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Comparative Economics and Operational Performance of Different Biofilter Media in Aquaponic Systems

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ABSTRACT

This study aimed to evaluate the economic and operational performance of three types of biofilter media: bio media, drip irrigation pipes, and polyvinyl chloride (PVC) corrugated pipes in three identical aquaponic systems. Each system included a plastic tank for rearing the Nile tilapia (*Oreochromis niloticus*), stocked with 160 fish per m^3. Water from the fish tank was channeled through a mechanical filter, followed by a biological filter, and then to the hydroponic component (mint cultivation). The design followed the deep water culture (DWC) method, with water ultimately flowing to a sump tank before returning to the fish tank. Key performance metrics included total ammonia nitrogen (TAN) removal efficiency, feed conversion ratio (FCR), plant growth, and long-term economic sustainability. The TAN removal efficiency in the bio media system was significantly the highest ($P< 0.05$), at 47.59 ± 0.01g/ m^3/ day. Drip irrigation pipes showed the lowest performance, removing only 16.80 ± 1.07 g/m^3/day. In addition, the bio media system had the best FCR, with the lowest value ($P< 0.05$) at 1.16 ± 0.01, indicating superior feed efficiency. In terms of plant growth, the bio media system produced the most leaves (720.00 ± 17.32 leaves), reached the tallest height (85 ± 3.46cm), and had the highest fresh biomass (300.00 ± 17.32g), all significantly higher than the other media types. Although the bio media system had the highest initial cost, it delivered superior performance in water quality management, fish growth, and plant productivity, resulting in a more cost-effective solution over time. Drip irrigation pipes, while the cheapest option, led to higher long-term costs due to their lower efficiency in TAN removal and poor feed conversion efficiency. PVC corrugated pipes provided moderate performance. This study suggests that bio media is the optimal choice for commercial aquaponic systems based on its long-term economic benefits.

INTRODUCTION

The growing global demand for sustainable fish production has spurred the development of advanced aquaculture techniques, particularly closed fish production systems, which offer a more environmentally conscious alternative to traditional open-water aquaculture. Recirculating aquaculture systems (RAS) represent a key innovation in this area, where water is continuously filtered, treated, and reused within the system, significantly reducing water consumption and preventing effluent discharge into natural ecosystems **(Timmons & Ebeling, 2019)**.

In RAS, maintaining high water quality is paramount for fish health and growth, as well as system efficiency. Fish excrete ammonia, a highly toxic compound, as a byproduct of protein metabolism **(Goddek *et al.*, 2021)**.

Bio filtration in RAS relies on the activity of nitrifying bacteria, particularly species of Nitrosomonas and Nitrobacter, which convert ammonia (NH_3) to nitrite (NO_2^-), and then to nitrate (NO_3^-). Nitrate is much less toxic to fish and can be utilized as a nutrient by plants in integrated systems viz. aquaponics. However, the efficiency of bio filtration depends largely on the type of bio filter media used, which provides the habitat for microbial colonization. The media's surface area, porosity, and material composition influence the rate of ammonia conversion, microbial growth, and overall system performance **(Schmautz & Graber, 2021)**. The selection of biofilter media not only affects water quality but also impacts the system's operational costs and long-term sustainability.

Aquaponic production has gained significant traction, offering both fresh vegetable yield and nutritious fish protein. Fish are cultured in tanks and fed a proper diet (fish food) that first introduces nitrogen to the system; in turn, the fish consume the feed, which begins processing or the breakdown of food into protein for meat production. Waste is carried to the filter, where solids are captured, and bacteria are present for nitrification to take place by specific beneficial bacteria cultured in the filter. Nutrient-rich water leaves the filter and is delivered to the plants, serving as a fertilizer. As plants absorb nutrients from the recirculated water, clean water exits the plant-growing area and returns to the fish tank **(Ngo-Hoang, 2023)**.

The biofilter media chosen for the system play a critical role in determining the overall success of these processes. Media that promote microbial colonization support nitrifying bacteria such as Nitrosomonas and Nitrobacter, which convert ammonia to nitrite and nitrite to nitrate, respectively **(Graber & Junge, 2019)**.

This study aimed to compare the economic and operational performance of three commonly used biofilter media in aquaponics: bio media, drip irrigation pipes, and PVC corrugated pipes. While the initial cost of biofilter media can widely vary, it is their long-term impact on water quality, fish feed efficiency, and plant productivity that ultimately determines their economic viability. By assessing these key metrics, this study provides insights into the most cost-effective biofilter media for commercial aquaponic systems.

MATERIALS AND METHODS

1. Study location and duration

The experiment was conducted at the Aquaponics Unit in the Faculty of Fish Resources, Suez University, Suez Governorate, Egypt. The study lasted for 120 days, from February to May 2023.

2. Experimental design

The experiment was conducted using three separate aquaponic systems, each utilizing one of the biofilter media under study: bio media, drip irrigation pipes, and polyvinyl chloride (PVC) corrugated pipes. Each system was stocked with the Nile tilapia, and planted with *Mentha* spp. (mint). The systems were monitored over a four-month period, during which water quality parameters, fish growth, feed conversion efficiency, and plant growth were measured. The total costs of operation and maintenance were recorded to assess economic performance. Three systems are typical in the general design, water cycle, and aeration system for 24h. It is controlled by the human factor and thermal unit.

3. System components and flow design

Each system included a 1000-liter plastic tank for rearing the Nile tilapia (*Oreochromis niloticus*). A key element of aquaponics, the fish tank plays a crucial role in raising healthy and strong fish. For the system to perform optimally, the fish in the tank must be comfortable and in a stress-free environment **(Ngo-Hoang, 2023)**. The stocking density was maintained at 160 fish per cubic meter. Water from the fish tank was channeled to a mechanical filter (200-liter cylindrical plastic tank) via PVC pipes (38cm in length, 2 inches in diameter) to remove particulate matter. After mechanical filtration, the water was directed to a biological filter (also a 200-liter cylindrical plastic tank) designed to facilitate nitrification. The treated water was then directed into a plant tank (dimensions: 100cm x 115cm x 4cm), where mint (*Mentha* spp.) plants were grown on floating rafts. Filtration plays a dual role, addressing both mechanical (solids removal) and biological (bacterial conversion) aspects of waste management originating from the fish, transforming waste into vital nutrients essential for plant growth **(Ngo-Hoang, 2023)**. The water then flowed from the plant tank into a sump tank (50-liter cylindrical plastic tank) through a 108cm long, 2-inch diameter pipe, and was subsequently recirculated back to the fish tank using a submersible pump (230 volts, 9 liters per minute flow rate) (Fig. 1).

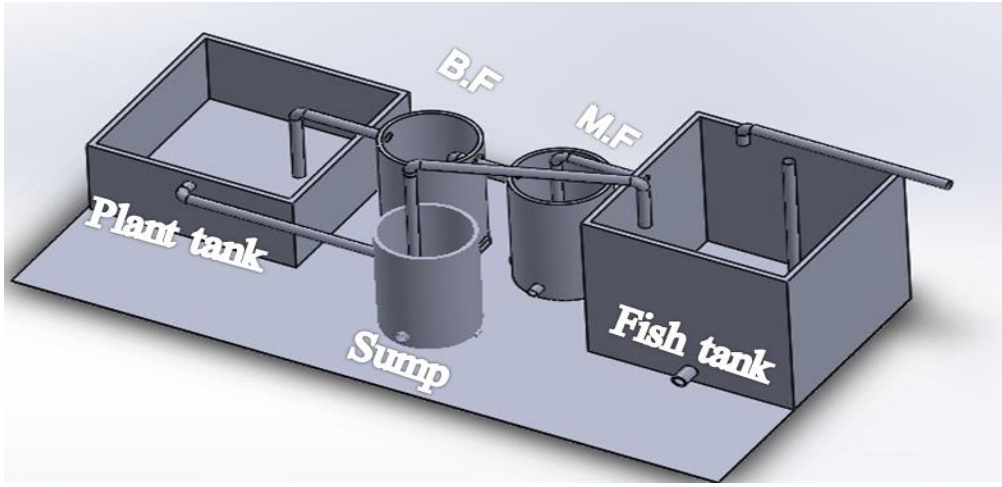


Fig. 1. Experimental design in aquaponic systems for the Nile tilapia (*O. niloticus*) using three bio filter media (bio media, drip irrigation pipes, and corrugated PVC plastic pipes) after 120 days

4. Biofilter media types

1. Bio media: A specialized, high-surface-area medium designed to maximize biological filtration by promoting microbial activity displayed a volumetric TAN removal (VTR) rate ranging from 400 to 1,200g TAN/m³ media/day. This medium was chosen for its high specific surface area and its effectiveness in supporting dense microbial populations, which are critical for an efficient nitrification **(Timmons & Ebeling, 2019)** (Fig. 2A)

2. Drip irrigation pipes: Originally designed for water distribution in agriculture, the medium was repurposed for biological filtration, achieving a VTR of 530g TAN/m³ media/day. It offers a cost-effective and easily manageable option with a moderate surface area **(Rakocy *et al.*, 2006)**.

3. PVC corrugated pipes: Widely used in plumbing applications, these pipes offer moderate surface area for biofilm development and are durable. They exhibited a VTR of 1g TAN/m3 media/day. This media type was selected for its durability and ease of handling **(Goddek *et al.*, 2019)** (Fig. 2C).

Fig. 2. Types of media used: **A**: Bio media K1 a VTR ranging from 400-1200g TAN/m3 media /day; **B**: Drip irrigation pipes a VTR of 530 g TAN/m3 media/day, and **C**: PVC corrugated a VTR of 1g TAN/m3 media /day

5. Biological filter design and manufacture

Design steps

The bio filter was designed to handle the nutrient load and maintain an optimal water quality based on the following calculations:

1. System water volume (Vs): 1m³ per tank.
2. Maximum fish load: Calculated as L=Water Volume × Final Fish Density. For 160 fish averaging 250g each, this equated to a biomass of 40kg/ m³.
3. Maximum daily feed input: Following **Rakocy (1989)**, the feed input was calculated as F= (Feed Percentage × Fish Load) =3%×40 kg=1.2 kg/day.
4. Feed protein content: Set at 30% to match commercial tilapia feed formulations and ensure sufficient nitrogen for plant growth **(Timmons & Ebeling, 2019)**. System operating temperature: Maintained at 28°C to optimize fish growth and microbial activity in the bio filter, as recommended by recent studies **(Goddek *et al.*, 2019; Zou *et al.*, 2021)**.
5. System operating salinity: 0ppt, suitable for freshwater fish and most hydroponic plants.
6. TAN production per Kg of feed: Calculated as 25.7g TAN/kg feed at 30% protein, based on established conversion rates **(Rakocy *et al.*, 2006; Timmons & Ebeling, 2019)**.

7. Total daily ammonia nitrogen (TAN) production: Estimated as 1.2kg/ day×25.7g TAN/kg feed = 30.8g TAN/day/tank.

6. Preparation and maintenance procedures

- Tank cleaning and preparation: Prior to the experiment, all tanks were cleaned with a 10% bleach solution, followed by thorough rinsing with DE chlorinated water and air-drying for 24 hours to eliminate any residual disinfectants. This protocol is consistent with recommendations from the Food and Agriculture Organization **(FAO, 2020)**.

- System assembly and testing: The aquaponic systems were assembled according to design specifications. Flow adjustments were made to ensure uniform distribution of water and prevent dead zones in the system **(Wongkiew, 2017)**.

- Filter media preparation: Biological filter media were pre-soaked in DE chlorinated water for 24 hours to remove contaminants and to ensure full saturation before installation. This step is crucial for promoting an immediate microbial colonization and effective nitrification once the system is operational **(Rakocy *et al.*, 2006)**.

7. Combined system formation

7.1. Fish preparation and stocking

- The Nile tilapia specimens were sourced from a fish farm belonging to Al-Yasmina Fish Production Company in Kabrit, Suez Governorate, Egypt. The average initial body weight was 15 grams per fish.

- Acclimation procedure: Fish were transported in oxygenated plastic bags and were acclimated in a quarantine tank for two weeks to prevent disease introduction into the system. Fish were acclimated to the aquaponic system water by gradually mixing transport water with system water over several hours, adjusting for temperature and pH. This procedure was repeated until the water parameters were equalized. Then, the fish were allowed to swim out of the bag. The fish were captured and were later released into the receiving tank, and distributed. This slow acclimation process minimizes stress, reduces the risk of shock, and show physiologically normal, as recommended by recent aquaculture guidelines **(FAO, 2020; Zou *et al.*, 2021; Paixão *et al.*, 2024)**.

- Stocking density: After acclimation, fish were stocked at a density of 160 fish/m^3, corresponding to a biomass of 40kg/ m^3. Fish were individually weighed using a digital scale to ensure an accurate growth monitoring and to adjust feeding rates accordingly.

7.2. Plant preparation and planting

Mint seedlings, with an average height of 10cm and root length of 18cm, were obtained from a certified nursery in Cairo, Egypt.

- Seedling preparation: Seedlings were inspected for pests and diseases, and roots were submerged in a mild fungicide solution for 30 seconds to prevent pathogen introduction into the system. Roots were then rinsed with clean water before planting **(Resh, 2022)**.

- Planting procedure: Seedlings were placed in floating rafts, ensuring that their roots were adequately submerged to maximize nutrient uptake. The fish-to-plant ratio was maintained at 1:2, based on recent studies suggesting this ratio for optimal nutrient cycling and growth balance **(Goddek *et al.*, 2019)**.

7.3. Maintenance

- Daily system checks: System components, including tanks, filters, and pumps, were daily inspected for functionality. Any malfunctions or clogs were addressed immediately to prevent system failure.
- Feeding regime: Fish were fed a commercial diet with 30% crude protein at 3% of their body weight, twice daily. Feeding rates were adjusted bi-weekly based on the average weight of a representative fish sample **(Timmons & Ebeling, 2019)**.

8. Experimental management

Aeration and water quality devices measurements

- Aeration was provided using three air blowers (Vortex® gas pump, 2500rpm, max pressure 36 KPA, max flow rate 250m³/ h). The blowers were alternated every 12 hours to ensure continuous aeration, without overworking any single unit.

- Water quality monitoring: Key parameters, including temperature, pH, DO, ammonia (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-), were daily measured using calibrated instruments (HANNA® portable DO meter, Lovibond Senso Direct Con200 conductivity meter, HANNA Microprocessor pH meter, Lovibond® MD 100 Ammonia meter, and API® kits). Salinity was measured using a refractometer (ATAGO; Japan). Additionally, data were logged electronically and reviewed weekly to detect any trends or deviations **(Suhl *et al.*, 2016)**.

9. Measurements

9.1. Water quality monitoring

Water samples were daily collected to measure concentrations of TAN, nitrite, and nitrate. TAN removal efficiency was the key indicator of each biofilter's ability to manage ammonia levels in the water, which directly affects fish health **(Schmautz & Graber, 2021)**. TAN removal efficiency was calculated based on the daily reduction in TAN concentration.

The efficiencies of the bio filters were calculated using the following equations:

Volumetric TAN removal rates (VTR, g m-3day-1) = 1.44 × (TANin - TANout) × Q × V-1 **(Oh, 2001)**.

Where, TAN_{in} is the concentration (mg/L) of total ammonia nitrogen in the biofilter inlet;

TAN_{out} is the concentration (mg/L) of total ammonia nitrogen in the bio filter outlet;

Q is total water flow (m^3 /day) through the filter;

V is the volume (m^3) of the filter bed, and 1.44 is a conversion factor.

All measurements were taken in triplicate following the methods described by **Eaton *et al.* (1995)**.

9.2. Fish growth and feed utilization

Fish were weighed weekly to monitor growth. All growth parameters and feed conversion ratios (FCR) were estimated as Mean ±SE. FCR was calculated as the amount of feed required for each kilogram of fish weight gain **(Timmons & Ebeling, 2019)**. A lower FCR indicates better feed efficiency, which translates into lower feed costs, a key component of aquaponic system economics.

Fish growth performance was evaluated using the following parameters:

Growth performance was evaluated through the following parameters: Weight gain (WG) = Wt – W0. Where, Wt = final weight; W0 = initial weight **(Goda *et al.*, 2007)**. The specific growth rate (SGR (% day-1)) = (Ln Wt – Ln W0) / t × 100. Where, Ln= Logarithm natural; t = rearing duration by days **(Goda *et al.*, 2007)**. FCR = Feed intake/ weight gain, and the feed efficiency (FE %)= (1/ FCR) × 100 **(Goda *et al.*, 2007)**. At the end of the experiment, all fish in each tank were netted and counted for survival rate determination **(Ayisi *et al.*, 2017)**. Survival rate= Number of fish at the end of the study/ number of fish initially stocked *100.

9.3. Plant growth measurement

Plants were measured for key growth parameters, including number of leaves, plant height, and fresh biomass. The results were used to evaluate the effect of biofilter media on nutrient availability and plant productivity **(Suhl *et al.*, 2016)**.

9.4. Economic analysis

An economic analysis was conducted by comparing the initial capital costs, operational costs (feed, water changes, energy use), and maintenance costs for each biofilter media. This analysis was designed to quantify the total cost of ownership and the return on investment (ROI) over the study period **(Pantanella *et al.*, 2012)**.

9.5. Total bacterial count

The bacteriological media of nutrient agar (NA; Lab M, UK) was prepared following the manufacturer's instructions. A 100ml water samples were collected separately from each system. Samples were wrapped in sterile bags inside a cool polystyrene box containing packed sterile ice to keep the temperature range at 4- 6°C during transportation **(FDA, 2001)**. Samples were cautiously transported to the laboratories of the Faculty of Fish Resources, Suez University, and analyzed instantly.

1ml of the water sample was added to 9ml of 0.1% sterile peptone water (PW; DM185D, MAST, UK) and vortexed for 2 minutes. Serial dilutions up to 10^4 were performed using the spread plate technique on nutrient agar (NA). These dilutions were incubated at 37°C for 24 hours in an incubator (JSGI-100T). The water samples reported as log colony-forming units per milliliter (log CFU/mL) **(FDA, 2001)**.

9.6. Statistical analysis

Data processing and analysis

Data analysis was conducted using SPSS version 22 (2014). One-way ANOVA was applied, followed by Duncan's test to identify significant differences among treatments. Significance was tested at the 0.05 level. All data are presented as the mean ± SE, except for microbial activity and bacterial count, which are presented as the mean ± SD.

RESULTS

1. Water quality parameters

Water quality is a crucial aspect of maintaining a balanced and productive aquaponic system since it directly influences both fish health and plant growth. In this study, the water quality parameters (temperature, pH and dissolved oxygen) across the three bio filter media treatments—bio media, drip irrigation pipes, and corrugated PVC pipes—were consistently monitored. No significant variations were found between treatments, indicating that all three media were able to maintain stable water conditions (Fig. 3).

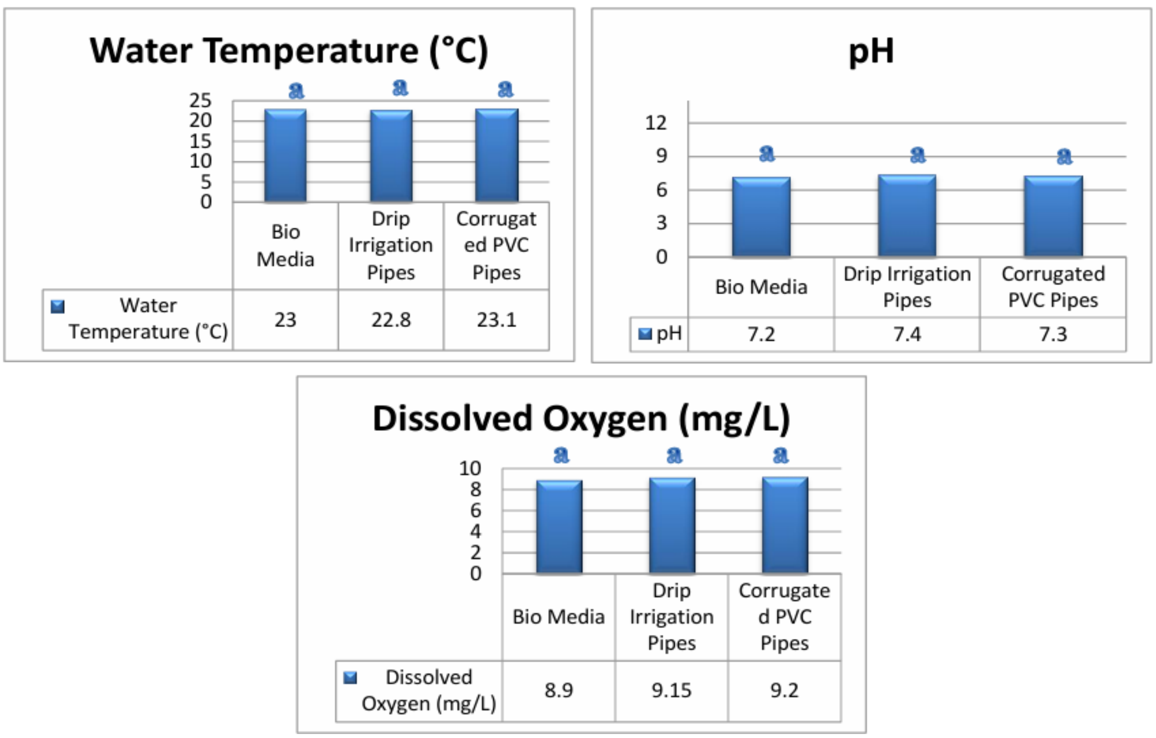


Fig. 3. Water quality parameters of the aquaponics system for the Nile tilapia (*O. niloticus*) using three biofilter media (biomedia, drip irrigation pipes, and corrugated PVC plastic pipes) after 120 days. Values (mean of triplicates ± SE) with different letters are significantly different (P< 0.05).

2. TAN removal efficiency

The bio media system exhibited significantly the highest TAN removal efficiency, averaging 47.59 ± 0.01g/m^3/day, followed by PVC corrugated pipes at 41.99 ± 2.15g/ m^3/ day. Drip irrigation pipes had the lowest performance, removing only 16.80 ± 1.07g/ m^3/ day (Fig. 4).

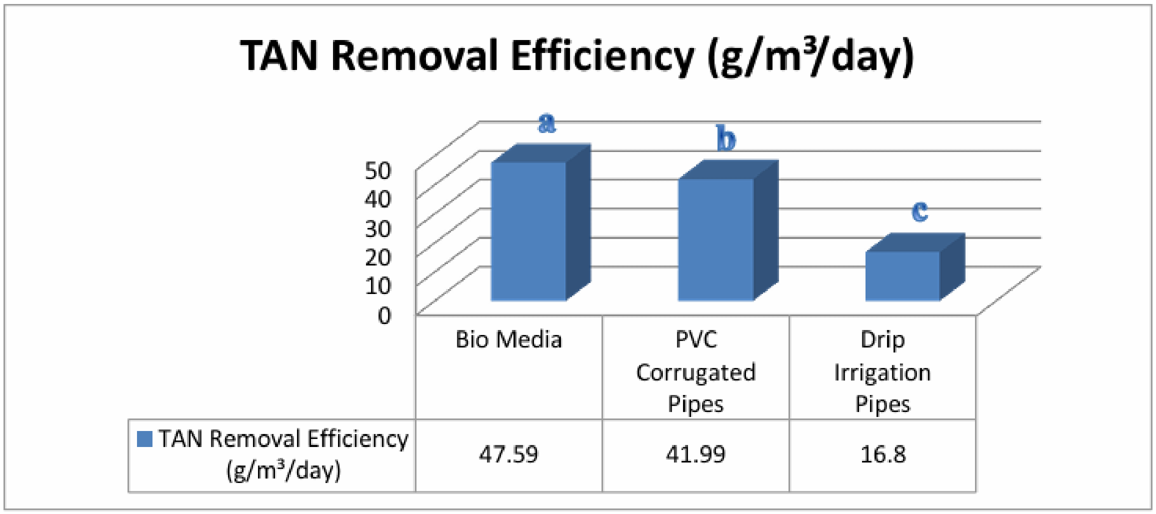


Fig. 4. Removal efficiencies of TAN in the aquaponics system for the Nile tilapia (*O. niloticus*) using three bio filter media (bio media, drip irrigation pipes, and corrugated PVC plastic pipes) after 120 days. Values (mean of triplicates ± SE) with different letters are significantly different ($P < 0.05$).

3. Nitrite and nitrate dynamics

The nitrite and nitrate dynamics were determined in systems utilizing three types of bio filter media: bio media, drip irrigation pipes, and PVC corrugated pipes. The results reveal significant differences in both nitrite removal and nitrate production between the treatments, highlighting the superior performance of bio media (Fig. 5).

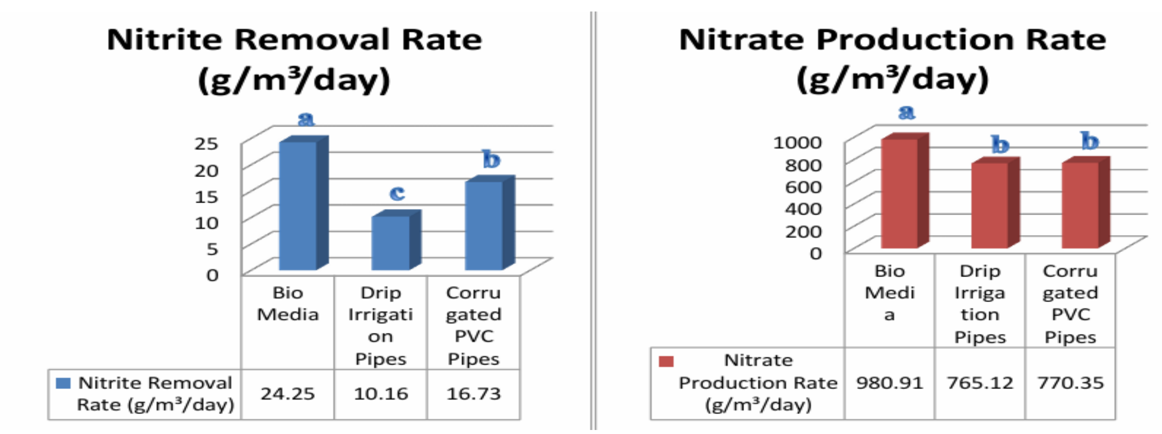


Fig. 5. Removal efficiencies of nitrite nitrogen (NO2-N) and nitrate nitrogen (NO3-N) production in the aquaponics system for the Nile tilapia (*O. niloticus*) using three biofilter media (biomedia, drip irrigation pipes, and corrugated PVC plastic pipes) after 120 days.

Values (mean of triplicates ± SE) with different letters are significantly different ($P< 0.05$)

4. Fish growth and feed utilization

There were significant differences between the treatments: bio media, PVC corrugated pipes, and drip irrigation pipes. The bio media system had the best FCR at 1.16 ± 0.01, indicating superior feed efficiency. Fish in the bio media system reached an average final weight of 137.5 ± 0.28g with a survival rate of 98.75 ± 0.36%. By contrast, the drip irrigation pipe system had the poorest FCR at 1.30 ± 0.03, with fish reaching a final weight of 123.5 ± 0.13g and a survival rate of 93.75 ± 0.36%. PVC corrugated pipes demonstrated a moderate performance, with an FCR of 1.22 ± 0.01 and a survival rate of 97.50 ± 0.72% (Table 1).

Table 1. Growth performance parameters in the aquaponics system for the Nile tilapia (*O. niloticus*) using three bio filter media (bio media, drip irrigation pipes, and corrugated PVC plastic pipes) after 120 days

Bio filter media	FCR	Final fish weight (g)	Survival rate (%)
Bio media	**1.16 ± 0.01^{b}**	**137.5 ± 0.28^{a}**	**98.75 ± 0.36^{a}**
PVC corrugated pipes	**1.22 ± 0.01 ^{a,b}**	**124.5 ± 0.57^{b}**	**97.50 ± 0.72^{a}**
Drip irrigation pipes	**1.30 ± 0.03^{a}**	**123.5 ± 0.13^{b}**	**93.75 ± 0.36^{b}**

Values (mean of triplicates ± SE) in same column with different letters are significantly different ($P< 0.05$).

5. Plant growth performance

Plants in the bio media system produced the most leaves (720.00 ± 17.32 leaves), reached the tallest height (85 ± 3.46 cm), had the highest fresh biomass (300.00 ± 17.32g), and showed significantly higher values compared to the other media types. There was no significant difference between the PVC corrugated pipes and drip irrigation pipes systems. The drip irrigation pipe system yielded the least productive plants, with only 630 leaves, a height of 78cm, and 220g of biomass. The PVC corrugated pipe system provided intermediate results (Table 2).

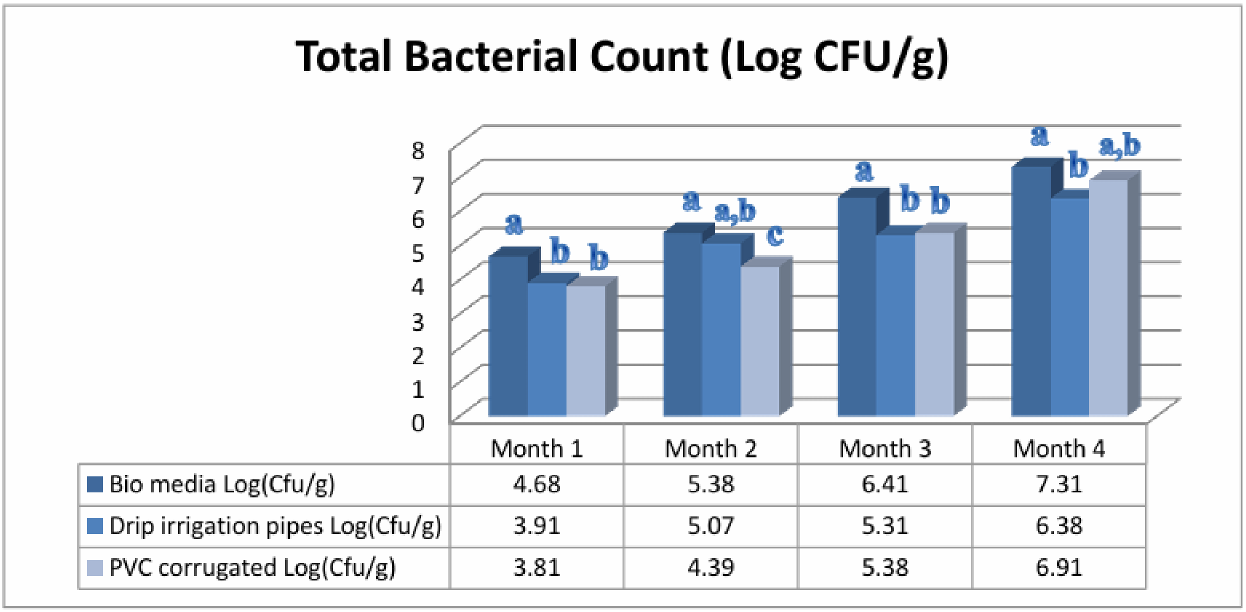
Table 2. Growth performance parameters of mint in the aquaponics system with the Nile tilapia (*O. niloticus*) using three biofilter media (biomedia, drip irrigation pipes, and corrugated PVC plastic pipes) after 120 days

Bio filter media	Number of leaves	Plant height (cm)	Fresh biomass (g)
Bio media	**720.00 ± 17.32^{a}**	**85 ± 3.46^{a}**	**300.00 ± 17.32^{a}**
PVC corrugated pipes	**640.00 ± 14.35^{b}**	**79.00 ± 3.02^{b}**	**230.00 ± 13.45^{b}**
Drip irrigation pipes	**630.00 ± 12.45^{b}**	**78.00 ± 2.15^{b}**	**220.00 ± 11.45^{b}**

Values (mean of triplicates ± SE) in same column with different letters are significantly different ($P< 0.05$).

6. Microbial activity and bacterial count

The results show that bio media supported the highest microbial activity, as evidenced by higher total bacterial counts, followed by PVC corrugated pipes, with drip irrigation pipes showing the least microbial activity, which was significantly lower (Fig. 6).



	Month 1	Month 2	Month 3	Month 4
Bio media Log(Cfu/g)	4.68	5.38	6.41	7.31
Drip irrigation pipes Log(Cfu/g)	3.91	5.07	5.31	6.38
PVC corrugated Log(Cfu/g)	3.81	4.39	5.38	6.91

Fig. 6. Total bacterial count of biological filter in the aquaponics system for the Nile tilapia (*O. niloticus*) using three bio filter media (bio media, drip irrigation pipes, and corrugated PVC plastic pipes) after 120 days. Values (mean of triplicates ± SD) with different letters are significantly different (P< 0.05).

The differences in microbial activity observed between the bio media, drip irrigation pipes, and PVC corrugated pipes can be attributed to the structural properties of the bio filter media. Bio media, with its higher surface area and porous structure, supports more extensive biofilm development and greater microbial diversity. This results in higher bacterial counts and improved system performance, as observed in this study.

7. Economic performance

Bio media offers the best overall economic value, with higher upfront costs more than offset by superior operational efficiency, better plant and fish yields, lower feed and maintenance costs, and longer system durability. For commercial-scale operations, bio media ensures maximum profitability over time.

Drip irrigation pipes present the lowest initial costs but incur significant long-term economic penalties due to poor water quality management, higher feed costs, frequent maintenance, and reduced plant productivity. These factors make them a less viable option for sustainable aquaponic operations, particularly in larger systems.

PVC corrugated pipes strike a balance between cost and performance, offering moderate efficiency in water quality management, feed conversion, and plant growth. However, they fall short of bio media in terms of long-term economic viability, making them better suited to small-to-medium-scale systems, where upfront cost is a key consideration (Table 3).

Table 3. Economic performance of using three biofilter media (biomedia, drip irrigation pipes, and corrugated PVC plastic pipes) in the aquaponics system for the Nile tilapia (*O. niloticus*) after 120 days

Factor	Bio media	Drip irrigation pipes	PVC corrugated pipes
Initial investment	**High (\$500-\$700/m³)**	**Low (\$100-\$150/m³)**	**Moderate (\$200-\$350/m³)**
Maintenance and longevity	**Best (10-15 years lifespan, low maintenance)**	**Poor (3-5 years, frequent replacement)**	**Moderate (5-10 years, moderate maintenance)**
Overall long-term costs	**Lowest (high profitability and system efficiency)**	**Highest (low efficiency, high operating costs)**	**Moderate (acceptable for small to medium systems)**

DISCUSSION

1. Water quality management

Goddek *et al.* (2021) emphasize the importance of maintaining stable water temperature, pH, and dissolved oxygen levels to support the health of both fish and plants. The results of this study suggest that all three bio filter media were effective at maintaining optimal water conditions, though the bio media exhibited slightly lower pH values, likely due to higher microbial activity.

Bio media provided the most efficient TAN removal, significantly improving water quality and reducing the risk of fish mortality due to ammonia toxicity. The high surface area of bio media supports robust microbial colonization, leading to faster nitrification. This finding aligns with previous studies demonstrating that media with higher surface areas promote more efficient biological filtration **(Graber & Junge, 2019)**. In contrast, drip irrigation pipes, with their limited surface area, performed poorly in TAN removal, leading to suboptimal water quality and higher operational costs due to increased water changes and disease management.

Nitrite, an intermediate product in the nitrification process, is toxic to fish and must be efficiently converted to nitrate to prevent harm. The study found that the bio media had the lowest nitrite concentration at the outlet (0.27 ± 0.02mg/ L) and the highest nitrite removal rate (24.25 ± 0.006g/ m^3/ day), indicating superior nitrite removal efficiency compared to the drip irrigation pipes and PVC corrugated pipes.

These results indicate that biofilters with a greater surface area-to-volume ratio such as bio media, with its larger surface area and optimized porosity, supported more robust microbial colonization and nitrification activity **(Goddek *et al.*, 2021)**. The drip irrigation pipes, due to their limited surface area, were less effective at supporting biofilm growth and microbial activity, resulting in lower TAN and nitrite removal efficiency.

Nitrifying bacteria, particularly *Nitrobacter*, are responsible for oxidizing nitrite into nitrate, a less harmful form of nitrogen that can be absorbed by plants **(Wongkiew *et al.*, 2020)**.

Similar findings have been reported by **Schmautz and Graber (2021)**, who demonstrated that biofilters with more surface area support larger bacterial colonies, improving both ammonia and nitrite removal. **Ling and Chong (2021)** also emphasize that a robust microbial community is essential for maintaining low nitrite levels in aquaponic systems, as nitrite toxicity can lead to oxidative stress in fish, negatively impacting their health and growth.

Nitrate is the final product of the nitrification process and serves as a critical nutrient for plants in aquaponic systems. The bio media treatment exhibited the highest nitrate concentration at the outlet (16.32 ± 0.23mg/ L) and the highest nitrate production rate (980.91 ± 15.62g/ m^3/ day), significantly surpassing both the drip irrigation pipes and PVC corrugated pipes, which had similar nitrate concentrations of 11.35mg/ L and production rates of approximately 765-770g/ m^3/ day.

The superior nitrate production in the bio media system is a direct result of its more efficient conversion of nitrite into nitrate. The high nitrate concentration indicates that the bio media not only enhanced the nitrification process but also ensured the availability of nitrate as a nutrient for plant growth. This is particularly beneficial in aquaponic systems, where nitrate serves as a primary nitrogen source for plants, directly influencing their growth and productivity **(Rakocy *et al.*, 2006)**.

The results align with the findings of **Graber and Junge (2019)**, who reported that biofilters with high nitrification efficiency significantly improve nitrate production, enhancing plant growth by supplying a steady stream of nutrients. Furthermore,

Pantanella *et al.* (2012) highlighted the critical role of nitrate availability in promoting robust plant growth in aquaponic systems, as nitrate is readily absorbed by plants and plays a key role in protein synthesis and overall biomass production.

2. Fish growth and feed utilization

The bio media system's superior feed conversion efficiency (FCR of 1.16 ± 0.01) can be attributed to better water quality, which reduced stress on fish and allowed for more efficient nutrient uptake **(Timmons & Ebeling, 2019)**. Lower FCR means that less feed is required to achieve the same level of growth, making bio media more economically viable in the long term. Drip irrigation pipes, on the other hand, resulted in higher FCR due to poor water quality, which impaired fish growth and increased feed costs.

The high FCR in the drip irrigation pipes system suggests that poor water quality led to higher feed consumption and reduced fish growth **(Timmons & Ebeling, 2019)**.

The superior FCR in the bio media system can be directly linked to better water quality and reduced stress on the fish. Studies have shown that fish exposed to elevated ammonia or nitrite levels exhibit reduced growth rates and lower feed conversion efficiency due to increased energy expenditure on coping with environmental stressors **(Ling & Chong, 2021)**. The bio media's ability to maintain lower ammonia and nitrite levels, as well as better total suspended solid (TSS) removal, reduced the physiological stress on the fish, allowing them to utilize feed more efficiently. This finding is consistent with previous research by **Suhl *et al.* (2016)**, who reported that fish in systems with better water quality exhibit significantly lower FCR values, resulting in more cost-effective production.

Elevated ammonia or nitrite concentrations, poor oxygenation, and high TSS levels can all contribute to increased fish mortality in aquaponic systems. In this study, the bio media treatment consistently outperformed the other two treatments in terms of nitrogen removal and TSS management, which likely contributed to the higher survival rate observed. This is supported by **Timmons and Ebeling (2019)**, who emphasize that effective bio filtration and TSS management are essential for reducing fish mortality in RAS and Aquaponic systems.

These findings align with previous research by **Schmautz and Graber (2021)**, who reported that bio filters with better nitrification efficiency and solid waste management capabilities tend to produce better fish growth and survival outcomes in aquaponic systems. The enhanced biofilm formation and higher surface area provided by the bio media likely contributed to its superior performance in this study.

3. Plant growth and nutrient cycling

Plant productivity in the bio media system was significantly higher than in the other systems, likely due to the enhanced nitrification and higher nitrate availability **(Pantanella *et al.*, 2012)**. Efficient nutrient cycling is critical for maximizing plant growth in aquaponic systems. Previous research has shown that improved nitrification leads to higher nitrate levels, which are essential for plant development **(Suhl *et al.*, 2016)**.

The enhanced biomass accumulation in the bio media system is likely due to the improved nitrogen availability, which is crucial for protein synthesis and plant tissue development. Nitrogen, particularly in the form of nitrate, is a key component of chlorophyll, amino acids, and proteins, all of which are essential for plant growth and biomass production **(Rakocy *et al.*, 2006)**. The higher nitrate levels in the bio media treatment provided the plants with the necessary building blocks for sustained growth, leading to higher biomass accumulation.

The results of this study suggest that bio media is the most effective bio filter medium for promoting plant growth in aquaponic systems. By providing better nitrogen conversion and superior water quality, bio media enhances the availability of essential nutrients such as nitrate, leading to improved plant health and productivity. This has important implications for the design and management of commercial aquaponic systems, where maximizing plant yields is a key factor in ensuring economic viability **(Goddek *et al.*, 2021)**.

This study's results are consistent with those of **Suhl *et al.* (2016)**, who found that bio filters with greater surface areas and more efficient microbial activity lead to better plant growth in aquaponic systems. The bio media, with its higher surface area and superior biofilm formation, provided a more efficient platform for nitrification, leading to better plant growth outcomes.

Water quality plays a crucial role in plant health, as poor water conditions can lead to nutrient imbalances, reduced root function, and stunted growth. In this study, the bio media system maintained the best water quality, with lower levels of TAN, nitrite, and TSS, which likely contributed to the superior plant growth observed. Elevated ammonia or nitrite levels can inhibit root function and disrupt nutrient uptake, leading to reduced growth **(Timmons & Ebeling, 2019)**. By maintaining lower concentrations of these toxic compounds, the bio media system ensured that the plants could access nutrients more effectively, resulting in better growth performance.

4. Microbial activity and bacterial count

Nitrifying bacteria, which thrive in biofilms attached to bio filter media, are crucial for the nitrogen cycle in aquaponic systems. These bacteria convert toxic ammonia, excreted by fish, into nitrite and then into nitrate, a form of nitrogen that is readily absorbed by plants **(Rakocy *et al.*, 2006)**.

The bio media exhibited the highest total bacterial counts, ranging from 4.68 ± 0.22 to 7.31 ± 0.50 Log CFU/g over the course of the study. This indicates that the bio media provided the most favorable environment for microbial colonization and biofilm development, likely due to its higher surface area and porosity. Bio filters with larger surface areas offer more attachment sites for nitrifying bacteria, such as *Nitrosomonas* and *Nitrobacter*, which are responsible for the conversion of ammonia to nitrite and nitrite to nitrate, respectively **(Timmons & Ebeling, 2019)**. The enhanced microbial activity in the bio media contributed to its superior performance in ammonia and nitrite removal, as discussed in earlier sections.

Additionally, the lower bacterial counts in the drip irrigation pipes and PVC corrugated pipes may be due to less optimal water flow characteristics in these systems. Efficient bio filter media not only provide ample surface area but also ensure consistent water flow to deliver ammonia and oxygen to the nitrifying bacteria. Bio media, with its more open structure, likely facilitated better water flow and nutrient exchange, further enhancing microbial activity **(Ling & Chong, 2021)**.

Studies by **Wongkiew *et al.* (2020)** and **Schmautz and Graber (2021)** have shown that bio filters with higher surface areas and porosity tend to support more robust biofilms, leading to an improved nitrification performance and a better overall system health.

5. Economic performance

Although bio media had the highest initial cost, its superior performance in water quality management, feed efficiency, and plant growth resulted in lower long-term operational costs, making it the most cost-effective option for commercial aquaponic systems **(Goddek *et al.*, 2021)**. Drip irrigation pipes, despite their lower upfront cost, incurred higher long-term costs due to poor performance in all key metrics, including TAN removal, fish growth, and plant productivity. PVC corrugated pipes provided a middle-ground solution but were still less efficient than bio media.

Long term economic impact

Systems using bio media require fewer water exchanges and experience lower rates of disease, contributing to significant cost savings. In commercial-scale aquaponics, even marginal improvements in FCR or survival rates can result in thousands of dollars in savings annually. The increased frequency of water exchanges, disease outbreaks, and reduced fish growth performance drive up operational costs. This makes drip pipes a poor choice for long-term profitability in commercial settings. Additionally, the poor water quality can lead to more frequent intervention, such as the addition of chemicals or antibiotics to control disease, further increasing costs. While PVC pipes reduce the need for constant water exchanges compared to drip pipes, they are still less efficient than bio media. The need for occasional water quality interventions can lead to moderate increases in operational costs. For small-scale systems, the balance between cost and performance may be acceptable, but for large-scale systems, these incremental inefficiencies can accumulate into significant expenses.

CONCLUSION

This study concludes that bio media is the most efficient and economically viable biofilter medium for aquaponic systems. Its superior TAN removal efficiency, improved feed conversion ratio, and enhanced plant growth make it the optimal choice for commercial-scale aquaponic operations. While drip irrigation pipes offer a lower initial investment, their poor long-term performance results in higher operational costs, making them unsuitable for large-scale systems. PVC corrugated pipes provide a more balanced solution but are less effective than bio media in terms of overall performance.

Future research should explore the development of lower-cost bio media that maintains high nitrification efficiency, further improving the economic sustainability of aquaponic systems.

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