INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 17 No. 7 (2025) 168-180
https://publisher.uthm.edu.my/ojs/index.php/ijie

Sustainable Water Quality Improvement in Small-Scale Tilapia Ponds Through Bio-DHS Filtration

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DOI: https://doi.org/10.30880/ijie.2025.17.07.017

Article Info

Received: 29 April 2025
Accepted: 13 October 2025
Available online: 31 December 2025

Keywords

SDGs, aquaculture, water quality, zero-exchange, Bio-DHS

Abstract

This study investigates the performance of Bio-Downflow Hanging Sponge (Bio-DHS) filtration in improving water quality for small-scale Tilapia aquaculture, addressing sustainability and resource efficiency challenges. The Bio-DHS system introduces a zero-exchange water management approach, eliminating the need for water replacement by only adding small amounts to compensate for evaporation and sampling losses. This method aligns with SDG 12 (Responsible Consumption and Production) by promoting efficient water use and minimising waste discharge. Results revealed progressive improvements in water quality, including reductions in Biological Oxygen Demand (BOD), Total Suspended Solids (TSS), and Chemical Oxygen Demand (COD). Dissolved Oxygen (DO) levels increased to 7.00 mg/L during full-capacity operation, while nitrification efficiency reached 41.66%, indicating effective nitrogen cycling. The Water Quality Index (WQI) improved from 54.31 (polluted, Class III) without filtration to 68.20 (slightly polluted, Class III) with Bio-DHS filtration. While Class III water is suitable for aquaculture, fishery and livestock drinking, further optimisation—such as extending Bio-DHS contact duration—could enhance quality for broader applications. By reducing pollutant loads in aquaculture, this system also supports SDG 14 (Life Below Water) by mitigating environmental impact and promoting cleaner water bodies. The Bio-DHS system is scalable and adaptable, making small-scale Tilapia fish ponds a viable, cost-effective solution for sustainable aquaculture in Malaysia. Future research should focus on optimising microbial development and operational parameters to achieve higher WQI classifications.

1. Introduction

Water quality is crucial in aquaculture systems, as it has a significant impact on fish health, productivity, and environmental sustainability [1], [2]. The aquaculture industry plays a vital role in meeting the growing global demand for freshwater fish, such as Tilapia, but continues to face challenges related to sustainability and environmental impact. In tank-based aquaculture, maintaining optimal water quality through effective aeration and regular water exchange is critical for the successful high-density production of Tilapia [3]. Among innovative solutions, the Recirculating Aquaculture System (RAS) offers a promising method to address these issues by minimising water exchange and improving waste management through advanced filtration systems. Central to RAS is the biological filtration process, which uses bio-filters to convert toxic ammonia produced by fish into less harmful nitrates, thereby maintaining optimal water quality [4]. Different bio-filter designs, such as moving bed and trickling filters, offer unique advantages in improving nitrification efficiency, with surface area maximisation and proper hydraulic flow being the main factors in their effectiveness.

Inspired by trickling filters, the Down-flow Hanging Sponge (DHS) utilises sponges instead of rock or gravel, providing a large surface area for microbial communities to break down organic pollutants. Originally developed for decentralised wastewater treatment in developing countries, the DHS system has demonstrated high efficiency in removing organic loads, nitrogen, and pathogens [5]. Its affordability and effectiveness have made it adaptable for treating industrial effluents, textile wastewater, and aquaculture waste [6]. In aquaculture, integrating Bio-DHS filters into RAS enhances its efficiency and sustainability. These filters leverage beneficial bacteria to oxidise ammonia, supporting high water quality with minimal water exchange [7]. The Bio-DHS system also shortens the filtration start-up phase compared to traditional methods, such as bio-floc, which require strict conditions and longer preparation times. Furthermore, the modular design and adaptability of Bio-DHS filters make them suitable for various scales of fish farming operations, from small to large systems. The zero-exchange system is designed to continuously recycle and treat water, conserving resources while preventing the discharge of pollutants into natural water bodies. Carps survived in an aquarium for approximately 425 days without any signs of disease, despite the absence of water exchange, confirming the success of the zero-exchange system [8]. The zero-exchange bio-floc technology (BFT) system has shown promise for sustainable Tilapia aquaculture, offering improved water quality and a reduced environmental impact, as reported in Manduca et al. [9]. Such an approach is particularly significant in tropical climates, where maintaining water stability and quality can be challenging. Meanwhile, Tilapia is a fish species that draws significant attention in global aquaculture, valued for its rapid growth, high production rate, and strong disease resistance [10]. It holds significant market value in the global fish trade and ranks as the second most farmed fish species worldwide [10], [11]. Tilapia is also robust and suited for bio-floc systems, as its ability to filter water enables it to consume suspended bio-flocs [12].

Malaysia is a fish-consuming country, with fish accounting for 60% of the total animal protein intake [13]. The country has seen significant positive development in its aquaculture industry in recent years, and Tilapia, being well-suited to Malaysia's tropical climate, plays a vital role in this growth. Tilapia farming is a significant component of Malaysia's freshwater aquaculture, with red hybrid Tilapia accounting for 94% of the country's total Tilapia production [14]. Despite the significant advancements in aquaculture, the application of Bio-DHS filters remains underexplored, particularly in small-scale fish farming. Minimal research exists on leveraging Bio-DHS filters to address aquaculture challenges, including limited land and water resources, high feed costs, disease management, and waste disposal, highlighting opportunities for sustainable public adoption. Furthermore, to the best of the authors' knowledge, studies on Bio-DHS applied to Tilapia fishponds yielded fewer research articles.

The novelty of the study lies in the development of a zero-exchange system utilising Bio-DHS filters for a Tilapia fishpond housed in a small-scale canvas tank. The research aims to demonstrate the effectiveness of the filtration system in nutrient removal, improving water quality, and promoting sustainability in small-scale Tilapia fish farming ponds. Its scalability and adaptability further highlight its potential for broader application in global aquaculture practices. This aligns with Sustainable Development Goals (SDGs) 12: Responsible Consumption and Production and 14: Life Below Water, which emphasise the sustainable management of aquaculture to protect aquatic ecosystems and minimise environmental harm.

2. Methods

2.1 Study Area

Fig. 1(a) shows the study area at Kampung Sungai Buloh, Melaka, located at a latitude of 2.436999 and a longitude of 102.161848. Approximately hundreds of Tilapia fish and start-up water used in the small-scale pond were sourced from the commercial pond in the same area to maintain the fish's original environment. Meanwhile, Fig. 1(b) illustrates the 1000-litre capacity pond situated under a roof within the study area.

(a) **(b)**

Fig. 1 *(a) Study area at Kampung Sungai Buloh, Melaka; and (b) Small-scale fish pond*

2.2 Bio-DHS Filter and Operating Conditions

The 1000-litre capacity canvas pond, as shown in Fig. 1(b), was used for the start-up study. The operation was divided into two phases: the first phase of Bio-DHS filtration (Days 1–20) and the 2nd phase of Bio-DHS filtration (Days 21–30). A 30-day duration is considered to monitor the stability of the Bio-DHS filter. During the first phase, the filter was filled with 500 pcs of DHS sponge, equivalent to 30% of the DHS quantity in operation. Meanwhile, during the second phase, the DHS quantity was increased to 1,700 pcs, reaching 100% of the designed capacity. The DHS sponge is a patented technology, and the detailed design of the Bio-DHS system used in this study is based on the work of Adlin et al. [8]. The DHS sponge, encased in a plastic net ring approximately 33 mm in diameter and in length, served as the biomass-retaining carrier. The sponge was placed in a small container (as shown in Fig. 2), equipped with an air pump and a submerged pump, installed within the canvas pond. A total of 100 Tilapia fish, relocated from a large natural soil pond in the study area, were introduced into the pond. During operation, as the fish feed, they produce faeces that contribute to wastewater in the pond. This wastewater flows into the Bio-DHS filter, passing through the biofilm formed around the DHS sponge. The bacteria in the biofilm treat the water by reducing nutrient levels, and the treated water is then continuously recycled back into the canvas pond. The pump operates with a flow rate of 828 L/h and a hydraulic retention time of 0.5–0.6 hours. To offset water loss due to evaporation and sampling, 5–10 litres of tap water were added weekly.

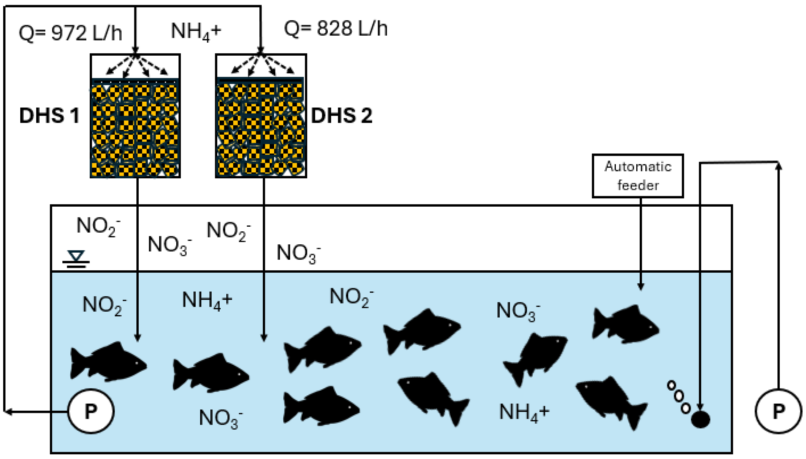

Fig. 2 *The Bio-DHS water filter*

2.3 Test Methods

2.3.1 In-situ Testing

The pH, temperature, Total Dissolved Solids (TDS), and Electrical Conductivity were measured in situ using portable HORIBA instruments [15].

2.3.2 Nutrient Concentrations Analysis

The Tilapia fishpond water samples were collected using four 50 mL centrifuge tubes and placed in an ice box before being transported back to the laboratory. Water quality parameters, including Nitrite, Nitrate, Phosphorus, and Ammoniacal Nitrogen, were analysed to determine nutrient concentrations using the Hach Method 8507, 8192, 8048, and 8038 [16]. Fig. 3(a) shows the Spectrophotometer DR5000 used in this study, and Fig. 3(b) shows some of the analysed samples. The equipment is located at Environmental Laboratory 2, School of Civil Engineering, College of Engineering, UiTM Shah Alam.


(a) **(b)**

Fig. 3 *(a) Spectrophotometer DR5000; and (b) Example of after analysing the samples*

2.3.3 Water Quality Analysis

Six physicochemical parameters were measured for the Water Quality Index (WQI): (i) Ammoniacal Nitrogen (AN), (ii) Biological Oxygen Demand (BOD), (iii) Total Suspended Solids (TSS), (iv) Chemical Oxygen Demand (COD), (v) Dissolved Oxygen (DO), and (vi) pH. AN (APHA method 4500-NH3 B and C), BOD (APHA method 5210B), TSS (APHA method 2540D), and COD (APHA method 5220D) analyses were performed in Environmental Laboratory 2.

Analyses for AN (APHA Method 4500-NH3 B and C), BOD (APHA Method 5210B), TSS (APHA Method 2540D), and COD (APHA Method 5220D) were conducted in Environmental Laboratory 2. Meanwhile, the DO was measured using portable HORIBA instruments [15]. The classification of the Water Quality Index (WQI) was determined by using the formula developed by the Department of Environment (DOE) Malaysia. The formula to calculate WQI is depicted in Eq. (1) [17]:

$$WQI = (0.22 \times SI_{DO}) + (0.19 \times SI_{BOD}) + (0.16 \times SI_{COD}) + (0.15 \times SI_{AN}) + (0.16 \times SI_{SS}) + (0.12 \times SI_{pH}) \quad (1)$$

where WQI = Water Quality Index, SI_{DO} = Sub-index DO (% saturation), SI_{BOD} = Sub-index BOD, SI_{COD} = Sub-index COD, SI_{AN} = Sub-index AN, SI_{SS} = Sub-index SS, and SIpH = Sub-index pH.

The required sub-index of each parameter in Eq. (1) can be calculated using information from Table 1. Table 2 and Table 3 display the classification for each parameter, while Table 4 determines the final status of the fishpond water sample according to the National Water Quality Standards (NWQS).

Table 1 *Sub-index of water quality parameters*

DO	$X \leq 8$	SIDO = 0
	$X \geq 92$	SIDO = 100
	$8 < X < 92$	$\text{SIDO} = -0.395 + 0.03X^2 - 0.0002X^3$
BOD	$X \leq 5$	$\text{SIBOD} = 100.4 - 4.23X$
	$X > 5$	$\text{SIBOD} = 108e^{-0.055x} - 0.1X$
COD	$X \leq 20$	$\text{SICOD} = 99.1 - 1.33X$
	$X > 20$	$\text{SICOD } 103e^{-0.0157x} - 0.04X$
AN	$X \leq 0.3$	$\text{SIAN} = 100.5 - 105X$
	$0.3 < X < 4$	$\text{SIAN} = 94e^{-0.573X} - 5(X-2)$
SS	$X \leq 100$	$\text{SISS} = 97.5e^{-0.00676X} + 0.05X$
	$100 < X < 1000$	$\text{SISS} = 71e^{-0.0016X} - 0.015X$
	$X \geq 1000$	SISS = 0
pH	$X < 5.5$	$\text{SIpH} = 17.2 - 17.2X + 5.02X^2$
	$5.5 \leq X < 7$	$\text{SIpH} = -242 + 95.5X - 6.67X^2$
	$7 \leq X < 8.75$	$\text{SIpH} = -181 + 82.4X - 6.05X^2$
	$X \geq 8.75$	$\text{SIpH} = 536 - 77X + 2.76X$

Table 2 *DOE Water Quality Index classification*

Class	Uses
Class I	Conservation of the natural environment Water Supply I - Practically no treatment necessary Fishery I - Very sensitive aquatic species
Class IIA Class IIB	Water Supply II - Conventional treatment Fishery II - Sensitive aquatic species Recreational involves body contact
Class III	Water Supply III - Extensive treatment required Fishery III – Common of economic value and tolerant species; livestock drinking
Class IV	Irrigation
Class V	None of the above

Table 3 *DOE water quality classification based on Water Quality Index*

Sub-index & Water Quality Index	Index Range		
	Clean	Slightly Polluted	Polluted
BOD	91 - 100	80 - 90	0 - 79
AN	92 - 100	71 - 91	0 - 70
SS	76 - 100	70 - 75	0 - 69
WQI	81 - 100	60 - 80	0 - 59

Table 4 *National Water Quality Standards*

Parameter	Unit	Class				
		I	II	III	IV	V
AN	mg/l	< 0.1	- 0.3	0.3 - 0.9	0.9 - 2.7	> 2.7
BOD	mg/l	< 1	1– 3	3 - 6	6 – 12	> 12
COD	mg/l	< 10	10 – 25	25 – 50	50 – 100	> 100
DO	mg/l	> 7	5 – 7	3 - 5	1 - 3	< 1
pH	-	> 7	6 - 7	5 - 6	< 5	> 5
TSS	mg/l	< 25	25 - 50	50 - 150	150 - 300	> 300
WQI	-	< 92.7	76.5 - 92.7	51.9 - 76.5	31.0 - 51.9	> 31.0

2.3.4 Performance of Sustainable Bio-DHS Filtration for Small-Scale Fishpond

The percentage removal efficiency based on WQI parameters and Nitrification efficiency was chosen to measure the initial performance of the Bio-DHS filtration at the early start-up. The percentage removal efficiency based on WQI parameters and nitrification efficiency was calculated using the general formula as in Han et al. [18] and Zhang et al. [19]:

$$\text{Removal Efficiency (\%)} = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \tag{2}$$

where C_{in} is the initial concentration (inlet), and C_{out} is the final concentration (outlet).

$$\text{Nitrification Efficiency (\%)} = \frac{\text{Nitrate} + \text{Nitrite}}{\text{Ammonia}_{in}} \times 100 \tag{3}$$

3. Results and Discussion

3.1 Nutrients in the Tilapia Fish Pond

The concentration profiles of nutrients in the Tilapia fish pond, as illustrated in Fig. 4, demonstrate distinct trends over the 30-day observation period. The permissible limits in Malaysia for aquaculture water quality parameters include nitrite (< 0.5 mg/L), nitrate (< 10 mg/L), phosphorus (< 0.1 mg/L), and ammoniacal nitrogen (NH_3-N) (< 0.05 mg/L) [18]. The NH_3-N exhibits a significant peak exceeding 20 mg/L around day 5, followed by a gradual decline. This concentration far exceeds the permissible limit of 0.05 mg/L, indicating a potential stressor for fish health if left unmanaged. Elevated NH_3-N levels may result from the accumulation of fish waste and uneaten feed. As stated in the methodology, at the early setup, the DHS quantity in the filter was only at 30% of the designed capacity. While this approach reduces initial expenses, it may limit the system's ability to establish a robust biofilm on sponge surfaces, potentially contributing to inconsistencies in NH_3-N removal. In the second phase of operation (Day 20 onward), the DHS quantity reaches 100% of the designed capacity. Ammoniacal nitrogen (NH_3-N) levels stabilised from Day 20. However, despite this stability, NH_3-N concentrations remained above permissible limits, likely because the biofilm was not fully developed on the DHS surfaces.

Phosphorus levels remained stable throughout the study, indicating controlled nutrient inputs or efficient nutrient assimilation within the pond ecosystem, particularly after day 15. Phosphorus stability aligns with findings that bio-floc systems efficiently utilise available nutrients, preventing excessive buildup [19]. Nitrite and nitrate levels exhibit relatively low concentrations, with nitrate levels slightly higher than those of nitrite. This indicates active nitrification, as the Bio-DHS filter promotes the conversion of toxic ammonia into less harmful nitrate forms. Studies on the Bio-DHS systems highlight their effectiveness in maintaining stable nitrogen profiles through nitrification [20].

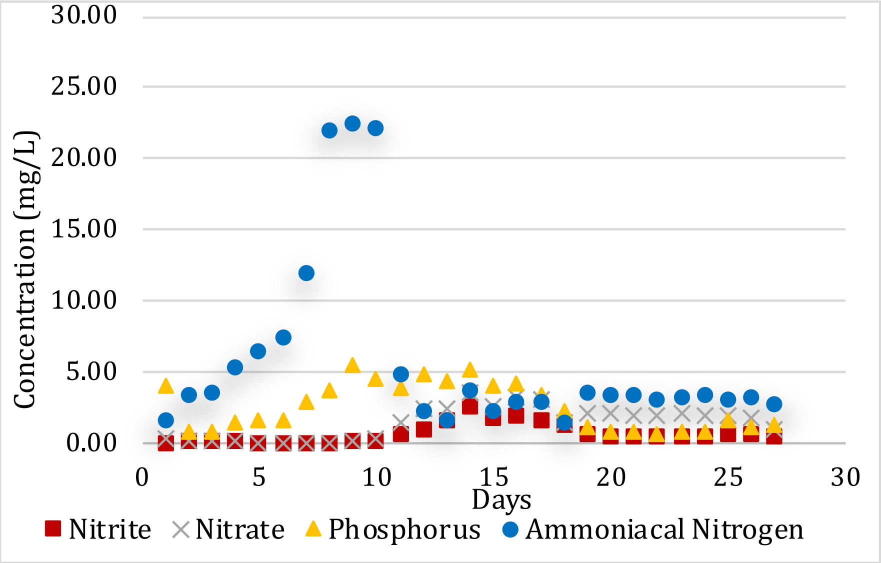

Fig. 4 *Concentration profiles of nutrients in the Tilapia fish pond*

Fig. 5 shows the pH and temperature levels in the Tilapia Fish Pond over a 30-day period. The pH values mostly remained within the permissible range for Tilapia aquaculture (6.5–8.0). A similar result is reported in Crab et al. [21], where Nile Tilapia nursery, utilising pH levels of 6.5–7.5, yields the best results in terms of growth, net yield, and efficiency. This stability is crucial for facilitating effective biological processes, such as nitrification and phosphorus assimilation. A stable pH environment supports the activity of nitrifying bacteria, which are essential for converting ammoniacal nitrogen into nitrate through the process of nitrification. However, significant fluctuations in ammoniacal nitrogen observed in the earlier discussion might be attributed to microbial activity affected by localised pH variations. The temperature data suggests relatively consistent values, aligning with the optimal range (24–28°C) for Tilapia farming. This range was within the acceptable ideal range for Tilapia at 20°C-35°C [22], [23], and simultaneously, it facilitates microbial biofilm growth and nutrient conversion efficiency in the Bio-DHS system. The stable pH and temperature contributed to moderate nitrite and nitrate levels, reflecting ongoing nitrification. Nitrite concentrations remained within the safe limit (<0.5 mg/L), suggesting effective conversion to nitrate. Similarly, phosphorus levels remained relatively consistent, indicating no excessive nutrient loading in the pond. However, early challenges in the ammoniacal nitrogen trend emphasise the need for optimised Bio-DHS material quantity and operation to enhance nutrient removal efficiency. Sustainable aquaculture practices rely on optimal biofilm growth for effective nutrient control. Thus, an insufficient quantity of DHS material may hinder ammonia conversion or delay the process.

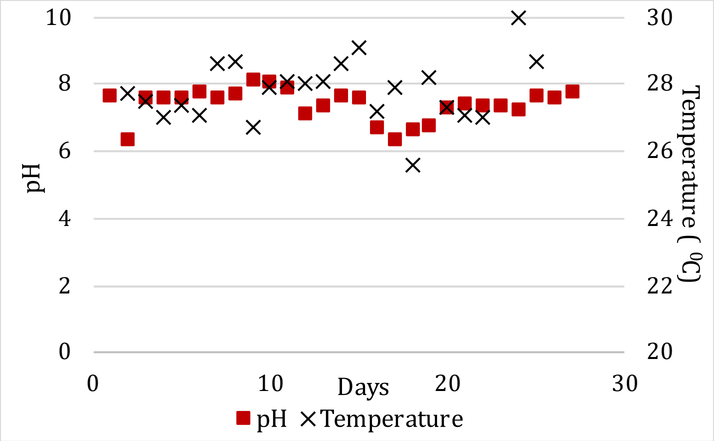

Fig. 5 *pH and Temperature in the Tilapia fish pond*

Fig. 6 depicts the total dissolved solids (TDS) and electrical conductivity (EC) in the Tilapia Fish Pond for 30 days. The TDS reflects the concentration of dissolved inorganic and organic materials in the pond water. It shows a gradual increase during the first 15 days and fluctuates between 200 and 400 mg/L after this point. The results are comparable to those reported by Obondo et al. [5], where the TDS ranged from (333.6 ± 17.8 mg/L to 529.5 ±

23.6 mg/L) in a fish culture system utilising the DHS filter. Meanwhile, the EC measure the water's ability to conduct electricity, which is directly proportional to the ionic concentration. It follows a similar upward trend, peaking near 600–700 µS/cm, indicating an accumulation of dissolved ions over time. The steady increase in TDS and EC in the first half of the study indicates ongoing nutrient release or mineral dissolution in the pond ecosystem, likely from feed input, fish excretion, or microbial processes [24]. The fish may also experience stress due to their relocation from a large natural pond to a smaller-scale aquarium pond. The faeces serve as a source of increased ammonia, as previously discussed in Fig. 4. Discharging this type of aquaculture wastewater into waterbodies could promote algal biomass growth [25].

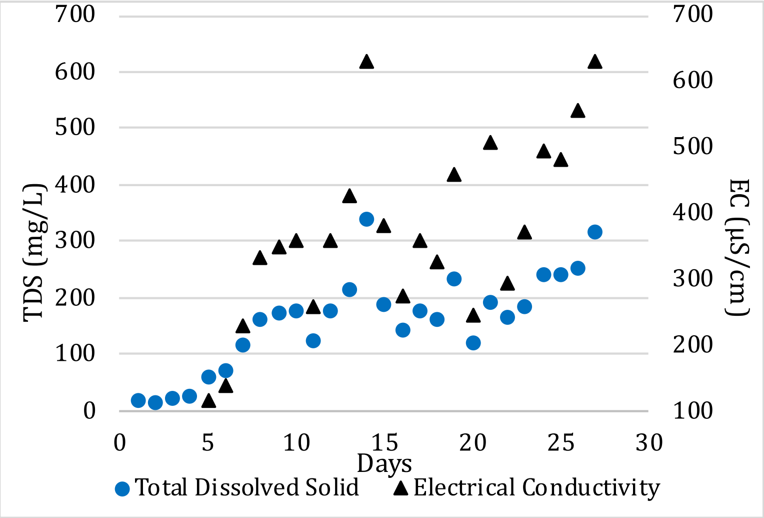

Fig. 6 *TDS and EC in the Tilapia fish pond*

After 15 days, the stabilisation of TDS levels suggests equilibrium between nutrient input and assimilation/removal processes in the pond, supported by the stable phosphorus levels and controlled nitrification. The higher EC compared to TDS could reflect the dominance of ionic species in the dissolved solids, particularly nitrates, which are major contributors to ionic strength in aquaculture systems. The EC in this study indicated that the aquatic environment is a freshwater habitat, characterised by its low salinity. Findings from Musa et al. [26] confirm that conductivity values below 1000 µS/cm signify freshwater, values above 1000 µS/cm indicate brackish water, and those exceeding 55,000 µS/cm represent marine water. Maintaining the TDS and EC within the optimal range is crucial for fish health. Excessive levels can stress fish by disrupting osmoregulatory functions [27]. Osmoregulatory functions refer to the physiological processes through which aquatic organisms regulate the balance of water and electrolytes (salts) in their bodies. The observed ranges for TDS (200–400 mg/L) and EC (300–700 µS/cm) appear suitable; however, further increases should be closely monitored to prevent deterioration in water quality.

3.2 Classification of Water Quality

Water quality in an aquatic system is a crucial aspect in the approach to nature, influencing the effectiveness of pollution measures. Table 5 depicts the sub-index parameters, and Fig. 7 illustrates the Water Quality Index (WQI) of Tilapia Fish Pond based on the DOE Classification. Before the Bio-DHS system's operation, the parameters, such as Dissolved Oxygen (DO), were critically low at 3.00 mg/L, while Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) were high, indicating significant organic pollution. The water quality in Lake Cilala, located in Bogor Regency, West Java, is in poor condition due to intensive fish aquaculture activities, as evidenced by the high Biochemical Oxygen Demand (BOD) level of 8.20 mg/L, indicating significant pollution [28]. Given the similarity of Malaysia's tropical climate to this region, it is expected that fish in the pond could produce a comparable BOD level in the absence of a filtration system. Furthermore, the Total Suspended Solids (TSS) at 340 mg/L highlighted poor water clarity and excessive particulates.

Table 5 *Sub-index parameters of the Tilapia fish pond*

WQI Parameter	Without Bio-DHS filtration	Sub-index value (Si)	1st phase Bio-DHS filtration	Sub-index value (Si)	2nd phase Bio-DHS filtration	Sub-index value (Si)
*DO (mg/l)	3.00	29.60	5.51	73.59	7.00	93.30
BOD (mg/l)	10.00	61.31	9.24	64.05	6.00	77.04
COD (mg/l)	11.00	84.47	20.00	74.44	25.00	68.56
AN (mg/l)	1.60	39.58	6.73	0.00	3.15	9.71
TSS (mg/l)	340.00	36.11	194.00	49.14	130.00	55.72
pH	8.00	91.00	7.39	97.53	7.40	97.46
WQI values		54.31		59.84		68.20

*DO converted to % saturation

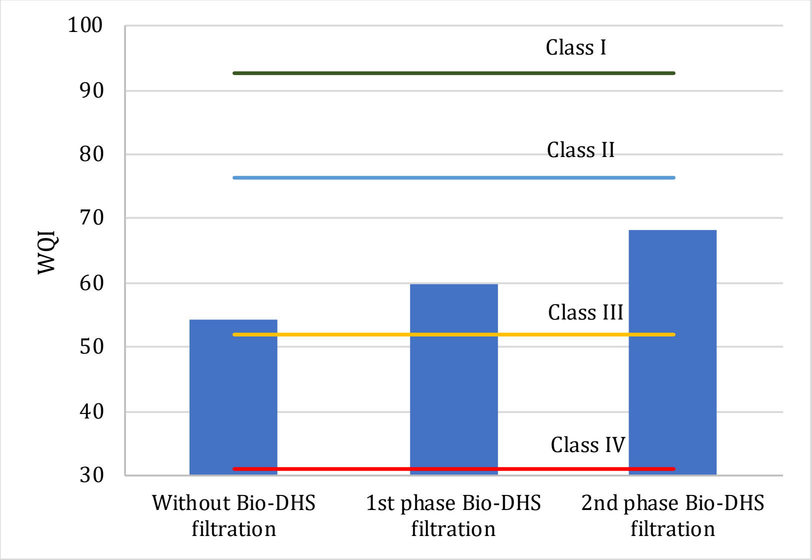

Fig. 7 *WQI of Tilapia fish pond based on DOE Classification*

The WQI value is 54.31, corresponding to Class III and classified as polluted. Tilapia is known for its resilience and ability to tolerate a wide range of environmental conditions [29]. Although some physicochemical parameters exceed the permissible limits set by the DOE, the fish can still grow in untreated aquaculture ponds. However, over the long term, the excessive buildup of organic matter and nutrients can have a detrimental effect on water quality and fish growth. To safeguard human health, it is also essential that fishponds adhere to good aquaculture practices, including the use of additional filtration systems. During the first phase of Bio-DHS filtration (Day 1–20), with 30% of the DHS quantity in operation, the DO level increased to 5.51 mg/L, and there were moderate reductions in BOD and COD levels. However, ammoniacal nitrogen (AN) exhibited a temporary increase, likely due to the early-stage nitrification process not yet fully established. The WQI value improved to 59.84, maintaining a Class III status but indicating a transition to a slightly polluted status.

In the second phase (Day 21–30), with the DHS quantity operating at full capacity (100%), the DO increased to 7.00 mg/L, indicating enhanced aeration and biological activity. A study using DHS-USB filtration by Obondo et al. [5] reported a similar trend, where the DO concentration at start-up is around 7 mg/L, then decreases over the first 20 days to around 6.5 mg/L. It then increases slightly over the next 10 days to around 7 mg/L. The trend is comparable to the DO trend in this study (without filtration, first-phase Bio-DHS filtration, and second-phase). Meanwhile, the BOD and COD levels continued to decline, indicating effective removal of organic matter. The results obtained, such as the BOD values, were found to be within the range (4.0 to 6.0 mg/L) for fish wastewater as reported in Bhatnagar et al. [24], indicating optimum fish activities. A similar trend in COD values, ranging from 11.9 to 25.6 mg/L, was observed using the DHS-aquaponic system in Adlin et al. [8], where the fluctuation could be attributed to the increased presence of residual fish feed and excreta in the water due to fish growth. The significant reduction in TSS (from 130 mg/L to 0 mg/L) and partial AN removal (from 3.15 mg/L to 0 mg/L) reflected the system's ability to effectively address both suspended solids and nitrogenous waste. The WQI reached 68.20, still within Class III but reflecting improvements in water quality and classified as slightly polluted. All the water samples for the three-phase conditions were classified as Class III, with a slight improvement in the WQI. The Class III is suitable for aquaculture fishery and livestock drinking. Similar findings were reported in

Wisnu et al. [30], where the WQI for the three artificial aquatic environments (concrete, earthen, and plastic pond/tanks) was classified as poor, suitable only for the culture of aquatic organisms. However, this study did not highlight any use of filtration systems. The efficacy of Bio-DHS systems in improving aquaculture water quality by integrating nitrification and denitrification processes is expected to be progressive after the start-up operation. Thus, further optimisation of the system, including longer operation periods or supplementary filtration methods, may be required to achieve higher water quality standards (Class II or I) for aquaculture sustainability.

3.3 Performance of Sustainable Bio-DHS Filtration for Small-Scale Fish Pond

The performance of a Bio-DHS filter for a small-scale Tilapia fishpond was calculated using Eq. (2) and Eq. (3), as described in the methodology. It is typically evaluated based on its ability to improve water quality parameters by removing pollutants. A stable condition is recorded at the second phase of Bio-DHS filtration, where the DHS sponge quantity is operating at full capacity. The percentage removal efficiency and nitrification efficiency measure the initial performance of the Bio-DHS filtration. Removal efficiency based on the selected WQI parameters, such as BOD, AN, and TSS, for the 2nd phase of Bio-DHS filtration is 35.06%, 53.27%, and 32.99%, respectively. Meanwhile, the calculated nitrification efficiency is 41.66%. A similar value of up to 43% of total nitrogen was reported in Abd El-Hack et al. [31], where the combined DHS system facilitates simultaneous nitrification and denitrification processes. Some microorganisms that grow in the bio-flocs of the culture water, such as nitrifying bacteria, transform toxic nitrogenous compounds (mainly ammonia and nitrite) to nitrate [7]. This indicates the Bio-DHS system in this study is able to maintain a balanced nitrogen cycle, thus supporting the health of the aquatic ecosystem in small-scale fishponds.

Throughout the filter's operation, no water exchange was performed in the canvas pond, promoting sustainability by conserving water resources. Only 5-10 litres of water were added periodically to compensate for evaporation and losses from water sampling. Sustainable water quality management in small-scale Tilapia fish ponds plays a critical role in ensuring the long-term success of aquaculture while minimising environmental degradation. The United Nations Sustainable Development Goal (SDG) 12 emphasises the need for responsible consumption and production patterns, particularly through the sustainable management of natural resources, such as water. In small-scale aquaculture, maintaining optimal water quality is essential to support healthy fish populations and prevent water pollution, which could otherwise lead to eutrophication and other environmental issues. Sustainable solutions, such as advanced filtration systems, offer a promising approach to improving water quality and promoting the responsible use of resources in fish farming. By enhancing water quality through these filtration systems, small-scale aquaculture operations can reduce their environmental impact, increase resource efficiency, and align with SDG 12. These systems provide a sustainable and effective solution for maintaining optimal water conditions, promoting responsible aquaculture practices that ensure the well-being of both fish and the surrounding environment.

4. Conclusion

This study examined the application of Bio-DHS filtration technology for nutrient removal in small-scale Tilapia fish ponds, addressing key challenges in aquaculture sustainability. The findings demonstrated the system's effectiveness in progressively improving water quality parameters, notably reducing Biological Oxygen Demand (BOD), Total Suspended Solids (TSS), and Chemical Oxygen Demand (COD). During the second phase, operating at 100% sponge capacity, Dissolved Oxygen (DO) levels increased significantly to 7.00 mg/L, reflecting enhanced aeration and biological activity. The nitrification efficiency reached 41.66%, supported by a stable nitrogen cycle and active microbial processes, though ammoniacal nitrogen (AN) removal remained suboptimal. The Water Quality Index (WQI) in Class III progressed from "polluted" to "slightly polluted," indicating a gradual enhancement in the pond's ecosystem health. The discharge of low-quality water from aquaculture can be regarded as industrial wastewater, which, like other untreated effluents, may contain harmful substances that pose toxic risks to humans, animals, and the environment even at low concentrations [32].

A notable feature of this study was the zero-exchange water management approach, where no water was discharged from the pond; only 5–10 litres were added periodically to compensate for evaporation and sampling losses. This zero-exchange strategy supports sustainability by conserving water resources, minimising waste discharge, and reducing the environmental footprint, aligning with Sustainable Development Goal (SDG) 12 for responsible consumption and production. Such water-efficient practices are particularly advantageous in resource-limited settings, making this approach ideal for small-scale aquaculture. Furthermore, the implementation of Bio-DHS filtration technology contributes to SDG 14, which focuses on conserving and sustainably using marine and freshwater ecosystems. By improving water quality and reducing pollutant loads in aquaculture, this system helps mitigate the environmental impact of fish farming, promoting cleaner water bodies and healthier aquatic life. The findings highlight the potential of small-scale Tilapia fish ponds as a sustainable option for public use and fish farmers in Malaysia's aquaculture industry. The Bio-DHS filtration system offers a cost-effective, scalable, and adaptable solution for water management, promoting responsible aquaculture practices. While further optimisation is needed to achieve Class I or II water quality, the system's innovative design and functionality pave the way for broader applications in sustainable aquaculture. Future studies should emphasise long-term monitoring, microbial community development, and supplementary enhancements to maximise its performance. This technology supports advancements in food security and environmental sustainability, particularly in Malaysia and other ASEAN countries with suitable climates for these types of fish.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Acknowledgement

The authors are deeply grateful to the Faculty of Civil Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia, and the United Nations Development Programme (UNDP) for their financial support and provision of resources and facilities through the ASEAN Blue Innovation Challenge Award.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Yamaguchi Takeshi, Adlin Nur, Norfariza Ab Wahab;* ***Data collection:*** *Norfariza Ab Wahab, Nurul Fariha Lokman;* ***Analysis and interpretation of results:*** *Nurul Fariha Lokman, Tay Chia Chay;* ***Draft manuscript preparation:*** *Suhaila Mohd Najib, Khusna Dwijayanti. All authors reviewed the results and approved the final version of the manuscript.*

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