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MORALITY BEFORE KNOWLEDGE

Design of CA/PEG composite membranes for nanofiltration water purification kit: Material optimization and microbiological efficacy

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ABSTRACT

Background: Access to microbiologically safe water is a critical challenge in post-disaster conditions, where surface water is often heavily contaminated by pathogenic microorganisms. **Methods:** This study adopts a comprehensive approach by first characterizing the microbiological load of post-flood well water using the Most Probable Number (MPN) method to establish filtration targets. Subsequently, a CA/PEG composite membrane was synthesized via a phase inversion technique, with PEG functioning as a porogen to enhance hydrophilicity. Five PEG loadings (1, 3, 5, 7, and 9% w/w) were screened using the immersion-precipitation phase inversion method; surface wettability was measured at five locations per membrane by the sessile drop method (5 µL deionised water, contact angle goniometer). The standard three-stage presumptive–confirmed–completed MPN procedure was applied to the collected post-flood well water samples. **Findings:** Field analysis of post-flood well water samples revealed a critical contamination level of 210 MPN/100 ml. In response, the synthesized 9% CA/PEG formulation was identified as the optimal core material, exhibiting superior super-hydrophilic properties (Contact Angle: 55.59°). Based on these material characteristics and the proposed multi-barrier design, the system is engineered to reduce Coliform contamination to <3.0 MPN/100 ml, complying with WHO and Indonesian standards (Permenkes No. 492/2010). **Conclusion:** As its primary contribution, this study formulates an evidence-based design for a portable water-filtration kit featuring a multilayer purification system consisting of a pre-filter, synthesized nanofiltration membrane, and UV sterilization as an integrated approach to producing microbiologically safe water. **Novelty/Originality of this article:** This conceptual design provides a strong scientific foundation for prototype development in subsequent research, while also demonstrating the potential of a technology that is not only technically effective but also aligned with the principle of *Hifz al-Nafs* within Maqashid al-Shariah and supportive of SDG 6 through the provision of a sustainable and accessible water-purification solution in emergency conditions. Note that the reported microbiological efficacy represents a projected design target; prototype-scale field validation remains the essential next step.

KEYWORDS: CA/PEG membrane; MPN; nanofiltration kit.

1. Introduction

Access to clean and safe water is a fundamental human right, yet the global water crisis continues to be a pressing challenge affecting millions of people worldwide (WHO, 2025). Current reviews indicate that 10% of the world's population lives in high or critical water stress countries, with urban scarcity projected to affect 1.7–2.4 billion people by 2050, potentially exacerbating food production losses in vulnerable regions like the Middle East and South Asia (Biswas et al., 2025). This scarcity is driven by population growth, rapid

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urbanization, and the intensified impacts of climate change on freshwater resources (Triadi et al., 2025). Estimates suggest that without significant intervention, two-thirds of the world's population may face a lack of access to clean freshwater by 2025 (Kusuma et al., 2021).

In the specific context of Indonesia, clean water is a fundamental necessity not only for survival but also as the primary means of purification (*thaharah*) in Islam (A'yun et al., 2024). However, as a country highly prone to hydrometeorological disasters, Indonesia frequently faces the challenge of post-disaster clean water crises, particularly following floods (Aeni & Khoirul Anwar, 2024; Escobar Carías et al., 2022). The relevance of this issue has become increasingly pressing, as evidenced by the disaster incidents in late 2025, where Indonesia experienced a significant escalation of hydrometeorological hazards due to a combination of extreme rainfall and maximum sea tide phenomena (BMKG, 2025). Disaster data from the end of 2025 revealed that flash floods striking provinces across Sumatra, including Aceh and North Sumatra, severely damaged vital sanitation infrastructure and cut off community access to piped clean water networks (BNPB, 2025). The impact on water quality during these events is multi-dimensional. Specifically, the heavy load of mud and debris sediment carried by flash flood currents caused a drastic increase in turbidity in surface raw water sources, exceeding the processing capacity of conventional community filtration systems (Ministry of Health's Health Crisis Center, 2025).

However, this hydrological vulnerability is not isolated to Sumatra; it represents a systemic failure affecting densely populated basins across Java as well. A critical case study of this recurring crisis is observed in Karangwangun Village, Babakan District, Cirebon Regency, West Java. Situated in the downstream basin of the Ciberes River, this area is designated as a recurring "red zone" where river overflow frequently creates a complex water matrix characterized by extreme turbidity and suspended solids (BNPB, 2025). Local reports highlight the severity of this issue, noting that sedimentation in the Ciberes River has drastically reduced its capacity, causing floodwaters to inundate the village with alarming frequency recorded up to 38 times in a single year (Tribun Cirebon, 2024). This empirical reality confirms that the water sources in Cirebon are not merely "flooded" but are heavily laden with mud and contaminants, necessitating the advanced filtration solution proposed in this study.

Unlike typical clear-water inundations, floodwater in Babakan is characterized by a high sediment load combined with agricultural runoff and domestic sewage, resulting in a complex and highly contaminated water matrix that poses significant filtration challenges (Rahman et al., 2021; World Bank, 2014; Ahmed et al., 2019). Preliminary surveillance conducted in this area indicates severe deterioration of water quality, including elevated microbial contamination and physicochemical degradation, which provides the empirical basis for this study (Sutrisno et al., 2020; Prasetyo & Handayani, 2022). The inability of existing local water treatment infrastructure to effectively manage sediment-rich and microbiologically contaminated floodwater highlights an urgent need for specialized, high-performance filtration systems specifically designed for complex floodwater matrices (Collins, 2009; WHO, 2019).

Although there are currently many portable water filtration devices on the market, the particular physicochemical complexity of floodwater severely restricts their applicability in post-disaster Indonesian contexts. Standard hollow-fiber microfiltration systems, like LifeStraw-style devices, are examples of conventional point-of-use (POU) filters that are mainly designed for relatively clear surface water (Fagerli et al., 2020; Pérez-Vidal et al., 2016). These traditional systems experience rapid pore blockage and irreversible fouling when exposed to the extreme mud turbidity, high suspended solids, and dense Natural Organic Matter (NOM) typical of Indonesian flash floods (J. Lee et al., 2022; Pitriani et al., 2023). This significantly reduces their operational lifespan and water flux. On the other hand, more sophisticated decentralized systems, like portable Reverse Osmosis (RO) units, offer better contamination rejection but require high-pressure operation by nature (Lourenço & Nunes, 2021; Nguyen et al., 2025). They are completely unfeasible in disaster areas with widespread power outages and collapsed infrastructure due to their high energy requirements. A low-energy, portable filtration system with highly fouling-resistant materials that can handle complicated, sediment-rich floodwater matrices is therefore a crucial technological gap for an intermediate solution (Das et al., 2022).

Beyond physical turbidity, water safety is further compromised by complex chemical contaminants, particularly Natural Organic Matter (NOM) (Triadi et al., 2025). NOM typically contains Humic Acid (HA) as a key component, derived from the decomposition of plant and animal material (Health Canada, 2020). The removal of NOM is particularly critical as it affects the taste and color of water, making it a challenging research topic in the development of advanced water purification technologies (Etemadi et al., 2018). Furthermore, alongside chemical pollutants, microbiological contamination represents a critical issue in water treatment processes. Total coliforms and *Escherichia coli* are typically used as indicator bacteria to assess the microbiological quality of water (Tongphrom et al., 2018), where the presence of *Escherichia coli* is strictly unacceptable in drinking water due to potential health hazards. In membrane-based filtration systems, bacterial adhesion to solid surfaces leads to biofilm formation and biofouling (Khoerunnisa et al., 2020). Fouling defined as the accumulation of membrane-rejected material on the surface or within pores significantly reduces membrane flux and rejection rates (Abu-Zurayk et al., 2023). Biofouling control is particularly crucial for Cellulose Acetate (CA) membranes, as these materials are notably more susceptible to microbial attack, which can degrade their surface integrity over time (Abu-Zurayk et al., 2023; Seyfollahi et al., 2019). Therefore, innovative solutions are urgently needed to address these interconnected physical, chemical, and biological challenges to secure a sustainable water supply.

Membrane technology has been widely applied in filtration processes for water treatment because it offers high pollutant removal efficiency at a lower overall cost (Alfiana et al., 2023). Other advantages include low energy consumption and the fact that it does not require the use of chemicals or produce harmful by-products (Seyfollahi et al., 2019). Ultrafiltration (UF) is a pressure-driven process (2–5 bar) capable of removing high-molecular-weight substances, bacteria, viruses, and organic compounds (0.01 to 0.1 μm) through mechanical separation (Abu-Zurayk et al., 2023; Alfiana et al., 2023). Nanofiltration (NF) is a promising high-pressure process with pore sizes between 1 nm and 5 nm, effective in removing dissolved pollutants (organic and inorganic) (Abu-Zurayk et al., 2023).

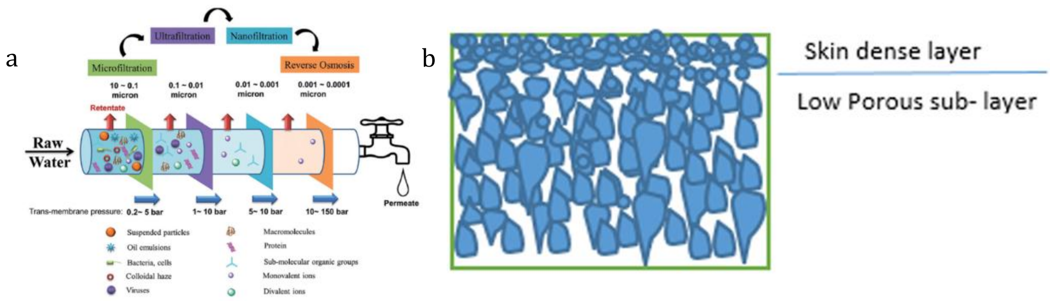

Fig. 1. (a) Illustrative schematic of a multistage membrane filtration process; (b) Nanofiltration membrane layers

Superior selectivity is provided by nanofiltration (NF), but its operational sustainability is often jeopardized by fouling, a complicated phenomenon in which rejected materials build up on the membrane's surface or inside its pores (Liu et al., 2024; Maeda, 2024). Due to the presence of heterogeneous contaminants, fouling mechanisms are especially complex in the particular context of post-disaster floodwater treatment (Zhao et al., 2025; Zhu et al., 2024). Pore blocking and cake layer formation are the main mechanisms, which are primarily caused by hydrophobic interactions between organic pollutants and the membrane surface (Mahamadou Harouna et al., 2019; Xu et al., 2020).

In particular, the hydrophobic moieties of Natural Organic Matter (NOM), like Humic Acid (HA), have a tendency to adsorb onto the hydrophobic acetyl groups of pure Cellulose

Acetate (CA) membranes (Mozia et al., 2005; Sabeti Dehkordi et al., 2015). This adsorption causes the effective pore size to decrease, which drastically lowers water flux and modifies the selectivity of the membrane (Dal-Cin et al., 1995). Moreover, biofouling poses a longer-lasting risk. By clinging to the membrane surface with extracellular polymeric substances (EPS), bacteria like Escherichia coli begin colonization (M. H. Lee et al., 2025). After adhering, these microbes create a cohesive biofilm that can eventually chemically break down the cellulosic polymer backbone and is impervious to hydraulic cleaning. For long-term device reliability in disaster areas, altering the surface chemistry to interfere with these hydrophobic and biological interactions is therefore not just an improvement but a basic requirement.

To counteract the inherent hydrophobicity of CA, Polyethylene Glycol (PEG) is integrated as a modifying agent. Chemically, PEG is a non-ionic, water-soluble polymer characterized by the repeating unit $-(CH_2CH_2O)_n-$ (Kramar & González-Benito, 2023). Its distinct molecular structure, particularly the abundance of ether oxygen atoms and terminal hydroxyl groups (-OH), accounts for its efficacy in membrane science (see Figure 2a). These polar groups serve as acceptors of hydrogen bonds. They draw water molecules to the membrane surface when they are in an aqueous environment, creating a tightly bound hydration shell (hydration layer) (Konstantinovsky et al., 2022). This hydration layer serves as an energetic barrier; in order for a hydrophobic foulant (such as bacteria or proteins) to adhere to the surface, it must first move these tightly bound water molecules, which is an unfavorable thermodynamic process.

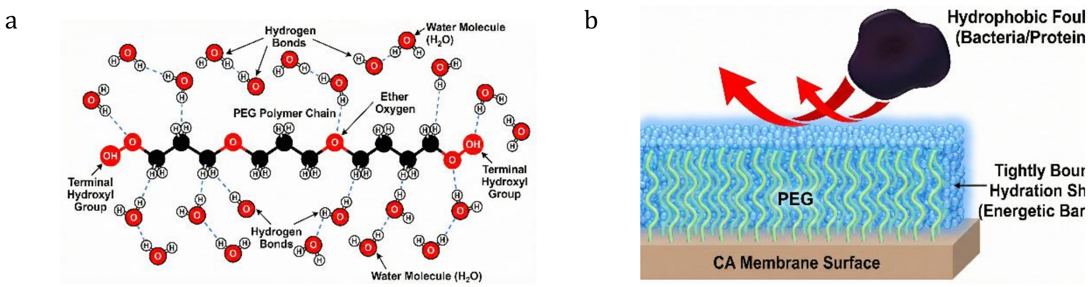

Fig. 2 (a) Schematic representation of the PEG polymer chain interacting with water molecules via hydrogen bonds formed at the ether oxygen and terminal hydroxyl sites; (b) Illustration of the antifouling mechanism on a CA membrane surface modified with PEG. The tightly bound hydration shell creates an energetic barrier that repels hydrophobic foulants (bacteria/proteins)

Additionally, the addition of PEG causes a phenomenon called steric hindrance. The water interface is reached by the flexible PEG chains that are grafted or trapped within the membrane matrix (Sanei et al., 2023). The steric repulsion theory states that foulants compress these polymer chains as they get closer to the surface, which lowers the conformational entropy of the chains. In order to prevent irreversible adhesion and biofilm formation, this entropy loss creates a repulsive force that essentially "pushes" the contaminants away (illustrated in Figure 2b).

To address fouling challenges and improve performance, research focuses on developing sustainable membrane materials. Cellulose Acetate (CA) is a semi-synthetic polymer that is biodegradable and has natural hydrophilic properties, is non-toxic, low-cost, and biocompatible, making it a preferred material in UF membrane preparation (Abu-Zurayk et al., 2023; Seyfollahi et al., 2019). However, the application of CA is limited due to its poor chemical resistance and low mechanical strength (Ravichandran et al., 2024). Work on composite CA membranes for water treatment reports that pure and composite CA suffer from poor mechanical strength and low chemical resistance, motivating reinforcement or blending to improve these properties (Andrade et al., 2021).

Polyethylene Glycol (PEG), a hydrophilic additive that can practically increase membrane hydrophilicity and improve structural properties, is used to get around these restrictions (Alfiana et al., 2023). Because PEG can create strong hydrogen bonds with water molecules to create a steric stabilization effect that keeps proteins and other biological molecules from interacting with the membrane surface, it is well known for its exceptional anti-fouling properties (Seyfollahi et al., 2019). Composite CA membranes embedded with PEG have been shown to improve: (1) Surface Hydrophilicity: Indicated by a lower water contact angle (Syahrir et al., 2025). (2) Anti-fouling: Protein adsorption (Bovine Serum Albumin – BSA) can be significantly reduced (for example, a reduction of up to 93.52% in CA/ND-PEG 0.5 wt.% membranes) (Shapouri et al., 2024). (3) Flux Recovery Ratio (FRR): Achieving high values (up to 95.2% in CA/ND-PEG 0.5 wt.%), indicating that the membrane is easy to clean (Jassim et al., 2024).

Other hydrophilic modifiers, like polyvinylpyrrolidone (PVP) or inorganic nanomaterials (like graphene oxide and TiO_2), are commonly used to improve membrane performance, but they have clear operational disadvantages for emergency portable kits. Despite its high hydrophilicity (Athanasekou et al., 2014; Bano et al., 2025), PVP has a strong propensity to leak out of the polymeric matrix during continuous filtration, which quickly reduces its long-term antifouling effectiveness (Sun et al., 2010). However, adding inorganic nanomaterials raises potential nanotoxicity concerns about nanoparticle leaching into purified drinking water, greatly increases fabrication costs, and necessitates sophisticated dispersion techniques to prevent particle agglomeration. PEG, on the other hand, provides a better synergistic balance: it creates strong steric hindrance, creates stable physical entanglements within the CA backbone, and is still very affordable and biocompatible, making it the perfect modifier for long-term, post-disaster applications (Comenge & Puntes, 2015; Wei et al., 2024).

Resolving the permeability-selectivity trade-off also depends on figuring out the exact PEG concentration. According to existing research, when faced with extreme floodwater turbidity, low PEG loadings (e.g., <5%) are insufficient to induce the significant macrovoid formation necessary to sustain high water flux (Moon et al., 2020). On the other hand, high concentrations (above 10%) can significantly raise the casting solution's viscosity, delaying demixing during the phase inversion process. The mechanical integrity of the membrane may be jeopardized by this delayed demixing, which paradoxically thickens the dense skin layer and limits permeability (Geleta et al., 2023). Consequently, the ideal thermodynamic threshold is thought to be 9% PEG. At this particular loading, PEG is anticipated to function as a highly efficient pore-forming agent, engineering an interconnected, finger-like sub-layer morphology that maximizes hydraulic flux while projecting a sufficiently dense hydration barrier to repel the severe biological foulants typical of Indonesian floodwaters (Aprillianti et al., 2024; Idris et al., 2022).

This study aims to develop a nanofiltration-based water purification system using a modified CA/PEG composite membrane to achieve optimal pollutant removal performance, particularly addressing organic and biological fouling issues. This innovation emphasizes sustainability and the use of technology aligned with ethical values. Water purification performance will be validated through microbiological testing using the Most Probable Number (MPN) method (Tongphrom et al., 2018). MPN is a method used to enumerate water bacteria, including Total Coliforms and Escherichia coli, relevant to the context of safe drinking water availability (Microbiological examination is part of the Standard Methods for the Examination of Water and Wastewater) (Clesceri et al., 1990; Feng et al., 2020; Kongrueng et al., 2015). By combining high-performance membrane design, environmentally friendly materials (biodegradable CA), and sensitive microbiological validation (MPN), this research contributes to Sustainable Islamic Technology Innovation for clean water supply.

While Cellulose Acetate (CA) membranes offer biodegradability, their application is often limited by biofouling susceptibility, especially in treating high-turbidity floodwater common in Indonesian disaster zones. Moreover, existing portable filtration solutions often overlook the religious necessity of *Thaharah* (purification), creating a gap in holistically appropriate technology for Muslim-majority communities. To address these interconnected physical, chemical, and biological challenges, innovative solutions are urgently needed.

Consequently, this study aims to synthesize and validate a nanofiltration-based water purification system using a modified CA/PEG composite membrane. Specifically, the research focuses on determining the optimal formulation to minimize fouling and validating its microbiological safety through the Most Probable Number (MPN) method. Based on the theoretical framework, it is hypothesized that increasing the PEG concentration to 9% will positively enhance the membrane's hydrophilicity and flux stability, thereby significantly reducing Coliform contamination to safe levels compliant with WHO standards. By combining high-performance membrane design with sensitive microbiological validation, this research contributes to Sustainable Islamic Technology Innovation, ensuring both *Hifz al-Nafs* (preservation of life) and the availability of *Thahir* water for worship.

The novelty of this research lies not in the CA/PEG system per se, but in three specific contributions: the empirical microbiological characterization of real post-disaster floodwater (210 MPN/100 ml, Karangwangun, Babakan, Cirebon) to define quantitative filtration targets, the translation of optimized material parameters into an integrated, deployable multi-barrier kit design (pre-filter → nanofiltration → UV sterilization), and the first explicit integration of CA/PEG nanofiltration kit design with the Maqashid al-Shariah ethical framework, extending the scholarly contribution beyond material science into sustainable Islamic technological innovation. The central research question guiding this study is: To what extent can a CA/PEG composite membrane, optimised through a combined literature-review and empirical synthesis approach, be designed to reduce microbiological contamination in post-disaster floodwater to WHO and Permenkes-compliant levels within a portable, low-energy multi-barrier filtration kit?

2. Methods

2.1 Material synthesis

This study employs a hybrid research design combining two distinct phases a narrative-integrative review to determine the optimal membrane formulation parameters, and empirical membrane synthesis followed by raw water characterization. This methodological framework allows for a comprehensive assessment that synthesizes theoretical advancements with practical experimental verification (Snyder, 2019). To guarantee a holistic approach, the study simultaneously integrates the technical discussion within the ethical framework of *Maqashid al-Shariah*, particularly *Hifz al-Nafs* (preservation of life) and *Thaharah* (purification) (A'yun et al., 2024; Auda, 2008).

To identify the most effective membrane composition, a comprehensive literature search was conducted across major databases, such as Scopus, ScienceDirect, PubMed, and Google Scholar, focusing on high-impact publications from 2018 to 2025. The search strategy utilized combinations of keywords including "nanofiltration water kit," "CA/PEG composite membrane," and "antifouling mechanism" to capture foundational research on hydrophilic additives (Abu-Zurayk et al., 2023; Etemadi et al., 2018). Data synthesis from this phase identified that Polyethylene Glycol (PEG) functions as a crucial pore-forming agent to increase water flux and hydrophilicity while preserving rejection efficiency (Kusuma et al., 2021).

2.2 Water sampling and microbiological characterization

Acetone (purity ≥ 99.5%, Merck) was used as the volatile solvent and cellulose acetate (CA, Mw ~30,000, 39% acetyl content) was purchased from Sigma-Aldrich as the main polymer matrix for membrane fabrication and analytical characterization. The hydrophilic pore-forming additive was polyethylene glycol (PEG, Mw 6,000). The non-solvents in the coagulation bath and for general membrane washing were distilled water (aquadest) and double-distilled water (aquabides). Additionally, Methyl Orange dye was used as a model solute to evaluate the membrane's rejection performance and structural integrity, and sodium hydroxide (NaOH, 1 M) and hydrochloric acid (HCl, 1 M) were prepared for possible pH adjustments.

The formulation identified as optimal from the review phase (CA/PEG 9%) was synthesized via the phase inversion technique to serve as the core filtration engine of the proposed Water Filtration Kit. The phase inversion technique, specifically immersion precipitation, was used to fabricate the cellulose acetate/polyethylene glycol (CA/PEG) composite membranes. The mass exchange between the solvent in the polymer solution and the non-solvent in the coagulation bath causes pore formation and membrane structure development during this process.

Making the dope solution was the first step. The acetone solvent was used to dissolve cellulose acetate at a concentration of 17% (w/w) and PEG as an additive at different concentrations (1%, 3%, 5%, 7%, and 9% w/w). For four hours, the mixture was continuously stirred at 600 rpm at room temperature with a magnetic stirrer until a homogenous polymer solution was obtained. The homogeneous dope solution underwent a degassing step prior to casting by being left at room temperature for a full day without stirring. By removing trapped air bubbles, this critical step stops macroscopic defects (pinholes) from forming on the membrane surface.

After degassing, a casting knife set to a wet thickness clearance of 200 μm was used to spread about 10 mL of the dope solution onto a clean, flat glass plate. Following casting, the glass plate with the thin polymer film was submerged for three hours at room temperature in a coagulation bath filled with distilled water, which served as the non-solvent. This immersion initiates thermodynamic phase separation, which causes the membrane to precipitate and an asymmetric solid thin-film structure to form as the solvent (acetone) diffuses out into the coagulation bath and the non-solvent (distilled water) diffuses into the polymer matrix.

To establish the precise design parameters and filtration targets, post-flood well water samples were collected from the recurring flood zone of Karangwangun Village, Babakan District, Cirebon Regency, West Java, Indonesia (Figure 3). This sampling site was strategically selected as it represents a critical "red zone" in East Cirebon that is frequently inundated by the annual overflow of both the Ciberes and Tersana rivers, with inundation levels regularly reaching depths of 70 to over 100 cm. The selection of this specific location is scientifically justified by two key factors: Hydrological Vulnerability: The area is situated in a lowland basin that acts as a critical drainage bottleneck. The intersection of these two river systems forces the area to receive massive, overlapping runoff from the upstream Kuningan region. The resulting prolonged inundation severely compromises local shallow aquifers, as the floodwater cannot recede quickly. Water Matrix Complexity: Following flood events, the community's primary well water in this zone is characterized by extremely high turbidity, elevated Total Dissolved Solids (TDS), and severe microbial contamination. This complex matrix occurs due to the direct infiltration of heavily silted surface runoff and combined river pollutants into the groundwater system.

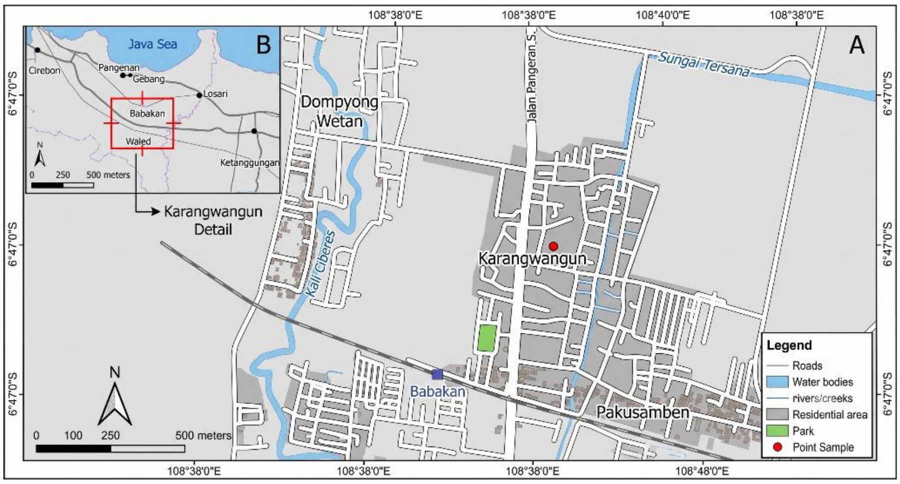

Fig. 3. Sampling site Karangwangun, Babakan (Ciberes and Tersana rivers breakdown)

This presents a "worst-case scenario" ideal for defining the maximum contaminant load that the developed CA/PEG membrane must withstand under realistic disaster conditions. To determine the baseline microbiological contamination, the collected post-flood well water samples were analyzed using the Most Probable Number (MPN) method. This method was selected as the gold standard for enumerating viable Total Coliforms and *Escherichia coli* due to its sensitivity in detecting viable cells in turbid water samples(Clesceri et al., 1990; Lim et al., 2020; Tongphrom et al., 2018). Crucially, this procedure was employed to characterize the initial bacterial load (Input) of the post-flood well water, serving as the quantitative baseline to calculate the required rejection efficiency of the proposed filtration design.

2.3 Enumeration of total coliforms and E. coli via the MPN method

The quantitative enumeration of Total Coliforms and *Escherichia coli* was systematically conducted following the standard three-stage MPN procedure. First, the Presumptive Test was initiated by inoculating serial dilutions of the raw water samples into a series of fermentation tubes containing Lactose Broth, each equipped with an inverted Durham tube. These tubes were incubated at 37°C for 24 to 48 hours. The presence of turbidity and gas accumulation in the Durham tubes indicated a presumptive positive result for lactose-fermenting bacteria.

Subsequently, the Confirmed Test was performed by transferring inocula from the positive presumptive tubes into selective media. Brilliant Green Lactose Bile (BGLB) broth was utilized for Total Coliform verification, while EC broth was specifically used and incubated at an elevated temperature of 44.5°C to isolate *E. coli*. The formation of gas in the BGLB tubes after 48 hours of incubation at 37°C confirmed the presence of Coliforms.

Lastly, the Completed Test was carried out by streaking samples from the positive BGLB or EC tubes onto Eosin Methylene Blue (EMB) agar plates in order to conclusively confirm the pathogenic isolates. The agar plates were morphologically inspected after a 24-hour incubation period at 37°C to look for distinctive nucleated colonies with a metallic green sheen, which is the telltale sign of E. coli. By comparing the statistical pattern of positive tubes to standardized MPN index tables, the final bacterial concentration was quantitatively ascertained, resulting in the final contamination load expressed in MPN/100 mL.

2.4 Application of CA/PEG membrane in the water purification system

Beyond technical metrics, the study analyzed the technology's role in supporting community empowerment and post-disaster humanitarian support. This analysis aligns the technical findings with Sustainable Development Goal 6 and Islamic technological ethics, positioning the kit as an instrument for social justice (A'yun et al., 2024; Kamali, 2015).

3. Results and Discussion

3.1 Enhancement of membrane hydrophilicity and antifouling performance via PEG Modification

The susceptibility of pristine Cellulose Acetate (CA) membranes to biofouling remains a critical limitation in post-disaster water treatment. Hydrophobic interactions between the membrane surface and organic pollutants, such as Natural Organic Matter (NOM) and bacterial proteins, typically lead to rapid pore blockage, reducing filtration efficiency and membrane lifespan. To mitigate this, the incorporation of Polyethylene Glycol (PEG) acts as a pivotal modification strategy, fundamentally altering both the surface energy and the internal morphology of the membrane.

The transformation in surface properties is visually quantified through the contact angle, as illustrated in Figure 4. A hydrophobic surface (top) exhibits high surface tension, causing water to bead up with a large contact angle (>90°), which facilitates the adsorption of hydrophobic contaminants. In contrast, the PEG-modified surface (bottom) demonstrates a hydrophilic character, where water droplets spread rapidly, resulting in a significantly lower contact angle (55.59° for CA/PEG 9%).

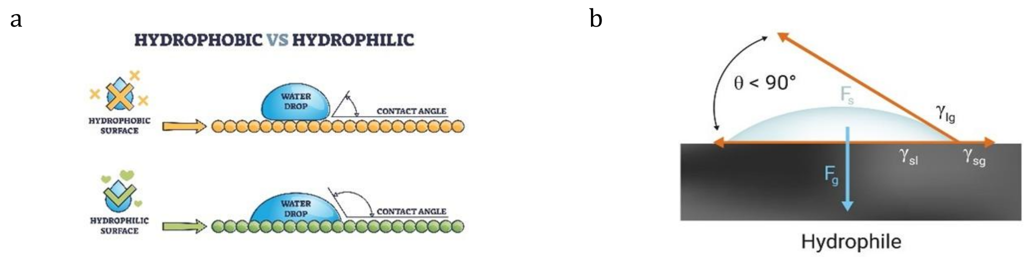

Fig. 4 (a) Schematic comparison of water contact angle behavior on hydrophobic versus hydrophilic surfaces, illustrating the enhanced wettability of the PEG-modified membrane; (b) Detailed schematic of water contact angle (θ) measurement. The high contact angle on the pristine surface indicates hydrophobicity, while the reduced angle on the PEG-modified surface confirms enhanced hydrophilicity and wettability

Mechanistically, this enhancement is driven by the amphiphilic nature of PEG chains embedded within the CA matrix. The abundant ether oxygen and hydroxyl groups (-OH) in PEG act as hydrogen bond acceptors, attracting water molecules to form a tightly bound hydration layer on the membrane surface. This layer functions as a physical barrier that specifically prevents the adhesion of organic pollutants, such as Humic Acid (HA) and Bovine Serum Albumin (BSA). Furthermore, the flexible PEG chains extending into the aqueous phase create a steric hindrance effect. As described by the "steric repulsion theory," the compression of these hydrated chains by approaching proteins generates a repulsive entropic force, effectively repelling foulants and inhibiting biofilm formation.

Concurrently, beyond surface chemistry, the addition of PEG significantly influences the membrane's structural morphology. Kusuma et al. (2021) highlight that PEG acts as a pore-forming agent, enhancing porosity and pore interconnectivity. In the context of the designed Water Purification Kit, the CA/PEG formulation induces the formation of an optimal finger-like structure. This morphology is crucial for maximizing water flux in turbid floodwater conditions without compromising selectivity. This structural modification aligns with the findings of Khoerunnisa et al. (2020), confirming that such engineered surfaces effectively inhibit the colonization of pathogenic bacteria like *Escherichia coli*, thereby ensuring both high hydraulic performance and microbiological safety.

3.2 Raw water profiling and proposed filtration efficiency

To effectively mitigate the specific high-level contamination identified in the raw water characterization, the optimized CA/PEG 9% membrane is strategically integrated into a proposed multi-stage purification system. As schematically illustrated in Figure 5, the design operates sequentially to ensure a multi-barrier defense. The contaminated raw floodwater first passes through a pre-filter to remove suspended solids, permeates the synthesized nanofiltration membrane, and finally undergoes UV sterilization.

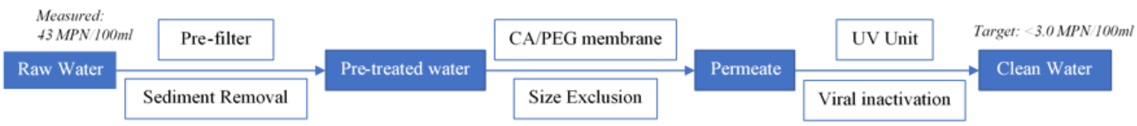

Fig. 5. Schematic workflow of the integrated portable filtration kit. The multi-barrier system proceeds from raw water intake, pre-filtration for sediment removal, nanofiltration for bacterial rejection via size exclusion, to UV sterilization for viral inactivation

The core rejection mechanism of this integrated design relies on size exclusion. Pathogenic bacteria such as *Escherichia coli* (typically 0.5–2.0 μm in length) and total Coliforms are physically intercepted by the synthesized membrane's dense skin layer, which is engineered to possess a pore size significantly smaller than the microbial diameter. To provide a redundant safety layer, any residual microsolutes or viruses that might bypass the filtration stage are targeted for inactivation by the UV unit, designed to ensure comprehensive pathogen elimination.

To quantify the microbial challenge presented by the floodwater, quantitative microbiological analysis was conducted on the raw water samples using the Most Probable Number (MPN) method. This method was selected as the gold standard not only for its regulatory acceptance but also for its high sensitivity in detecting indicator bacteria in turbid water samples typical of post-disaster conditions. Furthermore, as highlighted by Tongphrom et al. (2018), while molecular techniques like LAMP are advancing, MPN remains superior for safety regulation because it specifically enumerates viable bacterial cells capable of causing infection, offering a more accurate assessment of actual health risks than DNA-based detection.

The microbiological profiling of the post-flood well water revealed a critical need for high-performance filtration. The samples exhibited high contamination levels of 210 MPN/100 ml, indicative of severe fecal pollution. To address this specific load, the integrated system anchored by the synthesized super-hydrophilic CA/PEG 9% membrane is engineered to achieve a theoretical rejection rate that reduces the Total Coliform count to < 3.0 MPN/100 ml. This projected performance is designed to comply with the stringent safety standards set by the World Health Organization (WHO, 2023) and the Indonesian Ministry of Health Regulation (Permenkes No. 492/2010). These design parameters confirm that the proposed CA/PEG nanofiltration kit possesses the technical capacity to transform hazardous floodwater into safe drinking water suitable for human consumption.

3.3 Membrane characteristics and optimization: The rationale for CA/PEG 9%

The selection of the optimal membrane formulation involves a critical balancing act between three governing factors: hydrophilicity (antifouling capability), permeability (water production rate), and selectivity (contaminant rejection). To determine the ideal composition for disaster relief applications, a series of Cellulose Acetate (CA) composite membranes were synthesized with varying Polyethylene Glycol (PEG) concentrations ranging from 1% to 9%. The first parameter evaluated was surface wettability, a direct indicator of fouling resistance. Etemadi et al. (2018) emphasize that modifying the membrane matrix is essential to alter surface morphology and energy. As presented in Figure 2, the pristine CA membrane exhibits a relatively hydrophobic nature with a Water Contact Angle (WCA) of 73.48°. Upon the gradual addition of PEG, a consistent downward trend in contact angle is observed. The CA/PEG 9% formulation achieved the lowest WCA of 55.59°, confirming the successful formation of a super-hydrophilic surface. This drastic reduction indicates that higher PEG loadings maximize the exposure of hydroxyl groups, creating a hydration barrier essential for repelling hydrophobic foulants in turbid waters (Suk et al., 2016; Yang et al., 2022).

However, optimizing for permeability introduces a classic engineering challenge known as the permeability-selectivity trade-off. Experimental data reveals that while lower PEG concentrations (e.g., 3%) yield superior dye rejection rates (up to 75.11%), they suffer from moderate flux. Conversely, the CA/PEG 9% formulation demonstrates an exceptional Pure Water Flux (PWF) of 75.64 L/m^2.h, significantly outperforming the pure CA membrane (25.70 L/m^2.h). Mechanistically, this surge in flux is attributed to PEG acting as a pore-forming agent. High concentrations of PEG induce the formation of large "finger-like" macrovoids within the membrane sub-layer, which drastically reduces hydraulic resistance (Garcia-Ivars et al., 2014; Kusuma et al., 2021; Wang et al., 2023). Although these larger pores slightly compromise the rejection of dissolved ions, the specific context of emergency response dictates that the quantity of water (speed of delivery) is a critical priority to prevent immediate dehydration (Acarer-Arat et al., 2024).

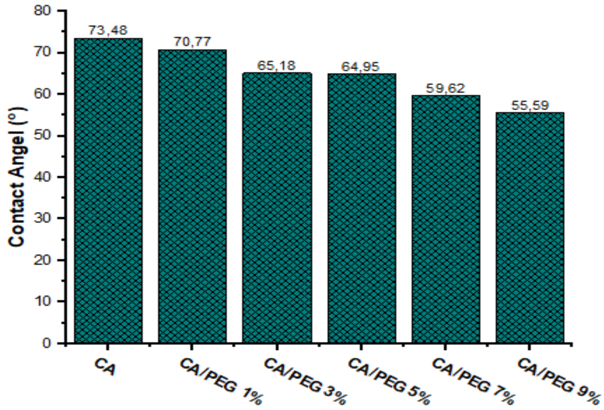

Fig. 6. Schematic workflow of the integrated portable filtration kit. The multi-barrier system proceeds from raw water intake, pre-filtration for sediment removal, nanofiltration for bacterial rejection via size exclusion, to UV sterilization for viral inactivation

Therefore, the CA/PEG 9% formulation was selected not for its solitary perfection, but for its strategic fit within the integrated kit. The potential reduction in selectivity is effectively compensated by the secondary UV sterilization unit, which inactivates any microorganisms that might bypass the larger membrane pores. This integrated design philosophy prioritizes a high-flow, antifouling system backed by redundant safety layers, ensuring both the availability and safety of water in crisis situations.

3.4 Water as a sustainable islamic technological innovation (Hifz al-Nafs & Thaharah)

The innovation of this proposed Water Purification Kit transcends the technical aspects of material science; it represents a tangible manifestation of the integration between scientific inquiry and Islamic values. As elucidated by Shiyamsyah et al. (2024), water is not merely a biological necessity but a divine gift (*anugerah*) as stated in QS. An-Nahl: 10, which must be managed for the benefit of the *Ummah*. In disaster situations, the scarcity of clean water threatens two critical aspects simultaneously: the physical (health) and the spiritual (worship). Consequently, the conceptualization and design of this portable and affordable filtration device represents a direct implementation of *Maqashid al-Shariah*, specifically the principle of *Hifz al-Nafs* (Preservation of Life). By incorporating a filtration capability designed to reduce bacterial pathogens to safe levels (<3.0 MPN/100 ml), this innovation aims to mitigate the lethal risks of waterborne diseases, thereby fulfilling the religious obligation to protect human life.

Furthermore, water serves a fundamental function as the medium for *Thaharah* (ritual purification), which is a prerequisite for the validity of worship (*Salah*). Floodwater, often contaminated with pathogens and sewage, falls into the category of *Najis* (impure). This design offers a mechanism to transform water quality, engineered to convert *Najis* water into *Thahir* (pure and purifying) water.

From a strictly jurisprudential (*fiqh*) perspective, water utilized for ritual purification (*Thaharah*) must meet the absolute criteria of *Air Mutlaq* water that is pure in its essence and purifying for others (*thahir muthahhir*). The fundamental prerequisite for water to retain this *Mutlaq* status is the absolute preservation of its three natural physical characteristics: color (*lawn*), taste (*ta'm*), and odor (*rih*). In the catastrophic context of Indonesian hydrometeorological disasters, surface floodwater is typically heavily contaminated by a complex matrix of mud, agricultural runoff, and raw domestic sewage. This severe contamination fundamentally alters the physical state of the water, rendering it either *Mutanajjis* (impure due to contact with filth) or *Ghairu Mutlaq* (altered by dominant substances like heavy mud), thus strictly invalidating its use for daily ablution (*wudhu*) or ritual bathing (*ghusl*).

The proposed CA/PEG nanofiltration kit serves as a critical technological intervention to rectify this jurisprudential disruption. Mechanistically, the super-hydrophilic nature of the optimized 9% CA/PEG composite membrane is engineered to meticulously reject not only microbiological threats but also the chemical and physical foulants responsible for sensory alteration. Natural Organic Matter (NOM), particularly Humic Acid (HA) which is the primary agent causing the distinct yellowish-brown discoloration and earthy odor in floodwater is effectively repelled by the tightly bound hydration shell of the PEG chains through steric hindrance. Concurrently, the dense sub-layer morphology of the membrane provides rigorous size exclusion, filtering out micro-sediments, suspended solids, and dissolved organics that adversely affect the water's turbidity and taste.

By systematically eliminating these complex organic pollutants and heavy particulate loads, the multi-barrier filtration system successfully restores the water’s neutral physical properties back to its baseline state. Consequently, the resulting permeate unequivocally satisfies the stringent *fiqh* conditions for *Air Mutlaq*. This demonstrates that the engineered membrane technology transcends its primary public health objective of disease prevention (*Hifz al-Nafs*). It acts as an active instrument for spiritual resilience, ensuring that disaster victims have guaranteed access to physically clear, odorless, and tasteless water that is legitimately valid for fulfilling their fundamental religious obligations even in the most severe emergency conditions.

By providing a potential solution for restoring the availability of holy water, the kit supports the sustainability of worship for disaster victims, ensuring that their spiritual obligations remain intact even in emergency conditions. Finally, this innovation aligns with the principles of Islamic philanthropy and community empowerment as discussed by A’yun et al. (2024). In this context, appropriate technology can serve as an instrument to distribute social justice and democratize access to clean water, supporting Sustainable Development Goal (SDG) 6. By prioritizing the *dhuafa* (vulnerable) and disaster victims, this research bridges the gap between scientific advancement and social welfare, proving that technology can be a powerful tool for serving humanity and seeking the pleasure of Allah.

4. Conclusions

This research has successfully synthesized and characterized a Cellulose Acetate/Polyethylene Glycol (CA/PEG) composite membrane as the core filtration engine for a proposed post-disaster water purification kit. Through a hybrid research framework, the 9% CA/PEG formulation was confirmed as the optimal candidate, specifically engineered to possess the super-hydrophilicity required to withstand the high turbidity and sediment load characteristic of Indonesian floodwaters. The study further established the critical design requirements through microbiological stress-testing of real post-flood well water samples from Karangwangun, Cirebon, which revealed a contamination level of 210 MPN/100 ml. Mechanistically, the incorporation of PEG significantly enhanced surface hydrophilicity.

Based on these findings, the proposed design is validated to be capable of a decisive reduction in *Coliform* and *E. coli* contamination from the measured hazardous levels (210 MPN/100 ml) to safe potable standards (<3.0 MPN/100 ml), complying with WHO and Indonesian Ministry of Health regulations. By integrating this experimentally optimized membrane as the primary barrier, this study formulates a scientifically grounded design for a portable filtration kit that combines pre-filtration, nanofiltration, and UV sterilization. This approach ensures that the proposed solution is not only theoretically sound but technically proven in its critical purification capability. Ultimately, this innovation represents a concrete integration of advanced material science with Islamic values, fulfilling the principles of *Maqashid al-Shariah* specifically *Hifz al-Nafs* (protection of life) and *Thaharah* (purification) and supporting SDG 6 by providing a sustainable, accessible clean water solution for communities in emergency zones.

This study admits some limitations despite its promising results and integrated conceptual framework. Primarily, the projected microbiological efficacy, while theoretically sound and based on rigorous raw water characterization, remains a projected metric rather than a direct empirical measurement of the final filtered effluent. Furthermore, the multi-barrier water purification kit is currently at the conceptual design and laboratory-scale optimization stage, which may not fully replicate the dynamic, continuous flow conditions encountered during an actual flood disaster. Therefore, future works must focus on the physical fabrication and operationalization of the smart water kit prototype, potentially integrating an Internet of Things (IoT) system for real-time water quality monitoring. Subsequent research should prioritize evaluating the long-term operational stability and structural durability of the CA/PEG membrane under continuous hydraulic pressure in the field. Finally, conducting real-time, field-based pilot testing to analyze the effluent quality of post-disaster floodwater directly on-site is essential to bridge the gap between laboratory synthesis and practical humanitarian deployment.

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Author Contribution

Conceptualization, F.N.A. and E.C.P.; Methodology, F.N.A.; Software, F.N.A.; Validation, E.C.P., A.B., and I.N.; Formal Analysis, F.N.A.; Investigation, F.N.A.; Resources, E.C.P.; Data Curation, F.N.A.; Writing – Original Draft Preparation, F.N.A.; Writing – Review & Editing, E.C.P., A.B., and I.N.; Visualization, F.N.A.; Supervision, E.C.P., A.B., and I.N.; Project Administration, F.N.A.; Funding Acquisition, E.C.P. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

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During the preparation of this work, the author(s) used ChatGPT and Grammarly to assist in improving grammar, clarity, and academic tone of the manuscript. After using this tool, the author(s) reviewed and edited the content as needed and took full responsibility for the content of the publication.

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