



Water quality in biofloc technology (BFT): an applied review for an evolving aquaculture

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Abstract

Biofloc technology (BFT) has been identified as an effective and sustainable aquaculture method, particularly beneficial for warm-water species in tropical areas. This technology is widely used in intensive aquaculture for several aquatic species due to its capacity to significantly reduce water exchange rates, benefiting both production systems and the environment. The efficacy of BFT in farming operations is directly related to a proper management of water quality parameters within the optimal range of the target species, as these parameters directly impact the yield of production units. Essentially, BFT functions as a water quality management system, converting harmful nitrogenous waste such as ammonia and nitrite into less harmful forms such as nitrates through microbial activity, ensuring the health of aquatic organisms. Key environmental factors such as temperature, dissolved oxygen (DO), pH, salinity, alkalinity, TAN, nitrite, nitrate, settleable solids (SS), and total suspended solids (TSS) can affect the growth of aquatic species and the functionality of the microbial community. This review brings (i) a comprehensive bibliometric analysis on biofloc and water quality, (ii) highlights optimal ranges, and (iii) key observations of several water parameters including temperature, salinity, nitrogenous compounds, SS, TSS, DO, phosphate, pH, and alkalinity in BFT rearing conditions for key aquatic species. Elements such as countries, thematic and keywords, and authors were explored, correlated, and discussed. In addition, this manuscript also (iv) discusses the presence of heavy metals and microplastics (MPs) in BFT culture water. A dedicated review on water quality in biofloc technology will contribute to future research and development (R&D) in this topic, support decision-making to improve farming operations, and can help further expansion of BFT-based aquaculture.

Keywords Aquaculture · Biofloc · Total suspended solids · Nitrogenous compounds · Heavy metals · Microplastic · Bibliometric analysis

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Introduction

The increasing aquaculture sector is expected to be a key contributor in addressing the growing demand for protein by the growing global population (FAO 2024). This sector incorporates a variety of culture systems, suitable for both small and large operations. These systems range from net pens in marine environments and deep lakes to earthen ponds, raceways, tanks, and a variety of recirculation setups. Each type of system is associated with its own unique ecological challenges. These challenges may include the discharge of surplus organic materials into nearby ecosystems, the emission of antibiotic and antiparasitic compounds into the environment, the spread of pathogens into farmed and wild populations, and concerns regarding the welfare of the animals (Carballeira Braña et al. 2021; Strand et al. 2022; Bagi et al. 2023). In regions where traditional land-based aquaculture is prevalent, and where the implementation of a clear-water recirculating aquaculture system (RAS) is prohibitively expensive, other land-based limited water exchange systems have been developed and adopted (Zhang et al. 2011). Among these, biofloc technology (BFT) has gained prominence in recent decades as an effective and economical method for cultivating a broad range of species in warmer and temperate regions (Hargreaves 2013; Yu et al. 2023a, b; Khanjani et al. 2024a). Initially, BFT was designed to minimize the environmental footprint of land-based aquaculture, primarily serving as a system for waste management and disease prevention (Khanjani et al. 2024b). BFT effectively maintains water quality for species, thereby lowering the demand for adding new water to aquaculture systems (Ekasari et al. 2015; Samocha et al. 2017). However, the application of BFT has been limited, as not all species are suitable for culture in BFT systems (Emerenciano et al. 2013). Certain biological traits are essential for organisms to adapt and overcome stress factors such as moderate levels of dissolved oxygen (DO), especially at high biomass (Emerenciano et al. 2013) and high stocking densities (Lima et al. 2019). Ideally, the selected species must be able to tolerate fluctuations in nitrogenous compounds (Widanarni et al. 2012), settleable solids (SS), and total suspended solids (TSS) (Browdy et al. 2012). Once all these aspects are taken into consideration, the minimal or zero water exchange in BFT systems contributes to water quality management, which fosters the growth and proliferation of key bacteria and other microbial communities (Martins et al. 2019). Changes on animal behavior and performance typically indicate the deterioration of water quality and recall the necessity for management intervention (Bagi et al. 2023). For instance, these behaviors may suggest increased ammonia or nitrite levels or reduced dissolved oxygen, prompting the need to enhance aeration, adjust key parameters such as alkalinity (Furtado et al. 2015), and modify microbial management. Thus, monitoring environmental parameters is crucial in BFT systems (Alkhamis et al. 2023). A comprehensive understanding of water quality parameters and their interconnection is vital for the success and maintenance of BFT-based aquaculture operations. For aquatic species to thrive, it is important to maintain environmental parameters such as DO, pH, TSS, total ammonia nitrogen (TAN), nitrite, and alkalinity within an optimal range to ensure proper performance and survival (Alkhamis et al. 2023). Numerous studies have been conducted to investigate how BFT impacts water quality (Pellegrin et al. 2022; Schweitzer et al. 2024). BFT has been shown to be more effective in removing inorganic nitrogen from water compared to traditional methods (Emerenciano et al. 2017). BFT also enhanced the growth of species such as catla (*Catla catla*), rohu (*Labeo rohita*), and mrigal (*Cirrihinus mrigala*) in polyculture systems (Deb et al. 2020). Additionally, the successful culture of

Penaeus vannamei and *Farfantepenaeus brasiliensis* postlarvae in BFT is explained by water quality and the use of the system's microbes as a food source, contributing to tissue development, health, and improved nutrition (Emerenciano et al. 2012; Suita et al. 2015). Routine monitoring, interpretation, and intervention of key water quality parameters are essential for maintaining a suitable environment, animal welfare, health, and performance, especially in BFT with high stocking density. However, in commercial biofloc-based shrimp and fish operations, farmers still struggle with water quality management, especially due to lack of understanding and proper follow-up actions (Day et al. 2016; Emerenciano et al. 2022a). In this review, a comprehensive bibliometric analysis on biofloc and water quality is presented. The manuscript highlights optimal ranges and key observations of several water quality parameters including temperature, salinity, nitrogenous compounds, SS, TSS, DO, phosphate, pH, and alkalinity in BFT rearing conditions for key aquatic species; and discusses the presence of heavy metals and microplastics (MPs) in BFT culture water. Finally, this review aims to (i) contribute to a more "holistic" understanding of BFT, with a key focus on water quality parameters and relevant management implications; and (ii) support decision-making to improve farming operations, and (iii) boost further R&D development of BFT-based aquaculture.

Bibliometric

Material and methods

This study aimed to review the research conduct on water quality in BFT. The Scopus database was accessed for works published between 1989 and 2024 using the following keywords ("biofloc" OR "biofloc system" OR "biofloc technology" AND "water quality" OR "dissolved oxygen", OR "temperature", OR "salinity", OR "heavy metal"). In total, 802 publications were found in the literature. Complete records and their references were extracted to be used as bibliometric data. The research process involved five steps including (i) gathering data, (ii) selecting the appropriate software, (iii) analyzing the data, (iv) visualizing the results, and (v) interpreting the results.

The data was analyzed and visualized using Excel 2019, VOSviewer version 1.6.16, and the Bibliometrix package for R (Aria and Cuccurullo 2017). For each of the records, author, country, and year of publication were directly accessed from the Scopus database (www.scopus.com/sources), and maps were created in Excel. VOSviewer was utilized to create the network of countries, journals, and keywords, including author and index keywords (Gao et al. 2018). Finally, the quality of the records was checked in Microsoft Excel, and duplicates, spelling errors, and incomplete records were corrected. Items that failed quality control were excluded from the study.

Three-field plot

Relationship between three elements including countries, keywords, and authors using Sankey plots was plotted. Three-field plots utilize colored blocks to represent the key findings of the analyses. The total number of links between the blocks determines their height.

Thematic map and evolution

For the thematic map, four clusters were identified and developed: (i) low density and centrality (emerging themes): The topics placed in the bottom left quadrant need further exploration due to underdevelopment or being emerging subjects. These subjects enjoy limited significance across the network and their development is slow within the network; however, they present attractive opportunities for future research. (ii) High density and low centrality (basic themes): The topics located in the top right quadrant constitute the primary axes in the body of research and are central to the developments in the field. These topics enjoy high relevance across and inside networks. By identifying and developing these topics, bibliometric studies highlight the opportunities for further investigation. (iii) High density and low centrality (niche themes): Topics in the top left quadrant are internally well-connected but have limited external connections, indicating their limited significance under current circumstances. (iv) High density and centrality (motor themes): Topics in the top right quadrant represent the major trends in the field and are central to the literature. They have high relevance and connectivity within and across the network. Given their centrality, bibliometric studies can shed light on their exact nature and guide future research. In the thematic map, the bubble sizes are determined by the number of publications in which the keyword appeared (García-Lillo et al. 2023).

For the R&D evolution, Sankey diagrams were utilized to illustrate themes and their development over time regarding water quality in biofloc technology (Xiao et al. 2022). In the Sankey plot, each box corresponds to a theme, with the size of the boxes indicating frequency (Xiao et al. 2022). The lines connecting the boxes show the evolution of a theme with line thickness corresponding to link strength.

Results

The number of “biofloc” publications increased exponentially between 1989 and 2024. The “biofloc and water quality” ones first exceeded 50 publications in 2017 (Fig. 1). These publications grew on average by close to 6.84% from 1989 to 2024 (Fig. 1). The

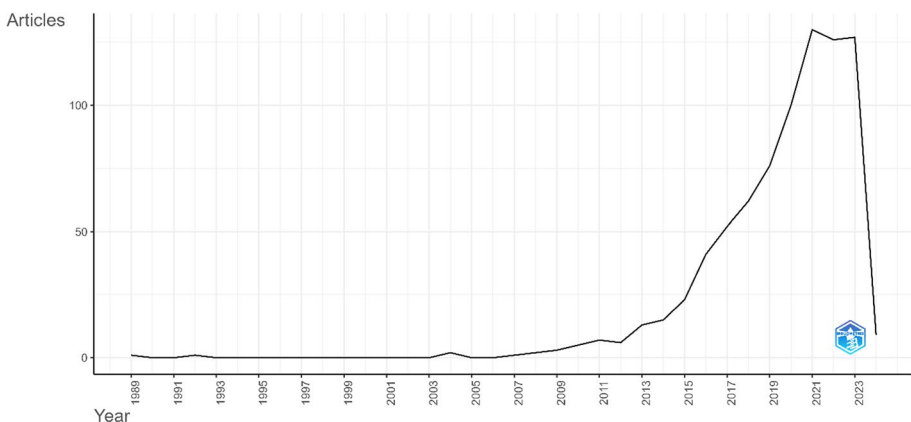


Fig. 1 Number of publications per year, as per bibliometric analysis of “biofloc and water quality” (1989–2024)

least active years were 1990,1991, 1993–2003, and 2005–2006 while the peak occurred in 2021 with 127 papers. As shown in Fig. 1, 802 studies were extracted from Scopus across 190 sources between 1989 and 2024. Overall, 2460 authors had contributed to the literature on the topic. The majority of the documents were general research articles ($n = 710$), followed by reviews ($n = 36$). The vast majority of the records were in English (95.7%).

Figure 2 provides a detailed graphical overview of research collaboration across the world. The top countries in terms of productivity of the field are Brazil, China, and India, respectively. The highest frequency of international collaboration was between Brazil and Mexico ($n = 198$), followed by Brazil and USA (130), China and Malaysia (90), Brazil and Australia (80), and China and USA (75). The blue colors in Fig. 2 indicate different scientific publications in the field of biofloc, whereas darker ones indicate higher number of publications.

The three-field plot

The flow in the three-field plots indicates that authors from Brazil, China, and Mexico have published the largest number of works on the subject (Fig. 3). As shown in the figures, there are geographical preferences for certain keywords. For instance, there is a strong relative preference among authors from Brazil for “biofloc”, “shrimp”, “*P. vannamei*”, and “*Oreochromis niloticus*”; and for authors from China, “biofloc” and “biofloc technology” were preferred.

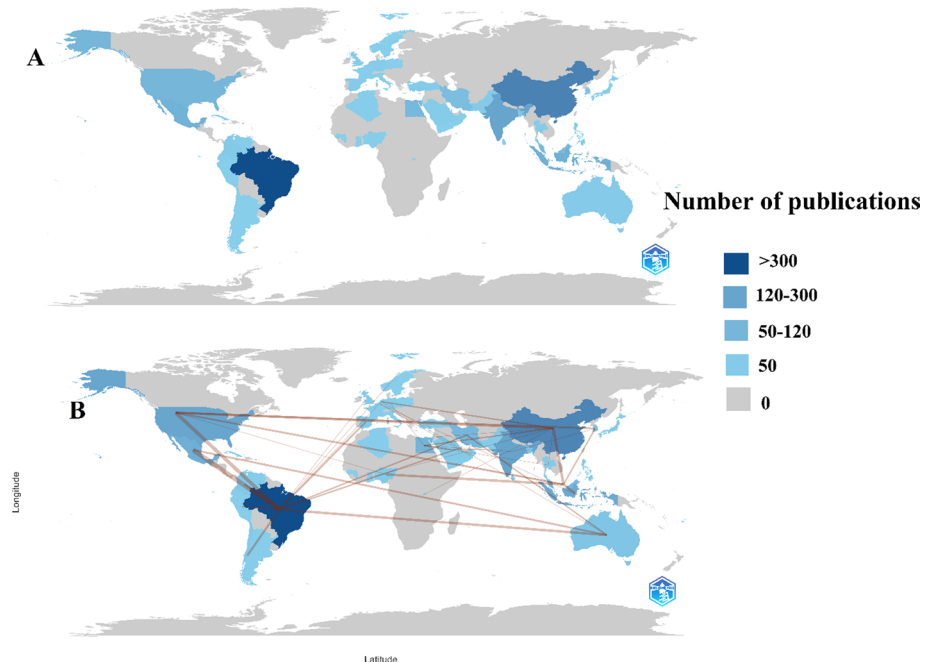


Fig. 2 Countries’ scientific production (A) and countries’ collaboration map (B) in the field

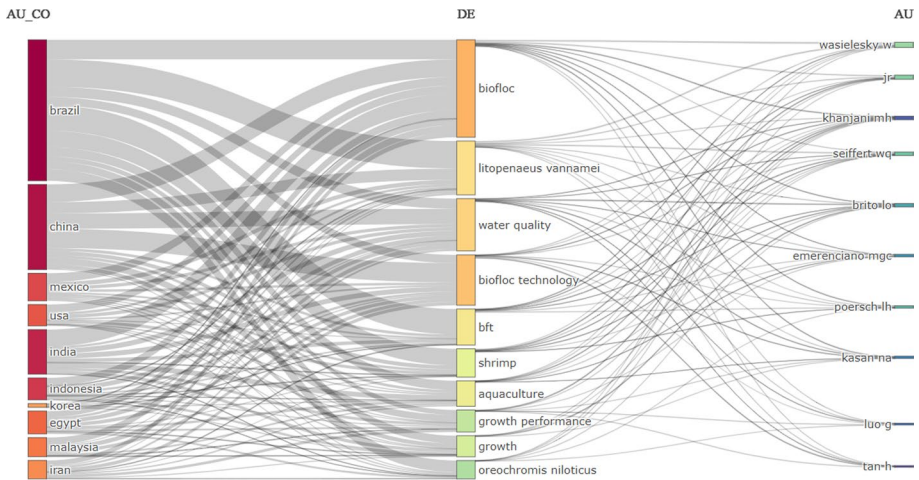


Fig. 3 Three-field plot for county of the corresponding country, keywords, and authors, as per bibliometric analysis of “biofloc and water quality” (1989–2024). The height of the rectangles corresponds to the sum of the relations originating between the elements and the thickness of the links represents the strength of the connections

Thematic map and evolution

According to the results of thematic map, biofloc, shrimp growth, probiotics, nursery, and heterotrophic bacteria are the motor themes. Moreover, aquaculture, sustainability, nitrification, biofloc system, microalgae, and *O. niloticus* are emerging themes that require further development (Fig. 4).

From a general perspective, it can be found that “biofloc” is present in all times. It is noticeable that the terms “water quality” and “nitrification” were first used in 2020–2024. In the following 4 years, they were further developed and sustained interest in the final period of 2022–2024. (Fig. 5).

Biofloc technology (BFT)

Research and practical application of BFT have been ongoing since the 1970s, starting at Ifremer-COP and reaching commercial viability by the late 1980s (Emerenciano et al. 2013). BFT as an aquaculture production system is evolving quickly; however, its core still emphasizes the growth of a large microbial population in water, leading to the formation of microbial aggregates known as “bioflocs” (Khanjani and Sharifinia 2024). These living microbial particles play a crucial role in controlling nitrogenous compounds in the culture water (Emerenciano et al. 2017). Both BFT and RAS utilize biological processes to achieve nitrogen removal, but their approaches differ significantly (Liu et al. 2021). For instance, besides the chemoautotrophic communities (nitrifying bacteria), BFT also relies on heterotrophic microorganisms for toxic N-compounds control (Khanjani et al. 2022). In addition, the typical “clear-water” environment found in RAS is not the case in BFT where some levels of suspended solids are expected but must be maintained within acceptable levels for the different aquatic species (Gaona

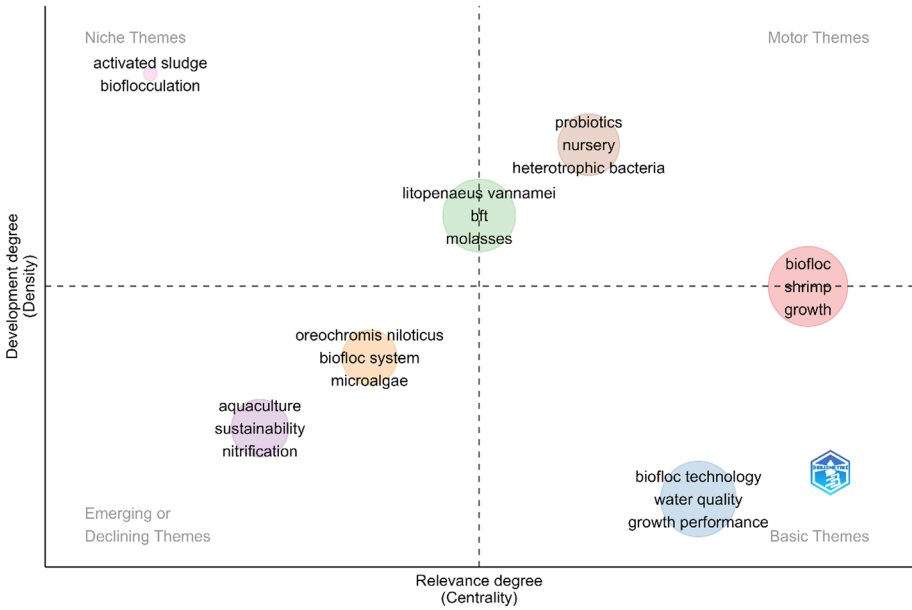


Fig. 4 Thematic map in “biofloc and water quality” research

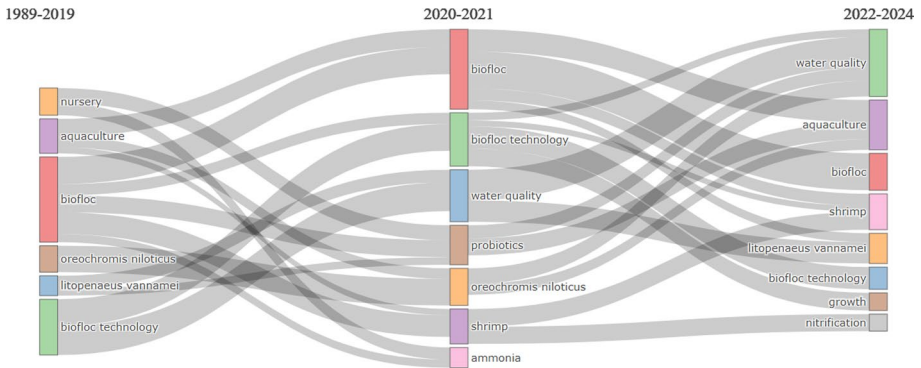


Fig. 5 Thematic evolution in “biofloc and water quality” research

et al. 2017; Emerenciano et al. 2017). Also, BFT systems are normally less expensive to set up and run than RAS, as well as offering several other biological benefits over traditional clear-water RAS (Liu et al. 2019).

There has been a marked increase in publications on BFT in aquaculture since 2015. These publications are not only related to laboratory scale, but also carried out in large commercial operations (Emerenciano et al. 2022a). In this sense, BFT is increasingly viewed as a sustainable alternative in aquaculture, particularly in tropical shrimp farming (Ulloa Walker et al. 2020; Emerenciano et al. 2021; El-Sayed 2021). One of the key attributes is the in situ circularity, in which bioflocs are able to control the nutrient content in the water by converting waste nitrogen into microbial biomass and serve as

supplemental feed for the cultured species (Khanjani et al. 2023a). Moreover, bacteria in the bioflocs offer additional health benefits by outcompeting pathogenic microbes and acting as natural probiotics (Deng et al. 2022; Bagi et al. 2023). Therefore, BFT is seen as a new chapter in the “blue revolution” (Stokstad 2010). Facilitated by minimal water exchange and circularity properties, BFT continuously boosts the recycle and reuse of nutrients within the culture medium (Raza et al. 2024). The system’s sustainability is further highlighted by (i) its high production efficiency and small footprint (da Silveira et al. 2020); and (ii) nutrition attributes due to improved feed efficiency as a result of continuous ingestion of protein and lipid-rich microbial aggregates (Khanjani et al. 2024b). This natural productivity (bioflocs) is crucial in preserving the water quality. Microorganisms are the central pivot in BFT operations (Emerenciano et al. 2021). Water quality is controlled through encouraging mainly heterotrophic and nitrifying bacterial growth and regulating photoautotrophic communities by maintaining among others (i) a suitable carbon-to-nitrogen (C:N) ratio. This ratio is essential for optimal growth of heterotrophic bacteria, which utilize carbon for maintenance of essential activities such as respiration, feeding, digestion, and reproduction (Emerenciano et al. 2021; Khanjani et al. 2023b, 2023c). But also (ii) high DO and alkalinity levels to ensure a proper nitrification process (Furtado et al. 2015).

In terms of C:N ratio management in BFT, it typically involves two phases (Emerenciano et al. 2021). Firstly, the development phase employing a specific C:N ratio (normally 10–20:1) and addition of an external carbon source such as grains and sugars (Wei et al. 2016); and secondly, the maintenance phase reducing or eliminating the external carbon inputs, depending mainly on TAN, NO₂ values, and desirable SS levels (Khanjani et al. 2024c).

Water quality parameters

A proper water quality management is crucial to the success of production cycles in aquaculture farms. BFT systems are particularly sensitive to fluctuations in factors such as temperature, DO, pH, salinity, suspended solids, alkalinity, orthophosphate, and nitrogenous compounds, but also other external factors such as light intensity and minerals. A holistic view of these parameters and their interconnection is crucial for effective and sustainable management. For that, Tables 1, 2, and 3 bring key information regarding BFT and water quality management. Table 1 summarizes water quality parameters in different studies conducted using a variety of aquaculture systems and BFT. Table 2 shows the suitable ranges of water quality parameters in the biofloc aquaculture system. And finally Table 3 shows the effects of manipulating different water parameters in BFT and the impact on animal performance in several species.

It is important to note that each species demands specific conditions that require regular monitoring to promote growth and ensure survival. Thus, water quality has a profound effect on the health of the organisms, survival rates, and the profitability of aquaculture (Tumwesigye et al. 2022). While parameters such as salinity is often relatively constant in the system, others such as alkalinity and DO may change, especially in high biomass, and interventions are needed. An in-depth understanding of key water quality parameters and their interactions in BFT is essential for decision-making and suitable interventions within the production cycles.

Table 1 Comparative analysis of water quality in clear water and biofloc systems across different studies

Rearing system	Cultivated species/life stage	T (°C)	S (g/L)	pH	A (mg CaCO ₃ /L)	DO (mg/L)	TSS (mg/L)	TAN (mg/L)	NO ₂ (mg/L)	NO ₃ (mg/L)	PO ₄ -P (mg/L)	Reference
BFT	<i>P. vannamei</i> /adult	30	34.2	7.1	126	4.0	546.7	0.38	0.23	22.9	54.5	Vinatea et al. 2009
BFT	<i>P. vannamei</i> /PL	29.16–31.28		7.33–7.76	215.33–273.33	6.61–6.94	190.92–304.38	0.12–0.35	0.026–0.035	6.97–10.73	0.54–0.66	Lim et al. 2021
BFT	<i>P. vannamei</i> /J	27.05–27.25	33.5	7.5–7.90	100–162.2	4.9–5.1	850–890	0.3–0.4	3.1–4.0	57.5–60.53	5–6.68	Furtado et al. 2011
CW		27	33	6.86	78	5.1	870	0.6	4.3	54.5	8.2	
BFT	<i>O. niloticus</i> /J	27.55–27.70		6.56–8.27	44.72–175.90	5.69–6.04	485–548.61	0.94–1.68	7.03–10.1	105–140	6.93–10.23	Martins et al. 2019
BFT	<i>Macrobrachium rosenbergii</i>	26.34–26.47		7.76–7.80	137.69–148.95	6.48–6.98	298.7–445.2	0.21–0.54	0.64–0.92	2.1–2.42		Islam et al. 2023
CW		26.39		7.85	139.78	6.75	168.4	0.71	1.98	3.12		
BFT	<i>Lates calcarifer</i> /J	27.2–27.5	0	7.8–8	94.6–96.0	7.5–7.7		0.42–0.45	0.9–0.94	0.13–0.17	0.081–0.098	Whangchai et al. 2022
BFT	<i>Clarias gariepinus</i> /J			7.3–7.76	177.13–263.53	7.51–7.79						Chen et al. 2020
BFT	<i>Litopenaeus setiferus</i> /N	27.49–28.02	5–35	8.50–8.03		7.61–5.33	7.25–6.6	0.11–0.29	1.37–1.47	87.34–92.34		Valenzuela-Jiménez et al. 2022
BFT	<i>P. vannamei</i> /J	28.38–30.79	35.3–36	7.36–7.76	133.4–229.7	4.49–4.91	280.16–460.5	1.0–5.91	1.97–8.97	3.97–14.88	2.7–3.67	Lara et al. 2017
BFT	<i>Colossoma macropomum</i> /J	25.78–25.97		6.32–6.97	11.13–6.67			0.34–1.98	0.67–0.59	2.60–5.09		dos Santos et al. 2020
BFT	<i>P. vannamei</i> /N	29.2	34.5–34.9		117–120	5.6		0.25–0.27	3.81–4.14	43.58–44.63	4.83–5.03	Gaona et al. 2016
CW		29.06	35.43		113.98	5.47		0.31	4.18	54.72	5.34	

Table 1 (continued)

Rearing system	Cultivated species/life stage	T (°C)	S (g/L)	pH	A (mg CaCO ₃ /L)	DO (mg/L)	TSS (mg/L)	TAN (mg/L)	NO ₂ (mg/L)	NO ₃ (mg/L)	PO ₄ -P (mg/L)	Reference
BFT	<i>Rhamdia quelen</i> /F	24.7–25.4	1.3–1.4	7.7–8.0	107.9–187.5	6.5–6.8	538.4–157.0	0.05–0.26	0.01–0.8	58.4–86.0	12.4–13.9	Poli et al. 2015
CW		25.35	0.3	7.7	83.7	6.7	-	0.11	0.02	20.3	6.9	
BFT	<i>P. vannamei</i>	29.7	33.0–33.7	7.5–7.8	133.3–218.4	4.8–5.5					4.0–9.1	Schweitzer et al. 2013
BFT	<i>P. vannamei</i> nauplius	30.8	30.6	8.27	171.6–174.1	7.49	304–618	0.27–0.29	0.23–0.32	7.21–8.83		Liu et al. 2022
CW		30.7	31	8.29	167.7	7.5	213	0.5	0.03	3.30		
BFT	<i>Piaractus brachypomus</i> /F	25.95–26.10		8.00	96.21–103.27	6.76–6.90	278.50–363.3	0.25	3.33	48.13–59.63		Angeles-Escobar et al. 2022
CW		26.01		7.74	58.37	6.82	7.20	0.33	0.31	21.73		
BFT	<i>P. vannamei</i> /N	23.08–23.16	25	76–7.8	138.68–153.52	5.99–7.39	285.08–493.5	0.24–0.57	0.61–0.93	2.09–2.56		Rajkumar et al. 2016
CW		23.29	25	7.8	138.89	6.57	158.5	0.78	1.89	3.21		
BFT	<i>P. vannamei</i> /I	27.86–28.17	37.23–38.49	7.74–7.93	116.71–159.29	5.68–5.85	306.37–745.2	2.54–3.42	0.73–10.28	0.38–1.73	0.51–4.82	Gaona et al. 2017
BFT	<i>O. niloticus</i> /F	28.20	10.5	7.9		6.7–6.9	191.8	0.3	0.6	25.4		Fleckenstein et al. 2018
CW		28.35	10.3	7.8		6.9–7.0	132.1	0.2	0.1	22.3		
BFT	<i>P. vannamei</i> /G and N	30.18	23.59	7.16		5.57	244.0	0.16	2.63	0.73	3.44	Pimentel et al. 2020
BFT	<i>O. niloticus</i> /I	27.54–27.68		7.10–7.50	56.11–70	6.40–6.51	635–841.5	3.56–3.70	0.56–0.99	321.18–466.82		Eid et al. 2021
CW		27.54		8.03	48.89	6.58	588.64	2.20	0.80	450.30		
BFT	<i>O. niloticus</i> /F	27.55–27.70		7.33–7.53	48.95–75.76	5.91–5.97	501.47–707.49	0.73–1.17	5.94–8.14	117.50–143.33	1.75–8.30	Martins et al. 2017

Table 1 (continued)

Rearing system	Cultivated species/life stage	T (°C)	S (g/L)	pH	A (mg CaCO ₃ /L)	DO (mg/L)	TSS (mg/L)	TAN (mg/L)	NO ₂ (mg/L)	NO ₃ (mg/L)	PO ₄ -P (mg/L)	Reference
BFT	<i>Labeo rohita</i> F	27.06		7.07		5.4	284.48	0.11	0.03	0.03		Kamiliya et al. 2017
CW		27.06		6.59		6.53	23.85	0.06	0.03	0.06		
BFT	<i>Eitroplus suratensis</i> ♂	25–25.3	0.095	7.66–7.69		7.43–7.65	1307–1318	0.008	0.23	0.2	0.36–0.39	Thilakan, et al. 2019
CW		25.6	0.094	8.32		7.17	1249.57	0.01	0.20	0.22	0.37	
BFT	<i>P. vannamei</i> PL	28.8–29.2	10.3–30.2	7.7–7.9	310–322	7.7–8.9	263–330	0.7–1.2	0.3–0.6	0.3–1.4	2.0–2.6	Ray and Lotz 2017
BFT	<i>O. niloticus</i> ♂	27.57–27.77	0–16	7.4–7.6	93–152	4.70–5.15	384.5–566.9	3.94–5.84	0.82–8.89	40.58–65.58	22.12–35.01	de Souza et al. 2019
BFT	<i>O. niloticus</i> F	23.2	0.3‰	8.1	198.0–301.8	7.1	154.9	1.6–2.0	0.5–1.1	6.8–13.6	5.7–7.6	Silva et al. 2017
BFT	<i>O. niloticus</i> ♂	23.97–24.19		7.72–7.85	159.7–168.77	6.17–6.32	465.9–750.5	0.14–0.25	0.10–0.29	44.76–142		Dilmi et al. 2022
CW		24.15		8.04	177.5	6.60	-	0.11	0.12	7.19		
BFT	<i>Gibelion catla</i> F	26.74–26.82		7.4–7.7	37.0–42.67	5.7–5.9	93.55–140.68	0.22–0.26	0.019–0.035	11.27–15.81		Solanki et al. 2023
BFT	<i>P. vannamei</i> PL	28.45–28.90	30.1–30.77	7.87–8.15	124.10–140.25	4.67–5.95	123.53–328.55	0.46–0.86	0.14–0.39	0.10–0.22	0.52–0.98	Pamigrahi et al. 2019
CW		28.45	30.15	8.58	150.25	6.94	60.58	1.45	0.75	0.67	0.43	
BFT	<i>P. vannamei</i> ♂	28.7–28.8	5.0‰	6.9–7.7	104.0–173.0	5.28–5.57	327.4–682.1	1.3–7.1	1.9–14.0	4.6–77.0		Huang et al. 2022b

Abbreviations: T temperature, S salinity, A alkalinity, DO dissolved oxygen, TSS total suspended solids, TAN total ammonia nitrogen, PL postlarvae, J juveniles, N nursery, F fry, G grow-out

Table 2 The suitable ranges of water quality parameters in the biofloc system

Parameter	Appropriate range	Considerations	Reference
T (°C)	26–32 °C	Optimal temperatures are species-specific. For instance, ranges from 26 to 28 °C are suitable for <i>P. vannamei</i> and tilapia species. Temperatures outside these ranges can lead to reduced growth and disturbances in physiological and behavioral activities. Excessive temperatures can cause a decrease in oxygen levels and increase stress during breathing	Ahmed et al. 2022; Emerenciano et al. 2017; Kim et al. 2019
S (g/L)	4–33	The salinity levels are species-specific and must be kept according to the tolerance range. In biofloc systems, the salinity level increases due to the limitation of water replacement and the accumulation of uneaten food waste	Khanjani and Alizadeh, 2023; Khanjani et al. 2020a
pH	6.5–8.5	Levels outside these ranges can impact growth and lead to disturbances in physiological and behavioral activities. In biofloc systems, high TSS/SS and respiration rates may cause pH reduction	Emerenciano et al. 2017; Ahamed et al. 2022
Alkalinity (mg CaCO ₃ /L)	Higher than 100 mg/L	High alkalinity minimizes the daily fluctuation in pH. In addition, higher alkalinity levels (> 100 mg/L) are critical to support TAN processing by heterotrophic and chemotrophic bacteria	Van Wyk and Scarpa 1999; Furtado et al. 2015; Emerenciano et al. 2017
DO (mg/L)	Higher than 5 mg/L	Higher levels (> 5 mg/L) will safely sustain fish-shrimp physiological responses, as well as microbial development. The stability of DO levels is dependent on several factors including TSS, SS, salinity, and temperature	Vinatea et al. 2009; Kuhn and Lawrence 2012;
TSS (mg/L)	200–500	Species and age dependent (e.g., normally young individuals are more resistant compared to their older counterparts). The level of TSS can significantly impact the dissolved oxygen level, pH, and alkalinity. High levels of TSS (e.g., > 500 mg/L) can impair the growth and survival of several cultured aquatic species	Schweitzer et al. 2013; Hargreaves 2013; Gaona et al. 2017
SS (mL/L)	5–15 mL/L for shrimp, and 5–20 for tilapia	Same as per TSS. High levels of SS (e.g., > 15 mL/L) can impair the growth and survival of several cultured aquatic species	Emerenciano et al. 2017

Table 2 (continued)

Parameter	Appropriate range	Considerations	Reference
TAN (mg/L)	Lower than 1 mg/L	Dependent on factors such as species-age, temperature, pH, and salinity. Three processes (photosynthesis, assimilation, and nitrification) play a significant role in controlling TAN in BFT	Ebeling et al. 2006a; 2006b; Emerenciano et al. 2017 Khanjani et al. 2022
NO ₂ (mg/L)	Lower than 1 mg/L	Mainly dependent on factors such as species-age and salinity. Nitrite-oxidizing bacteria are slow growers and quite sensible to environmental changes	Vinatea et al. 2010; Emerenciano et al. 2017
NO ₃ (mg/L)	Lower than 200 mg/L	Mainly dependent on factors such as species-age and salinity. For some species only toxic at higher levels (e.g., > 400 mg/L). High concentration of TSS and SS can boost nitrate levels in water	Emerenciano et al. 2017; Gaona et al. 2017
PO ₄ (mg/L)	0.5–20 mg/L	Accumulation is expected BFT systems. Bacteria and algae, as well as TSS and SS can play a role with PO ₄ fluctuations	Silva et al. 2013; Emerenciano et al. 2017; Liu et al. 2018
Heavy metals (HMs)	Unknown	Salinity and feed inputs can play a key role on HMs accumulation and toxicity	Deswati et al. 2022

Abbreviations: *T* temperature, *S* salinity, *A* alkalinity, *DO* dissolved oxygen, *TSS* total suspended solids, *TAN* total ammonia nitrogen

Table 3 Manipulation of water quality parameters and impact on performance in biofloc technology in target aquaculture species

Cultured species	IBW (g)	Influent parameter	Relevant rearing conditions	Main findings	Reference
<i>P. vannamei</i>	1.91	WT (15, 21, 27, and 33 °C)	<i>P. vannamei</i> shrimps were stocked in the tanks at a density equivalent to 200 shrimps/m ² (or 40 shrimps per tank), for 60 days	Shrimp reared at 15 and 33 °C displayed higher activity of antioxidant enzymes as a defense mechanism against the overproduction of ROS triggered by temperature stress	de Souza et al. 2016
<i>P. vannamei</i>	6.5	WT (15, 21, 27, and 33 °C)	The experimental setup comprised of 12 tanks, each with a capacity of 250 L. Shrimps were then stocked in these tanks at a density of 150 shrimps/m ²	Shrimp subjected to 15 and 21 °C temperatures exhibited increased enzyme activities. Moreover, this adverse temperature condition might directly or indirectly induce stress in the animals	de Souza et al. 2014
<i>Paralichthys olivaceus</i>	27.96	WT (20, 22, 24, 26, 28, and 30 °C)	The experimental system included 12 tanks, each with a capacity of 250 L. <i>P. olivaceus</i> fish were stocked in each tank, with a total of 10 fish per tank. This configuration led to a total of 120 fish being stocked across the 12 tanks. The fish were grouped into six water temperature categories, with duplicates for each category	The research shows that temperatures exceeding 26 °C led to hematological alterations and oxidative stress in juvenile <i>P. olivaceus</i> fish in a biofloc system	Kim et al. 2019

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>Farfantepenaeus brasiliensis</i>	0.015	WT (21, 24, 27, 30, 33 °C)	A 30-day nursery phase trial was conducted at different temperatures. <i>F. brasiliensis</i> (PL23) were stocked in each of the 25 tanks, with a density of 600 shrimps/m ² . Each tank had a volume of 150 L	<i>F. brasiliensis</i> shrimp nursed at 27 °C in a super-intensive biofloc dominated system demonstrated superior growth performance, including increased productivity, quicker growth, and higher survival rates	Hostins et al. 2015
<i>P. vannamei</i>	0.004	WT (24, 28, and 32 °C) Salinity (10, 20, and 30 g/L)	The experimental setup involved 27 indoor plastic tanks, each with a total capacity of 500 L, but only 200 L were used. PL14 were grown in a nursery at a density of 2000 PL per cubic meter in BFT for a duration of 4 weeks	The optimal conditions for achieving the highest specific surface area of FW, SGR, productivity, and survival were determined to be a temperature of 27.25 °C and a salinity of 25.5 g/L	Ponce-Palaofox et al. 2019

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>P. vannamei</i>		WT (°C), TSS	The BFT systems were operated using molasses or white sugar as a carbon source, creating a favorable heterotrophic environment with C:N ratios all very close to 10	The bioflocs have a richer elemental composition in terms of nitrogen and phosphorus. Systems with higher WT and higher TSS have a greater ability to absorb and immobilize these elements in the bioflocs	Pimentel et al. 2020
		WT (15, 20, 25, and 30 °C)	Each temperature group contained three replicates in a randomized block design. To ensure sufficient mixing intensity and saturated DO, a bubbling diffusive air stone was used in each reactor. Glucose was added to achieve a C:N ratio greater than 20	The study concluded that biofloc bacteria can enhance the effectiveness of sludge treatment at 25 °C. At this temperature, a significant amount of ammonia nitrogen removal was achieved in just 3 h without increasing the nitrite and nitrate concentrations in the SBRs. The process was found to be more efficient at 25 °C than in the other three temperature groups	Yao et al. 2013

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>O. niloticus</i>	3.68	NaHCO ₃ CaCO ₃ Ca(OH) ₂ for alkalinity and pH correction	The fish were distributed into experimental units, with each unit having a useful volume of 37.5 L. There were 25 fish per tank. When the TAN levels in the tanks reached a value higher than 1.0 mg/L, molasses was added to correct the C:N ratio. The C:N ratio was adjusted to a ratio of 15:1 by adding molasses	The recommendation of using NaHCO ₃ and Ca(OH) ₂ for alkalinity and pH correction in Nile tilapia nursery in BFT systems. These practices can enhance fish growth and net yield while potentially providing economic benefits through the judicious use of these compounds	Martins et al. 2017

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>P. vannamei</i>	6	Alkalinity and suitable sources (Ca(OH) ₂ , Na ₂ CO ₃ , NaHCO ₃)	The experiment was conducted using juveniles stocked in 150-L 12 tanks at a density of 333 shrimp/m ³	It is evident that calcium hydroxide and sodium bicarbonate are effective compounds for increasing alkalinity in BFT cultures. These compounds successfully elevated alkalinity levels, which is important for maintaining stable water conditions and supporting optimal fish health and growth. The study also revealed that maintaining adequate levels of alkalinity and pH is crucial for water quality and zootechnical performance in BFT cultures. When alkalinity concentrations remained below 100 mg CaCO ₃ /L and pH levels were consistently below 7 for extended periods, both water quality and the performance of the fish were negatively affected	Furtado et al. 2011

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>Artemia franciscana</i>		Alkalinity: 75, 150, 225, and 300 mg CaCO ₃ /L	A total of 35 pairs of <i>Artemia</i> (male and female) were cultured in 50-mL tubes under biofloc conditions for a period of 3 weeks	In this study, an alkalinity level of 150 mg per liter of calcium carbonate was found to significantly improve the performance of biofloc production com- pared to other alkalinity levels. It is recommended for the production of biofloc for <i>Artemia</i> feed- ing from the nauplii to the adult stage	Naserizadeh et al. 2020
<i>P. vannamei</i>	0.2	Alkalinity: 75, 150, 225, and 300 mg CaCO ₃ /L	12 experimental units, each with a total volume of 50 L, were filled with 30 juvenile shrimp. This stocking density resulted in a density of 150 shrimps/m ² . The shrimp were kept in these units for a duration of 49 days as part of the experiment	Bioflocs were successfully formed during the rearing of <i>P. vannamei</i> without the need for water renewal when the alkalinity levels exceeded 70 mg CaCO ₃ /L and pH levels were above 7.38. The treatments with higher alkalinity levels, specifically at 300 mgCaCO ₃ /L, exhibited favorable nitrification rates and zootechnical performance	Furtado et al. 2015

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>O. niloticus</i>	3.68	pH: 6.5, 7.5, 8.3	The experiment took place over a period of 60 days in indoor tanks. Each experimental unit, with a volume of 37.5 L, was stocked with 25 fish. Liquid sugar cane molasses was used to correct the C:N ratio, with a ratio of 15:1	Maintaining a pH range of 6.5–7.5 in biofloc systems can lead to improved growth, higher net yield, and reduced FCR in tilapia nursery production. This pH range enhances the efficiency of the biofloc system for tilapia rearing	Martins et al. 2019
<i>P. vannamei</i>	6.56	pH: 7.1–7.6; 7.6–8.1	The experiment was carried out in nine indoor fiberglass tanks, each with a water volume of 90 L. The shrimp were transferred to these tanks at a density of 30 shrimp per tank and were kept there for a period of 48 days. The BFT method was employed, and sodium bicarbonate was used to adjust the pH levels	The study's findings indicate that adjusting the pH of the culture water in BFT systems from 7.6 to 8.1 yielded better results compared to adjusting it from 7.1 to 7.6. These results will be valuable for shrimp producers aiming to maintain appropriate pH and alkalinity levels in their BFT systems	Zhang et al. 2017
<i>P. vannamei</i>	0.24	Salinity: 2, 4, and 25 g/L	The shrimp were grown at a density of 300/m ² , with molasses and wheat bran serving as carbon sources. The C:N ratio was about 20:1, and the entire process took 40 days	The highest growth performance and survival rates were seen at a salinity level of 25 g/L. However, it was also found that the shrimp could be successfully raised at a salinity level of 4 g/L	Maica et al., 2012

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>P. vannamei</i>	1.79–1.89	Salinity: 9, 18, and 36	Pacific white shrimp were stocked at 50 individuals/m ² for 60 days	Salinity affects natural communities and production of <i>P. vannamei</i>	Decamp et al. 2003
<i>P. vannamei</i>	2.56	Salinity: 10 and 32 g/L	This research was conducted in indoor 300-L fiberglass tanks, with each tank holding a total water volume of 180 L. Each tank was populated with 70 individuals, corresponding to a biomass of 1 g/L. To stimulate the development of bioflocs and maintain an optimal C:N ratio of 15:1	The trial found that <i>P. vannamei</i> exhibited superior performance in their juvenile stage when an artificial diet was supplemented with biofloc at a salinity level of 32	Khanjani et al. 2020a

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>Litopenaeus setiferus</i>	0.1	Salinity: 5 and 35 g/L	Juvenile shrimps weighing 0.1 g were distributed across six fibreglass tanks, with each tank housing 3000 juveniles (equivalent to 150 shrimps/m ²). These juveniles were allowed to acclimatize for five days. Three groups were set up and monitored over the course of the experiment, which lasted 90 days. During the experimental period, molasses was added in a 6:1 C:N ratio whenever the Ammonia level exceeded 1 mg per liter	The biofloc system has been found to be effective in stabilizing and enhancing conditions for <i>L. setiferus</i> , a highly potential penaeid species for farming, under high salinity conditions. However, during the experimental phase, the system was designed to stimulate oxidative stress, leading to increased cellular damage at low salinity levels due to high oxygen consumption under fasting and postprandial conditions	Valenzuela-Jiménez et al. 2022
Red tilapia	13.78	Salinity: 5, 10, 15, and 20 g/L	Red tilapia fry were stocked in each biofloc unit at a rate of 150 fish per cubic meter. Jaggery was used as the carbon source to maintain a C/N ratio of 15:1	The current research indicates that when reared in higher salinity conditions using inland saline groundwater, red tilapia demonstrated improved growth efficiency, survival rates, biochemical indicators, and carcass quality	Kumari et al. 2021

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>P. vannamei</i>		Salinity: 10, 20, and 30 g/L	<i>P. vannamei</i> (PL8) were stocked at 4000 shrimp/m ³ for 54 days	Operating at a low salinity of 10‰ can significantly reduce salt usage by approximately 50% compared to a 20‰ treatment, resulting in substantial cost savings for production facilities. This research contributes to demonstrating the versatility of salinity options for shrimp production in commercial-scale biofloc systems	Ray and Lotz 2017
<i>P. vannamei</i>	74.46 mg	Salinity: 8, 21, and 32 g/L	Shrimps were cultivated in 300-L fiberglass tanks, each filled with 130 L of water, achieving a density of 1 post-larva per liter. This culture was maintained for a period of 28 days	The study concludes that a high salinity level of 32 ppt enhances the growth and survival of the biofloc supplemented Pacific white shrimp in a BFT system	Khanjani et al. 2020b

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>O. niloticus</i>	1.75	Salinity: 0, 4, and 8 g/L	Fingerling fish were reared for 37 days in tanks, each having a water volume of 140 L. The stocking density was one fish per liter	The study suggests that salinity levels of 4 and 8 g/L can enhance water quality, growth performance, survival, and carcass composition of Nile tilapia fingerlings in a biofloc system. This finding implies that brackish waters can be effectively used for sustainable aquaculture in the rearing of Nile tilapia	Khanjani and Alizadeh 2024
<i>O. niloticus</i>	93.8	Salinity: 0, 4, 8, 12, and 16 g/L	Tilapia were cultivated for 90 days in fibreglass tanks, each with a volume of 800 L. The stocking density was set at 30 fish/m ³	The study suggests that BFT, developed at salinities ranging from 0 to 16 g/L, is suitable for the culture of tilapia. The water quality was maintained in proper conditions for fish performance, with high rates of survival	de Souza et al. 2019

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>O. niloticus</i>	40	Salinity: 0, 4, 8, 12, and 16 g/L	The experiment was conducted for 70 days in 150-L fibreglass tanks, with 60 fish being kept in each tank	The study found that nitrite peaks occurred later and were higher in salinities of 12 and 16 g/L compared to other treatments. Water that was salinized, particularly within the range of 4 to 8 g/L, can be recommended for use in a biofloc tank to enhance the growth performance of Nile tilapia during the initial culture phase	de Alvarenga et al. 2018
<i>O. niloticus</i>	15.62	Salinity: 0, 10, and 20 g/L	The experiment was conducted for 150 days in tanks with a volume of 0.6 m ³ and a density of 2.6 kg/m ³ of fish. Glucose was added to the tanks at a rate of 50% of the feed level to ensure the ideal C/N ratio for the progress of the BFT	The variations in salinity levels in the Biofloc technology (BFT) system resulted in a notable difference in the abundance of microorganisms at the genus level. However, the bacteria genus <i>Cetobacterium</i> was present in all three groups	Luo et al. 2017
<i>P. indicus</i>	0.11	Salinity: 5‰, 15‰, 25‰, 30‰, and 35‰	<i>P. indicus</i> , PL in the BFT with C:N ratio of 15:1 during nursery phase in different salinities, for 40 days <i>P. indicus</i> were stocked at the density of (1.2 PL/L)	The lower salinity rearing with biofloc did not show significantly lower growth than optimum range of salinity in case of <i>P. indicus</i> PL	Das et al. 2023

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>Lates calcarifer</i>	11	DO	Asian sea bass (at a density of 30 fish/m ³) were raised in 50-ton ponds for 100 days	The study successfully established the use of aeration devices and optimized feeding frequencies to enhance oxygen levels in 60-ton freshwater recirculating aquaculture ponds and the biofloc system for Asian seabass rearing. This approach proved to be more efficient than using an ejector, as it increased dissolved oxygen levels through the use of small bubbles and a large specific contact area	Whangchai et al. 2022
<i>Piaractus mesopotamicus</i>	20.70	TSS levels (0, 1500, 3000, 4000, 5000, 6000, and 7000 mg/L)	The treatments were maintained in a static system using 8 L tanks, with 6 L of usable volume, and aeration. Only the water collected for water quality analysis was replaced. Molasses, a carbon-rich substance, was used to adjust the carbon to nitrogen ratio to 15:1	Pacu juveniles exhibited tolerance to TSS concentrations of up to 5000 mg/L, which are not typically utilized in BFT systems. The LC50-96 h (lethal concentration that causes mortality in 50% of the population within 96 h) of TSS for pacu was estimated to be 5477 mg/L	Pellegrin et al. 2022

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>P. mesopotamicus</i>	28.41	TSS levels (0, 250, 500, 750, and 1000 mg/L)	80-L tanks with a useful volume of 60 L were utilized. Each tank contained six fish, resulting in a total of 18 fish per treatment. The duration of the experiment was 5 days	The exposure of fish to elevated TSS concentrations, particularly 750 and 1000 mg/L, resulted in increased levels of blood glucose, pH, erythrocytes, hemoglobin values, and hematimetric indices on the first day. However, by the fifth day, most of these parameters stabilized at varying TSS concentrations. It is important to note that TSS concentrations of up to 250 mg/L are recommended for BFT system production	Pellegrin et al. 2022

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>Rhamdia quelen</i>		TSS: in three concentrations up to 200, 400–600, 800–1000 mg/L	A 21-day trial was conducted to assess the effectiveness of biofloc technology in the growth of <i>R. quelen</i> . The fish were reared at a density of 25 larvae per liter of water. The purpose of the experiment was to evaluate the performance and potential benefits of using BFT in the production of <i>R. quelen</i>	The control treatment in the experiment recorded the lowest survival rate (10.2%) due to an infestation of <i>Ichthyophthirius multifiliis</i> on the 15th day. However, no infestation was observed in the biofloc treatments, resulting in a significantly higher mean survival rate (46.9%) compared to the control. The study suggests that <i>R. quelen</i> larvae can be successfully grown in a biofloc system with TSS concentrations of up to 1000 mg/L. However, it was found that the best growth occurred in tanks with a higher percentage of volatile suspended solids (up to 200 mg/L) and clear water achieved through the daily addition of dextrose	Poli et al. 2015

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>P. vannamei</i>	6.8	TSS: in three concentrations: 200, 400–600, 800–1000 mg/L	Juvenile shrimp were stocked in twelve 850-L tanks at a stocking density of 459 shrimps/m ³ . The study spanned a period of 44 days, during which the growth and development of the shrimp were monitored and evaluated. The purpose of the study was likely to assess the performance and productivity of the shrimp at the given stocking density and tank size over the 44-day period	According to the study, intermediate levels of bioflocs, specifically TSS concentrations ranging between 400 and 600 mg/L, were found to be more suitable for the super-intensive culture of <i>P. vannamei</i> shrimp. This finding suggests that maintaining TSS concentrations between 400 and 600 mg/L can be beneficial in supporting the successful super-intensive culture of <i>P. vannamei</i> shrimp	Schweitzer et al. 2013
<i>P. vannamei</i>	0.72	Low solids and high solids	Eight raceways with a volume of 50 m ³ each were randomly assigned to one of two treatments: T-LS and T-HS. The T-LS treatment had settling chambers adjacent to the raceways with a volume of 1700 L and a flow rate of 20 L/min. On the other hand, the T-HS treatment had settling chambers with a volume of 760 L and a flow rate of 10 L/min	The study suggests that the management of biofloc concentration can have an impact on nitrogen cycling pathways and shrimp production. This indicates that controlling the level of biofloc concentration in the system can influence the efficiency of nitrogen removal and utilization, which in turn can affect the overall productivity of shrimp	Ray et al. 2011

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>P. vannamei</i>	Nauplius (N5)	TSS, 300 and 600 mg/L	In the 14-day study, the focus was on investigating the nursery phase of the nauplius (N5) stage of <i>P. vannamei</i> in a BFT system	As the TSS levels increased, there was an increase in nitrate and total nitrogen concentrations. On the other hand, alkalinity and pH decreased with increasing TSS levels. Based on the findings, it suggests that a BFT system with TSS levels below 300 mg/L can achieve better performance in the nursery phase of <i>P. vannamei</i> nauplii. This indicates that maintaining a lower TSS level in the system can have a positive impact on the overall water quality and the development of the nauplii	Liu et al. 2022

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>Carassius auratus gibelio</i>	6.4	TSS concentrations (10, 300, 600, 800, and 1000 mg/L)	A tank with a volume of 1.80 m ³ was filled with freshwater. The tank was stocked with gibel carp at a density of 250 individuals. The experiment lasted for a duration of 30 days. Molasses was added to the tank 2 h after each feeding. The molasses addition was done at a C/N ratio of 15	The optimal TSS concentration for gibel carp culture was found to be within the range of 600–800 mg/L. This suggests that maintaining TSS levels within this range can promote better growth and performance of gibel carp in the system. Furthermore, the study results indicated that bioflocs produced in the BFT system had the ability to enhance the innate immunity of gibel carp	Zhang et al. 2018
<i>Piaractus brachipomus</i>	2.7	TSS, 200–300 and 400–600 mg/L	Fish fingerlings were exposed to different TSS concentrations in a biofloc system for a period of 45 days. The TSS concentrations were likely varied to assess their effects on fish growth and performance	The findings suggest that maintaining a TSS concentration between 200 and 300 mg/L in biofloc systems is optimal for cultivating red pacu fingerlings without compromising their health and growth. This information can be valuable for fish farmers and aquaculture practitioners in optimizing biofloc system conditions for red pacu fingerling production	Angeles-Escobar et al. 2022

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>O. niloticus</i> , <i>Sciaenops ocellatus</i> , and <i>P. vannamei</i>	85 tilapia, 2 shrimp, and 71 red drum	TSS	The experiment compared the use of tilapia to control suspended solids (biological treatment) to control systems without tilapia. The initial mean weights and stocking densities were: 2 g and 250 ind/m ³ for shrimp; 71 g and 1.04 kg/m ³ for red drum; and 85 g and 5.12 kg/m ³ for tilapia	The study suggests that Pacific white shrimp, red drum, and tilapia can be successfully cultured in an integrated multispecies system using BFT. This indicates that these three species can coexist and thrive in the same system, which can have potential benefits such as resource utilization and waste management	Poersch et al. 2021
<i>P. vannamei</i>	4.54	TSS 100–300, 300–600, and 600–1000 mg/L	In the 42-day trial, different treatments with three ranges of TSS were tested. Shrimp juveniles were stocked at a density of 372 shrimps/m ³	The findings emphasize the importance of carefully managing TSS concentrations (between 100 and 300 mg/L) during the formation and maintenance of biofloc systems. By maintaining TSS within the recommended range and reducing variations, aquaculture practitioners can optimize water quality, enhance nutrient recycling, and support the overall health and performance of the cultured organisms	Gaoma et al. 2017

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>P. vannamei</i>	6.2	TSS 30 and 400 mg/L	The experimental design was carried out with three treatments, (1) BFT: cultivation of <i>Ulva lactuca</i> in effluent from shrimp cultivation in a BFT, with 400 mg/L of TSS; (2) DEC: cultivation of <i>U. lactuca</i> in effluent from shrimp culture in a BFT, after a period of decantation of solids, with 30 mg/L of TSS; (3) VS: cultivation of <i>U. lactuca</i> in standard von Stosch enrichment solution at a concentration of 10 mL/L, for 35 days	Cultivation of <i>U. lactuca</i> in shrimp effluent water with a TSS level of 30 mg/L resulted in significantly lower TSS levels compared to the BFT groups, which had a TSS level of 400 mg/L. This method can be used to improve water quality and reduce environmental impacts associated with shrimp farming	Carvalho et al. 2023
<i>O. niloticus</i> and Samhong mustard (<i>Brassica juncea</i> L.)		Heavy metals: Cu, Fe, and Zn	Fish ponds were filled with 0.88 m ³ of water, and 1000 fish with a length of 2–3 cm were added. The rearing period for the fish was 42 days	The concentrations of Cu (copper), Fe (iron), and Zn (zinc) in the fish ponds were within the ranges of 0.0036–0.02260 mg/L, 0.5269–1.1013 mg/L, and 0.0215–0.2581 mg/L, respectively. While only the Cu concentrations did not exceed the quality standard, the growth of <i>O. niloticus</i> and <i>B. juncea</i> was fast, and fish survival was high (> 95%)	Deswati et al. 2022

Table 3 (continued)

Cultured species	IBW (g)	Influential parameter	Relevant rearing conditions	Main findings	Reference
<i>O. niloticus</i>	8.32	MPs	Nile tilapia were exposed to MPs made of polystyrene with a diameter range of 32–40 µm. The exposure was conducted in a BFT system for a duration of 28 days. Three different treatment groups were used: 0 items/L (control group), 80 items/L (equivalent to 30 µg/L), and 800 items/L (equivalent to 300 µg/L)	It can be concluded that MPs had no significant effects on nitrification in the BFT systems or on the digestive activity of tilapia. The presence of MPs did not significantly influence the microbial communities in the BFT systems or the gut microbiota of the tilapia	Hu et al. 2023

Abbreviations: *IBW* initial body weight, *WT* water temperature, *C:N* carbon to nitrogen ratio, *GIFT* genetically improved farmed tilapia, *DO* dissolved oxygen, *TSS* total suspended solids, *T-LS* treatment-low solids, *T-HS* treatment-high solids, *ROS* reactive oxygen species, *FW* final weight, *SGR* specific growth rate, *SBRs* sequencing batch reactors, *PL* postlarvae, *PPT* parts per thousand, *MPs* microplastics

Temperature

Water temperature is a key determinant of the health and survival of cultured organisms as fluctuations in temperature can adversely affect growth and survival (Whang-chai et al. 2018; Cheng et al. 2018). Temperature also influences various chemical and biological parameters, including DO and the rate of chemical reactions (Mubiana and Blust 2007; Hostins et al. 2015). Increasing water temperatures can result in a drop in DO, leading to respiratory distress marked by difficult breathing and heightened oxygen exchange on the surface of the gills (Lewis et al. 2012). Temperature also affects physiological pathways, behaviors, and reproduction, leading to changes in maturation and stages of reproduction such as ovulation, hatching, and embryogenesis (Narum et al. 2013; Kim et al. 2017). Microbial metabolism is similarly affected by temperature (Price and Sowers 2004). Very cold temperatures (4 °C) promote deflocculation compared to cool temperatures (18–20 °C), likely due to reduced microbial activity in the flocs (Wilen et al. 2000). In warmer waters (30–35 °C), sludge bulking occurs, characterized by high sludge volume index ($SVI \geq 500$ mL/g), due to overproduction of extracellular polymeric substances (Krishna and Van Loosdrecht 1999). At moderate temperatures (20–25 °C), flocs are more stable with a medium SVI of around 200 mL/g. It can be challenging to adjust water temperature in BFT ponds, particularly in outdoor farms, due to the costs associated with temperature regulation (Phulia et al. 2012). Temperature greatly impacts biofloc characteristics. Lower temperatures restrict biological processes including the activity of microbial organisms (Arnosti et al. 1998; Garcia et al. 2011; de Souza et al. 2016). This could impede the growth of biofloc microorganisms and lower the rate of nitrification. This effect is most pronounced when the cold exposure is sudden. Experiences from activated sludge systems suggest suitable organic matter biodegradation and nitrification under sub-20 °C conditions, but extremely low temperatures may potentially lead to a complete cessation of nitrification (Johnston et al. 2019). The mechanisms underpinning the relationship between temperature and nitrification are still unclear, but changes in the interactions between microorganisms are one of the possibilities. An overwintering experiment in tilapia culture showed that existing bioflocs withstood <4 °C temperatures and still carried out nitrogen removal (Crab et al. 2009). Water temperature is also critical for white shrimp *P. vannamei*. Extreme temperature fluctuations might lower immune resistance, increasing vulnerability to *Vibrio* infection (Cheng et al. 2005). Since many viral infections in shrimp are affected by temperature, it is advisable to maintain water temperature at around 29 °C or higher, especially to control viruses involved in white spot syndrome (Lim et al. 2021). In BFT, the optimal temperature range for shrimp is around 30 °C (27–33 °C for giant freshwater prawn, 28–30 °C for Pacific white shrimp, and 28–32 °C for the giant tiger prawn). However, shrimp can endure lower temperatures at the cost of growth. A study by de Souza et al. (2016) found the best results at 27 °C, with shrimp showing superior growth and reduced oxidative stress. Tilapia can survive in cold conditions (<5 °C), but will not feed at <15 °C (Crab et al. 2009). Similar temperature preferences are observed in African catfish (*Clarias gariepinus*), channel catfish (*Ictalurus punctatus*), and milkfish (*Chanos chanos*). On the other hand, species like gray mullet (*Mugil cephalus*) and common carp (*Cyprinus carpio*) thrive below 30 °C, but require temperatures above 20 °C (Bagi et al. 2023).

Tables 2 and 3 provide detailed information on the suitable temperature ranges for shrimp and tilapia, and the impact of varying water temperatures on biofloc system

performance and the cultivated species. A study by Ponce-Palafox et al. (2019) observed a decrease in pH with rising temperatures in BFT shrimp aquaculture, particularly at 32 °C, mirroring results from similar research in the past (Hostins et al. 2015; de Souza et al. 2016). Additionally, at 32 °C, there tends to be an increase in TAN, nitrites, nitrates, TSS, and SS, aligning with findings from the literature (de Souza et al. 2014; Hostins et al. 2015).

pH and alkalinity

Maintaining proper pH is crucial in BFT (Martins et al. 2019). It is recommended to maintain pH within the 7.0–8.5 range to ensure the desired functioning of the system (Emerenciano et al. 2017). Even minor changes in pH can significantly impact the biochemical processes in water (Suchithra et al. 2016; Ahammed et al. 2022). For instance, marine shrimp culture exhibits optimal growth in neutral to mildly basic environments (pH=7.0–9.0) (Van Wyk and Scarpa 1999). pH is a determinant in nearly all chemical reactions, impacting both water chemistry and the physiology of shrimp (Lemonnier et al. 2004). pH < 6.5 or > 9.5 has been linked to inhibited growth in Penaeidae species. The optimal pH range for shrimp culture (7.0–9.0) is also conducive to the proliferation of heterotrophic and nitrifying microorganisms (Chen et al. 2006; Van Wyk and Scarpa 1999).

Previous research has indicated that the downward pH trend observed in biofloc systems may be attributable to bacterial production (Azim et al. 2008; Lim et al. 2021), increased respiration by heterotrophic microbes, and elevated CO₂ levels (Emerenciano et al. 2012; Miao et al. 2017; Vinatea et al. 2010; Gaona et al. 2016). McIntosh (2001) highlighted that higher densities lead to increased respiratory rates and elevated CO₂ levels, subsequently causing pH reduction. A study conducted in Belize showed that *P. vannamei* exhibited resilience to pH levels between 6.8 and 7.3. Conversely, Wasielesky et al. (2006b) report that pH < 7 adversely affects the growth of *P. vannamei* in BFT culture. Hence, it is essential to conduct experimental studies regarding the impact of alkalizers on the quality of water and the performance of *P. vannamei*.

pH has a significant influence on bacterial growth, with the optimal range for heterotrophic bacteria being between 7.0 and 10.0 (Mayo and Noike 1996); the figure for autotrophic species is 7.0–8.0 (Chen et al. 2006). Factors such as inorganic nitrogen levels, total biomass of bacteria, DO, pH, and temperature are known to influence the rate of nitrification (Chen et al. 2006). The role of alkalinity in nitrification is also significant, with studies highlighting the substantial influence of inorganic carbon levels, particularly in the production of nitrite from ammonia (Chen et al. 2012). Several studies have assessed the effect of pH on nitrification rate in the context of bioreactors and effluent treatment. Martins et al. (2019) observed no significant pH-dependent effects on the initial stage of nitrification, as the total conversion of ammonia to nitrite remained consistent across different treatments. However, the subsequent phase displayed a correlation with pH, particularly regarding the rate of nitrification. The maximum nitrite-nitrogen concentration occurred at pH=6.5. Various experiments, such as the study by Jiménez et al. (2011), have demonstrated robust nitrification at pH=7.5, and a cessation of the process at pH=6.5. In contrast, Tarre and Green (2004) observed active nitrification at pH=4.3 in a bioreactor. Villano et al. (2010) illustrated that pH is fundamental to the composition of the biofloc microbial community, promoting adaptability to environmental shifts and the regulation of nutrient uptake and metabolism (Lauro et al. 2009). The research by Martins et al. (2019) further indicates

the feasibility of sustaining nitrification at pH=6.5 through managing the composition of microbial flora.

Alkalinity is defined as the capacity to neutralize acids and maintain pH stability (Furtado et al. 2015). Biofloc culture water tends to decrease pH over time, so demand for alkalizing agents increases (Ebeling et al. 2006b; Lim et al. 2021). Given that pH values outside the 7.0–8.0 range can significantly affect biochemical reactions and physiological processes, dolomite must be steadily supplied to restore and maintain water alkalinity. There are no definitive guidelines regarding maximum alkalinity levels, but alkalinity should be maintained above 100 mg CaCO₃/L, especially in salt water culture conditions (Crab et al. 2009; Furtado et al. 2011). Higher alkalinity levels (up to 300 mg CaCO₃/L) have been associated with improved nitrification and shrimp growth (Furtado et al. 2015). Van Wyk and Scarpa (1999) state that *P. vannamei* requires alkalinity > 100 mg CaCO₃/L for optimal shrimp growth, also noting that higher alkalinity levels can reduce daily pH fluctuations. In a BFT system for *P. vannamei* culture with a density of < 610 shrimp/m², Vinatea et al. (2010) utilized 0.12 g/L pure NaHCO₃ to elevate alkalinity when values were below 60 mg CaCO₃/L. In freshwater conditions, studies on Nile tilapia in BFT systems have presented the consumption of alkalizing agents and decreased pH (Alvarenga et al. 2018; Azim & Little 2008; Pérez-Fuentes et al. 2016). In BFT systems, pH can decrease due to decreased alkalinity, elevated CO₂, and increased respiration (Vinatea et al. 2010). Therefore, it is essential to maintain proper alkalinity levels via supplementation of alkalizing agents such as sodium carbonate, calcium hydroxide, and sodium bicarbonate before and during the production cycles (Boyd et al. 2016).

Maintaining pH in the 7.5–7.9 range and an alkalinity of 100–162.2 mg CaCO₃/L in BFT systems remarkably improves productivity (Furtado et al. 2011). Furthermore, when alkalinity is maintained in the 40–160 mg CaCO₃/L range, TSS, ammonium, nitrite, and nitrate are unaffected (Piérri 2012). However, alkalinity > 160 mg CaCO₃/L has been linked to increased pH, boost biomass of heterotrophic and ammonium-oxidizing bacteria, and a decrease in nitrite-oxidizing bacteria (Piérri 2012). Water alkalinity and pH are also affected by the solids management (Schveitzer et al. 2013). These authors found that the amount of alkalinity and pH in *P. vannamei* biofloc water is higher with 200–400 mg/L of TSS when compared to higher levels (400 to 600 mg/L, and 800 to 1000 mg/L). This higher level of alkalinity in 200–400 mg/L of TSS could be a response to denitrification as pointed out in past studies (Ebeling et al. 2006a; Ray et al. 2010a, b, 2011).

Salinity

Salinity range can play a major role in biofloc development and impact the microbial community (Maicá et al. 2014). Table 2 shows the most common values of salinity in BFT, where its optimal levels are species-specific. Table 3 shows the effects of different salinities on the characteristics of BFT systems and cultured species. For instance, Hakanson (2006) observed a trend for suspended particle aggregation and floc size to increase with higher salinity. Studies conducted by Maicá et al. (2012) and Khanjani et al. (2020a) with *P. vannamei* indicate a progressive increase in biofloc levels (settling solids), reaching its peak at elevated salinity levels. The same trend was observed by Decamp et al. (2003) also highlighting a decrease in pH at higher salinity (36 g/L) in comparison to lower salinity treatments (18 and 9 g/L) in zero-water-exchange *P. vannamei* juvenile culture. According to the authors, this phenomenon is attributed to enhanced photosynthetic activity at lower salinities. This trend was also noted by Maicá et al. (2012) with *P. vannamei* biofloc-based

culture where higher biofloc levels were observed at 25 g/L, leading to lower pH as a result of high microbial respiration (Wasielesky et al. 2006a).

Several studies also highlighted that salinity changes in water can also impact the meat nutritional quality (Huang et al. 2004; Khanjani et al. 2020a; 2020b).

In BFT, Khanjani et al. (2020a) demonstrated an increase in dry matter, protein, lipid, and ash in shrimp corroborated with rising salinity. The relationship between protein content and salinity was further investigated by Liang et al. (2008) and Maicá et al. (2014). Maicá et al. (2014) reported higher ash and lipid content in shrimp at higher salinities, emphasizing the influence of biofloc-based culture on shrimp biochemistry, as indicated by elevated ash and lipid levels in no-exchange treatments compared to controls. Khanjani et al. (2020a) observed elevated biofloc protein content at higher salinity levels. However, Ju et al. (2008) and Maicá et al. (2014) reported elevated protein levels at minimum salinity. With the increase in salinity, a decrease in biofloc lipid content was noted, with the highest and lowest levels respectively observed at 10 and 32 g/L (Khanjani et al. 2020a). Biofloc ash content was also directly correlated with salinity (Maicá et al. 2014), the same trend corroborated by Ju et al. (2008), who reported ash percentages of 18.3 and 40.7% at 5 and 32 g/L, respectively. Valenzuela-Jiménez et al. (2022) conducted a comprehensive study on the effect of low (3 g/L) and high (35 g/L) salinities on oxygen consumption, performance, oxidative stress, and antioxidant activity in outdoor BFT culture of *Litopenaeus setiferus*. The study revealed improved feed utilization and FCR with higher salinity and reduced weight gain and survival in low salinity. The poor performance in low salinity is attributed to the unbalanced ionic composition and nitrite toxicity (Soares de Moura et al. 2021).

Dissolved oxygen (DO)

Suitable DO level is an important factor for proper development of bioflocs (De Schryver et al. 2008). Studies indicated a correlation between DO and the growth and densification of bioflocs (Wilén and Balmer 1999). Suboptimal settling characteristics in bioflocs were found at reduced DO (0.5–2.0 mg/L), evidenced by an SVI of 250 mL/g. In contrast, a higher DO (2.0–5.0 mg/L) reduces SVI to approximately 100 mL/g (Phulia et al. 2012). However, it is possible for bioflocs with larger SVI to develop under diminished DO conditions. For instance, these bioflocs can be consumed by the cultured species before the bioflocs settle to the bottom (Khanjani and Sharifinia 2024). Nonetheless, culture conditions with high concentration of suspended particles (bioflocs) can obstruct the gill structures of fish and shrimp (Emerenciano et al. 2013).

BFT with shared environment of cultured animals and microbes (bioflocs) can face substantial oxygen demand (Yu et al. 2023a, b). Especially in intensive farming systems, shrimp and fish typically require high DO levels, normally exceeding 5 mg/L (Patkaew et al. 2024). A culture medium with high biofloc concentration can significantly elevate the demand for oxygen, occasionally surpassing the requirements of cultured species themselves (Raza et al. 2024). In addition, the oxygen requirements can differ between in situ and ex situ biofloc systems. The DO demand in in situ systems relates to the sum of cultured species and bioflocs requirements, whereas in ex-situ systems where bioflocs are formed externally in a decoupled biological reactor, the primarily oxygen demand relates to the microbial communities (Ulloa-Walker et al., 2020). In this sense, in biological reactors, a minimal DO requirement of 1 mg/L can address the needs of biofloc organisms (Kuhn

and Lawrence 2012). For effective in situ and ex situ operations, the biofloc facility must incorporate emergency power sources to counteract potential power outages, as inadequate aeration can swiftly lead to critically low DO levels and mortalities (Vinatea et al. 2009). Vinatea et al. (2009) found that in the absence of aeration, a DO concentration of 4.1 mg/L could plummet to a critical level (0.65 mg/L) within 31.8 and 34.7 min in superintensive (610 shrimp/m²) *P. vannamei* culture, depending on the presence or absence of light. Their subsequent study (Vinatea et al. 2010) revealed a higher oxygen consumption rate in superintensive BFT shrimp culture under illuminated conditions up to 20 min after aeration was stopped, at which point the dark condition had higher oxygen consumption. To enhance DO and aeration efficiency in BFT systems, several aeration devices have been evaluated, including paddle-wheels, venturis-nozzles, blowers with diffusers, submerged double helix aerators, and mixed combinations (Pasco 2015; Piñeros-Roldan et al. 2020). The suitable device or combination in BFT will depend on cultured species selection (e.g., shrimp or fish), phase (nursery or grow-out), tank and pond design, and water depth, among other characteristics (Piñeros-Roldan et al. 2020).

Total suspended solids (TSS) and settling solids (SS)

TSS and SS are examples of critical water quality parameters utilized for assessing biofloc concentrations in culture conditions (Soaudy et al. 2023). However, depending on the method selected, accuracy and time consumption can vary drastically. This can be partially solved as some studies reveal correlation among SS, TSS, water transparency, and turbidity (Ray et al. 2010a, b; Schweitzer et al. 2013; Khanjani et al. 2021), meaning more cost-effective ways to monitor the biofloc concentrations.

The optimal values of SS and TSS for biofloc systems are presented in Tables 2 and 3. It is important to note that optimal TSS ranges can vary by species. For instance, Avnimelech (2012) recommends 200–400 mg/L for tilapia. Hatem et al. (2013) recommend a maximum TSS range of 220–250 mg/L for tilapia to avoid gill clogging, but higher levels may be detrimental for earlier tilapia stages (or nursery phase) as highlighted by Emerenciano et al. (2017). In contrast, Poli et al. (2015) observed no significant variation in *Rhamdia quelen* fish larvae survival across a TSS range of 200–1000 mg/L, indicating the animals' tolerance to high biofloc environments. Fingerling stage (5.7–10.2 g) of red cachama (*Piaractus brachypomus*) tolerates TSS levels ranging from 384 to 645 mg/L with survival rates between 84 and 99% (Ueno-Fukura et al. 2019). Similar levels were found by Angeles-Escobar et al. (2022) for the same species with levels ranging from 200 to 600 mg/L; however, optimal performance was achieved at TSS=200–300 mg/L. For fish, species, phase of culture, and natural conditions in the wild seem to have impact on the animal's ability to tolerate high TSS levels in culture conditions. For marine shrimp, the literature is more abundant regarding TSS and its impact on performance, water quality, and health. The most common range of TSS maintained in biofloc systems for shrimp is between 400 and 600 mg/L (Avnimelech 2012; Gaona et al. 2011; Samocha et al. 2007; Schweitzer et al. 2013). Higher TSS levels have been associated with negative performance of *P. vannamei* (Vinatea et al. 2010; Schweitzer et al. 2013). Studies suggest that TSS levels below 600 mg/L are most suitable for shrimp farming in biofloc systems (Ray et al. 2010a, b; Schweitzer et al. 2013). Regarding *P. vannamei* nauplii, Liu et al. (2022) recommend TSS level < 300 mg/L to achieve improved performance in larviculture. TSS can also have a key impact on water quality parameters. Ray et al. (2011) found that at TSS=200 mg/L, nitrite and nitrate levels are lower while ammonium and phosphate levels are higher

compared to TSS = 300 mg/L. In the same study, the growth rate was also higher (1.7 g/week) at 200 mg/L than at 300 mg/L (1.3 g/week), and at TSS = 800–1000 mg/L, shrimp experienced poor growth and significant gill obstruction. The authors suggested that lack of suitable substrates for nitrifying bacteria, rapid denitrification in settling chambers, or algal nitrate assimilation can have a severe impact on N-compounds fluctuations (Ray et al. 2011). In the same context, Schweitzer et al. (2013) recommend maintaining TSS between 200 and 600 mg/L for optimal growth and system stability. According to both studies, low TSS conditions exhibited faster shrimp growth and enhanced environment conditions, highlighting the role of biofloc concentrations on nitrogen cycling. In addition, maintaining TSS in suitable conditions helps the functionality of biofloc systems, emphasizing the balance between bacterial oxygen demand and system productivity (Hargreaves 2013).

Throughout the culture cycle, TSS tends to increase if not properly managed (e.g., use of clarifiers; Ray et al. 2011; Gaona et al. 2011). Higher TSS levels can decrease DO, pH, alkalinity, and ammonia, but promoting nitrate accumulation (Avnimelech 2012; Gaona et al. 2017). Furtado et al. (2011) also observed that changes in pH and alkalinity can impact TSS levels. However, saturated culture conditions with high TSS levels may also result in higher nitrite concentrations (Samocha et al. 2007; Luo et al. 2013). The addition of external organic carbon sources can help reduce ammonia levels (Lin and Chen 2001), but unlikely to control nitrite levels especially in high TSS conditions with DO, pH, and alkalinity fluctuations. Suitable ranges of these parameters are critical to ensure proper chemoautotrophic bacteria metabolism, especially nitrite-oxidizing bacteria (Ebeling et al. 2006b). Low levels of TSS may result in a more stable culture environment, avoiding triggered competition for DO, micronutrients, and space by heterotrophic and chemoautotrophic (nitrifying) bacteria (Luo et al. 2013).

In terms of practicality, SS is considered a cost-effective way to measure solids concentration in BFT, especially in commercial operations (Avnimelech 2012). Lim et al. (2021) in a 70-day *P. vannamei* culture cycle reported insignificant SS in the first 30 days, followed by a significant increase during days 35–70. Low SS levels have been suggested to enhance the overall biofloc conditions and system stability (Lim et al. 2021).

The red-bellied pacu (*Piaractus brachypomus*) has demonstrated a notable tolerance to varying levels of SS. In juvenile stages (33.5–182.6 g), SS concentrations of 56.6 ± 20.7 mL/L were tolerated (Brú-Cordero et al. 2017). The tolerance of different SS levels may be species-phase related, having impact on other water quality parameters, animal performance, and health.

Nitrogenous compounds

Nitrogen, an essential element for all living organisms, is supplied through dietary proteins which are digested and used to synthesize various biomolecules (Wei et al. 2016). Nitrogen accounts for approximately 5% of an organisms' dry weight (Sigeo 2005). Within aquatic ecosystems, nitrogen exists in both organic and inorganic forms. Organic nitrogen is primarily derived from residual feed, animal waste, dead matter, and urea. In contrast, inorganic nitrogen encompasses ammonia and ammonium ($\text{NH}_3/\text{NH}_4^+$), nitrite (NO_2^-), nitrate (NO_3^-), and to a lesser extent, nitrogen gas (N_2) (Jiménez-Ojeda et al. 2018). In aquatic environments, especially BFT conditions, heterotrophic bacteria and protozoa are critical organisms capable of utilizing undissolved nitrogen (Sigeo 2005) sourced by organic matter continuously added to the systems. Understanding the different nitrogen pathways, acting microorganisms and suitable compounds ranges are key for proper water

quality maintenance and decision-making in BFT (Khanjani et al. 2022). Some of these compounds can be highly toxic (e.g., NH_3 and NO_2^-), and poor water quality management can lead to system collapse and high mortality rates (Lin et al. 2023). At high concentrations, these compounds may impair oxygen transport and induce gill irritations and lesions, as well as lead to hypoxia, enzymatic dysfunctions, and impair T4 hormone production (Abakari et al. 2021).

Table 2 presents suitable nitrogen compound concentrations in biofloc systems for different species and Table 4 presents the microorganisms involved in the removal of nitrogenous compounds in BFT. The successful operation of BFT largely hinges on the effective management of water quality, especially conversion of harmful nitrogenous compounds. In a stable BFT environment, parameters such as ammonia and nitrite must be maintained within acceptable ranges and continuously converted into benign compounds and biomass through microbial processes (Khanjani et al. 2022). Ebeling et al. (2006a) and Khanjani et al. (2022) present a stoichiometric framework for nitrogen removal in BFT while considering microbial growth and metabolic kinetics. The framework provides information on substrate requirements, biomass production, and the outcomes of primary nitrogen removal pathways, namely algal assimilation, autotrophic nitrification, and heterotrophic assimilation.

Algal assimilation is often the predominant pathway for nitrogen removal in outdoor BFT systems, with continuous light exposure (Zemor et al. 2019). On the other hand, in conditions where photosynthetic activity is suppressed (e.g., using shading or indoor environments), chemoautotrophic nitrification and heterotrophic assimilation are considered the prevalent pathways for nitrogen removal (Avnimelech 2012; Samocha et al., 2017). Algae assimilate CO_2 into organic carbon, and ammonia is directly incorporated into algal biomass. Normally, the need for external organic carbon supplementation is reduced, except to promote mixotrophic growth (Cecchin et al. 2018), and fluctuations of alkalinity and pH are less common while nitrogen is assimilated during photosynthesis (Mohsenpour et al. 2021). However, in these systems, there is a risk of algal population crashes, abruptly releasing nitrogen back into the water (NO_2 spikes) and causing sudden mortalities (Samocha et al. 2017). In these systems, aeration and mixing are still needed to maintain optimal DO.

In more controlled shaded or indoor BFT culture conditions, ammonia oxidation followed by nitrite oxidation (nitrifying bacteria) and ammonia assimilation by heterotrophic bacteria were found as main pathways for toxic N-compounds control (Khanjani et al. 2024c). In addition, denitrification, transforming nitrate into N_2 (Samocha 2019), and integrated systems using plants (Pinho et al. 2022) are also presented as potential tool to prevent N accumulation in BFT (Deng et al. 2020; Rajta et al. 2020). Nitrification via

Table 4 Microorganisms involved in the removal of nitrogenous compounds in the biofloc system (Ebeling et al. 2006a; Jiménez-Ojeda et al. 2018; Khanjani et al. 2022)

	Heterotrophic	Chemoautotrophic	Photoautotrophic
Main energy source	Organic matter	Inorganic compounds	Solar radiation
Main nitrogen source	NH_4^+	NH_4^+ , NO_2^-	NH_4^+ , NO_3^-
Main carbon source	Organic	Inorganic	Inorganic
Dominant process	Assimilation	Nitrification, conversion	Photosynthesis, assimilation, removal
Relative growth rate	Fast	Slow	Dependent on sunlight, fast

Abbreviations: NH_4^+ ammonium, NO_2^- nitrite, NO_3^- nitrate

chemoautotrophic bacteria produces nitrate while minimal biomass is added to bioflocs due to the slow growth of nitrifying microorganisms. In heterotrophic pathway, proper organic carbon management is mandatory, both requiring substantial aeration and alkalinity/pH control (Khanjani et al. 2024b). Collectively, these processes offer BFT operators various strategies to manage harmful nitrogenous compounds (Leong et al. 2021; Roy et al. 2019). Emerenciano et al. (2022a) bring a comprehensive review summarizing several intensive penaeid systems including biofloc technology and similar microbial-based systems (e.g., Synbiotics, Aquamimicry, semi-biofloc). The authors highlighted the role of the different microbial-based farming techniques, and its direct effect on microbial pathway and ultimately nitrogen removal. Therefore, the selection and management of culture conditions are directly linked to N-compounds management in BFT-based aquaculture.

Phosphate

Monitoring and maintaining phosphate (PO_4^{3-}) levels in aquaculture systems is crucial for recirculation management and effluent discharge. Due to its limited water exchange condition, in BFT, phosphate tends to accumulate over time; however, it can vary according to the biofloc approach and culture conditions (Emerenciano et al. 2022b). Lim et al. (2021) found a direct correlation between phosphate levels, time, and TSS in BFT. High (PO_4^{3-}) levels may cause reduction in N:P ratio, leading to cyanobacteria outbreaks and less prevalence of desirable photosynthetic organisms such as chlorophytes and diatoms (Smith 1983). In a healthy and stable BFT, these groups should be prevalent in the phytoplankton assemblage, known as key phosphate consumers. Unlike nitrogen, phosphorus does not volatilize, so the forms present in water include organic forms and residual orthophosphate (Silva et al. 2013).

Luo et al. (2014) observed lower phosphate concentrations in BFT systems compared to RAS systems, suggesting active microbial phosphate cycling in bioflocs. Ray and Lotz (2014) also reported reduced phosphate levels, attributing this to uptake by algae and heterotrophic bacteria, as corroborated by Longnecker et al. (2010) and Liu et al. (2018). Feed input directly influences phosphate levels (Montoya et al. 2000). Feed and animal waste are the primary sources of phosphorus in water (Barak et al. 2003). In BFT systems, *P. vannamei* can incorporate up to 35% of the system's total phosphorus intake, with the remaining phosphorus existing in dissolved and particulate forms (Silva et al. 2013). However, fish and shrimp are normally resistant to phosphate concentrations, as shown by the absence of reports of phosphate toxicity (Silva et al. 2013). Due to its limited literature, there is a need for more R&D to better elucidate the phosphate role in BFT-based culture conditions.

Heavy metals and microplastics: key considerations for BFT

Heavy metals (HMs) are a group of naturally occurring elements with high atomic weight that are often toxic to humans and animals (Mitra et al. 2022). These elements can enter aquaculture systems through various sources, including feed, water, sediment, and air (Hossain et al. 2023a). Once in the system, HMs can accumulate in the tissues of fish and other aquatic organisms, and may pose a health risk to consumers. There is little information regarding BFT-based aquaculture and heavy metals. There is evidence that BFT systems are capable of removing HMs from the culture environment (Deswati et al. 2022; Habib et al. 2023a; 2023b). In *O. niloticus* culture, Habib et al. (2023b) found that BFT

was effective in removing HMs (Cu, Cd, Zn, Pb, and Cr) with lower concentrations compared to an earthen pond system. In an integrated tilapia (*O. niloticus*) and Samhong mustard (*Brassica juncea* L.) biofloc-based culture, Deswati et al. (2022) observed a notable reduction in Cu levels on day of culture (DOC) 42 onwards. The authors suggested that biofloc-based aquaponics may mitigate metal concentrations via microbial activity and plant absorption while preserving water quality (Deswati et al. 2022). In terms of microbial community, cyanobacteria are a type of bacteria typically found in both freshwater and marine BFT-based aquaculture (Khanjani et al. 2022). These microbes can produce extracellular polymeric substances (EPS) able to foster particle aggregation (bioflocs), bind to HMs, and act as a carrier throughout the system (Lama et al. 2016). The suspended particles (bioflocs) can now be easily removed utilizing settling chambers (Ray et al. 2011; Gaona et al. 2011). In a study by Bender et al. (1991 and 1994), the cyanobacterium *Oscillatoria* sp. was shown to be effective at removing a variety of HMs from water, including Mn, Pb, Cd, Cu, Zn, Co, Cr, and Fe. The authors observed that HM levels in water treated with *Oscillatoria* sp. was significantly lower than those in untreated water.

As per HMs, there is also limited information regarding BFT-based aquaculture systems and microplastics. Microplastics (MPs) are plastic particles < 5 mm and present a considerable challenge in the field of aquaculture. MPs have been observed in a range of aquaculture settings, including aquaculture ponds (Ma et al. 2020), rice-fish co-culture systems (Lv et al. 2019), estuarine aquaculture areas (Liu et al. 2023), RAS systems (Lu et al. 2019), and BFT systems (Hu et al. 2023). In koi carp culture, accumulative MP uptake can lead to severe consequences, including reduced feed intake and potential starvation (Ouyang et al. 2021). MPs have been also shown to interfere with digestive enzymes, trigger the release of immune cytokine digestive tract in guppy fish (Huang et al. 2020), cause behavioral changes, affect energy reserves and food composition, and disrupt liver function in guppy (Lai et al. 2021; Yin et al. 2018). In addition, MP infiltration into fish muscle tissue is also important from a consumer health perspective (Yang et al. 2020; Zitouni et al. 2020) as MPs may impact human health (Hossain et al. 2023b).

As MP pollution in aquaculture has garnered increasing attention in recent years, BFT may emerge as a promising mitigation strategy (Hossain et al. 2023b; Meng et al. 2023), especially due to its rich microbial biodiversity (Hu et al. 2023). The exponential growth of diverse microbial population including fungi, protozoa, and bacteria (Khanjani et al. 2022) may enable a fast MP decomposition (Abakari et al. 2022). These microorganisms can break down the plastic into smaller molecules, which can then be further degraded by other processes (Li et al. 2022; Wu et al. 2022). The study found that the biofloculants produced by *Bacillus enclensis* had a flocculating activity of 93%, and they were able to reduce microplastic pollution by up to 80% (Shukri et al. 2022). Amini et al. (2022) found that a variety of bacteria, including *Pseudomonas* sp., *Bacillus* sp., and *Vibrio* sp., have been shown to be able to degrade microplastics. In addition, biodegradation of microplastics was observed in *Pseudomonas* sp. MB4 at a rate of 20% per day (Huang et al. 2022a), *Bacillus cereus* B-1 at a rate of 10% per day (Li et al. 2022), and *Pseudomonas aeruginosa* B-3 at a rate of 15% per day (Wu et al. 2022), both groups commonly present in BFT aquaculture conditions. Those rates can be affected by numerous factors, such as the type of plastic, the concentration of bacteria/fungi, and the environmental conditions (Amini et al. 2022; Meng et al. 2023).

In BFT systems, Hu et al. (2023) examined the impact of polystyrene particles with 32–40 µm diameter range in Nile tilapia (*O. niloticus*) cultivation for 28 days. The study revealed that exposure to 0.80 and 800 particles/L did not affect water quality (including

nitrification), water (biofloc) and gut microbial communities, tilapia growth, or digestive enzyme activity. However, changes in crude protein and lipid content were observed, as well as an increase in the hepato-somatic index, suggesting potential interference with liver digestive absorption. The authors revealed that MPs were not detectable in tilapia feces from day 16. The highest concentration of MPs was found in the liver followed by the gills, while microparticles were not observed in muscle tissue. These studies may indicate that BFT microorganisms may tolerate water containing MPs without affecting water quality, animal performance, nitrification, and other key microbial properties. It may also help to degrade MPs, thereby presenting a promising area for future research into MP remediation. However, due to its limitation, further toxicological studies are needed to better illustrate the role of BFT aiming to overcome MPs challenges in aquaculture (Wei et al. 2021, 2022).

Conclusions and perspectives

The present review emphasizes the importance of proper water quality management in BFT, and to maintain key parameters such as N-compounds, temperature, salinity, TSS, SS, pH, DO, and alkalinity in optimal levels. Routine monitoring, interpretation, and intervention are essential to sustain a desirable environment, animal welfare, health and performance. There is still a lack of understanding related to water quality and BFT, especially in commercial biofloc-based shrimp and fish operations. Developing a comprehensive bibliometric analysis, this review intended to combine relevant water quality literature in fish and shrimp biofloc systems, and support decision-making to improve farming operations. In the future, BFT is expected to play a major role as suitable technology for pond water quality management. The present study underscores the importance of understanding the complex interactions within BFT systems and the potential of bioflocs to mitigate the environmental impacts, including HMs and MPs.

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Mohammad Hossein Khanjani, Alireza Mohammadi, Maurício Gustavo Coelho Emerenciano prepared figures and tables.

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Declarations

Competing interests The authors declare no competing interests.

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