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Low-cost water treatment system using submerged membrane filtration in developing countries

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ABSTRACT

In this study, we investigated the possibility of installing membrane-based water treatment technology in Indonesia. Due to high turbidity in river water, tremendous amount of chemicals (mainly coagulants) are often used in the water treatment process in Indonesia. Consumption of such chemicals can be alleviated using membrane filtration since complete rejection of particulate matter can be achieved by membranes without the necessity of coagulation. A pilot-scale membrane filtration unit was continuously operated for more than three months at an existing drinking water treatment plant in Bandung, Indonesia. The results indicated that the operation under a membrane flux of 45 $L/m^2/h$ and chemical maintenance cleaning frequency of once per two days was very stable, and almost no detectable membrane fouling was seen at this operating condition. At this condition, the operating expenditure of the membrane-based water treatment system was estimated to be nearly equal to that of a conventional water treatment system based on coagulation, sedimentation, and sand-filtration. A stable membrane filtration can also be achieved at a membrane flux of 50 $L/m^2/h$ and chemical maintenance cleaning frequency of once per week. The operating expenditure of this condition was estimated to be lower than that of the conventional treatment. However, the removal of iron and manganese by the membrane-based water treatment system was relatively poor; suggesting that some pretreatment for removing dissolved compounds is necessary. Results suggest that membrane-based water treatment systems are one of the economically attractive choices in Indonesia as long as cost-effective pretreatment is developed.

Keywords: Low-cost water treatment; Submerged membrane filtration; Surface water

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1. Introduction

Membrane separation, by which complete removal of particulate matter can be achieved, is currently gaining much attention in the field of drinking water treatment. The advantages of drinking water treatment using membrane are complete removal of pathogenic organisms (e.g. *Cryptosporidium*) [1], ease of disinfection, and reduced footprint of treatment plants. The reduced footprint is a particularly attractive advantage because conventional water treatment systems require a large space for sand filters (indispensable in conventional water treatment using coagulation/sedimentation and sand-filtration) that can be omitted in the use of membrane-based treatment plants. This advantage of the membrane technology would be particularly useful for constructing decentralized drinking water treatment and distribution systems (i.e. small-scale water treatment plants are appropriately distributed in a city) [2,3]. In a decentralized drinking water treatment system, the length of pipeline required for distributing the treated water to each household can be greatly reduced. This feature of decentralized drinking water treatment is particularly useful in developing countries in which large-scale pipelines have not been constructed all over the cities yet. On the other hand, the dominant disadvantage of membrane technology is high operation and maintenance costs. To widely apply the membrane technology in water treatment, problems associated with high costs need to be addressed. In other words, when the costs associated with membrane treatment decreases, this technology would become a very attractive choice for drinking water treatment in developing countries.

In Indonesia, tap water treatment is often suffered from the raw water qualities. Generally, the river waters in Indonesia have high turbidity. In addition, the concentration of organic matter is also high in areas that have been affected by wastewater discharge. Such features of the raw water quality would increase the treatment costs to obtain clean water. Conventional water treatment methods including coagulation, sedimentation, and sand-filtration are widely applied in Indonesia. In such treatments, huge amounts of coagulants are required due to the high turbidity and organic contents. This, in turn, causes an increase of costs associated with chemical consumption. In addition, high turbidity in the raw water would also increase the frequency of sand filter cleaning. As a result, the labor costs in operating the treatment plants would also increase. If the problems mentioned above could be solved by applying membrane technology, this technology would become economically competitive among the other drinking water treatment technologies.

In the membrane filtration of river water, two different types of membrane module (i.e. pressurized and submerged membrane modules) can be applied [4]. Pressurized membrane modules can be operated with higher membrane flux than submerged membrane modules. However, suspended solids contained in feed water could easily be captured in the pressurized membrane module, so these types of membrane modules are generally less tolerant of turbid feed water [4]. On the other hand, a submerged type of membrane module can be applied to feed waters with high suspended solid concentration. This type of membrane module is applied in membrane bioreactors; in which mixed liquor suspended solid concentration levels reach 10 g/L (approximately two orders of magnitude higher than turbid river water). On the basis of the information mentioned above, it can be said that the submerged type of membrane modules are the optimal choice when applying the membrane technology to the treatment of feed water with high turbidity.

In this study, we evaluated the applicability of submerged membrane to the treatment of high-turbidity surface water (i.e. river water) in Indonesia. Since the effectiveness of particle removal is not affected by the coagulation in the water treatment using membrane, we attempted to reduce the operation costs by omitting coagulation and sedimentation. A pilot-scale membrane filtration apparatus was installed at the existing water treatment plant in Bandung, Indonesia, and was continuously operated for elucidating the performance of submerged membrane filtration of turbid river water without any coagulant dose. On the basis of the data obtained in this study, the economic competitiveness of the water treatment using submerged membrane is discussed.

2. Materials and methods

2.1. Feed water

In this study, the raw water that was used as feed water for the PDAM Bandung water plant was used as feed water for the pilot-scale membrane filtration unit. In the PDAM Bandung, the river water is delivered from two different intake points located on the north side and south side of the treatment plant. The river waters obtained from the two intake points are mixed in the treatment plant, and the mixed river water is used as raw water for the treatment plant (Table 1).

Table 1
Characteristics of raw water used in this study[a]. Concentration of organic matter is expressed as $KMnO_4$ consumption in mg/L[a]

	Turbidity[b] (NTU)	pH[b]	Temperature[b] (℃)	Fe[c] (mg/L)	Mn[d] (mg/L)	Organic matter[e] (mg/L)
Raw water	25.6 ± 39.7	6.8 ± 0.3	22.2 ± 0.8	1.8 ± 2.2	1.2 ± 0.9	10.5 ± 4.8

[a]Values are given ± standard deviation.
[b]n = 68.
[c]n = 59.
[d]n = 57.
[e]n = 62.

2.2. Continuous operation of pilot-scale water treatment apparatus equipped with submerged membrane

A pilot-scale membrane filtration unit installed at PDAM Bandung water treatment plant was continuously operated for evaluating the performance of direct membrane filtration of river water without the use of coagulation/sedimentation. A picture of the pilot-scale membrane filtration unit is presented in Fig. 1. One membrane module (UHS-620A, Asahi Kasei Chemicals, Tokyo, Japan) made of polyvinylidene fluoride (PVDF) was submerged in a membrane filtration basin with an effective volume of 235 L. The membrane module had an effective membrane area of 50 m^2, and the nominal pore size of the microfiltration (MF) membrane was 0.08 μm. The maximum suction pressure that could be applied to the membrane module was −80 kPa, and therefore, the membrane was cleaned when the operating pressure reached to −80 kPa.

The membrane filtration unit was operated with the following operational cycle: 15–30 min filtration,

Fig. 1. Pilot-scale membrane filtration unit used in this study.

1–1.5 min backwashing and air-scrubbing, and 2–10 min drain and refilling of raw water. During the filtration period, constant-flow rate membrane filtration was carried out. The water level was kept constant by controlling the feed pump during this period. After the filtration period terminated, the membrane module was backwashed using membrane permeate with a backwash flux of 40–60 L/m^2/h (0.96–1.44 m^3/m^2/d). During the backwashing, coarse bubbles were also introduced from the bottom of the membrane module to facilitate the removal of foulants accumulated on the membrane surface. After the backwashing and air-scrubbing had been terminated, the concentrated feed water contained in the membrane filtration tank was drained, and then, new river water was introduced in the tank. Taking the volume of concentrated feed water drained during backwashing, the recovery in the operation was determined as a percentage of feed water collected as treated water (i.e. membrane permeate) based on a unit volume of feed water supplied to the membrane filtration tank.

In addition to the regular physical membrane cleaning mentioned above, a short time and short interval of chemical membrane cleaning (denoted as enhanced flux maintenance or EFM, hereafter) was also carried out. In EFM, chemical cleaning solution comprised of sodium hypochlorite (500–1,000 mg/L as free available chlorine) was introduced in the membrane filtration tank and the membrane module was soaked in the solution for 30–60 min. The EFM was conducted for maintenance cleaning. In our experience, the application of EFM allowed us to operate the membrane filtration unit under higher membrane flux or lower transmembrane pressure (TMP). The EFM was performed once per two days in Run 1 and once per a week in Runs 2 and 3.

In this study, we carried out three separate continuous operations (Runs 1–3). The operating conditions examined in each run are summarized in Table 2. In Run 1, the pilot-scale membrane filtration unit was operated under our initial target operating

Table 2
Operating conditions in each run

	Membrane flux ($L/m^2/h$)	Recovery (%)
Run 1	45	94.6
Run 2	50	94.7
Run 3	55	95.6

conditions at which the operation cost becomes almost equal to the water treatment cost in the existing local water treatment plant utilizing a conventional coagulation, sedimentation, and sand-filtration. As discussed later, the operation in Run 1 was very stable and the development of membrane fouling was marginal. Therefore, we decided to examine the operating conditions at which operating cost of submerged membrane process can be lowered further in the subsequent runs (i.e. Runs 2 and 3) by increasing membrane flux and decreasing the frequency of EFM.

2.3. Cost estimation

The operating expenses (i.e. operation and maintenance costs) of conventional water treatment systems and submerged membrane process were calculated based on the information on units costs (e.g. chemical, electricity, and so on) obtained from local water treatment organizations. In this study, a drinking water treatment system comprised of coagulation, sedimentation, and sand-filtration was selected as a model for conventional drinking water treatment, because the existing drinking water treatment plant in which the pilot-scale experiment was carried out is currently operated under the arrangement mentioned above. Taking the high turbidity in the raw water into consideration, direct filtration (i.e. sand-filtration without applying sedimentation) is not likely to be applicable. Therefore, the comparison of the operational cost of membrane-based drinking water treatment against the one of the drinking water treatment utilizing coagulation, sedimentation, and sand-filtration is thought to be suitable for estimating the applicability of membrane filtration in a drinking water treatment in Indonesia.

For operating expense in the conventional water treatment based on rapid sand-filtration, the costs associated with coagulation/sedimentation and gravity sand-filtration were calculated on the basis of the price of chemicals used in coagulation process and the power cost required for backwashing of the filter media, respectively. In the case of cost estimation of membrane-based water treatment process, the costs associated with replacing membrane, chemical consumption, and power consumption were calculated. The cost for membrane replacement was calculated based on the membrane surface area required for treating a unit volume of river water, which is directly related to membrane flux selected for the operation and the expected membrane lifetime suggested by the membrane manufacture (i.e. five years). The costs for chemicals in membrane-based water treatment process are comprised of chemicals required for membrane cleaning. It should be noticed here that the costs required for coagulant was excluded from the chemical cost in membrane-based water treatment process, since the objective of this study was investigation on the possibility of applying direct membrane filtration (i.e. membrane filtration without any pretreatment) to drinking water treatment in Indonesia. In the cost associated with power consumption, the power consumed by feed and suction pumps and air-compressor was included. In this study, we did not include the difference in capital cost in our estimation.

2.4. Analytical methods

The concentrations of iron and manganese were determined in accordance with standard methods [5]. The concentration of organic matter was estimated by determining the consumption of potassium permanganate, which is also described in the Japanese industrial standards [6]. In a preliminary measurement, 10 mg/L of potassium permanganate consumption was found to be roughly corresponding to 1 mg/L of total organic carbon concentration. Turbidities of the feed water and treated water were determined using an online turbidity meter (HACH Surface Scatter 6, HACH Filter Trak 66).

3. Results and discussion

3.1. Water quality

Fig. 2 shows the changes in turbidity in the feed and treated waters. As seen in Fig. 2, sudden increases in turbidity were repeatedly measured in the feed water. However, such fluctuations were not reflected in the treated water; the turbidity of the treated water remained stable and fairly low compared to that of the feed water. This result clearly indicates that the suspended solids have been almost completely removed by the membrane. The turbidity in the treated water was always lower than that of the drinking water standard in Indonesia (i.e. 5 NTU). On this basis, it can be said that the quality of treated water would not be suffered from the fluctuation in turbidity

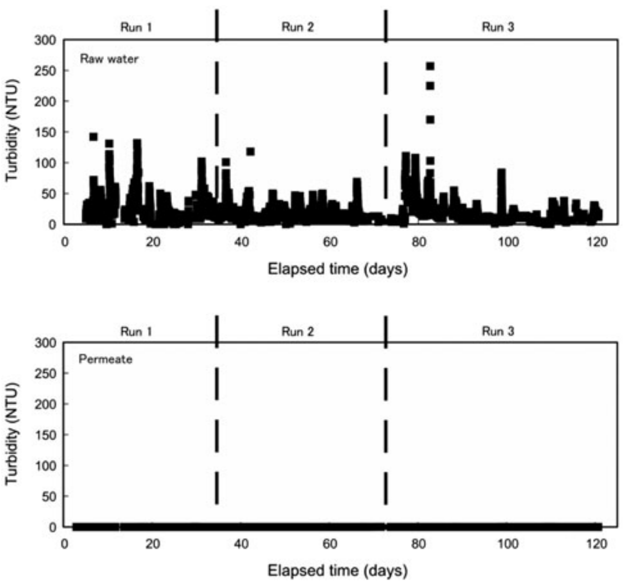

Fig. 2. Changes in turbidity of feed and treated waters.

in the feed water. Rather, feed water turbidity would have significant effect on the development of membrane fouling as discussed later.

Fig. 3 shows the concentration of organic matter in feed and treated waters. In this study, we evaluated the concentration of organic matter using the consumption of $KMnO_4$ by the organic matter contained in the sample waters. Although the $KMnO_4$ consumption in the feed water was significantly fluctuated, that in the treated water was relatively stable during the continuous operation. It is well-accepted that coagulation is effective pretreatment for improving the removal of humic substances, which are dominant components in natural organic matter, suggesting that omitting the pretreatment with coagulation may result in deterioration in the removal rate of organic matter. The results presented in Fig. 3, however, indicate that direct MF membrane filtration is still capable for removing organic matter contained in real river water. Since the concentration of organic matter in the treated water satisfied the drinking water standard in Indonesia (10 mg/L as $KMnO_4$ consumption) in most of the measurements carried out in this study, the direct MF membrane filtration can be considered as an effective drinking water treatment method for removing organic matter from river water.

Fig. 4 shows the concentration of iron and manganese in feed and treated waters. The removal of iron by the membrane was relatively poor, especially in the early stage of the continuous operation. These results are probably due to the fact that a portion of iron contained in the feed water was a dissolved form with reduced state (i.e. Fe(II)). After day 50 of continuous operation, the removal of iron by the membrane significantly improved. The detailed mechanisms of this improvement are currently unclear. One possible explanation might relate to the changes in distribution of iron with different oxidation numbers (i.e. Fe(II)/Fe(III)). The investigation on this issue would be particularly important for establishing the

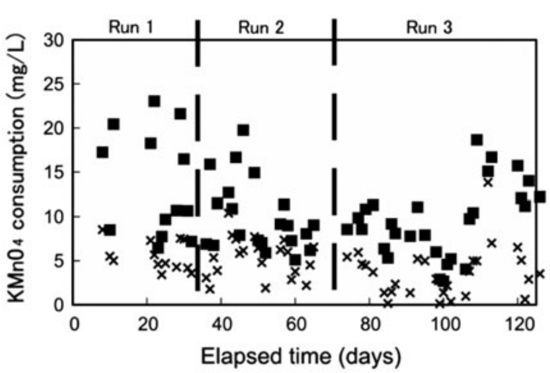

Fig. 3. Changes in concentrations of organic matter evaluated by consumptions of potassium permanganate. Squares: raw water, crosses: permeate.

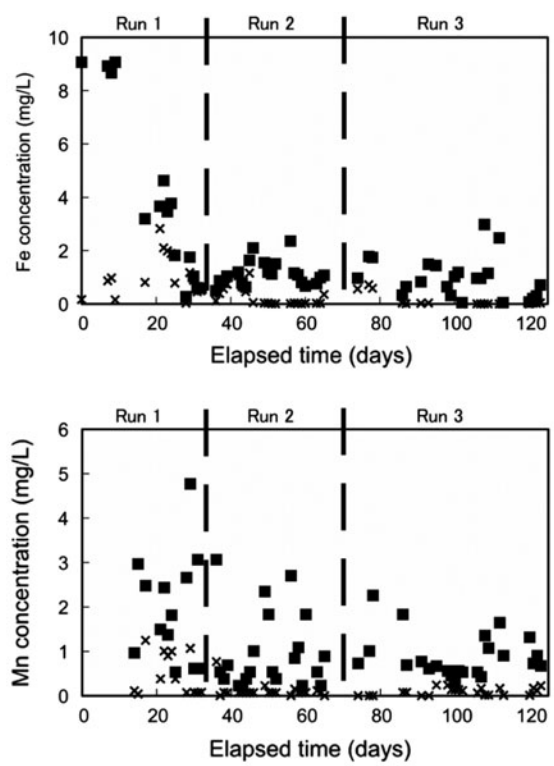

Fig. 4. Concentration of iron (top) and manganese (bottom) in feed and treated waters. Squares: raw water, crosses: permeate.

countermeasures for less effective removal of iron by the MF membrane used in this study. In contrast, manganese was relatively well removed by the membrane irrespective of the manganese concentration in the feed water, with a few exceptions at the early stage of the continuous operation. This result implies that a major portion of manganese contained in the feed water was in the oxidized form (e.g. Mn(IV)).

In general, dissolved compounds such as Fe(II) and Mn(II) are not removed by MF membrane. Unfortunately, the concentrations of iron and manganese in the treated water sometimes exceeded the drinking water standard in Indonesia (0.3 mg/L for iron and 0.4 mg/L for manganese). These findings imply that pretreatments for oxidizing dissolved iron and manganese may be required if treating feed water with high concentration of dissolved iron and manganese (i.e. reduced state of these compounds).

3.2. Development of membrane fouling

Fig. 5 shows the changes in TMP during the continuous operation of the pilot-scale membrane filtration unit. The data shown in Fig. 5 were adjusted to 25℃-equivalent values in consideration of the influence of water viscosity on required TMP. As seen in Fig. 5, operation was very stable and almost no increase in TMP was seen in Run 1. This result suggests that the membrane was over-cleaned in Run 1; stable membrane filtration was likely to be achieved with a reduced maintenance cleaning (i.e. EFM) frequency. Therefore, we decided to increase the membrane flux from 45 to 50 $L/m^2/h$ and decrease the frequency of EFM from once per two days to once per week in Run 2.

Many researchers reported that a degree of membrane fouling developed during filtration of a unit volume of feed water increased as membrane flux increased [7–10]. In this study, although the rate of increase in TMP increased slightly, continuous operation under increased membrane flux was very stable and no severe membrane fouling was observed. In Run 2, the TMP was far below the maximum suction pressure of 80 kPa, suggesting that further increase in membrane flux would be possible. In Run 3, membrane flux was increased from 50 to 55 $L/m^2/h$. The frequency of EFM was kept at once per week (the same frequency as in the Run 2). In Run 3, the rate of increase in TMP increased further. Gradual increase in TMP continued throughout the Run 3, and eventually, the TMP in the continuous operation was destabilized. This result strongly suggests that the maximum membrane flux for sustainable membrane filtration at the chemical maintenance cleaning intensity examined in this study (i.e. once per week EFM) was 50 $L/m^2/h$. To increase the sustainable membrane flux further, investigation on cost-effective EFM methods including frequency, concentration, and type (e.g. alkali, acid, and/or oxidant, etc.) of chemical cleaning agent is of critical importance. As discussed later, development of cost-effective pretreatment methods is also an important topic for future study.

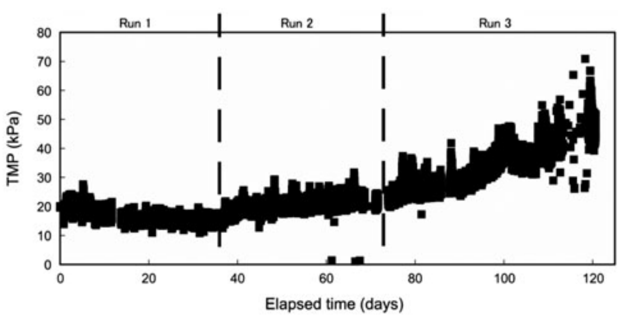

Fig. 5. Change in TMP during the continuous operation.

3.3. Cost evaluation

The results of cost evaluation are presented in Fig. 6. Generally, membrane technologies are thought to be costly in water treatment. For the feed water examined in this study, however, significant reduction in the cost associated with chemical consumption was

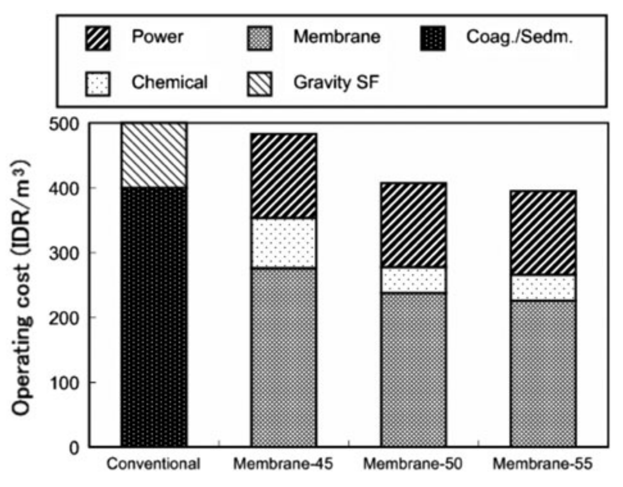

Fig. 6. Operating expenses of conventional drinking water treatment process and membrane-based drinking water treatment process operated with different membrane flux. Membrane-45, membrane-50, and membrane-55 are corresponding to membrane filtrations operated with membrane fluxes of 45, 50, and 55 $L/m^2/h$, respectively. Currency exchange rate between IDR and USD is IDR 10,000 for 1 USD.

achieved since no coagulant was required in our membrane-based treatment system, while huge amounts of coagulant are required in the water treatment based on conventional coagulation, sedimentation, and sand-filtration. In our calculation, conventional coagulation and sedimentation processes require approximately 400 IDR/m^3 in the water treatment plant in which the pilot-scale experiment was carried out. On the other hand, the cost associated with chemical consumption became approximately one-fifth compared with the conventional water treatment by omitting coagulation prior to membrane filtration. The increase in operating expenditure associated with the installation of membrane filtration was therefore totally offset by the decrease in the cost associated with chemical consumption; the operating expenditure estimated for the operating conditions in Run 1 was almost the same with that of the existing conventional water treatment system in Indonesia. This achievement alone is also attractive when we consider the applicability of membrane technology for constructing decentralized drinking water treatment systems. Generally, the cost of water treatment using membrane is not sensitive to plant capacity. The above-mentioned cost evaluation revealed that small-scale water treatment plants (indispensable for decentralized drinking water treatment system) can be operated without any substantial increase in operating expenditure in comparison with the currently operated conventional water treatment systems as long as submerged membrane filtration technology is installed. Decentralized drinking water treatment systems are likely to be particularly attractive for developing countries where the coverage of water supply systems needs to be increased further.

The results obtained in Run 2 further reinforce the attractiveness of membrane technology for treating water with high turbidity. Owing to the reduction in the frequency of chemical maintenance cleaning and increase in membrane flux, the operating expenditure in Run 2 was further reduced by approximately 15% compared with operating conditions examined in Run 1. Achieving stable membrane filtration at such operating conditions strongly suggests that submerged membrane filtration is one of the most attractive choices for upgrading existing water treatment plants in developing countries since operating expenditures of large-scale water treatment plants can also be reduced by installing this treatment process. It is worth noting that, in addition to the reduced operating expenditure, footprints of water treatment plants can also be reduced by installing membrane technology. The reduced footprint required for treating a unit volume of drinking water would also be an attractive point in developing countries in which population is growing rapidly.

As stated in Section 3.1, organic matter contained in the raw water was effectively removed by the direct membrane filtration carried out in this study. Although a portion of dissolved organic matter was supposed to be remaining in the treated water, the concentration of organic matter evaluated by $KMnO_4$ consumption was below the drinking water standard in Indonesia (10 mg/L as $KMnO_4$ consumption) in most of the measurements carried out in this study. On the other hand, the removal rates of iron and manganese sometimes became insufficient. To keep the water standard for such compounds, some pretreatment may be required in front of the membrane filtration if feed water contains dissolved iron and manganese at high concentrations. Several pretreatment methods for removing dissolved metals, including chlorination [11], addition of potassium permanganate [12] or hydrogen peroxide [13], and manganese sand-filtration, [13] have been currently proposed. Biological removal of these metals could also be promising technology [14,15]. The installation of such pretreatments also increases the operating expenditure. While the costs associated with pretreatment for removing dissolved compounds need to be included in the cost evaluation of membrane-based drinking water treatment, this topic is beyond the focus of this study that is investigation of possibility of applying direct membrane filtration for the drinking water treatment in Indonesia. Further investigation on cost-effective pretreatments for removing dissolved metals in front of membrane filtration is particularly important for reinforcing the economic competitiveness of membrane technology in the field of water treatment. Some pretreatment methods for removing dissolved metals are known to mitigate the development of membrane fouling [16,17], and therefore, are thought to have potentials to increase sustainable flux in the continuous membrane filtration. Although the incorporation of pretreatment would be an additional cost factor, such application may be justified when sustainable membrane filtration can be achieved at higher membrane flux operation.

The results obtained in this study clearly indicate that membrane-based water treatment systems are not costly relative to conventional methods or even more cost effective than the conventional water treatment systems based on coagulation, sedimentation, and sand-filtration. To generalize the findings mentioned above, pilot-testing using other river waters is obviously important. When the submerged membrane filtration is applied for treating feed water containing hydrophilic organic macromolecules at high concentrations, membrane fouling is expected to become more severe [18,19], and stable operation with higher membrane fluxes might not be achieved. To increase the economic competitiveness of membrane-based water treatment technology in such cases, the development of cost effective pretreatment is apparently important. Accumulation of fundamental knowledge on fouling mechanisms in the direct membrane filtration of surface water with submerged membrane filtration unit is therefore also required.

4. Conclusions

In this study, the applicability of submerged membrane filtration without any chemical dosing to the treatment of river water containing high turbidity was investigated. Basically, the operation of the pilot-scale submerged membrane filtration unit was very stable and can be continued for three months without any irregular membrane cleanings. Increase in membrane flux and decrease in frequency of regular maintenance cleaning did not affect the rate of membrane fouling development. Owing to its higher membrane flux and less frequent maintenance cleaning, operating expenditure of the membrane-based water treatment system was equal or even lower in comparison with the conventional water treatment system based on coagulation, sedimentation, and sand-filtration. Although some pretreatment for removing dissolved metals may be required, depending on feed water quality, the results obtained in this study clearly indicate that water treatment using membrane is economically competitive for treating surface water containing high turbidity.

Acknowledgments

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