Engineering Nano Filtration-Based Clean Water Technology to Improve Coastal Public Health

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Abstract *: The clean water crisis is still a major problem in Indonesia's coastal regions, especially in areas with high levels of salinity and complex biological pollution. This study aims to examine the application of nanofiltration technology based on activated carbon zeolite composite material to improve the quality of water suitable for consumption for coastal communities. The research method used an experimental approach by testing the effectiveness of the filtration system against physical parameters (turbidity, color, conductivity), chemical (pH, nitrates, ammonia), and microbiological (E. coli and coliform). The test results showed that the use of a 50–80 nm porous nano-zeolite layer was able to reduce turbidity by up to 93%, TDS by up to 85%, and suppress the number of coliform bacteria by up to 99.5%. The cost analysis also shows economic efficiency because the basic materials used are relatively cheap and easy to obtain in the local area. These findings confirm that nanofiltration engineering is not only a technological solution, but also an ecological and social approach to guarantee sustainable access to clean water in coastal areas.*

Keywords *: Nano filtration, clean water, coastal public health*

Abstrak : Krisis air bersih masih menjadi masalah utama di wilayah pesisir Indonesia, terutama di wilayah dengan tingkat salinitas tinggi dan polusi biologis yang kompleks. Penelitian ini bertujuan untuk mengkaji penerapan teknologi nanofiltrasi berbasis material komposit zeolit karbon aktif untuk meningkatkan kualitas air layak konsumsi bagi masyarakat pesisir. Metode penelitian yang digunakan adalah pendekatan eksperimental dengan menguji efektivitas sistem filtrasi terhadap parameter fisika (kekeruhan, warna, konduktivitas), kimia (pH, nitrat, amonia), dan mikrobiologi (E. coli dan coliform). Hasil pengujian menunjukkan bahwa penggunaan lapisan nanozeolit berpori berukuran 50–80 nm mampu menurunkan kekeruhan hingga 93%, TDS hingga 85%, dan menekan jumlah bakteri coliform hingga 99,5%. Analisis biaya juga menunjukkan efisiensi ekonomi karena bahan dasar yang digunakan relatif murah dan mudah diperoleh di daerah setempat. Temuan ini menegaskan bahwa rekayasa nanofiltrasi bukan hanya solusi teknologi, tetapi juga pendekatan ekologis dan sosial untuk menjamin akses berkelanjutan terhadap air bersih di wilayah pesisir.

Kata Kunci : Nanofiltrasi, air bersih, kesehatan masyarakat pesisir

INTRODUCTION

Access to clean water is a fundamental need for human life and is an important indicator of sustainable development, especially in coastal areas that have complex ecosystem characteristics and unique environmental challenges. Coastal communities in various regions in Indonesia face difficulties in obtaining water suitable for consumption due to limited freshwater sources, seawater intrusion, and pollution from anthropogenic activities such as mining, tourism, and domestic waste (Rahman et al., 2022; Hidayat & Putri, 2020). According to the World Health Organization (WHO, 2021), more than 2.2 billion people in the world do not have access to safe drinking water, and most live in coastal areas or small islands. This condition is exacerbated by global climate change that affects rainfall patterns, causing salinity intrusion into groundwater and lowering surface water quality (Ahmed et al., 2021). Therefore, technological innovation in water treatment is a strategic need to ensure the sustainable availability of clean water for coastal communities.

In this context, nanofiltration technology engineering has emerged as one of the potential solutions to address the clean water crisis in coastal areas. This technology uses a material with a particle size at the nanometer scale that has a high surface area and excellent adsorption properties to organic and inorganic contaminants (Zhao et al., 2020). Through the application of nanomembranes, water treatment can be carried out with high efficiency and produce water with a purity level close to distillation water (Khan et al., 2021). The main principle of nanofiltration is filtration based on particle size as well as electrostatic interactions between the membrane surface and pollutant molecules, which allows the separation of heavy metal ions, bacteria, and harmful chemicals from the water (Li et al., 2019). In recent years, research on the use of nanomaterials such as graphene oxide, titanium dioxide (TiO_2), and carbon nanotubes has shown promising results in improving the performance of seawater and brackish water filtration (Singh et al., 2022).

Nano filtration technology not only excels in filtration efficiency, but also has the potential to be adapted in small-scale water treatment systems that suit the geographical and social conditions of coastal communities. Most of Indonesia's coastal areas face limited clean water infrastructure and dependence on shallow wells that are easily contaminated (Susanto et al., 2021). Through an applied technology engineering approach, nanofiltration systems can be developed into portable, energy-efficient, and environmentally friendly devices, so that they can reach remote areas without requiring large operational costs (Yuan et al., 2020). Innovations like this are in line with the Sustainable Development Goals (SDGs) agenda, especially the sixth goal, which is to ensure the availability of clean water and decent sanitation for all (UNDP, 2022).

The quality of public health is highly dependent on access to clean water. In coastal areas, waterborne diseases such as diarrhea, cholera, and skin infections are serious problems due to poor sanitation and limited water sources (Faruque et al., 2020). Research by Hasan et al. (2021) shows that more than 40% of children in coastal areas of Bangladesh experience health problems due to the consumption of water with high salinity levels. Similar things are also found on the coast of Indonesia, where high levels of TDS (Total Dissolved Solids) and heavy metals in groundwater contribute to the increasing rates of kidney disorders and hypertension in the community (Putra & Yuliana, 2022). In this context, the application of nanofiltration is not only a technical solution, but also a public health intervention that is able to reduce the risk of water-based diseases through the provision of water suitable for consumption with hygienic standards.

From an environmental engineering perspective, the use of nanomaterials in water filtration systems creates new opportunities in the development of sustainable water treatment technologies. Nanocomposite-based membranes are able to improve water permeability, decrease fouling, and extend the operating life of filtration systems (Nguyen et al., 2021). For example, graphene-based membranes are capable of filtering heavy metal ions to 98% efficiency, while the use of TiO_2 nanocomposites can decompose toxic organic compounds through photocatalysis mechanisms (Zhang et al., 2020). The application of this system in coastal areas also allows the combination with renewable energy, such as solar power, to produce an efficient and environmentally friendly self-filtration system (Elimelech & Phillip, 2011).

In addition to the technical aspects, the successful implementation of nanofiltration technology is also determined by the social acceptance and sustainability of the system in the context of the local economy. Community participation in clean water management is a key factor so that technology can be operated and maintained sustainably (Puspitasari et al., 2020). Therefore, the design of the technology must consider socio-technical aspects, including ease of use, maintenance costs, and the availability of local materials for membrane regeneration. This participatory and educational approach in the application of technology can increase environmental literacy and strengthen public awareness of the importance of water resource conservation (Rahman et al., 2022).

Furthermore, the integration of nanotechnology innovations with public policies is an important agenda in the management of coastal water resources. The government can play a role through community-based water management programs that facilitate collaboration between researchers, industry, and the community in the development of clean water treatment systems based on appropriate technology (Santoso et al., 2021). In addition, regulatory support and research funding need to be strengthened so that nano-filtration innovations can be commercialized and widely applied in water-vulnerable areas. In the academic context, interdisciplinary research between the fields of environmental engineering, materials chemistry, and public health is essential to produce innovations that are relevant to the social and ecological needs of coastal communities.

Thus, nanofiltration-based clean water technology engineering represents a synergy between science, technology, and public health in responding to the challenges of the global clean water crisis. Its implementation in Indonesia's coastal areas is expected to improve the quality of life of the community, strengthen environmental resilience, and encourage the achievement of sustainable development. Further research is needed to optimize system efficiency, assess socio-economic impacts, and develop application models that are adaptive to local conditions. Through an integrated scientific approach, nanofiltration technology has great potential to be a transformative solution for water resilience and coastal public health in the future.

METHOD

This research was carried out at the Environmental Engineering Laboratory of the University of Mataram for the initial design and testing stage of the nano filtration system, as well as in Kertasari Village, West Sumbawa Regency, as a field test location. The research was conducted during March to July 2025, covering the design process, fabrication, water quality testing, and analysis of system performance under real-world environmental conditions. The selection of the Kertasari location is based on coastal hydrogeological conditions that are susceptible to seawater intrusion and high TDS levels in community well water sources, so it is representative to test the effectiveness of nanotechnology-based filtration systems.

Materials and Tools

The main materials used include natural zeolite measuring 50–80 nm which functions as an absorber of heavy metal ions and dissolved cations, coconut shell activated carbon to adsorb organic compounds and improve the taste of water, and nonwoven fabrics as a pre-filter layer to resist coarse particles. As a filtration container, a 4-inch diameter PVC tube with a length of 60 cm is used which is designed to be pressure-resistant and easy to disassemble. Sample water was taken from three coastal community wells with brackish water characteristics and an initial conductivity value of >2,000 µS/cm. Sampling was carried out by *composite sampling* to obtain a representation of the average water condition in the area.

Filtration Design

The filtration system is designed in the form of a vertical column with four main layers: (1) pre-filter nonwoven fabric at the top for initial filtration; (2) a layer of activated carbon 10 cm thick as an organic adsorption medium; (3) 5 cm thick nano-zeolite layer for ion exchange and absorption of inorganic contaminants; and (4) a layer of silica sand 15 cm thick at the bottom as a fine filter as well as a media support. The filtration process takes place by gravity with a flow flow of 1 liter per minute without the assistance of a pump to maintain energy efficiency and simplicity of the system.

Test Parameters

Water quality is tested before and after filtration including physical, chemical, and biological parameters. Physical parameters include turbidity (NTU), TDS, and electrical conductivity. The chemical parameters consist of pH, nitrates (NO_3^-), and ammonia (NH_3), while the biological parameters include total coliform and Escherichia coli using the Most Probable Number (MPN) method.

Data Analysis

The measurement data were analyzed descriptively quantitatively to assess the effectiveness of contaminant reduction in each parameter. The results were compared with drinking water quality standards based on the Minister of Health Regulation No. 492/Menkes/Per/IV/2010. In addition, a cost-benefit analysis was carried out by calculating the ratio between the total material cost of the filtration system and the volume of consumable water produced during the 30-day operation period to assess its economic feasibility for the implementation of coastal communities.

RESULTS AND DISCUSSION

Physical and Chemical Performance of Nano Filtration

The results of laboratory and field tests show that the nanofiltration system designed in this study is able to significantly improve coastal water quality on various physical, chemical, and biological parameters. In general, the system's performance shows high contaminant removal capability with an average efficiency above 80% for most indicators. These findings reinforce the potential of nanomaterial-based filtration technology as an appropriate solution for the provision of clean water in coastal areas affected by salinity intrusion and pollution.

In detail, the test results showed a decrease in water turbidity from an average of 12.6 NTU to 0.9 NTU, which means that the efficiency of the allowance reached 93%. This decrease indicates that the combination of pre-filtered layers, silica sand, and activated carbon is effective in retaining suspended particles and fine sediments. The high turbidity reduction also indicates the optimal functioning of the filtration system without significant fouling or blockage during the test period. Research by Susanto et al. (2021) and Khan et al. (2021) shows that porous media with a nanoparticle size is able to increase filtration efficiency up to two times compared to conventional media. This is because the large specific surface area of nanozeolite allows the adsorption and ion exchange process to take place faster and more stable.

In addition, Total Dissolved Solids (TDS) decreased from 1100 mg/L to 165 mg/L, with an elimination efficiency of 85%. The final TDS value is below the drinking water quality standard threshold (500 mg/L) according to the Minister of Health Regulation No. 492/Menkes/Per/IV/2010. The decrease in TDS shows that the filtration system is able to reduce the content of dissolved salts such as sodium, chloride, and magnesium that are commonly found in coastal brackish water. The main mechanism that occurs is the exchange of ions on the surface of the nanozeolite, where heavy metal ions and salts are trapped in the crystal structure of aluminosilicate. These results are consistent with the findings of Li et al. (2019) who reported that the sodium ion elimination efficiency reached 80–90% using zeolite-based nanocomposite membranes.

The electrical conductivity parameter also decreased to 78% from the initial value, indicating a reduced concentration of electrolyte ions in the water after the filtration process. This confirms the effectiveness of the system in overcoming salinity problems which are often the main obstacles for coastal communities in obtaining fresh water. Decreased conductivity is closely related to reduced TDS, as the two are correlated with the amount of solute. In this study, the relationship between TDS and conductivity showed a determination coefficient (R^2) of 0.91, which means that the two parameters strongly influence each other on filtration effectiveness.

The role of each layer in the system is crucial. The nano-zeolite layer is a key component in the absorption of metal ions and fine particles, thanks to its high specific surface area (50–80 nm) and selective ion exchange capabilities against cations such as Ca^{2+}, Mg^{2+}, and Na^{+}. Meanwhile, coconut shell activated carbon serves as an effective organic adsorbent to lower levels of odor and taste causing compounds, such as phenols and volatile compounds. The combination of these two media creates a synergistic mechanism, where activated carbon lowers the organic load before the water passes through the zeolite layer, so that ion absorption efficiency is increased and fouling can be minimized. Similar research by Zhao et al. (2020) showed that the integration of activated carbon and nano zeolite can lower COD by up to 70% and significantly improve water clarity.

In terms of chemical parameters, the test results showed that the pH value increased from 6.2 to 7.1, indicating that the filtered water was in a neutral condition and safe for consumption. This increase in pH is related to the exchange activity of H^{+} and OH^{-} ions on the surface of zeolite as well as the removal of organic acid compounds by activated carbon. Neutral conditions are essential to maintain the chemical stability of drinking water as well as prevent corrosion of the piping system. In addition, the content of nitrate (NO_3^{-}) and ammonia (NH_3) has also decreased by up to 80%, mainly due to the adsorption and ion exchange process in the zeolite layer. These results show the system's ability to address inorganic pollution sourced from agricultural activities and domestic waste.

Overall, the results of the study show that the combination of nano zeolite and activated carbon is able to work synergistically and efficiently in improving coastal water quality. The filtered water has the characteristics of clear, odorless, and has a neutral taste, with all test parameters meeting the national drinking water quality standards. The high efficiency obtained without the need for external pressure or large electrical energy also confirms that this technology is environmentally friendly and sustainable, in accordance with the principle *of a low-cost, low-energy water treatment system* (Elimelech & Phillip, 2011). Thus, this nano filtration system is not only feasible to be applied in the laboratory, but also has great potential for field applications as a sustainable clean water solution for Indonesia's coastal communities.

Effectiveness of Microbiology

The results of the test on biological parameters show that the nano-zeolite and activated carbon filtration system provides a very significant removal of microorganisms, especially against water-polluting indicator bacteria such as *Escherichia coli* (*E. coli*). Before the filtration process, the number of *E. coli colonies* was recorded at an average of 110 CFU/100 mL, which indicates that the sample water is not suitable for consumption and has the potential to cause health problems such as diarrhea, dysentery, and gastrointestinal infections (Faruque et al., 2020). However, after going through the four-layer filtration system designed in this study, the amount of *E. coli* decreased drastically to 0–1 CFU/100 mL, which means that the elimination efficiency reached about 99.5%.

Based on the drinking water quality standards according to the Minister of Health Regulation No. 492/Menkes/Per/IV/2010, water with *E. coli* content ≤1 CFU/100 mL has met the standard for water suitable for consumption, so this result confirms the success of the filtration system in achieving this standard.

The effectiveness of this microorganism removal is due to the physical and chemical interactions on the surface of the nano filtration media. Zeolite layers measuring 50–80 nm have fine pores that are able to withstand particles and microbes larger than 0.1 µm. In addition, zeolites are catalytic and adsorptive, which allows for electrostatic bonds to occur between the cell wall of negatively charged bacteria and the surface of positively charged zeolite (Zhao et al., 2020). This process causes the microbial cell wall to be disrupted so that bacteria lose viability. Similar results were found by Li et al. (2019), who reported that the use of nanozeolites in water filtration systems was able to lower *E. coli* by up to 98% through the absorption mechanism of metal ions as well as the inhibitory effect of cellular metabolism.

The role of coconut shell activated carbon in this filtration system is also very important. Activated carbon not only serves as an adsorbent of organic compounds, but also creates an anaerobic micro-environment in the media layer that inhibits the growth of aerobic microorganisms such as *E. coli* and *Enterobacter sp.*. The high porosity properties of activated carbon (up to 1000 m^2/g) enlarge the contact area between the water and the surface of the medium, thus allowing the binding of organic molecules that are the source of nutrients for bacteria (Singh et al., 2022). With reduced sources of nutrients, microbes cannot reproduce optimally. This is in line with the findings of Nguyen et al. (2021), who stated that the combination of activated carbon and zeolite results in a filtration system with a dual effect—organic removal and microbial inactivation.

In addition to physical and chemical elimination, there may be partial photocatalytic mechanisms that contribute to microbial inactivation, especially in field tests conducted in open areas with high sunlight intensity. The activated zeolite surface can produce hydroxyl radicals (•OH) when exposed to UV light, which is known to have strong oxidative properties against the biological components of bacterial cells (Zhang et al., 2020). Although these effects were not the main focus of the study, the natural conditions of the coastal environment rich in UV light may amplify the antimicrobial effects of filtration systems.

From a public health perspective, the results of this microbiological exemption have very important implications. *E. coli* is a major indicator of fecal contamination, and its presence is often associated with an increased risk of waterborne infectious diseases (Hasan et al., 2021). By decreasing the concentration of *E. coli* to near zero, the risk of disease transmission can be significantly reduced. This means that the application of nanofiltration technology not only serves as a technical effort to provide clean water, but also as a preventive health intervention that is able to reduce the burden of diseases of coastal communities.

Overall, nano-zeolite and activated carbon filtration systems have proven to be effective, simple, and environmentally friendly in lowering microbiological contamination. Another advantage of this system is that it does not require additional chemicals such as chlorine or ozone, thus avoiding the risk of the formation of harmful side compounds. Thus, this technology has the potential to be widely applied in coastal areas that have limited clean water infrastructure. The results of this study support the concept *of low-cost decentralized water treatment* recommended by Elimelech and Phillip (2011), where a simple system based on nanotechnology can provide sustainable water for low-income people in remote areas.

Cost Analysis and Social Sustainability

The results of the economic evaluation show that the cost of manufacturing nanotechnology-based clean water filtration units for household scale is relatively low and very affordable for coastal communities. The total cost of materials and assembly of the unit, including PVC tubes, nano zeolite media, coconut shell activated carbon, silica sand, and nonwoven fabrics as pre-filters, is only around Rp. 350,000 with a service life of 12 months. If calculated based on the average production capacity of 200 liters of water per day, then the total water that can be produced during its lifetime is about 73,000 liters per year. Thus, the effective cost per liter of clean water is only around Rp0.05, much cheaper than the price of refillable gallons of water which ranges from Rp. 1,000-1,500 per liter in coastal and remote rural areas.

This comparison shows that nano-zeolite and activated carbon filtration systems have very high economic efficiency. In terms of *cost-benefit ratio (CBR),* the value of the comparison between benefits (access to water suitable for consumption) and investment costs shows a ratio of more than 20 times compared to commercial bottled water sources. This efficiency is also due to the low energy requirements as the system works with natural gravity flow without an electric pump. This makes this technology ideal for application in areas that do not have adequate electricity infrastructure, such as many coastal villages in West Sumbawa Regency.

In addition to the direct economic benefits, the study also highlights the social and public health impacts following the application of nanofiltration technology. Based on interviews with 15 user households during the first two months of use, as many as 87% of respondents reported a significant improvement in water clarity, taste, and odor, as well as a decrease in cases of diarrhea and digestive complaints that were previously common due to the consumption of brackish well water. These findings reinforce the view that improving clean water quality directly contributes to public health status, especially children and the elderly who are more susceptible to water-based diseases (WHO, 2022).

From a socio-cultural aspect, this technology is easy to adopt by coastal communities because the design is simple, uses local materials that are easy to find, and does not require high technical expertise in assembly or maintenance. This is in accordance with the principle *of appropriate technology* emphasized by Schumacher (2011), which is an efficient, cheap, and can be operated by local communities with limited resources. A participatory approach is also the key to its successful implementation. In the process of introducing the system, the research team involved residents in training in the manufacture, installation, and maintenance of filtration units. This activity not only improves people's skills, but also fosters a sense of ownership of the system they use.

This sense of ownership has a positive impact on the sustainability of the use of technology. Based on field observations, most of the residents carried out pre-filter cleaning and replacement of the activated carbon layer independently according to the guidelines provided. Thus, the sustainability of the system does not depend on external interventions, but grows organically from public awareness. This model is in line with the concept *of community-based water management* (CBWM), where communities become the main actors in managing water resources independently and sustainably (UNESCO, 2021).

In addition, the long-term socio-economic value of the implementation of this system is quite large. With the decrease in household expenditure on drinking water, people have a greater opportunity to allocate income to other needs such as education and family nutrition. Increasing access to clean water also reduces the burden of health costs due to waterborne diseases. In the long term, this supports the achievement of the Sustainable Development Goals (SDG 6) on universal access to clean water and sanitation.

Overall, nano-zeolite filtration systems based on local materials not only offer technical and economic efficiency, but also have a real social impact on improving the quality of life of coastal communities. The integration between technological innovation and community empowerment makes this approach an ideal model for the development of sustainable clean water technology in remote areas of Indonesia.

CONCLUSION

This study confirms that nanofiltration technology based on zeolite-activated carbon composites is an effective and applicable innovation in improving coastal water quality, both from physical, chemical, and microbiological aspects. The four-layer filtration system is designed to reduce the turbidity level of water by up to 93%, TDS by up to 85%, and the number of coliform bacteria by up to 99.5%, making it meet drinking water quality standards according to the Minister of Health Regulation No. 492/Menkes/Per/IV/2010. This high performance is achieved thanks to the synergy between the adsorption of metal ions by nano zeolites and the removal of organic compounds by activated carbon, which works effectively without the need for additional chemicals.

In addition to being technically superior, this system is also economical and sustainable, with an operational cost of around IDR 0.05 per liter of clean water. The ease of assembly, the availability of local materials, and the ability to operate without electricity make it very suitable for the social conditions of coastal communities who have limited infrastructure. The results of field tests showed a positive impact in the form of a reduction in water-based disease cases and an increase in user satisfaction. However, to ensure the long-term sustainability and efficiency of the system, further research is needed to optimize the multi-stage filtration design, evaluate performance at various salinity levels, and test the system's ability against complex chemical contaminants often found in coastal areas.

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