquaculture production systems and can significantly affect the health and performance of farmed fish and shrimp. Although there is a general consensus on the importance of water quality, many farmers still underestimate the negative impacts of marginal water conditions aquaculture outcomes. Adequate water DO and CO2 levels in fish and shrimp farming are essential, including for controlling feeding rates, phytoplankton density and several other key parameters. Photo by Fernando Kubitza.

Although there is a general consensus on the importance of water quality, many farmers still underestimate the negative impacts of marginal water conditions aquaculture outcomes. In this series of articles, we will discuss key water quality parameters and how they impact the health, performance and economics of fish and shrimp production.

Dissolved oxygen (DO) is essential for the survival of fish and shrimp and for various biological processes in aquatic environments. Invariably, DO is the first limiting factor of production in intensive aquaculture systems. Hence the importance of aeration to prevent DO deficits. Daily DO monitoring allows farmers to forecast DO declines in ponds and adjust pond management before performance and health of the fish and shrimp are impaired. Control of phytoplankton, reduction of feeding rates, partial harvest of ponds, partial water exchange, use of aerators, and others are major strategies to prevent DO from reaching uncomfortable or lethal concentrations.

Through their gills, fish and shrimp perform respiration (Fig. 1). The higher the oxygen (O_2) and the lower the carbon dioxide (CO_2) concentrations in the water, the easier the respiration. Carbon dioxide has an antagonistic effect on oxygen, and its excess in water can cause asphyxiation of fish and shrimp. High CO_2 in water elevates blood CO_2, a condition called hypercapnia, which interferes with oxygen binding capacity of hemoglobin (fish) and hemocyanin (shrimp), impairing the oxygen uptake and distribution through the body. Hypercapnia can also cause a drop in blood pH (respiratory acidosis), which impairs metabolism.

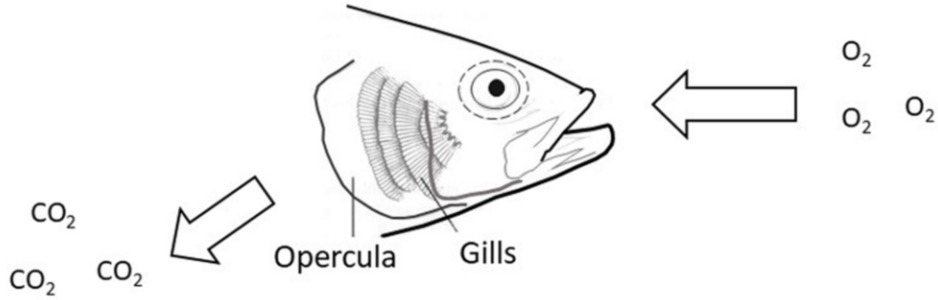

Fig. 1: Illustration of respiration in fish. Oxygen (O2) and carbon dioxide (CO2) diffusion through gill lamellae. For shrimp, respiration works the same.

Oxygen and carbon dioxide dynamics in aquatic environments

DO and CO_2 concentrations in water are influenced by temperature, salinity, altitude, rain and wind. However, it is significantly more affected by production factors such as pond phytoplankton density, feeding rate, fish and shrimp biomass, feed quality, among others. For this, each pond or tank has its unique gas dynamics, requiring individual monitoring. In intensive pond aquaculture, DO and CO_2 fluctuations are primarily driven by microalgae photosynthesis and respiration.

On sunny days, “green water” ponds often become supersaturated with oxygen and depleted of free CO_2 by afternoon when pH normally exceeds 8.3. At night, without photosynthesis, the respiration of microalgae, fish, shrimp, and other aquatic organisms consumes oxygen and releases CO_2, often leading to lower DO e pH, and higher CO_2 by early morning. Excessive phytoplankton amplifies the daily swings on water DO, CO_2 and pH (Fig. 2). Aeration is typically applied at night to maintain adequate oxygen and control CO_2 buildup. To minimize pH variation, farmers must strength the buffer system through liming, and control the phytoplankton with partial water exchange, algaecides, use of suspended clay and surface macrophytes for shading and nutrient manipulation.

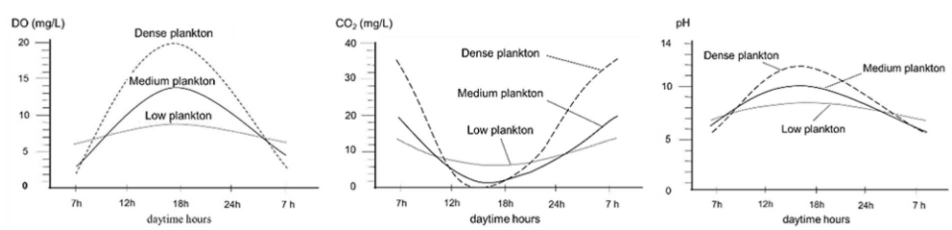

Fig. 2: Daily variation of dissolved oxygen (DO), carbon dioxide (CO2) and pH in waters with different phytoplankton abundance. Dense phytoplankton (intense green, low transparency water) causes large daily fluctuations in DO, CO2 and water pH. DO and CO2 change in opposite ways.

Pond water may be saturated, undersaturated, or supersaturated with oxygen (Fig. 3). DO in saturated water is in equilibrium with atmospheric O_2. At 28 degrees-C and sea level, freshwater is saturated at around 7.8 mg per liter of oxygen (100 percent saturation at 0 ppt salinity). For seawater with 40 g of salt per liter, DO saturation occurs at about 6.3 mg per liter (100 percent saturation at 40 ppt salinity). Using aerators in supersaturated water results in oxygen loss to the atmosphere.

Nonetheless, turning on the aerators for few hours at mid-day to move down DO supersaturated surface water is an efficient way to mix pond water and increase O_2 at the sediment-water interface. Shrimp tend to stay near the pond sediments where they often find natural food resources, and they **benefit from this mixing** (https://www.globalseafood.org/advocate/proper-water-circulation-in-aquaculture-ponds-part-2/). Thus, the concept of oxygen saturation is crucial for managing water aeration and circulation, determining the appropriate time to activate aerators. In intensive systems (e.g., RAS and BFT) aerators often run continuously due to high oxygen demand from fish and shrimp, as well as from microorganisms in biofilters or on suspended flocs.

Pure water at 25 degrees-C and sea level is saturated with CO_2 at 0.46 mg per liter. In

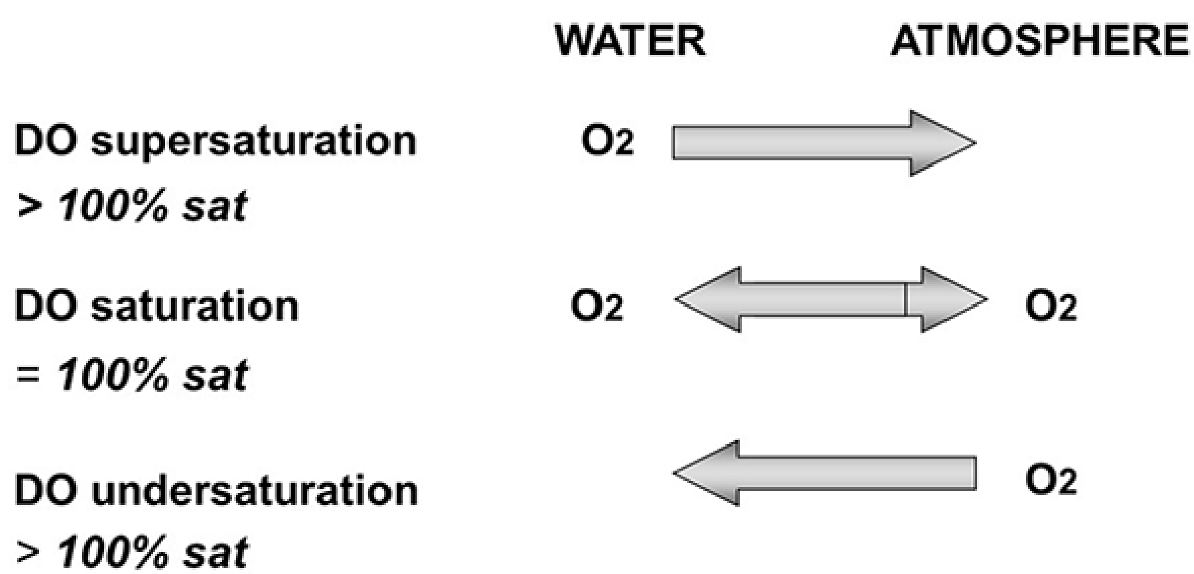

Fig. 3: Representation of water oxygen saturation conditions and oxygen diffusion direction.

aquaculture ponds CO_2 results mainly from the respiration of algae, aquatic plants, fish, shrimp, zooplankton, benthonic organisms and microbials. Along the production cycle, respiration can exceed photosynthesis, the primary mechanism for CO_2 removal. This leads to a significant building up of CO_2, exceeding 25 mg per liter. CO_2 higher than 40 mg per liter are commonly seen in biofloc systems. Concentrations above 60 mg per liter can occur in water used for transporting fish.

Carbon dioxide can be accurately measured by titration using water quality test kits. Chemical titration tests can also be used to measure DO. However, the use of digital DO meters allows for faster readings of DO at different ponds and tanks. DO meters measure oxygen in milligrams per liter (mg per lister) or as a percentage of saturation (percent). At many farms, oxygen is monitored throughout the night, and aerators are turned on when levels drop to 3–4 mg per liter or around 40–50 percent saturation. Some systems use real-time oxygen sensors placed in each pond (Fig. 4), which are usually integrated with control panels that activate aerators sequentially according to preset oxygen thresholds.

Fig. 4: Real-time oxygen sensors that can remotely activate aerators when a low DO limit is reached.

Effect of carbon dioxide on fish and marine shrimp

Although easy to measure, carbon dioxide is often overlooked in aquaculture. Levels above 10 mg per liter require corrective actions such as: (a) liming to increase alkalinity and hardness, and thus, the buffering system, (b) controlling phytoplankton to reduce nighttime respiration, (c) reducing feeding rates, and (d) increasing aeration. In intensive biofloc systems (BFT), CO_2 levels often exceed 40 mg per liter, causing respiratory stress in fish and shrimp. Key strategies to prevent high CO_2 and low oxygen in BFT include regular pH and alkalinity adjustments (using hydrated lime and sodium bicarbonate), enhanced aeration and removal of excess suspended solids.

Nile tilapia

Hamad et al. (2023) (https://doi.org/10.1016/j.aquaculture.2023.739239) found that daily 12-hour exposure to high CO_2 (15 to 30 mg per liter), even keeping constant DO saturation at 100 percent, reduced growth by 38 percent and worsen FCR by 30 percent in 114-gram juvenile Nile tilapia compared to fish kept at optimal levels (DO 100 percent saturation, CO_2 < 3 mg per liter). As well, diurnal fluctuations in DO (4 percent to 100 percent saturation) and CO_2 (3 to 30 mg per liter), mimicking green water pond conditions, reduced growth by 61 percent and worsened feed conversion ratio (FCR) by 43 percent. While survival was unaffected over 35 days, both high CO_2 and Low DO – individually or combined – negatively impacted appetite, growth and FCR. These results highlight the need to maintain proper DO and CO_2 levels, particularly at night, even for resilient species like Nile tilapia.

Marine shrimp

In a RAS study by **Casillas-Hernández et al. (2021)** (https://doi.org/10.1111/are.15198), Pacific white shrimp (*Penaeus vannamei*) exposed to high CO_2 levels (36 mg per liter) showed reduced survival (58 percent vs. 92 percent), lower growth (60 percent of control), and poorer FCR (2.8 vs. 2.3) compared to shrimp in low CO_2 water (12 mg per liter). The high CO_2 water had a lower pH (6.7 vs. 7.3), which may have posed additional stress to shrimp. Histological damage was observed in muscle, hepatopancreas and gill tissues of shrimp exposed to high CO_2.

Kubitza, Water Quality, Table 1

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Treatments	Control	Night time low DO	Night time high CO2	Night time low DO / high CO2
DO (% sat; hours/day)	100%; 24h	4-40%; 12h	100%	4-40%; 12h
CO2 (mg/L; hours/day)	< 3; 24h	< 3; 24h	15-30; 12h	3-30; 12h
Feed intake (% BW/d)	2.00	1.98	1.61	1.12
Growth (%/day)	1.65	1.19	1.02	0.64
Relative growth (%)	100	72	62	39
FCR (feed conversion ratio)	1.24	1.68	1.61	1.77
Survival (%)	100%	100%	100%	100%

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Table 1: Combined effect of DO and CO2 daily fluctuation regimen on feed intake, growth, feed conversion ratio (FCR) and survival of 114-gram juvenile Nile Tilapia during a 35-day growth study (adapted from Hamad et al. 2023). BW: body weight.

Effects of DO on fish performance and health

Oxygen levels of 60–70 percent saturation (above 4.5 mg per liter) are generally required for optimal health and performance in tropical fish. Tolerance to low DO varies by species and is influenced by temperature, CO_2, ammonia and nitrite. While fish species such as Nile tilapia and the Amazonian tambaqui and pirapitinga can survive near-zero DO for hours, prolonged exposure reduces growth, feed efficiency and increases disease susceptibility and handling stress.

In a study by **Tsadik and Kutty (1987)** (https://www.fao.org/4/ac168e/ac168e00.htm), juvenile Nile tilapia kept in clear water at 90 percent oxygen saturation (7.0 mg per liter) gained 4 to 14 times more weight than those at 40 percent (3.4 mg per liter) or 15 percent (1.2 mg per liter) saturation (Table 2). Low oxygen levels reduced feed intake and worsened feed conversion. A fourth group, kept in green water with daily oxygen fluctuations from 3 to 16 mg per liter, had the best feed conversion ratio (0.96), likely due to phytoplankton, but achieved only 37 percent of the weight gain seen in fish maintained in clear water at stable high oxygen levels (7 mg per liter).

Kubitza, Water Quality, Table 2

Parameters	Clear water		Green water	
	High DO (7 mg/L)	Med. DO (3.4 mg/L)	Low DO (1.2 mg/L)	DO fluctuates (3 - 16 mg/L)
Initial weight (g)	7.8	8.6	8.2	8.3
Final weight (g)	27.3	14.0	9.8	15.6
Weight gain (g/fish)	19.5	5.4	1.6	7.3
Feed intake (g/fish)	29.3	12.7	8.7	6.9
FCR (feed conversion ratio)	1.51	2.35	5.52	0.96
Relative weight gain (%)	100	28	8	37

Table 2. Effect of DO on growth and FCR of Nile Tilapia in clear and in green water (phytoplankton rich water). Adapted from Tsadik and Kutty (1987).

In water with 30 to 36 percent DO saturation, weight gain of channel catfish (*Ictalurus punctatus*) was only 41 to 45 percent compared to fish in water with nearly 100 percent DO saturation. Fish kept at 60 to 70 percent DO saturation showed intermediate growth (Table 3).

Kubitza, Water Quality, Table 3

Andrews et al. (1973) *			Buentello et al. (2000)**		
DO Sat	WG (g/fish)	WG relative	DO Sat	WG (%)	WG relative
100%	159	100%	100%	224	100%
60%	124	78%	70%	158	71%
36%	65	41%	30%	100	45%

Table 3: Effect of DO saturation on weight gain (WG) of channel catfish, Ictalurus punctatus.
https://doi.org/10.1577/1548-8659(1973)102%3C835:TIODOO%3E2.0.CO;2
https://doi.org/10.1016/S0044-8486(99)00274-4

Evans et al. (http://dx.doi.org/10.1111/j.1749-7345.2006.00069.x) reported that juvenile Nile tilapia exposed for 24 hours to a DO near 1 mg per liter and challenged with *Streptococcus iniae* experienced 27 to 80 percent mortality, compared to 0 percent in fish kept under adequate DO previously to the challenge. Similarly, in a study by **Welker et al.** (http://dx.doi.org/10.1111/j.1749-7345.2006.00069.x), channel catfish exposed to low DO (2 mg per liter) for two hours had lower immune response and presented higher mortality (36 percent) after a challenge with *Edwardsiella ictaluri* compared to 12 percent mortality for fish kept at DO of 6 mg per liter. These studies show that low oxygen impairs immune response and increases susceptibility to pathogens.

A 1979 pond study by researchers in the southern U.S. demonstrated how increased stocking and feeding rates negatively affect water quality, fish performance, and profitability in channel catfish culture (Table 4). Ponds stocked at 5,000, 10,000, and 15,000 fish per hectare received 34, 56 and 78 kg of feed/ha/day, respectively. Higher feeding rates led to lower morning DO levels, typically accompanied by elevated CO_2, excess nutrients and organic matter buildup. Such conditions lead to excessive phytoplankton blooms, which increase water pH at afternoon hours, thus the risk of ammonia toxicity to fish. Despite identical feed and genetics, feed conversion (1.3, 1.7, 2.5), average final weight (604, 440, 390 grams), and survival (99 percent, 93 percent, 83 percent) worsened with increased stocking density, clearly linking water quality to fish performance and health.

For the same study, economic estimates indicate the highest profit at the lowest stocking rate, contradicting the common belief that higher production yields higher profits. Improved FCR, growth and survival at lower stocking and feeding rates significantly reduced feed, fingerling and overall production costs. Time to reach minimum catfish market size of 1 pound would also be shorter at the lowest stocking rate. Many farmers overlook pond carrying capacity and operate at unsustainable densities without adequate monitoring or resources such as aeration and water exchange. As this study shows, poor water quality directly leads to poor growth, survival, FCR and economic returns.

Kubitza, Water Quality, Table 4

							Cost estimates (USD/kg fish)[1]				
SD fish/ha	FR	Mean DO	S%	FW (g)	GY (kg/ha)	FCR	Feed	Juv.	Other	Total Cost	Profit[2] (USD/ha)
5,000	34	4.5	99	604	2,990	1.3	0.72	0.33	0.47	1.52	2.93
10,000	56	3.1	93	440	4,100	1.7	0.94	0.49	0.45	1.88	2,542
15,000	78	2.1	83	390	4,860	2.5	1.38	0.62	0.42	2.42	389

Table 4: Effect of stocking density (SD) and feeding rate (FR, kg/ha/day) on average morning DO (Mean DO, mg/L) and its impact on channel catfish final weight (FW), survival (S%), gross yield (GY) and feed conversion ratio (FCR) in non-aerated, low water exchange ponds. Adapted from the original. Production cost and profit estimates were added by Kubitza.
1 Values in USD/kg of fish; Feed cost USD 0.55/kg; Juveniles USD 0.20/100g fish.
2 Sales price at USD 2.50/kg.

Effect of DO on shrimp performance and health

DO levels above 70 percent saturation should be maintained in marine shrimp culture, corresponding to 4.4 mg per liter at 40 ppt salinity and 28°C. Aeration is essential in intensive shrimp farming. A 2011 study by researchers in Thailand showed that Pacific white shrimp (*Litopenaeus vannamei*) exposed to low oxygen (< 2 mg per liter) had reduced survival and growth (Table 5). Shrimp in water with DO above 4 mg per liter grew faster and had higher survival rates. Shrimp kept in low oxygen water had decreased hemocyte counts and weakened immune responses, showing lower and lowered survival after a challenge *Vibrio harveyi*.

Kubitza, Water Quality, Table 5

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	DO (mg/L)		
Parameter	**> 4**	**2 to 4**	**< 2**
Final weight (g)	28.2	25.0	25.9
Survival (%)	92	81	57
Total hemocytes count (x 10^5/mL)	201	199	161
Phagocytosis (%)	37.3	37.0	26.3
PO activity	299	289	268
SOD (unit/mL)	47.9	45.1	36.0
Survival to *Vibrio harveyi* infection (%)	56	40	26

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Table 5: Effect of DO (mg per liter) on final weight, survival, immune response and tolerance to Vibrio harveyi infection on Pacific white shrimp (adapted from the original. Prophenoloxidase (PO), a major innate defense system in invertebrates, is the melanization of pathogens and damaged tissues. Superoxide dismutase (SOD) is an antioxidant enzyme necessary for life in all oxygen metabolizing cells.

A study on combined culture of Pacific white shrimp and Pacific blue shrimp (*Litopenaeus stylirostris*) assessed the optimal DO moment to start aeration (Table 6). Turning on aerators at 65 percent dissolved oxygen saturation resulted in better survival, production and feed conversion compared to later start of aeration at 40 percent or 15 percent DO saturation. While earlier aeration increased energy costs, it led to higher survival rates, better feed efficiency and greater net profit per hectare.

Kubitza, Water Quality, Table 6

On set of aeration at:	GY	*L. vannamei S%*	*L. stylirostris S%*	FCR	Energy use	Net profit (USD/ha)
	kg/ha				**kW.h/kg**	
15% sat (1.1 mg/L)	2,976	42%	24%	2.64	1.15	20,147
40% sat (2.8 mg/L)	3,631	55%	32%	2.21	1.37	24,545
65% sat (4.6 mg/L)	3,975	61%	47%	1.96	2.27	26,696

Table 6: Effect of DO saturation at the time of onset aeration on gross yield (GY), survival (S%), feed conversion rate (FCR), use of energy and net profit in the combined pond production of Pacific white and blue shrimp (from McGraw et al., 2001).

Final remarks

Maintaining adequate water DO and CO_2 in fish and shrimp farming is essential. Improving alkalinity and water hardness (the buffer system of water) by liming and controlling feeding rates and the phytoplankton density are strategies to reduce problems with high CO_2. Control of phytoplankton, feeding and stocking rates and providing supplemental aeration are keys to prevent low DO.

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