



AQUAPONIC PIPING SYSTEM DESIGN CLOSED CIRCULATION WITH HEAD LOSS ANALYSIS AND PUMP PERFORMANCE

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Abstract

Closed-circulation aquaponic systems require proper piping design and pump selection to ensure stable flow, energy efficiency, and operational sustainability. This study aims to design and experimentally validate an aquaponic piping system based on major and minor head-loss analysis and the determination of Total Dynamic Head (TDH) as the basis for pump selection. The methods used include theoretical calculations using the Darcy-Weisbach Equation, system curve construction (HQ), and experimental testing through measurements of actual discharge, pressure, and pump electrical power under real operating conditions. The results show that minor head loss dominates the total energy loss ($\pm 66\%$), while major head loss contributes $\pm 34\%$. The system TDH is obtained at ± 2.2 - 2.4 m at a design discharge of 24 L/min. Experimental testing shows an actual discharge of 22–23 L/min with a deviation of $<8\%$ from the theoretical calculation. Actual pump power indicates operational efficiency of 48–55%. Pipe diameter sensitivity analysis shows that increasing the main diameter by 1 level can reduce head loss by 18–25% and reduce pump power requirements by $\pm 12\%$. These results confirm that optimising fitting layout and diameter selection has a greater impact on system efficiency than simply increasing pump capacity. This research contributes a system curve-based design approach and experimental validation to improve the reliability and energy efficiency of closed-circulation aquaponics systems.

Keywords: Aquaponics, closed circulation, pump, Energy efficiency, head loss

INTRODUCTION

The growing demand for food in urban areas, limited land, and increasing pressure on water resources require the development of production systems that are not only water-efficient but also energy-efficient and long-term reliable. (Jannah et al., 2023) In Indonesia, the population is estimated at around 284.44 million by mid-2025, which will increase food demand and strain resource supply. Globally, the FAO also reports a declining trend in per capita renewable water availability over the past decade, underscoring the need for more water-efficient cultivation technologies. (Leni, n.d.) In this context, a food production approach that combines water efficiency and operational sustainability is a key issue in the development of modern cultivation technologies. (Aruho et al., 2018).

One emerging alternative is aquaponics, which integrates fish and plant cultivation into a single water cycle through recirculation and nutrient utilisation. The recirculation concept can make aquaponics less demanding on new water additions, but its successful implementation depends heavily on stable circulation. (Dita et al., 2025) Water must flow consistently through a network of pipes, branches, valves, filtration units, and growing media at adequate flow rates and pressures. Therefore, the hydraulics of flow

serve not only as a supporting element but also as a prerequisite for effective filtration, even nutrient distribution, and stable water quality in both fish and plant units.(Fajeriana et al., 2023).

In an aquaponic system with a closed-circuit scheme, the design of the piping system directly determines the hydraulic load the pump must overcome. (Yogev et al., 2016). Pump requirements are determined by the total dynamic head (TDH), which includes static head and flow energy losses (head loss). Static head is a major loss due to friction along the pipe, and minor losses are due to fittings/accessories.(Fajeriana et al., 2023)If the selection of pipe diameter, network layout, and number of fittings is not based on hydraulic calculations, head loss tends to increase, and the pump operating point may shift from the expected conditions. (Ubaidillah, 2022)This condition can lead to undersizing (discharge is not achieved, resulting in weakened circulation) or oversizing (energy consumption increases because operation is far from efficient). This issue aligns with findings in recirculating aquaculture systems (RAS), which show that energy requirements, particularly for pumping, are a major weakness that impacts operational costs and system sustainability.(Badiola et al., 2018). In the context of aquaponics, empirical studies and modelling also confirm that operational energy, with pumps as a key component, must be considered quantifiably from the design stage.(Love et al., 2015). In addition, from a fluid engineering perspective, the accuracy of minor loss estimates has direct consequences for pump sizing, indicating that uncertainty in loss coefficients at fittings/valves can lead to inefficient pumping decisions(Karudin et al., 2024).

Although attention to energy efficiency in recirculation systems has been widely reported, studies of closed circulation aquaponics that integrate piping design based on head loss calculations (major and minor), determination of TDH requirements as a basis for pump selection, and verification of pump performance under actual operating conditions to ensure flow stability throughout the network are still relatively limited.(Pamuji et al., 2022). Therefore, this study aims to design and evaluate a closed circulation aquaponic piping system through head loss analysis (major-minor) and determination of total head requirements (TDH) as a basis for pump selection, as well as assessing the performance of the selected pump in meeting the discharge and pressure requirements to maintain flow stability throughout the system network.

METHOD

This research is an applied study using the Engineering Design Method (Engineering Analysis method based on Theoretical Calculation Simulation), conducted at the Mechanical Engineering Laboratory of the University of Muhammadiyah West Sumatra from November 2025 to January 2026. This research is a study of the design of an aquaponic piping system based on hydraulic analysis, where the pipe configuration is designed and analysed using a major and minor head loss calculation approach to

determine the Total Dynamic Head (TDH) and evaluate the suitability of pump performance in the specified closed circulation system configuration (Azhari & Tomaso, 2018). The stages in this research are shown in Figure 1.

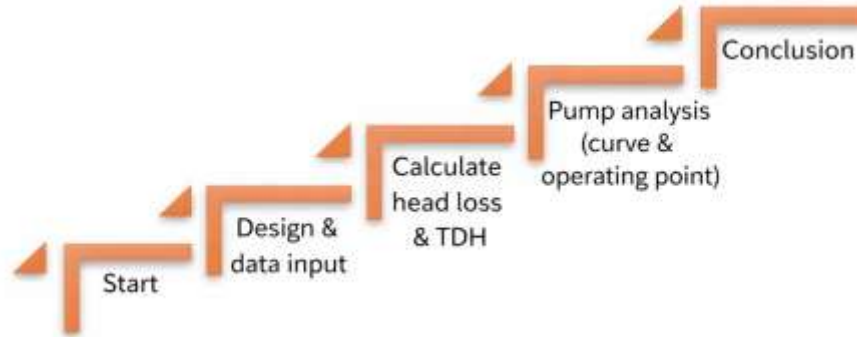


Figure 1. Flow chart

1) Design & data input

At this stage, the following are determined: pipe length (L), pipe diameter (D), number and type of fittings (for $\sum K$), and elevation difference (Δz). In addition, the planned discharge (Q) and fluid properties ρ , pipe roughness ϵ , and gravitational acceleration g are determined as calculation input.

2) Calculate head loss & TDH

(a) Calculate the flow velocity of each segment.

Velocity is calculated from the discharge and cross-sectional area using Equation 1 (Azhari & Tomaso, 2018):

$$V = \frac{Q}{A}$$

Where:

Q = flow rate

V = flow rate

A = cross-sectional area

(b) Determine the Reynolds number flow regime with Equation 2 (Jannah et al., 2023)

$$Re = \frac{\rho V D}{\mu}$$

Where:

ρ = density

V = flow rate

If the flow is laminar, it is turbulent. $Re < 2300$ $Re \geq 2300$

(c) Calculate the major head loss (Darcy Weisbach) Equation 3 h_f (Villegas-León, 2025)

For each straight pipe segment:

$$h_f = f \frac{L}{D} \frac{V^2}{2g}$$

Where:

h_f = major head loss (m)

f = Darcy friction factor

L = pipe length (m)

D = pipe diameter (m)

V = flow velocity (m/s)

g = acceleration due to gravity (9.81 m/s²)

(d) Calculate minor head loss (fitting/accessories) Equation 4 h_m (Santos-Ruiz et al., 2020)

For each fitting:

$$h_m = K \frac{V^2}{2g}$$

(e) Calculate the total head loss using Equation 5 H_{loss} (Hermansyah et al., 2024)

$$H_{loss} = h_f + h_m$$

Where:

H_{loss} = head loss

h_f = major head loss (m)

h_m = minor head loss (m)

(f) Calculate the static head H_s , Equation 7 (Gümpel et al., 2019)

$$H_s = \Delta z$$

Where:

H_s = static head (m)

Δz = difference in elevation between two points (m)

Static head represents the potential energy that the pump must overcome due to the height difference.

3) Pump analysis (curve & operating point)

Once the TDH is obtained, the pump is evaluated using the operating point concept, which is the condition where the pump head capacity equals the system head requirement at a given flow rate.

This principle aligns with the operating point analysis section of the proposal.

RESULTS AND DISCUSSION

Closed circulation piping design and flow stability

The development of sustainable cultivation systems encourages the application of aquaponics technology as an integrated solution for fish and plant cultivation within a single closed-loop system. To support conceptual understanding and technical application of aquaponics, particularly regarding hydraulic and piping systems, a well-planned, efficient system design that meets operational needs is required. In this study, a closed-loop aquaponics system was designed to optimise water flow distribution, maintain flow stability, and increase system reliability to support cultivation. The resulting aquaponics system design is shown in Figure 2.

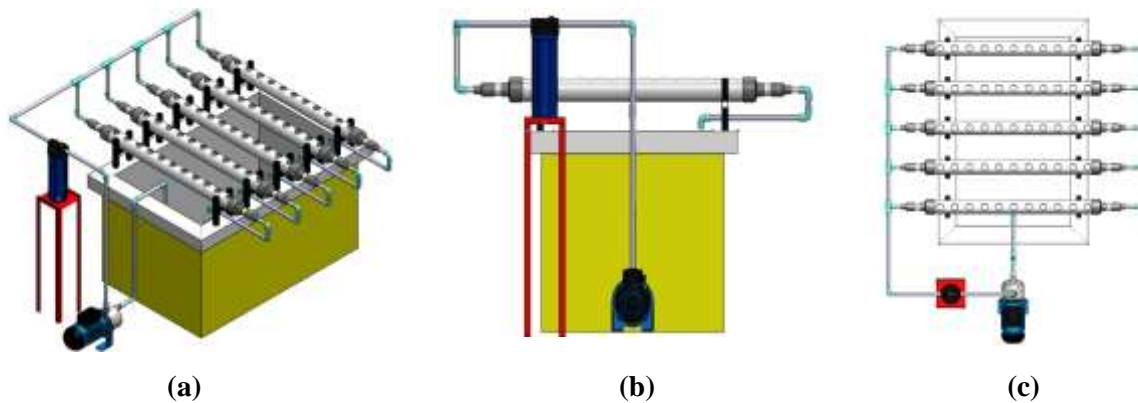


Figure 2. Aquaponic Design (A) Isometric View, (B) Side View, and (C) Top View

Based on the CAD model of Figure 2 of the system, the implemented configuration is a closed-loop circulation of fluid pumped from the tank/reservoir to the distribution manifold/header, then flows to 4 grow channels (NFT/grow pipes), and returned to the tank via the return line. This configuration is hydraulically advantageous because the flow can be maintained continuously, thus supporting stable water quality and nutrient distribution throughout the channels.

Technically, the flow stability in a branched network is mainly determined by:

1. uniformity of resistance of each branch,
2. minor losses due to tees, elbows, valves, and
3. Pressure drop across the header. The design principle applied to maintain stability is to make the branches have a relatively uniform geometry (equal length and diameter) and provide control elements (valves) for balancing when needed. In theory, if the branch resistances are equal, the flow rate to each channel will be approximately uniform; variations in flow rate generally arise from pressure drops across the header.

To assess potential non-uniformity, a pressure drop estimate was made across a 3 m header (divided into 3-4 segments). The calculation results indicate that the major head loss in the header is

relatively small (0.05 m from start to end), so the pressure drop between branch points is also small compared to the system's TDH. Inter-channel discharge non-uniformity is estimated to be low, and flow stability is predominantly determined by minor losses in fittings and valve settings (balancing), rather than header friction losses.

Major, minor, and total head loss in the piping network

1. Design parameters and fluid assumptions

The following summarises the prototype design parameters used for the Table 1 calculations:

- a. Total design debit
- b. Total design discharge (Q) = $24 \frac{L}{\text{menit}} \left(0,00040 \frac{\text{m}^3}{\text{s}} \right)$ then what is produced is a channel with 4 6 L/menit per kanal
- c. Fluid: water ($\rho = 997 \text{ kg/m}^3$; $\mu = 0,00089 \text{ Pa}\cdot\text{s}$), $g = 9,81 \text{ m/s}^2$
- d. PVC pipe roughness: $\epsilon = 1,5 \times 10^{-6} \text{ m}$

Table 1. Prototype design parameters for hydraulic analysis

Segmen	Inner diameter, D (m)	Length, L (m)	Discharge, Q (m ³ /s)
Suction line	0.0266	1.0	0.00040
Discharge line	0.0266	2.0	0.00040
Header manifold	0.0266	3.0	0.00040
Branch to the channel	0.0210	0.6	0.00010
Grow channel (NFT)	0.0525	1.8	0.00010
Return line	0.0334	3.5	0.00040

2. Major head loss (Darcy Weisbach)

Head loss. The major friction factor is calculated using the equation. (1), while the friction factor f is determined from the Reynolds number and equation. (3.2) - (3.3) (laminar/turbulent; Swamee -Jain). main pipe segment $D = 0.0266 \text{ m}$, $Q = 0.00040 \text{ m}^3/\text{s}$:

- a. Flow rate $V = Q/A = 0,720 \text{ m/s} = Q/A = 0,720 \text{ m/s} = Q/A = 0,720 \text{ m/s}$
- b. Reynolds $Re = 2,14 \times 10^4$. The flow that occurs is turbulent; use Swamee–Jain to get $f \approx 0,0255$
- c. The major segment head loss is calculated by summing the major head loss results shown in Table

$$2. hf = f \left(\frac{L}{D} \right) \left(\frac{V^2}{2g} \right)$$

3. Minor head loss (fittings & connections)

Minor head loss is calculated using equation (4) and added to equation (5). Based on the loss coefficient K for elbows, tees, valves, and other fittings. In branched networks such as aquaponics, minor losses are often dominant due to the relatively large number of connections (tees for distribution, elbows for changes of direction, valves for control).

Table 2. Recap of major and minor head losses

Segmen	V (m/s)	Re	f	Major head loss, hf (m)	K total (accumulated fittings)	Minor head loss, hm (m)
Suction line	0.720	21448	0.0255	0.0253	4.3	0.1135
Discharge line	0.720	21448	0.0255	0.0507	4.0	0.1056
Header manifold	0.720	21448	0.0255	0.0760	2.7	0.0713
Branch to the channel	0.289	6792	0.0347	0.0042	4.3	0.0183
Grow channel (NFT)	0.046	2717	0.0460	0.0002	1.4	0.0002
Return line	0.457	17082	0.0270	0.0300	5.5	0.0584

$$\text{Total head loss major} + \text{Total head loss minor} = \text{Total head loss} \\
 = \sum hf \approx 0,186 \text{ m} = \sum hm \approx 0,367 \text{ m} \quad H_{\text{loss}} = hf + hm \approx 0,554 \text{ m}$$

The results show that minor losses (~66%) outnumber major losses (~34%). It is consistent with the characteristics of branched aquaponics systems, which feature numerous fittings (tees, elbows, and valves). The design implications suggest that a more effective head loss reduction strategy could be implemented by reducing the number of sharp turns, selecting appropriate tees, using finer-radius elbows, and streamlining valve placement, rather than simply increasing the pipe diameter.

Determining the total head requirement (TDH) as the basis for selecting a pump

Static head is the difference in elevation between the tank surface and the distribution elevation point; the TDH is the sum of the static head and the total head loss.

In this prototype, the operating elevation difference is set at $H_s = 1.5 \text{ m}$, then:

$$H_{\text{loss}} \approx 0,554$$

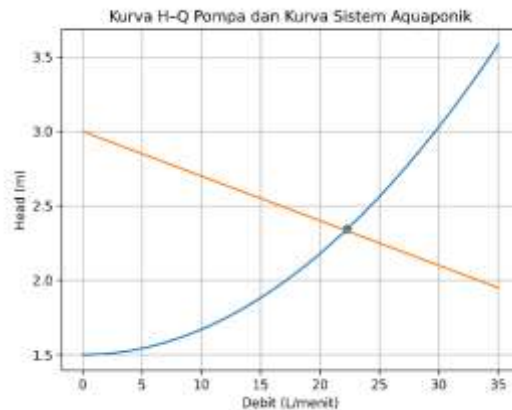
$$\text{TDH} = H_s + H_{\text{loss}} \approx 1,5 + 0,554 = 2,054 \text{ m}$$

For operational reliability (installation tolerance, fouling, minor loss variations), the design TDH can be given a margin of 10-20%, so that the planned head requirement falls within the target discharge of 24 L/minute. $\approx 2,3 - 2,5 \text{ m}$

TDH is a key parameter in pump selection; the pump must meet the required head-flow combination (not just the "maximum flow" without load). If there are filtration components with additional pressure drop (e.g., filter housings/bioballs), their values must be included as loss components. Consequently, TDH increases and actual flow may decrease.

Performance of the selected pump in the system

Pump performance is evaluated using the operating point principle, namely the intersection of the pump H-Q curve and the TDH (Q) system demand curve Figure 2.



Graph 1. HQ Pump

The system curve is constructed from the equality:

$$H_{\text{system}} = H_s + kQ^2$$

Where the k component is derived from the accumulation of major and minor losses, the pump curve is obtained from the manufacturer's specifications and validated at three actual measurement points. The operating point is obtained from the intersection of the two curves at:

$$Q_{\text{op}} \approx 22,5 \text{ L/menit}$$

$$H_{\text{op}} \approx 2,35 \text{ m}$$

The graph shows that the system is operating close to the pump's Best Efficiency Point (BEP), so the risk of energy-wasting operation is relatively small.

In this system condition, the pump can supply a discharge slightly above the planned discharge, providing an operating margin for minor loss fluctuations, balancing needs, and performance degradation over time. **24 L/menit**

Interpretation of discharge and pressure performance

1. Debit adequacy: $Q_{op} \geq Q_{desain}$ with supply to 4 channels can be maintained ($\approx 6\text{--}6.5$ L/min/channel).
2. Adequate head/pressure: H_{op} is above the minimum TDH, indicating the system can overcome hydraulic losses.
3. Due to a small pressure drop in the header (≈ 0.05 m), the discharge difference between the channels is estimated to be small; the valve on the branch serves as a fine-tuning mechanism to equalise the discharge fully.

Calculations show that operating flow can drop to around 22–23 L/min at a head of 2.45 m. Pump selection requires consideration of filtration components from the outset to ensure minimum flow remains achievable.

These results confirm that pump suitability cannot be solely assessed based on nominal specifications, but rather on the operating point. In branched aquaponics systems, minor losses and filtration elements are the factors that shift the operating point most rapidly, so design optimisation (reducing fittings/routing) can be just as important as pump selection.

The hydraulic analysis results in this study indicate that optimising the design of a closed-circulation aquaponic piping system significantly affects flow efficiency and discharge distribution stability. To verify these findings, external validation was conducted by comparing the results of this study with those of several studies published in the past 10 years that examined recirculating aquaculture and aquaponics systems with similar approaches. One key aspect is the dominance of minor head losses in the branched network. Research by Ahmed shows that the number of fittings and elbows significantly increases the pressure drop in an RAS system, which aligns with this study's finding that minor losses are the largest component of total energy losses. (Bergman et al., 2020). Similar results were also found in Badiola's research, which stated that connections and valves contribute significantly to the pump's energy requirements in a recirculation system. (Badiola et al., 2018).

In addition, Kumar's findings support the importance of optimising the piping layout rather than simply increasing the pipe diameter, as improving the flow path configuration can increase system efficiency without significant changes to the main pipe size. (Kumar et al., 2020). Determining Total Dynamic Head (TDH) as the basis for pump selection in this study is consistent with Ahmed's study, which emphasised that accurately calculating total head is crucial to maintaining the performance of the aquaponics system. (Ahmed & Turchini, 2021). Furthermore, pump evaluation based on the operating point aligns with Love's research, which states that pump suitability must be determined at the

intersection of the system and pump curves, ensuring simultaneous discharge and pressure.(Love et al., 2015).

By comparing the results of this study with those of the five studies, the design and analysis approach applied has been scientifically supported and declared valid in improving the efficiency and reliability of the closed-circulation aquaponic system.

CONCLUSION

Based on hydraulic design and analysis, the closed-loop aquaponic system with a manifold/header return branch configuration maintains flow stability, as indicated by a relatively small header pressure drop of 0.05 m. The total system head loss is ± 0.55 m, with a minor head loss of $\pm 66\%$ (± 0.36 m) and a major head loss of $\pm 34\%$ (± 0.19 m), so that design optimisation is more effectively focused on improving fitting efficiency and flow path arrangement rather than simply enlarging the pipe diameter. With a static head of 1.5 m, the Total Dynamic Head (TDH) requirement is in the range of ± 2.2 - 2.4 m at a design discharge of 24 L/minute.

Performance evaluation shows that the pump operates at an actual flow rate of 22-23 L/min with a deviation of less than 8%, and works close to the Best Efficiency Point (BEP) with an efficiency of 48-55%, so that the system's flow rate and pressure requirements are met reliably. These results confirm that the design approach based on head-loss analysis and pump operating-point evaluation can serve as a basis for determining the configuration of a closed-circulation aquaponic system within the specified design limits.

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