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Innovative porous mortar filters: wastewater purification for clean water

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ABSTRACT

Water scarcity is a major global challenge that affects both developed and developing countries, with Indonesia serving as a prime example. Indonesia's archipelagic nature, combined with its dense population, exacerbates the severity of water scarcity. The increased population density in these areas raises the demand for water resources, putting a strain on the available supply. The purpose of this research was to create porous mortar filters (PMFs) with different ratios (1:4, 1:5, and 1:6) by incorporating 10, 15, and 20% adsorbent material by weight of fine aggregate. The research was carried out in three stages: determining PMF properties, preparing synthetic wastewater, and assessing treatment effectiveness. Various PMF compositions consistently achieved notable success, with reductions in total dissolved solids and turbidity exceeding 25 and 75%, respectively. The PMF performed admirably in eliminating bacterial concentrations, achieving a 100% removal rate, and was critical in efficiently reducing metals, with compositions achieving over 80% reduction for manganese (Mn) and 38% reduction for iron (Fe). PMF emerges as a practical solution as a cost-effective and simple water treatment technology, particularly suitable for areas with limited technological infrastructure and resources, providing accessible water treatment for communities facing challenges in this regard.

Key words: adsorbent material, porous mortar filters, water quality, water scarcity

HIGHLIGHT

- Porous mortar filters contribute to the improvement of water quality by addressing physical, biological, and chemical aspects through their adept filtration properties. This technology effectively mitigates issues related to total dissolved solids, turbidity, bacterial concentrations, and various chemical contaminants, thereby serving as a comprehensive solution for enhancing overall water quality.

GRAPHICAL ABSTRACT

1. INTRODUCTION

Water scarcity is a serious issue affecting both industrialized and developing countries worldwide. Various factors contribute to water shortage, including increased water demand owing to population growth, urbanization, industry, and inadequate water management techniques (Tzanakakis *et al.* 2020). Water scarcity has far-reaching repercussions, affecting various elements of human existence, agriculture, and the environment, including in Indonesia. The cause is a combination of geographical and climatic factors such as excess water during the rainy season and scarcity during the dry season (Fulazzaky 2014). Indonesia ranks as the 16th most water-stressed nation global. The issue is compounded by the over-extraction of groundwater in urban areas, where the availability of safe drinking water is crucial. A significant number of individuals rely on shallow wells and unregulated groundwater sources, leading to depletion and saltwater intrusion, while inadequate access to clean water and sanitation facilities in rural areas impacts public health and hygiene (Carrard *et al.* 2019). Furthermore, climate change intensifies Indonesia's water scarcity, with rising temperatures, altered rainfall patterns, and an uptick in extreme weather events such as droughts and floods straining water resources (Ebi & Nealon 2016; Pawitan 2018). Recognizing the gravity of the situation, the Indonesian government has taken action by implementing various measures, including improved water management, conservation efforts, and infrastructure development (Basuki *et al.* 2022).

Water treatment infrastructure is an important part of maintaining safe and potable water access, especially in locations where water quality is an issue (Wang *et al.* 2018). While membrane filtration systems are frequently employed for this purpose, they have several drawbacks. These systems frequently necessitate a large amount of energy to sustain the high hydraulic pressure required for successful filtration (Shahid *et al.* 2023), providing challenges in areas with intermittent or limited access to electricity. Furthermore, membrane materials, maintenance, and replacement costs might be prohibitively expensive in resource-limited places, particularly rural areas (Othman *et al.* 2022). Innovative techniques, such as porous concrete, have arisen to solve these difficulties, primarily for rainwater management and stormwater control (Lee *et al.* 2013; Xu *et al.* 2018; Faisal *et al.* 2020). By enabling rainwater to permeate the earth, minimizing surface runoff during floods, and replenishing groundwater supplies, porous concrete provides a long-term solution (Liu & Li 2020). Furthermore, several studies have shown that porous concrete increases the quantity and quality of surface runoff infiltrating into porous concrete, making it a vital tool for water purification initiatives targeted at providing clean domestic water access (Thives *et al.* 2017; Braswell *et al.* 2018; Liu & Li 2020; Teymouri *et al.* 2020; Alimohammadi *et al.* 2021; Singer *et al.* 2022). This approach has resulted in the creation of porous mortar filters (PMFs), which can play an important role in cleaning water for household consumption, particularly in locations where traditional water treatment infrastructure is limited.

PMF is a novel technique for water filtration, providing an effective and long-term solution to water quality issues. PMFs function by passing water through a porous material, thereby efficiently eliminating pollutants (Taghizadeh *et al.* 2007; Thives *et al.* 2017; Faisal *et al.* 2020; Teymouri *et al.* 2020; Alimohammadi *et al.* 2021; Harada 2023). The concept is that water is released through mortar pores, namely gel pores with a diameter of <10 nm and capillary pores with a diameter of >10 nm, while large capillary pores have a size $50\ \mathrm{nm} < d < 10\ \mu\mathrm{m}$ (Dong *et al.* 2017). The relationship between the capillary pores that form the filtration path can improve water's physical and biological quality because it is segmented by gel pores (Saleem *et al.* 2019). In this study, improving water quality with PMF can be enhanced further by integrating adsorbent materials into the PMF mixture. This method enables the removal of specific chemical compounds and pollutants, zeolite and activated charcoal (AC) as adsorbent materials are used in PMF as a partial replacement of fine aggregate. Zeolites are microporous minerals with a high surface area that can selectively adsorb various cations and molecules (Vasconcelos *et al.* 2023). AC, also known as activated charcoal, is a highly porous form of carbon that can adsorb a wide range of contaminants, including organic compounds, odors, and impurities (Saleem *et al.* 2019; Thinojah & Ketheesan 2022). Zeolite–AC is a promising method for reducing the levels of manganese (Mn) and iron (Fe) in water. This combination can effectively adsorb and remove these two metals from the water, enhancing its quality (Siabi *et al.* 2021). This research aims to develop PMF by integrating adsorbent materials into the PMF mixture to improve water quality in terms of physical, biological, and chemical parameters. The PMF can be manufactured locally using easily available materials, allowing them to be used in various places with distinct water quality challenges. Overall, the development and implementation of PMF offer great promise for improving access to clean water and alleviating water scarcity challenges in various global regions.

2. EXPERIMENTAL WORK

The experiments of this work were carried out in the Integrated Laboratory of Universitas Gorontalo and the Technical Implementation Unit of the Water Quality Laboratory Installation Service of the Gorontalo District Health Service. The experimental investigation comprised three stages. The first stage was the determination of PMF properties, which involved bulk density, porosity, and infiltration rate. The second stage includes making synthetic wastewater (SWW). The last stage involved SWW treatment, which is carried out to test total dissolved solids (TDS), turbidity, *E. coli*, total coliforms, Mn, and Fe, then the results were evaluated and analyzed.

2.1. Material

The materials used to make PMF were cement, fine aggregate, zeolite, AC, and water. Portland cement and fine aggregate were the materials used to prepare all mixes of PMF. The cement used was Type I Portland Cement (OPC) based on SNI 15-2049-2004. The fine aggregate, zeolite, and AC had a maximum diameter of 0.60 mm and minimum diameter of 0.30 mm (size was retained on the #50 sieve and passed through the #30 sieve). The water to cement ratio (w/c) was essential to produce adequate strength. The w/c ratios were relied on 0.45. Some physical properties of materials were indicated in Table 1.

2.2. PMF mixing and casting

Initially, the cement, fine aggregate, zeolite, and AC were stirred for roughly 1 min with a mechanical mixer. Water was added and continuously blended for one more minute. The resulting mixture was put into PMF pipes (76.2 mm diameter and 150 mm height) (Figure 1) and hand compacted using a tamping rod composed of a straight steel bar with a circular cross-section and hemispherical ends. The mortar sample was scooped into the pipe in three equal thicknesses (50 mm) and compressed in between. Five tamps were used to condense each layer. Tap the side of the pipe with a hammer once the three layers have been tampered with the rod. Tampering and tapping allowed the sample to be compacted by removing trapped air in the mortar. To achieve a flat surface flush with the top of the pipe, the mortar was smoothed with a mortar float or trowel. The PMF was soaked for 72 h (3 days), which is normally done after 24 h. The PMF was then placed in the curing tank. The curing tank had to be kept at a temperature of 20 ± 2°C. The mixture design of PMF prepared for this study is presented in Table 2. Specimens were coded with names consisting of cement, fine aggregate ratios, and percentage of zeolite/AC to the weight of fine aggregate.

2.3. Making of synthetic wastewater

The ingredients prepared in this investigation for making SWW were 100 g of clay < passing through a 0.075 mm sieve (No. 200)), 0.5 L of leachate from the Talumelito Gorontalo Leachate Processing Plant, and 200 L of clean water. All ingredients were mixed in a 600-L container and stirred using a stick for 10 min. Different SWWs were used for PMF with AC and zeolite. Three samples of each SWW were taken to be tested for concentration for TDS, turbidity, *E. coli*, total coliform Mn, and Fe.

2.4. Physical characterization

The bulk density, porosity, and infiltration rate were studied in this work to designate PMF.

2.4.1. The bulk density

The bulk density or unit weight of PMF is the mass or weight of the PMF required to fill a pipe of a specified unit volume. It is a crucial property in construction and engineering as it reflects concrete's density, influencing its strength, durability, and overall performance. Variations in bulk density can arise from different mix compositions, aggregates, and admixtures, impacting mortar's mechanical and thermal properties (Malik *et al.* 2021). The bulk density was calculated using

Table 1 | Properties materials

Physical properties	Unit	Fine aggregate	Cement	Zeolite	AC
Volume weight	kg/m^3	1,260	1,402	1,340	1,375
Water content	%	3.63	–	3.10	4.40
Mud content	%	0.3	–	–	–
Apparent specific gravity	–	2.81	3.05	2.50	1.96
Bulk specific gravity (saturated surface dry (SSD) basic)	–	2.64	–	2.09	1.76
Bulk specific gravity (on dry basic)	–	3.43	–	1.81	1.56
Absorption	%	2.20	–	15.08	12.74

Figure 1 | The PMF specimen: AC (left) and zeolite (right).

Table 2 | PMF mixing proportions

Parameter	Value	Unit
Fine aggregate size	0.30–0.60	mm
Zeolite size	0.30–0.60	mm
AC	0.30–0.60	mm
Fine aggregate–cement ratio (M)	4:5:6	–
Water–cement ratio	0.45	–
Percentage of zeolite/AC to the weight of fine aggregate	10:15:20	%
Thickness of PMF	150	mm
Diameter of PMF	76.2	mm
Curing time (pre-soaking treatment)	3	days

Equation (1).

$$D = \frac{w_d}{V} \tag{1}$$

where D is the density of PMF (kg/m^3); w_d is the weight of PMF sample air-dried for 24 h (kg); and V is the volume of PMF (m^3).

2.4.2. Porosity

The total porosity was calculated using the material composition, while the effective porosity was calculated using the volumetric approach (Akkaya & Çağatay 2021). The porosity of pervious concrete typically ranges from 15 to 35% (Bonicelli & Pianeta 2019). The porosity of pervious concrete influences its qualities, such as compressive strength, flexural strength, permeability, and storage capacity (Xie *et al.* 2020). As a result, it is regarded as a critical parameter in many design calculations. The water displacement method can be used to determine porosity (Faisal *et al.* 2020). Equation (2) was used to compute the percentage of porosity in PMF.

$$P = \frac{w_{\mathrm{ssd}} - w_d}{w_{\mathrm{ssd}} - w_w} \tag{2}$$

where P is the total porosity of PMF (%); w_{ssd} is the weight of a PMF sample saturated surface dry condition (kg); w_w is the weight of a PMF sample submerged in water (kg); w_d is the weight of a PMF sample air-dried for 24 h (kg); and V is the volume of PMF.

2.4.3. Infiltration rate

The infiltration rate of PMF is a key characteristic that defines its ability to allow water to pass through its porous structure and into the ground below. PMF is intentionally designed to be highly permeable, with interconnected voids or gaps that enable water to infiltrate at a relatively rapid rate. The infiltration rate was calculated from Equation (3).

$$I = \frac{Q}{A} \tag{3}$$

where I is the infiltration rate (L/m^2); Q is the permeate flow discharge (L/s); and A is the surface area of PMF (m^2).

2.5. Synthetic wastewater treatment testing

This research uses a column system method to test the PMF's ability to improve water quality. The schematic of the laboratory experiment can be seen in Figure 2, and the test variable is presented in Table 3.

3. RESULTS AND DISCUSSIONS

3.1. Impact of PMF mixing composition on bulk density, porosity, and infiltration rate

The composition of a PMF influences its bulk density, porosity, and infiltration rate, and knowing the impact and interaction between these elements is critical for developing effective PMFs. The composition of PMF, namely the type and ratio of aggregates, cement, and adsorbent materials utilized, directly impacts its bulk density. A higher proportion of aggregates and a lower cement concentration lowers the bulk density, making the mortar more porous (Li *et al.* 2017). Thus, the quantity AC-1:4 and Z-1:4 exhibit the maximum value of bulk density, as shown in Figure 3(a). It can be attributed to the thickness of cement paste around the aggregates that develops as the cement content augments. For example, in mixes that are fabricated using AC-1:6/Z-1:6 and AC-1:4/Z-1:4 with changing cement content from 1:6 to 1:4, the bulk density, at the age of 3

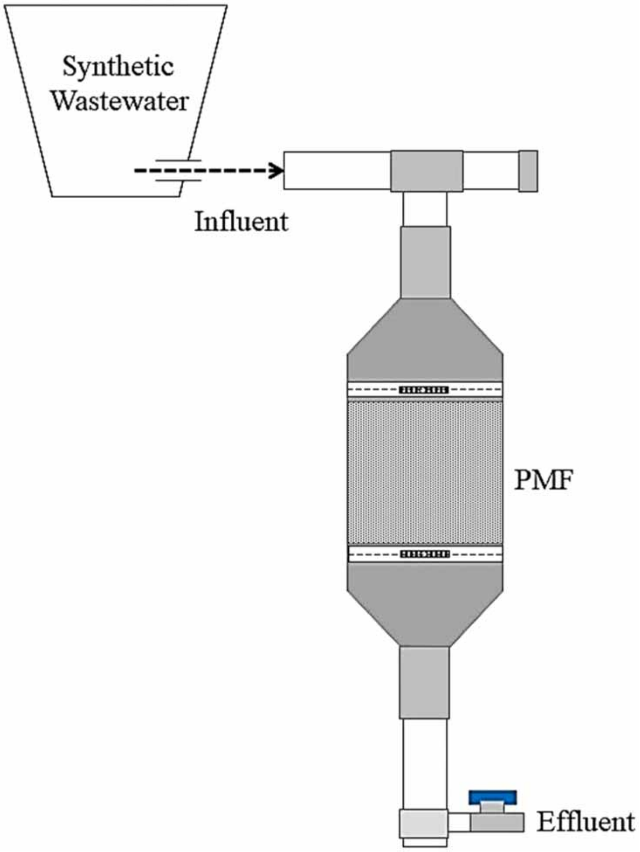

Figure 2 | SWW test apparatus.

Table 3 | The variables used in the experiment

Experiment content	Variables
Influent water	SWW
Influent total volume test items	200 L
Operation mode	Falling head operation
Initial water quality of SWW for PMF with AC (PMF_{AC})	TDS 30.2 mg/L, turbidity 26.0 NTU, *E. coli* 1.3 CFU/100 mL, total coliform 11.3 CFU/100 mL, Mn 0.85 mg/L, and Fe 0.21 mg/L
Initial water quality of SWW for PMF with zeolite (PMF_{Z})	TDS 29.3 mg/L, turbidity 27.0 NTU, *E. coli* 2.7 CFU/100 mL, total coliform 1.7 CFU/100 mL, Mn 0.98 mg/L, and Fe 0.23 mg/L

days, is enhanced by about 7%. Because of the decreased bulk density, there is more void space within the material, which adds to enhanced porosity.

The porosity of PMF is closely related to its composition, as it measures the empty spaces or voids within the mortar structure (Lian *et al.* 2011). A higher porosity improves the mortar's ability to hold and move water, making it a useful material for water purification. As a general case for all experiments, the porosity decreased as the cement mass increased. For the cement content of AC-1:6 and Z-1:6, PMF exhibited the maximum value of porosity, while AC-1:4 and Z-1:4 showed the minimum value, as displayed in Figure 3(b), which indicates that more cement content gives lower porosity. This mainly occurs due to the increment of paste materials that fill the cavities between and around the aggregates. For example, using AZ/C-1:4 and AZ/C-1:6 with the alteration of cement content from 1:4 to 1:6, the obtained porosity was 25.46% (CA), 40.17% (CA), 29.29% (Z), and 41.52% (Z), respectively.

The infiltration rate, or the rate at which water can flow through the PMF, is positively related to porosity. Higher porosity indicates a higher volume of linked spaces, allowing water to flow more easily through the material (Lian *et al.* 2011). As a result, increasing porosity in the composition can improve PMF infiltration (Thives *et al.* 2017). PMF reached the peak infiltration rate in the AC-1:6 and Z-1:6 mixtures, showing an increase in the infiltration rate as the cement mass decreases. AC-1:4 and Z-1:4, on the other hand, have the lowest infiltration rates. The more the quantity of paste elements inside the PMF mixture, which tends to fill the vacuum spaces between and around the aggregates, the more inverse the relationship between cement content and infiltration rate. As the cement content increases, so do the paste ingredients, reducing the linked voids within the mortar structure (Lederle *et al.* 2020). As seen in Figure 3(c), this inhibits the passage of water through the material, resulting in a lower infiltration rate.

3.2. Influence of mixing composition on TDS and turbidity reduction

The composition of PMF's mixing can considerably impact its ability to reduce TDS and turbidity in water. TDS is the concentration of dissolved ions and minerals in water, whereas turbidity is the cloudiness or haziness caused by suspended particles in water (Adjovu *et al.* 2023). When employed in water quality management, the composition of PMF influences how successfully it can treat water quality in terms of lowering TDS (Yogafanny 2023) and turbidity (Taghizadeh *et al.* 2007). The kind and amounts of aggregates, cement, and adsorbent elements in PMF have an important role in defining its porosity. These elements are critical for the PMF's capacity to maintain and remediate water quality. The interconnected voids and pores within the mortar structure allow water to infiltrate, and various pollutants, such as TDS and suspended particles, can be trapped and filtered out during this process (Winston *et al.* 2020; Boulven *et al.* 2021). Fine-grained aggregates and a well-balanced mix design of PMF can result in a mortar matrix with smaller pores that are more effective at trapping and removing fine particles, thereby reducing turbidity (Boulven *et al.* 2021).

The water quality measurement results of the AC and zeolite-added PMF are shown in Figure 4. The initial TDS and turbidity concentrations of the SWW used in this study were 30.2 mg/L and 26.0 NTU for PMF_{AC}, as well as 29.3 mg/L and 27 NTU for PMF_{Z}, respectively. The results showed that the TDS concentrations tended to decrease by 16.5–23.3 mg/L for PMF_{AC} and 12.4–22.7 mg/L for PMFz. In addition, turbidity concentrations tended to decrease by 4.6–7.6 NTU for PMF_{AC} and 4.8–8.1 NTU for PMF_{Z}. The composition of cement, fine aggregate, and absorbent material in PMF does not have a significant influence on the differences in TDS concentration and turbidity for 1:4, 1:5, and 1:6. However, these three compositions can reduce TDS concentration and turbidity by more than >25 and 75% respectively, whether PMF

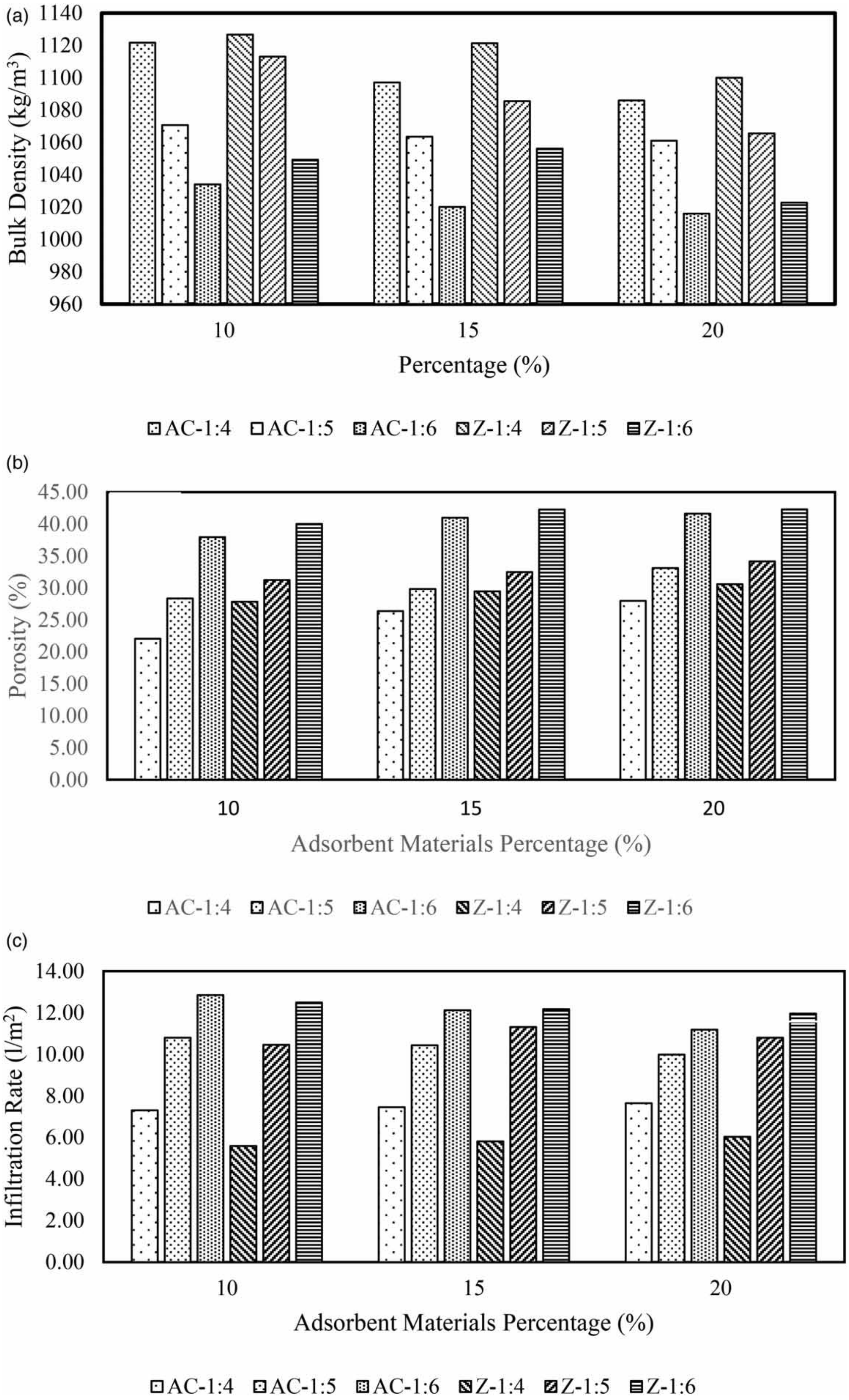

Figure 3 | Impact of mixing composition on (a) bulk density, (b) porosity, and (c) infiltration rate.

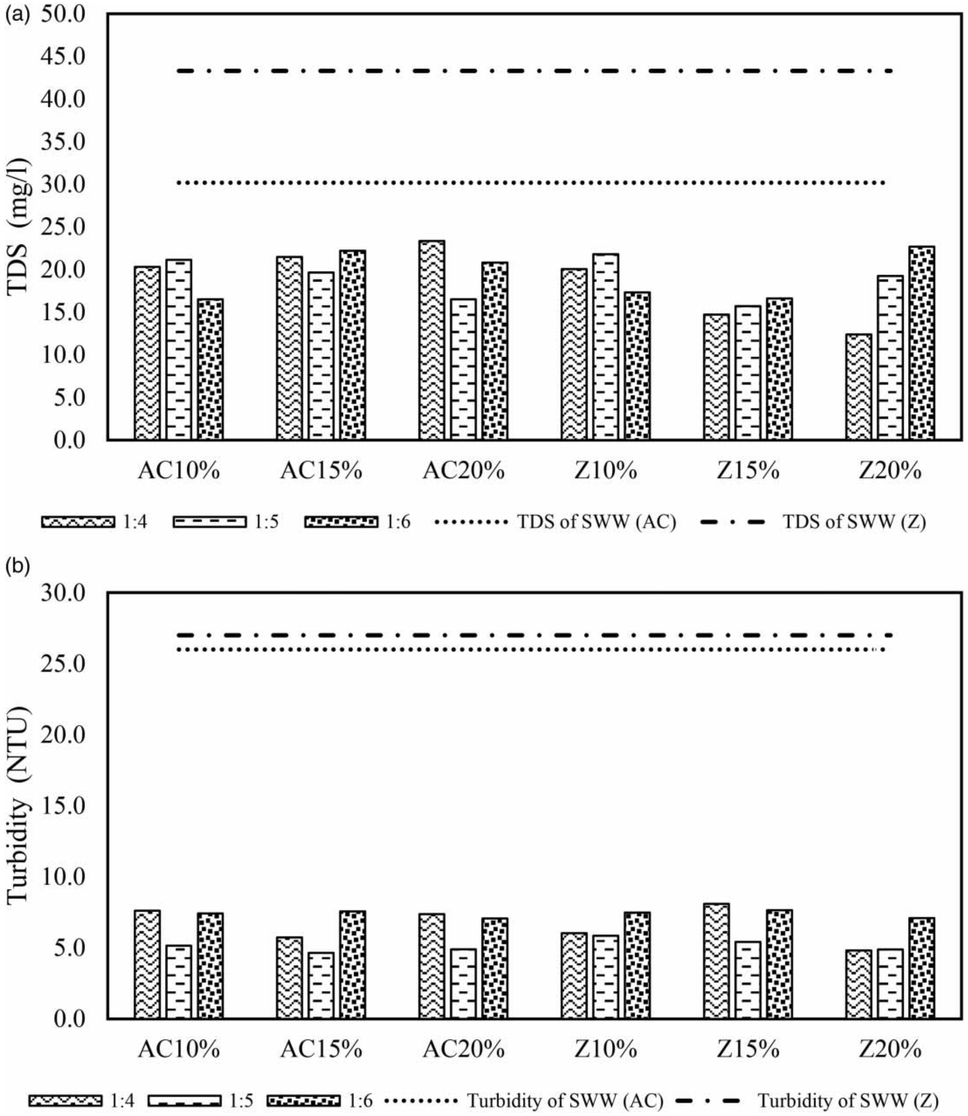

Figure 4 | Influence of mixing composition on (a) TDS and (b) turbidity reduction.

uses AC or zeolite (Table 4). Standard Quality for water hygiene and sanitation purposes based on Regulation of the Minister of Health of the Republic of Indonesia Number 2 of 2023 for TDS and turbidity are <300 mg/L and <3 NTU, respectively. Therefore, TDS is appropriate based on the standards above, while turbidity did not meet quality standards.

The differences in the types of pores formed in each PMF mixture composition, specifically gel pores (<10 nm) and capillary pores (0.01–0.0005 μm) (Vernocchi *et al.* 2023), influence the reduction of TDS and turbidity levels, making the cement

Table 4 | Effect of adding adsorbent materials to water quality of SWW on TDS and turbidity removal percentage

	AC						**Zeolite (Z)**					
	TDS			**Turbidity**			**TDS**			**Turbidity**		
Adsorbent materials percentage	**1:4**	**1:5**	**1:6**	**1:4**	**1:5**	**1:6**	**1:4**	**1:5**	**1:6**	**1:4**	**1:5**	**1:6**
10%	33%	30%	45%	72%	81%	73%	34%	28%	43%	78%	78%	72%
15%	29%	35%	26%	79%	83%	72%	51%	48%	45%	70%	80%	72%
20%	23%	45%	31%	73%	82%	74%	59%	36%	25%	82%	82%	74%

and fine aggregate composition less impactful on these parameters. Gel pores, which are finer and more interconnected, are effective at trapping and removing dissolved fine particles that cause turbidity, thereby contributing to TDS and turbidity reduction in SWW. Capillary pores, which transport water through capillary forces, can have varying effects on TDS and turbidity reduction depending on their size and connectivity. When gel pores dominate the PMF structure, they can significantly contribute to the reduction of TDS and turbidity, compensating for the potential impact of cement and fine aggregate composition.

3.3. Influence of mixing composition on *E. coli* and total coliform reduction

The addition of AC and zeolite to the PMF mix can significantly reduce the amount of *E. coli* and total Coliform bacteria in water (Buang *et al.* 2018; Asghari *et al.* 2022; Alvarino *et al.* 2023). AC and zeolite are highly porous materials with strong adsorption properties that can capture and immobilize microorganisms and bacteria. The porous structure of AC and zeolite allows for a large surface area for the adsorption of organic compounds and microorganisms (Burchacka *et al.* 2021). When *E. coli* and total coliform bacteria come into contact with AC and zeolite in the PMF, they can become trapped and adsorbed on the surface of the charcoal and zeolite. This method physically removes bacteria from SWW, lowering its concentration as it passes through the PMF. Furthermore, the chemical properties of AC and zeolite can help to reduce microbial growth by promoting chemical interactions that inhibit bacterial growth (Alvarino *et al.* 2023). The use of AC and zeolite in PMF creates a powerful synergistic effect, leveraging the superior adsorption and ion exchange properties of both materials. This method significantly improves the PMF's ability to reduce microbial contaminants, resulting in better water quality and environmental protection. In addition, gel pores of mortar or concrete with a diameter of <10 nm, which are mostly of 0.01–0.0005 μm (Kumar & Bhattacharjee 2003). They can function to filter *E coli* and total coliform bacteria measuring (1.0–1.5 × 2.0–6.0 μm) (Vernocchi *et al.* 2023), where the size is larger than the size of gel pores. Bacteria and other smaller particles may pass through the pores on the surface of PMF. However, the pores on the PMF may trap them due to the wide range of pore sizes from nanoscale pores to microscale pores and pore structure (Boulven *et al.* 2021). Table 5 shows that all PMF variations can remove 100% of *E. coli* and total coliform from SWW. In line with the findings of Taghizadeh *et al.* (2007), it has been discovered that PMF has the ability to significantly reduce bacterial concentrations. Standard Quality for water hygiene and sanitation purposes based on Regulation of the Minister of Health of the Republic of Indonesia Number 2 of 2023 for *E. coli* and total coliform are 0 and 0 CFU/100 mL, respectively. Therefore, *E. coli* and total coliform were appropriate based on the standards above.

3.4. Influence of mixing composition on Mn and Fe reduction

The addition of AC and zeolite to PMF can significantly improve its ability to reduce Mn and Fe concentrations in water (Batrisya & Suyanta 2021; Fikri *et al.* 2022). They contribute to the reduction of these metals when added to the PMF mix through a combination of physical adsorption and chemical interactions. In addition, they have a large internal surface area with numerous tiny pores capable of capturing and retaining Mn and Fe ions (Burchacka *et al.* 2021; Asghari *et al.* 2022). They also allow it to form chemical bonds with these metals, effectively removing them from the SWW as they pass through the PMF (Harada 2023). When designed properly, the combination of AC and zeolite in a PMF creates a synergistic effect, combining the superior adsorption properties of both materials. This method improves the metal-removal capacity of SWW, ensuring efficient water treatment. The water quality measurement results of the AC and zeolite-added PMF for reducing Mn and Fe are shown in Figure 5. The initial Mn and Fe concentrations of the SWW used in this study were 0.85 and 0.21 mg/L for PMF_{AC}, respectively, and 0.98 and 0.23 mg/L for PMF with zeolite. Mn concentrations decreased by 0.02–0.16 mg/L in

Table 5 | Effect of adding adsorbent materials to the water quality of SWW on *E. coli* and total coliform removal percentage

	AC						**Zeolite (Z)**					
	E. coli			**Total coliform**			***E. coli***			**Total coliform**		
Adsorbent materials percentage	**1:4**	**1:5**	**1:6**	**1:4**	**1:5**	**1:6**	**1:4**	**1:5**	**1:6**	**1:4**	**1:5**	**1:6**
10%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
15%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
20%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

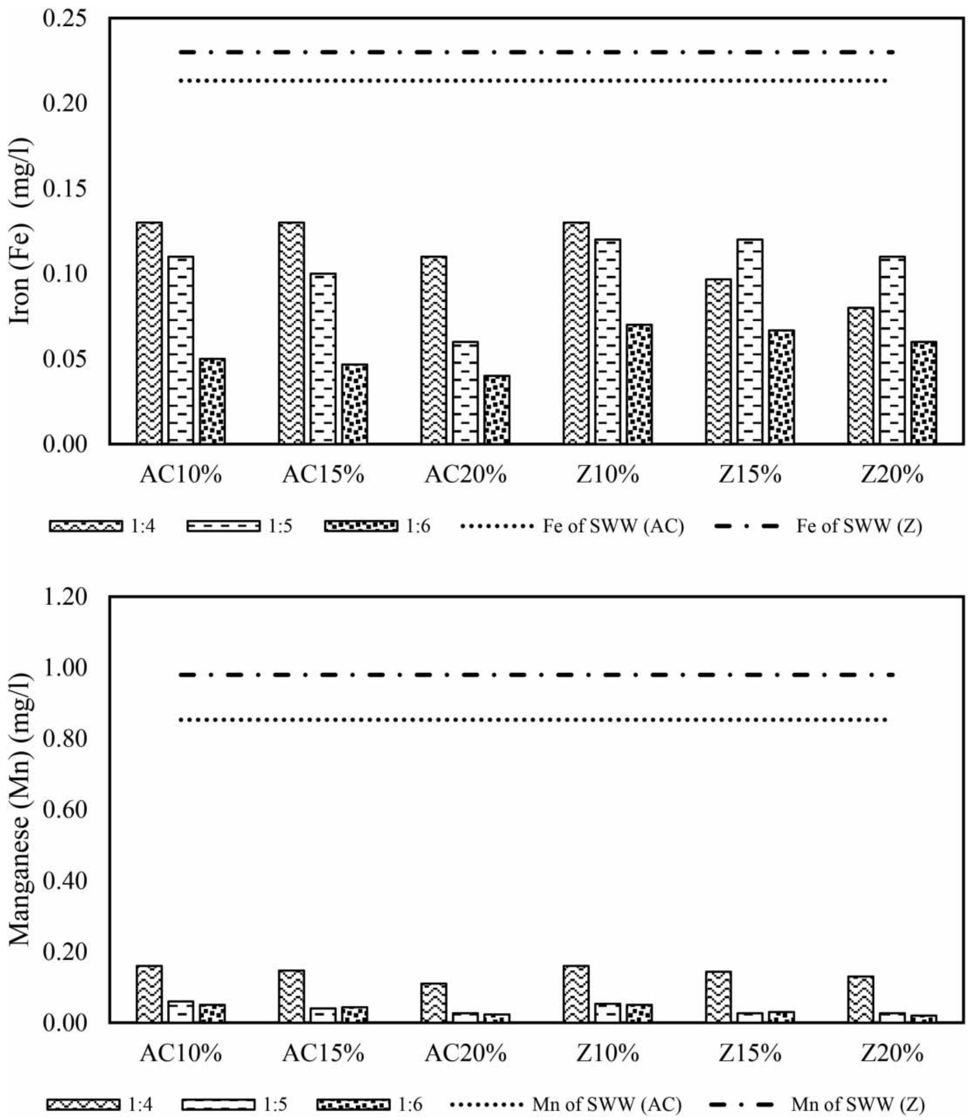

Figure 5 | Influence of mixing composition on (a) Manganese (Mn) and (b) Iron (Fe) reduction.

PMF_{AC} and 0.02–0.16 mg/L in PMF_z. Furthermore, Fe concentrations in PMF_{AC} decreased by 0.04–0.13 mg/L, while PMF_Z decreased by 0.06–0.13 mg/L. The differences in Mn and Fe for 1:4, 1:5, and 1:6 have a significant influence on the composition of cement, fine aggregate, and absorbent material in PMF. These three compositions, on the other hand, can reduce Mn and Fe by more than >80 and 38% respectively, whether PMF uses AC or zeolite (Table 6). Standard Quality for water

Table 6 | Effect of adding adsorbent materials to the water quality of SWW on Manganese (Mn) and Iron (Fe) removal percentage

	AC						**Zeolite (Z)**					
	Manganese (Mn)			**Iron (Fe)**			**Manganese (Mn)**			**Iron (Fe)**		
Adsorbent materials percentage	**1:4**	**1:5**	**1:6**	**1:4**	**1:5**	**1:6**	**1:4**	**1:5**	**1:6**	**1:4**	**1:5**	**1:6**
10%	81%	93%	94%	39%	34%	77%	81%	94%	94%	39%	44%	67%
15%	83%	95%	95%	39%	53%	78%	83%	97%	96%	55%	44%	69%
20%	87%	97%	97%	48%	72%	81%	85%	97%	98%	63%	48%	72%

hygiene and sanitation purposes based on Regulation of the Minister of Health of the Republic of Indonesia Number 2 of 2023 for Mn and Fe are 0.1 and 0.2 mg/L respectively. Therefore, Mn and Fe were appropriate based on the standards above.

4. CONCLUSIONS

The PMF with AC and zeolite emerges as an admirable solution for improving water quality, demonstrating notable success across multiple dimensions – physical, biological, and chemical parameters. Its effectiveness is particularly evident in the reduction of biological and chemical elements reaching 80–100%, which aligns with Standard Quality for water hygiene and sanitation purposes based on Regulation of the Minister of Health of the Republic of Indonesia Number 2 of 2023. While the impact on physical parameters varies, the overall positive results position PMF as a versatile technology capable of addressing a wide range of water quality issues. What distinguishes PMF is its usability and low cost, making it not only a powerful tool for improving water quality but also a practical solution in areas with limited water resources or dealing with low-quality water sources. The adaptability of PMF to such diverse conditions emphasizes its practicality and potential to play a pivotal role in ensuring access to clean and safe water, particularly in areas where more complex water purification methods may be logistically or economically challenging to implement.

The limitation of this study is the interconnectivity of pores which is crucial for ensuring a continuous flow of water through the PMF, allowing for filtration and potential purification. Difficulties in establishing proper interconnections may result in uneven water distribution, reducing the overall efficiency of the PMF in water purification. Future research may explore the integration of PMF with incorporating innovative materials with superior filtration properties or engineering the PMF at the nanoscale to enhance its ability to capture and remove contaminants.

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AUTHOR CONTRIBUTIONS

MRO was responsible for the conceptualization and design of the experiment, data collection, analysis, and manuscript writing. II actively participated in the experimental procedures, performed data analysis, and contributed to the interpretation of results. RH critically reviewed the manuscript and offered valuable insights. LD contributed to the experimental design data collection, and provided valuable feedback during the analysis and interpretation stages. The combined efforts of all authors resulted in a comprehensive and impactful laboratory experiment.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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