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Hydraulic Performance Evaluation Of Multi-Layer Natural Media Filtration Systems Using A Structural Scoring Approach

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ABSTRACT

This study proposes a structural scoring model to evaluate the hydraulic performance of a simple multi-layer natural media filtration system based on appropriate technology principles. The model integrates pore size hierarchy and layer importance to quantify the structural arrangement of filtration media. Six filtration materials, including biofill, sand, zeolite gravel, coconut coir, palm fiber, and charcoal, were arranged into seven different layer combinations and tested under laboratory conditions with two replicates per treatment. A fixed water volume of 300 mL was filtered, and flow rate was calculated based on total filtration time.

The results showed substantial variation in hydraulic performance, with flow rates ranging from $6.80 \times 10^{-7}$to 2.70×10^{-6}m³/s. The highest flow rate was observed in configurations dominated by coarse pore structures, whereas the lowest flow rate occurred in configurations containing finer media distributions and higher hydraulic resistance. Pearson correlation analysis produced a moderate negative relationship between structural score and flow rate ($r = -0.587$), indicating that higher structural scores tend to reduce flow velocity due to increased internal resistance within the layered filtration system. Linear regression analysis generated the equation $Q = 4.50 \times 10^{-6} - 3.99 \times 10^{-8}S$, confirming the inverse relationship between structural arrangement and hydraulic behavior.

The findings demonstrate that media arrangement plays a more important role than material composition alone in determining filtration performance. The proposed structural scoring model provides a simple and practical approach for evaluating and optimizing low-cost filtration systems, particularly for resource-limited and emergency conditions.

INTRODUCTION

Access to clean water remains a crucial challenge, especially in emergency situations such as natural disasters when infrastructure is damaged and access to safe water is limited. Communities often face difficulties in meeting basic sanitation needs due to disruption of water supply systems and environmental degradation (Fikri et al., 2022). Therefore, water treatment solutions that are simple, affordable, and easy to implement are needed to ensure sustainable access to clean water. The appropriate technology approach, which emphasizes the use of local materials and simple operational mechanisms, has been widely recognized as an effective strategy to address water scarcity in emergencies. The application of household-scale or decentralized water treatment technology is considered more practical and sustainable than centralized systems, especially in disaster-affected areas with limited infrastructure.

Simple filtration systems based on natural media such as zeolite, sand, charcoal, coconut fiber, biofill, and gravel are widely applied as low-cost alternatives for water treatment because the materials are easily obtained and capable of improving water quality effectively (Dwivedi & Nidheesh, 2025; Rajamani et al., 2024; Samuel & Sunitha, 2025). Natural filtration mechanisms occur through physical filtration, adsorption, sedimentation, and particle trapping within the pore structure of the media, thereby reducing suspended solids and improving water clarity. Filtration performance is not only determined by the characteristics of individual materials, but also by the arrangement of media layers within the filtration column. The structure and sequence of filtration media play an important role in controlling flow distribution, hydraulic behavior, and filtration efficiency in simple water treatment systems (Alim et al., 2017; Printsypar et al., 2018).

In porous filtration systems, fluid movement is strongly influenced by pore structure, permeability, hydraulic resistance, and the connectivity between media layers. Variations in media arrangement can generate different flow distributions and residence times, which subsequently affect contaminant retention and overall filtration performance. Improper media configuration may induce preferential flow pathways and unstable hydraulic conditions, reducing the effectiveness of the filtration process. Therefore, optimization of media arrangement becomes an important factor in improving the hydraulic performance and operational stability of low-cost filtration systems.

To address this issue, this study introduces a structural scoring model that combines pore size ranking and layer importance weighting to evaluate filtration configurations. The purpose of this study was to analyze the relationship between media arrangement and hydraulic performance and to evaluate whether the proposed structural scoring model can predict filtration behavior in simple filtration systems.

RESEARCH METHODS

Study area and research design

This study was conducted on April 23, 2026, at the Vocational School of IPB University. The equipment used in this study consisted of a 1.5-liter used plastic bottle, which functioned as a filtration container. The equipment used in this study consisted of a 1.5-liter used plastic bottle, which functioned as a filtration container. The study utilized an experimental design involving a multi-layer filtration system consisting of six distinct materials: biofill (BF), sand (S), zeolite gravel (Z), coconut fiber (C), fiber (F), and charcoal (Ch). Seven different configurations of media arrangements were evaluated, as presented in Table 1 below.

Table 1. Combinations of Filtration Media Layers (from top to bottom)

Combination	Layer Arrangement
C1	BF-C-S-Ch-F-Z
C2	Ch-S-F-C-Z-BF
C3	S-Ch-BF-Z-C-F
C4	C-BF-Z-S-Ch-F
C5	F-Z-S-BF-C-Ch
C6	Z-F-Ch-C-S-BF
C7	S-C-Ch-F-BF-Z

The research procedure was carried out by arranging the filtration media inside the bottle according to the treatment combinations. The test water was then poured from the top of the filtration device. The time required for the filtered water to completely exit from the bottom of the device was recorded using a timing instrument. The parameters observed in this study included filtration time (minutes and seconds) and the visual quality of the filtered water, which was assessed based on its level of clarity.

Filtration procedure

A fixed volume of 300 mL of water was poured into the filtration column for each experimental run. The filtration time was measured from the moment water entered the system until the last droplet exited the bottom layer. The filtration column was filled sequentially according to the predefined combinations. Care was taken to maintain consistent packing density and avoid excessive compaction of the media.

Each treatment was tested in two replicates under identical conditions. Each treatment in this study was conducted using two replicates as part of a preliminary exploratory assessment intended to compare the hydraulic performance of different filtration media configurations. Similar small-scale experimental studies have also applied limited replication during initial system evaluation stages to identify general performance trends and operational behavior (Saputra et al., 2022). Although the use of two replicates limits statistical robustness, the approach remains sufficient for identifying comparative hydraulic tendencies among filtration configurations. Nevertheless, this limitation has been acknowledged, and future studies are recommended to include additional replicates and expanded datasets for stronger statistical validation.

The time required for complete filtration was recorded using a stopwatch. Flow rate was calculated using the following equation:

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

where:

Q = flow rate (m^3/s)

V = water volume (3×10^{-4} m^3)

t = filtration time (s)

Observed parameters

The primary parameter observed in this study was the hydraulic performance of the filtration system, represented by:

1. **Filtration Time (s)**
   The total time required for 300 mL of water to pass through the system.
2. **Flow Rate (m^3/s)**
   Calculated based on the filtration time.
3. **Hydraulic Stability**
   Evaluated using the coefficient of variation (CV) between replicates.
4. **Structural Score**
   Calculated by combining pore size ranking and layer importance.

Hydraulic Stability

Hydraulic stability category in this study was developed based on the interpretation of the value of the coefficient of variation (CV) which is commonly used to evaluate the level of homogeneity, consistency, and repeatability of experimental data. Low CV values show small variations between measurements so that the system is considered to have a more stable and homogeneous behavior. Similar approaches are also widely used in hydraulic analysis and soil science to evaluate the stability of flow parameters, the variability of porous media, and the consistency of experimental results (Zhang et al., 2025). Here is the formula for calculating it:

$$\mathrm{CV} = \frac{\mathrm{SD}}{\bar{\mathrm{Q}}} \times 100\%$$

CV = coefficient of variation (%)

SD = standard deviation of flow rate

$\bar{Q}$ = average flow rate (m^3/s)

In this study, the interpretation is modified into the context of filtration to represent the stability of flow distribution and consistency of hydraulic performance between configurations of filtration media. Modification of this approach is done by adopting the principle of evaluation of repeatability and hydraulic stability previously used in the study of hydraulic and porous media, then applied to the analysis of the flow behavior of layered filtration systems. The category of hydraulic stability was adapted from the general interpretation of the coefficient of variation widely used in experimental and environmental variability analysis, then modified into the context of porous filtration systems. The classification used in this study is presented in Table 2.

Table 2. Classification of hydraulic stability by coefficient of variation (CV)

CV (%)	Stability Category
<5	Very Stable
5–10	Stable
10–20	Moderately Stable
20–40	Unstable

CV (%)	Stability Category
40–60	Highly Unstable
>60	Extremely Unstable

Structural Scoring Model

Scoring approach is a quantitative evaluation method used to represent the characteristics of the system into the form of numerical values based on a certain ranking and weighting. The structural scoring Model was developed by adapting the concept of weighted evaluation and hierarchical assessment which is widely applied to multicriteria decision-making methods, such as the Analytical Hierarchy Process (AHP), where each parameter is given a value and weight based on its importance (Saaty, 1980). The concept is modified into the context of porous filtration by combining the ranking of the pore size of the media and the level of importance of the coating to represent the structural configuration of the filtration system. A simplified scoring model was developed to evaluate the arrangement of filtration media:

$$\text{Score} = \sum(Vr \times U)$$

Where:

Vr = pore size ranking value of each material

U = layer importance (1 = top layer, 6 = bottom layer)

The ranking value of each filtration media is determined based on the pore size hierarchy approach which represents the level of permeability and fluid flow ability in each material. Media with larger pore sizes generally have higher permeability and lower hydraulic resistance, allowing the flow to take place more quickly (Hołaj-Krzak et al., 2025; Nouira et al., 2025). The highest value is given to zeolite gravel because this material has a relatively large particle size with a wide interparticle space resulting in high permeability and low hydraulic resistance. The structure on zeolite gravel allows water to flow faster and serves as the main distribution line in layered filtration systems. In addition, zeolite has a more porous structure so that it can maintain adsorption capacity without significantly reducing flow ability. These conditions cause this medium to represent the layer with the largest flow capacity in the filtration system.

Conversely, media with smaller pores produce greater flow resistance and increase fluid residence time within the filtration system (Kim et al., 2025). This approach is used to quantitatively describe the relationship between pore structure, flow distribution, and hydraulic behaviour in layered filtration systems (Zhou et al., 2026). Sand is given the lowest value because it has the smallest pore size and gap between grains compared to other media so as to produce the highest hydraulic resistance. The denser pore structure causes the water flow rate to be slower and increases the residence time of water in the filtration medium. While these conditions are beneficial for fine particle filtration processes and increased filtration contact, the high flow resistance makes sand the lowest permeability level in the filtration media hierarchy. The pore ranking values were assigned as follows:

Table 3. Ranking values for every materials

Material	Value
Zeolite gravel (Z)	6
Coconut fiber (C)	5
Fiber (F)	4

Material	Value
Biofill (BF)	3
Charcoal (Ch)	2
Sand (S)	1

Data analysis

Descriptive statistical analysis was used to calculate mean and variability (standard deviation and coefficient of variation) of flow rates. Correlation analysis was performed to evaluate the relationship between structural score and flow rate. The strength and direction of the relationship were assessed using Pearson correlation. Pearson correlation analysis was applied to quantify the relationship between structural score and flow rate. The Pearson correlation coefficient (r) was calculated using the following equation:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{(\sum(x_i - \bar{x})^2)(\sum(y_i - \bar{y})^2)}}$$

Where:

r = Pearson correlation coefficient

x_i = structural score value

y_i = flow rate value

$\bar{x}$ = mean structural score

$\bar{y}$ = mean flow rate

This approach allows assessment of whether the proposed scoring model can explain variations in hydraulic behavior. A linear regression model was applied to describe the relationship between structural score and flow rate:

$$Q = a + b \times \text{Score}$$

Where:

Q = flow rate

Score = structural score

a, b = regression coefficients

Data Visualization

A scatter plot was generated to illustrate the relationship between structural score and flow rate, with a fitted regression line to identify trends.

RESULTS AND DISCUSSION

Hydraulic performance of the filtration system

This study was conducted to determine the effect of different combinations of filtration media layers on the performance of a simple water filtration device, particularly in terms of filtration speed and the visual quality of the filtered water. Each layer combination has a different media arrangement, resulting in varying water flow characteristics and filtration capabilities.

In general, the filtration media used in this study have distinct functions. Coarse-porosity media such as zeolite gravel and sponge facilitate faster water flow, while fine-porosity media such as sand, charcoal, and coconut fiber function to filter fine particles and improve water clarity. Therefore, variations in the arrangement of media are expected to influence the balance between flow rate and filtration quality. Observations were conducted on the time required for water to pass through all media layers, as well as the visual quality of the filtered water produced. The results of the filtration time measurements for each treatment combination are presented in Table 4.

Table 4. Filtration Time

Combination	Replication 1 (s)	Replication 2 (s)	Average (s)
C1	420	465	443
C2	170	230	200
C3	179	205	192
C4	180	320	250
C5	174	184	179
C6	78	194	136
C7	420	342	381

Based on Table 4, there are significant variations in filtration time among the different media combinations. Combination C6 shows the fastest filtration time, while combinations C1 and C7 show the longest filtration times. This indicates that the arrangement and type of filtration media strongly influence the water flow rate within the system.

High filtration speed in certain combinations is likely caused by the dominance of coarse-porosity media, which allows water to flow more quickly with minimal resistance. In contrast, combinations with longer filtration times tend to contain fine-porosity media layers that slow down water flow due to more intensive particle filtration processes.

Flow Rate (Derived Parameter)

Table 5. Water Flow Rate

Combination	Replication 1 (m^3/s)	Replication 2 (m^3/s)	Average (m^3/s)
C1	7.14×10^{-7}	6.45×10^{-7}	**6.80×10^{-7}**
C2	1.76×10^{-6}	1.30×10^{-6}	**1.53×10^{-6}**
C3	1.68×10^{-6}	1.46×10^{-6}	**1.57×10^{-6}**
C4	1.67×10^{-6}	9.38×10^{-7}	**1.30×10^{-6}**
C5	1.72×10^{-6}	1.63×10^{-6}	**1.68×10^{-6}**
C6	3.85×10^{-6}	1.55×10^{-6}	**2.70×10^{-6}**
C7	7.14×10^{-7}	8.77×10^{-7}	**7.96×10^{-7}**

The calculated flow rate indicates the existence of hydraulic performance variations in various combinations of filtration media, which indicates that the media configuration and pore structure play an important role in controlling the flow distribution and hydraulic resistance within the porous system. Media with larger pores and lower internal resistance tend to produce higher flow rates, whereas fine porous media increase resistance and extend fluid residence time inside the filtration column (Kalmakhanova et al., 2026; Zhang et al., 2026). Therefore, the filtration rate represents the balance between the driving force and the internal resistance and is therefore the main indicator of the hydraulic behavior of the system.

The highest average flow rate is observed in the C6 combination, which indicates a low hydraulic resistance due to the predominance of large pores and a less dense structure of the medium. These conditions allow water to flow faster through the filtration media, but a shorter residence time can limit the interaction between contaminants and the media, potentially reducing the efficiency of pollutant removal (González-Juárez et al., 2026; Panda et al., 2026). In contrast, C1 shows the lowest flow rate indicating higher hydraulic resistance and longer water residence time. These conditions favor increased particle retention and adsorption processes, although they have the potential to increase head loss due to particle accumulation in the medium.

Consistency analysis between replicates showed differences in structural stability in each combination. C5 exhibits the most stable hydraulic behavior with very little variation in discharge between repeats, demonstrating relatively uniform pore distribution and media packaging. In contrast, C6 shows the highest variability, which indicates the formation of preferential flow paths (preferential flow) or channeling due to heterogeneity of media structure and uneven flow distribution (Liu et al., 2026; Najafpoor et al., 2026). These conditions decrease the effective filtration volume and result in less consistent system performance.

In general, the results indicate a trade-off between hydraulic conductivity and filtration efficiency. Media with high permeability support greater flow capacity, but tend to reduce the effectiveness of contaminant removal due to reduced contact time between fluid and filtration media (Pachaiappan et al., 2022). Therefore, optimal filtration performance requires a balance between flow rate, hydraulic resistance, residence time, and stability of the media structure within the filtration column.

Table 6. Hydraulic Stability

Combination	$\bar{Q}$ (m^3/s)	SD (m^3/s)	CV (%)	Stability Category
C1	6.80×10^{-7}	4.88×10^{-8}	7.2	Stable
C2	1.53×10^{-6}	3.25×10^{-7}	21.3	Unstable
C3	1.57×10^{-6}	1.56×10^{-7}	9.9	Stable
C4	1.30×10^{-6}	5.18×10^{-7}	39.9	Unstable
C5	1.68×10^{-6}	6.36×10^{-8}	3.8	Very stable
C6	2.70×10^{-6}	1.63×10^{-6}	60.4	Extremely unstable
C7	7.96×10^{-7}	1.15×10^{-7}	14.5	Moderately stable

The coefficient of variation (CV) was used to evaluate the hydraulic stability of each filtration configuration (table 5). The results show that C5 exhibited the highest stability (CV = 3.8%), followed by C1 and C3, which were classified as stable systems. In contrast, C6 showed extremely high variability (CV = 60.4%), indicating unstable flow conditions and possible preferential flow pathways. The variability observed in certain combinations suggests that media arrangement significantly influences flow consistency, likely due to differences in pore distribution and packing structure.

Structural Scoring Analysis

In terms of visual water quality, the C1 combination produces the clearest water compared to other combinations. The result indicates that a slower filtration process provides a longer contact time between water and the filter media, allowing fine particles to be removed more effectively. The findings demonstrate a relationship between filtration rate and the quality of filtered water. Combinations with faster filtration time tend to produce less optimal water quality, whereas combinations with longer filtration time produce clearer water. Contact time between water and filter media depends on flow velocity, so filtration efficiency (turbidity reduction, bacterial removal, and related parameters) varies according to the duration of contact.

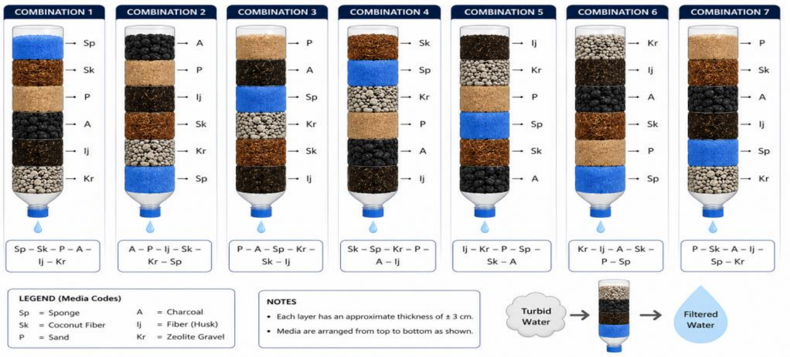

Figure 1. Filtration media combinations (arrange from top to bottom)

In addition to technical aspects, the findings also carry practical implications for community application. The simple filtration device shows potential for use in emergency conditions such as natural disasters, where access to clean water remains limited. Utilization of readily available materials and low-cost components enables the device to serve as an alternative solution aligned with the concept of appropriate technology.

Table 7. Structure and Material Scoring

Combination	L1	L2	L3	L4	L5	L6	Score
C1	3	10	3	8	20	36	80
C2	2	2	12	20	30	18	84
C3	1	4	9	24	25	24	87
C4	5	6	18	4	10	24	67
C5	4	12	3	12	25	12	68
C6	6	8	6	20	5	18	63
C7	1	10	6	16	15	36	84

The structural scoring results indicate that C3 achieved the highest score (87), representing the most optimal arrangement of filtration media (Table 7). This configuration follows a hierarchical pore distribution, allowing a gradual transition from coarse to fine media. Such an arrangement promotes controlled flow distribution and progressive particle removal throughout the filtration column. In contrast, C6 obtained the lowest score (63), reflecting poor media arrangement and the absence of a structural gradient. This configuration is likely to induce preferential flow, where water bypasses portions of the media, reducing filtration effectiveness. Overall, the ranking results confirm that filtration performance is strongly influenced by the vertical arrangement of media layers rather than material composition alone. The dominance of structural arrangement in determining filtration performance is consistent with the behavior of multi-layer filtration systems, where hydraulic retention time and flow distribution are regulated by media configuration. Proper layering enables stable discharge and effective contaminant removal by controlling flow pathways and residence time within the system (Fauzi et al., 2024).

Furthermore, the hierarchical arrangement observed in high-scoring configurations (e.g., C3, C2, and C7) supports gradual filtration processes similar to those found in biosand filtration systems. In addition, the relationship between structural score and filtration performance can be explained through pore size and resistance dynamics. Configurations with well-organized pore gradients increase flow resistance while improving contaminant removal through mechanisms such as size exclusion and adsorption. Granular filtration systems have been shown to significantly reduce turbidity through these mechanisms when pore structure and media arrangement are optimized (Mudau et al., 2022).

Overall, these findings demonstrate that the structural scoring model effectively captures the influence of media arrangement on filtration performance. The results highlight that optimal filtration is achieved not by material selection alone, but by designing a hierarchical pore structure that ensures controlled flow, sufficient residence time, and uniform distribution throughout the system.

Relationship between structural score and flow rate

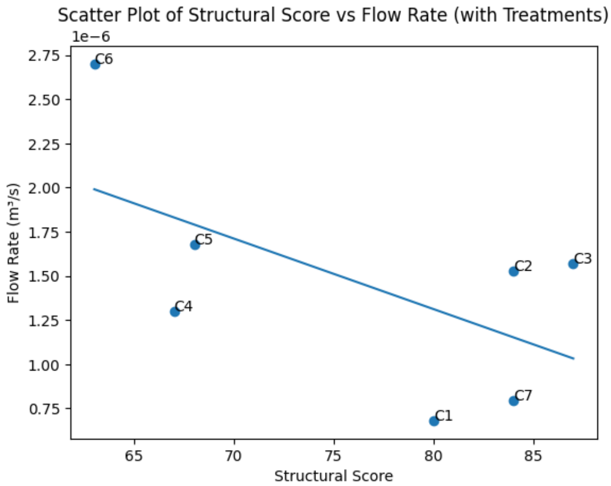

Figure 2. Relationship between structural score and flow rate

Figure 2 illustrates the relationship between structural score and flow rate in the layered filtration system. The analysis demonstrates a negative relationship between the two variables, indicating that higher structural scores tend to reduce flow rate due to increased hydraulic resistance within the filtration media arrangement. Pearson correlation analysis produced a correlation coefficient of r = −0.587, indicating a moderate negative relationship between structural score and hydraulic performance. This result suggests that filtration configurations with more hierarchical and structurally optimized media arrangements generally exhibit lower flow rates and longer residence times within the porous system. Linear regression analysis generated the following equation:

$$Q = 4.50 \times 10^{-6} - 3.99 \times 10^{-8} \text{ Score}$$

Where:

Q = flow rate (m^3/s)

S = structural score

The regression coefficient a represents the intercept, while the slope coefficient b indicates that increasing structural score decreases flow rate. The negative slope confirms that higher structural organization within the filtration media increases internal resistance and slows water movement through the system. The coefficient of determination (R2=0.344R^2 = 0.344R2=0.344) indicates that approximately 34.4% of the variation in flow rate can be explained by structural score. The scatter plot also reveals deviations from the regression trend, particularly in configuration C6, which exhibited the highest flow rate despite having the lowest structural score. This behavior may indicate the formation of preferential flow pathways caused by non-uniform media arrangement and uneven pore distribution. Such conditions reduce hydraulic resistance and accelerate water flow but may decrease filtration effectiveness due to shorter contact time between water and filtration media.

Overall, the results demonstrate that the structural scoring model is capable of representing general hydraulic trends within the filtration system. The findings further emphasize that filtration performance is strongly influenced by hierarchical pore arrangement and media structure rather than material composition alone.

CONCLUSION

This study demonstrates that the performance of a simple water filtration system is primarily governed by the structural arrangement of media layers rather than the material composition alone. The proposed structural scoring model successfully represents the hierarchical pore distribution within the filtration system and shows strong predictive capability in describing hydraulic behavior. A clear inverse relationship between structural score and flow rate confirms that configurations with higher structural optimization exhibit increased hydraulic resistance and reduced flow rates. This reflects the fundamental principle of porous media filtration, where effective particle removal requires sufficient resistance and contact time.

Among the tested configurations, C3 showed the most optimal performance, achieving a balance between flow rate and structural efficiency, while C6 exhibited the least effective structure due to its low score and unstable flow behavior. Although water quality was assessed qualitatively, the results indicate that slower filtration tends to produce clearer water, supporting the importance of residence time in filtration processes. The findings of this study provide practical insights for the design of low-cost filtration systems and highlight the importance of hierarchical media arrangement. The proposed scoring model offers a simple yet effective approach for optimizing filtration performance and has potential applications in appropriate technology development, particularly in emergency and resource-limited conditions.

This study has several limitations, including the limited number of experimental replicates ($n = 2$), the use of visual observation for water clarity assessment, and the relatively small dataset used for correlation analysis. Therefore, the findings should be interpreted as preliminary evidence of hydraulic performance trends rather than definitive statistical conclusions. However, this research primarily focused on hydraulic performance evaluation and did not comprehensively assess physicochemical or microbiological water quality parameters. Therefore, future studies are recommended to incorporate measurable water quality indicators such as turbidity, TDS, pH, DO, BOD, COD, and microbial contamination parameters. In addition, more extensive experimental replication and long-term performance testing are necessary to improve the reliability and robustness of the findings.

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