Effects of recirculation and separation times on nitrogen removal in baffled membrane bioreactor (B-MBR)

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ABSTRACT

In this study, we investigated the effects of recirculation and separation times on removals of organic matter, nitrogen, and phosphorus in a baffled membrane bioreactor (B-MBR) treating real municipal wastewater. A pilot-scale B-MBR experimental apparatus was operated under two different sets of recirculation and separation times. The results revealed that, irrespective of operating conditions, the biochemical oxygen demand (BOD) and concentration of total nitrogen (T-N) in the treated water can be lowered to less than 3 and 5 mg/L, respectively. Although T-N was effectively removed in the two different operating conditions, increase in the fraction of recirculation time results in tiny deterioration of nitrogen removal efficiency in the B-MBR. Phosphorus removal efficiency was also slightly decreased as the fraction of recirculation time (ratio between recirculation and separation times) was increased. The results of the measurement of dissolved oxygen (DO) profiles at different points of the B-MBR apparatus indicate that the increase in DO concentration in the anoxic zone of the B-MBR becomes much more pronounced by increasing recirculation intensity. On the basis of the results obtained in this study, it can be concluded that efficient removal of BOD, T-N, and total phosphorus can be achieved by the B-MBR as long as appropriate recirculation intensity is selected.

Key words | baffled membrane bioreactor, nitrification/denitrification in a single reaction tank, recirculation intensity, simultaneous removal of organic matter and nutrients, wastewater treatment

INTRODUCTION

Membrane bioreactors (MBRs) have various advantages compared with conventional biological wastewater treatment processes (e.g., conventional activated sludge process), including small footprint, superior treated water quality, and ease of operation (automation) (Judd 2006). These features of MBRs make this technology a viable choice in up-grading existing wastewater treatment facilities or constructing a decentralized wastewater treatment system. Because of strict rejection of particulate matter by the membrane, the treated water from MBRs does not usually contain any suspended solid. Owing to this feature, MBRs can be a suitable technology for pretreatment of reverse osmosis membrane, which is often utilized in wastewater reclamation and reuse. Therefore, it can be said that the MBR is also an important technology in the field of wastewater reclamation and reuse.

Recently, the number of installations of MBRs has been increasing. However, such installations are unevenly distributed globally, and the most of the large-scale treatment plants are located in Asia Pacific (especially in China) and north America (especially in the United States) (Meng et al. 2012, 2017). High operation and maintenance costs are generally a big obstacle for widespread application of this technology. Reduction in operation and maintenance costs is obviously important for further expansion of the application of MBRs. Among the cost factors in operating MBRs, the cost associated with energy consumption accounts for the largest fraction (Kraume & Drews 2010). Although specific energy consumption in the operation of MBRs significantly decreased by the intensive research and development efforts (Krzeminski et al. 2017), it is still higher than other well-adopted wastewater treatment technologies such as the conventional activated sludge process at present. Further reduction in specific energy consumption in operating MBRs is obviously required.

In the operation of MBRs, aeration generally accounts for the largest energy consumption. Generally, two different
types of aeration are performed during the operation of MBRs, namely the aeration for preventing membrane fouling by eliminating foulants from membrane surface (membrane aeration) and the one aimed to supply dissolved oxygen (DO) to the biomass responsible for removing constituents contained in raw wastewater (biology aeration). In typical MBRs treating municipal wastewater, the energy consumption associated with membrane aeration tends to be higher than that associated with biology aeration; energy consumption associated with membrane aeration is reported to account for 35–74% of the energy consumption of the entire wastewater treatment process based on the MBR (Gil et al. 2010; Verrecht et al. 2010; Krzeminski et al. 2012). Reduction in energy consumption associated with membrane aeration is of critical importance for reducing operation cost of MBRs. In a previous study, we have achieved a stable MBR operation using a modified membrane element, which is comprised of a hollow-fiber membrane element with long fiber length (3 m) (Miyoshi et al. 2018). According to the estimation performed in our previous study, specific energy consumption in the entire wastewater treatment system based on the modified MBR (i.e., sewage lifting and sludge treatment were not included in the estimation) becomes less than 0.4 kWh/m³ (Miyoshi et al. 2018). This specific energy consumption is one of the best performances reported in the literature. However, the above-mentioned value is still higher than those of the conventional activated sludge process (typically 0.2–0.3 kWh/m³ in a medium- to large-scale wastewater treatment facility) (Fenu et al. 2010).

To establish an economically competitive wastewater treatment system based on the MBR, further reduction in energy consumption during the operation is obviously required. Apart from membrane aeration, operating the bioreactor also consumes huge energy, especially when nitrogen removal is required. For removing nitrogen through nitrification and denitrification reactions, installing an additional anoxic tank and recirculating mixed liquor suspension between the two tanks are required. This modification in plant configuration results in additional installations of a sludge recirculation pump and a mixer for agitating the anoxic tank. These apparatuses also consume substantial energy during the operation of an MBR with the above-mentioned configuration. To overcome this problem, a baffled MBR (B-MBR) has been proposed (Kimura et al. 2008a). In a B-MBR, baffles are inserted in the reaction tank and feed water is added in an appropriate way. By utilizing this method, both nitrification and denitrification can be promoted in a single reaction tank. As a result, the sludge recirculation pump and anoxic tank mixer can be omitted.

In this research project, we combine the two energy-saving approaches (i.e., energy-efficient MBR with modified membrane units and B-MBR). For efficient use of this combination, detailed information on suitable operational settings of the B-MBR is indispensable. In B-MBR operation, mass transfer between zones separated by the baffles only takes place during the recirculation period. On the other hand, both nitrification and denitrification are mainly promoted during the separation period. These features of the B-MBR suggest that the ratio of the times devoted for these periods is critically important for optimizing the operation conditions of a B-MBR. On this basis, we investigated the effect of recirculation and separation period on treatment performance of a B-MBR in this study.

MATERIALS AND METHODS

Concept of B-MBR

The details of the concept of the B-MBR can be found elsewhere (Kimura et al. 2008a). Figure 1 shows the schematic description of the B-MBR. In the B-MBR, baffles are inserted into the bioreactor of a submerged MBR, and a membrane unit is installed in one side of the zone separated by the baffles (in this study, interior zone of the baffles). In the zone in which the membrane unit is installed, membrane aeration and, when necessary, biology aeration are carried out. The highest and lowest water levels are set at higher and lower points than the top of the baffle, respectively. And the feed water is introduced intermittently with a flow rate higher than the one associated with membrane filtration. When the water level exceeds the top of the baffle, the mixed liquor suspension contained in the zone in which the membrane unit is installed overflows into the other zone due to the lifting power associated with the aeration carried out at this zone. This period is denoted as recirculation period hereafter. Due to the recirculation caused by this overflow, the mixed liquor suspension in the zone in which the...
membrane unit is located, which contains nitrate and DO, is provided into the other zone. During the operation, the water level is gradually decreased by the membrane filtration, and eventually becomes lower than the top of the baffles. This period is denoted as separation period hereafter. At the separation period, aeration is carried out only in the zone at which the membrane unit is installed. Therefore, the zone at which the membrane unit is not installed becomes anoxic, and denitrification proceeds in this zone. On the other hand, the zone at which the membrane unit is installed becomes aerobic due to the aeration (both membrane and biology aerations), and nitrification proceeds in this zone. The water level eventually reaches the lowest level. At this moment, the addition of the feed water is initiated, and the water level increases to the highest level again. By repeating this operation cycle, both nitrification and denitrification are promoted in a single reaction tank. Since mass transfer between the two zones only takes place during the recirculation period, the duration of recirculation period per one cycle is thought to be an influential factor on nitrogen removal, during which recirculation of nitrate to the anoxic zone is necessary. On the other hand, a certain duration is also required for the separation period to promote sufficient nitrification and denitrification reactions.

**Continuous operation of pilot-scale B-MBR**

A pilot-scale B-MBR experimental apparatus installed in an existing municipal wastewater treatment plant connected to a combined sewer system (Soseigawa Wastewater Treatment Center, Sapporo, Japan) was continuously operated. The B-MBR operated in this study was equipped with a membrane unit comprised of a hollow-fiber microfiltration membrane fabricated by polytetrafluoroethylene. This membrane is the same as the one used in our energy-saving MBR reported previously (Miyoshi et al. 2018), though the effective length of the hollow-fiber used in this study (0.8 m) was considerably shorter than that used in our previous study (3 m). The nominal pore size of the membrane used was 0.2 μm. In the bioreactor, two identical membrane units were submerged and operated side-by-side. These units can be operated independently to each other. Each membrane unit had an effective membrane surface area of 30 m², and as a result, total membrane surface area in the reactor was 60 m². Membrane filtration was carried out intermittently (9-min filtration/1-min relaxation). During the continuous operation, the membrane fluxes of both units were set at 0.25 m³/(m² d). This membrane flux is the net flux taking the relaxation in the intermittent membrane filtration into account (i.e. gross flux of 0.278 m³/(m² d) for 9-min filtration corrected for 1-min relaxation with no filtration). The B-MBR apparatus had an effective volume of 3.7 m³. The hydraulic retention time (HRT) and the solid retention time (SRT) during the continuous operation were 5.9 hours and 26.6 days, respectively. The mixed liquor suspended solids concentration in the reactor was in the range of 9,000–11,000 mg/L. In the B-MBR operated in this study, membrane aeration and biology aeration were separately performed. The air-flow rate of membrane aeration was set at 18 m³/hr (corresponding to a specific air demand per membrane surface area (SADₘ) of 0.30 m³/(m² hr)), the value of SADₘ adopted in this study is typical in many full-scale MBRs currently in operation (Verrecht et al. 2010, 2011; Judd 2013). It should be noticed here that, as mentioned above, we used a hollow-fiber membrane with relatively short fiber length compared with the one used in a full-scale MBR. Reduction in SADₘ is likely to be possible by increasing the vertical length of the membrane fiber (Miyoshi et al. 2018). The air-flow rate of biology aeration was controlled so that the average DO concentration in the interior zone of the baffle becomes approximately 2.0 mg/L.

**Influence of separation and recirculation duration on treated water quality**

In the pilot-scale B-MBR apparatus used in this study, the water level was controlled by the water level sensors located at highest and lowest water levels during the operation. Therefore, the highest and lowest water levels can be altered by changing the location of the corresponding water sensors. In this study, the distance between the two water sensors was fixed to avoid the changes in operation time per one cycle (OTPC) during the experiment. In this experiment, the OTPC was in the range of 16–18 min. This range of OTPC was reported to be suitable for nitrogen removal in the previous publication (Kimura et al. 2008a). Then, the locations of the water level sensors were vertically altered to change the ratio of recirculation and separation periods in one operation cycle; the time of recirculation increased when the water level sensors were set at higher positions. In this study, the ratio between recirculation and separation times is expressed as the fraction of recirculation time, which is defined as the time accounted for the recirculation period divided by the OTPC of the corresponding operation cycle. Altering the fraction of recirculation time by changing the location of highest and lowest water levels also caused a change in HRT. However, the difference in the HRT in the experimental conditions examined in this study was less than 0.5%, and therefore is thought to be negligible.
Table 1 lists the operating conditions of the pilot-scale B-MBR. In Table 1, the average DO concentration in the interior zone of the baffle and the average air-flow rate of biology aeration in each run are also presented. In this study, we operated the pilot-scale B-MBR under two different fractions of recirculation time. This experiment was performed from 13th June to 25th June. Before the initiation of this experiment, the pilot-scale B-MBR was continuously operated under the same HRT and SRT for more than 2 months, and therefore, it can be judged that the acclimatization of biomass was completed at the beginning of this experiment. Irrespective of the fraction of recirculation time, we attempted to maintain the average DO concentration at a constant level. As a result, the air-flow rates of biology aeration were different between the two runs performed in this study. Each run was carried out for 1 week, and the feed water and treated water were taken and analysed three times in each run. The samples of both feed and treated waters were collected as composite samples of 24 hours, taking the diurnal fluctuation in the wastewater into account.

### Tracer test

To evaluate the mixing state in the B-MBR tank, we performed a tracer test. In this test, NaCl was introduced in the interior zone of the baffles slightly before the initiation of feed water supply. Then the changes in electrical conductivity were recorded at five points in the reactor. Two of the five points were selected from the interior zone of the baffles (shallow and deep depths), and the other points were selected from the exterior zone, at the same place as Points A to C in Figure 2 (at the middle depth). The electrical conductivity was recorded for one B-MBR cycle (i.e., from one initiation of the feed water supply to the next one). Based on the change in electrical conductivity at each point, the time required for reaching complete mixing of the B-MBR was evaluated.

### Analytical methods

The biochemical oxygen demand (BOD) and the concentrations of total nitrogen (T-N), ammonium-nitrogen (NH₄⁺-N), and total phosphorus (T-P) were measured in accordance with the Japanese standard method ([Japan Sewage Works Association](https://www.jswa.or.jp)). Luminescent DO meters (HD-200FL equipped with DO-2000, Horiba, Kyoto, Japan, and HQ40d, Hach, Loveland, CO, USA) were used for the measurement of DO concentration in the pilot-scale B-MBR apparatus. The DO profiles were measured at four different points in the pilot-scale B-MBR apparatus: one point is in the interior zone of the baffles and the others are different positions in the exterior zone of the baffles (Figure 2). Because the interior zone of the baffles is rigorously mixed by the aeration, only one DO sensor was set for measuring the DO profile in the interior zone. On the other hand, it was expected that the DO profiles in the exterior zone of the baffles had great spatial distribution since no external mixing force was applied during the separation period. Therefore, the DO profiles at the three points located in the exterior zone of the baffle (i.e., Points A–C) were measured at three different depths simultaneously (i.e., 0.5, 1.0, and 1.5 m below the top of the baffles).

### RESULTS AND DISCUSSION

#### Development of membrane fouling

In the continuous operation of the pilot-scale B-MBR, the development of membrane fouling was not severe; the increase in trans-membrane pressure in the two membrane units were 4 and 6 kPa during the 2 weeks of operation. This insignificant membrane fouling would be partially

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**Table 1**

<table>
<thead>
<tr>
<th>Operating conditions of pilot-scale B-MBR.</th>
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</thead>
<tbody>
<tr>
<td>Run 1</td>
</tr>
<tr>
<td>Fraction of recirculation time</td>
</tr>
<tr>
<td>DO concentration in interior zone of baffle</td>
</tr>
<tr>
<td>Air-flow rate of biology aeration</td>
</tr>
<tr>
<td>pH (feed water) (n = 2)</td>
</tr>
<tr>
<td>pH (treated water) (n = 2)</td>
</tr>
<tr>
<td>Temperature (feed water) (n = 2)</td>
</tr>
<tr>
<td>Temperature (treated water) (n = 2)</td>
</tr>
</tbody>
</table>

*aAverage value of each experimental period.*
due to low membrane fluxes adopted in the continuous operation. The development of membrane fouling can be significantly mitigated by decreasing membrane flux during the continuous operation (Kimura et al., 2008b; Miyoshi et al., 2013). It should be noticed here that the pilot-scale B-MBR was operated without any maintenance cleaning (e.g., chemically enhanced backwashing). As reported in our previous study, the membrane used in this study is capable of being operated under higher membrane fluxes (i.e., 0.5–0.6 m³/(m² d) as net flux) when appropriate maintenance cleaning is applied (Miyoshi et al., 2018).

Treated water quality of pilot-scale B-MBR

Figure 3 shows the changes in water quality indices during the pilot-scale experiment. The average values in each run are also summarized in Table 2. The concentrations of each constituent in the feed water were consistently lower in Run 2. This difference was attributed to the rainfall in Run 2; as mentioned above, the wastewater treatment plant is connected to a combined sewer system. In both runs, BOD was removed very well. The average BOD in the treated water in these two runs was comparable to those found in the typical full-scale MBRs which are already in operation in Japan; most of them are operated with a biological process with the modified Ludzack–Ettinger (MLE) process (Itokawa et al., 2014). This result suggests that the BOD removal capacity of the B-MBR is at least comparable to that of the MBR with MLE process. With regard to the nitrogen removal, the B-MBR operated in this study also exhibited excellent removal efficiency. In both runs, the T-N concentration in the treated water was less than 5 mg/L. Taking into account the regulation on the treated water from the MBR with recycled nitrification/denitrification process in Japan (less than 10 mg/L), the results of this pilot-testing also revealed that the B-MBR can satisfy

Table 2  | Qualities of feed and treated water of B-MBR. units are mg/L.

<table>
<thead>
<tr>
<th>Run 1 (n = 3)</th>
<th>BOD</th>
<th>T-N</th>
<th>NH₄-N</th>
<th>T-P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed water</td>
<td>125.6 ± 20.3</td>
<td>26.3 ± 4.7</td>
<td>15.7 ± 3.2</td>
<td>2.7 ± 0.4</td>
</tr>
<tr>
<td>Treated water</td>
<td>1.9 ± 0.8</td>
<td>2.7 ± 1.2</td>
<td>0.6 ± 0.4</td>
<td>0.1 ± 0.0</td>
</tr>
<tr>
<td>Run 2 (n = 3)</td>
<td>Feed water</td>
<td>90.6 ± 25.5</td>
<td>18.3 ± 6.8</td>
<td>11.0 ± 7.0</td>
</tr>
<tr>
<td>Treated water</td>
<td>0.9 ± 0.6</td>
<td>3.0 ± 1.8</td>
<td>0.1 ± 0.0</td>
<td>0.3 ± 0.3</td>
</tr>
</tbody>
</table>

Values are given ± standard deviation.
the requirement for nitrogen removal. In nitrogen removal, nitrification was likely to be completed because only a small amount of NH$_4^+$-N was detected in the treated water of the B-MBR. This result indicates that the denitrification reaction is the rate-limiting step in the nitrogen removal of the B-MBR. In the pilot-scale B-MBR apparatus operated in this study, phosphorus was also removed well. In the Japanese regulation on the treated water quality of MBRs, a target of less than 0.5 mg/L (set as maximum value of dairy-averaged concentration) is set for the MBR with recycled nitrification/denitrification process with coagulant dose. The T-P concentrations in treated water of the B-MBR in Run 1 satisfied the requirement mentioned above. On the other hand, in Run 2, the T-P concentration in the treated water once exceeded 0.5 mg/L. These results suggest that the operating conditions adopted in Run 1 were more suitable for phosphorus removal than those in Run 2. In the previous study reported by Kimura et al. (2008a), it was suggested that enhanced biological phosphorus removal may partially account for the enhanced phosphorus removal in the B-MBR. Although the detailed mechanisms by which the efficient phosphorus removal was achieved have yet to be elucidated for the pilot-scale B-MBR used in the current experiment, it is expected that such enhanced phosphorus removal also played a role in the phosphorus removal in the B-MBR found in the present study. It can also be suggested that the B-MBR is capable of satisfying the regulation on phosphorus removal without the coagulant dosages as long as appropriate operating conditions are selected. The treated water qualities achieved in this experiment were generally in accordance with the results reported in the previous publication (Kimura et al. 2008a).

By comparing the results of these two runs, it can be seen that the BOD in the treated water was lower in Run 2, which is in accordance with the BOD load to the B-MBR in each period. On the other hand, the removal efficiencies of T-N and T-P in Run 2 were lower than those in Run 1; the concentrations of T-N and T-P in the treated water in Run 2 were higher than those in Run 1 despite the concentrations of these items in feed water being lower in Run 2. For nitrogen removal, sufficient recirculation is indispensable for transferring nitrate formed in the interior zone of the baffle (aerobic zone) to the exterior zone (anoxic zone). However, during the recirculation, DO supplied in the interior zone is also transferred to the exterior zone. If the excess DO is supplied to the exterior zone, the denitrification process deteriorates due to the elevated DO concentration or excess consumption of BOD in the oxidation/reduction reaction in which oxygen is used as the electron acceptor. The excess introduction of DO into the exterior zone (anoxic zone) may also have adverse effect on phosphorus removal if the elevated phosphorus removal in B-MBR is associated with a biological phosphorus removal, as suggested in the previous study (Kimura et al. 2008a). To investigate the reasons for the differences in treatment performance in the two runs, the profiles of DO concentrations at different positions of the reactor were measured.

**Profiles of DO concentration in pilot-scale B-MBR**

Figures 4 and 5 show the profiles of DO concentration at different positions of the pilot-scale B-MBR apparatus in Runs 1 and 2, respectively. In Run 1, although the DO concentration in the interior zone of the baffle had a significant time-course variation, the increases in DO concentration in the exterior zone were marginal irrespective of the horizontal position (i.e., Points A–C). Especially, the DO concentrations at the middle or deep points (i.e., 1.0 and 1.5 m from the top of the baffle) were less than 0.2 mg/L throughout the operating cycle. This result indicates that an anoxic condition suitable for denitrification was successfully created in Run 1, which is in accordance with the excellent nitrogen removal found in this run. On the other hand, in Run 2, the DO concentrations in the exterior zones increased in accordance with the profile of DO concentration in the interior zone of the baffles. At the shallow point (i.e., 0.5 m from the top of the baffle), the DO concentrations in the exterior zones became almost equal to that in the interior zone. At the Point A, even the DO concentration at the middle point also reached the same level to that in the interior zone. A similar, but less pronounced, profile was also seen in the DO profile determined at the middle point of Point C. Despite such significant increases in the DO concentrations at shallow or middle points, the DO concentrations at deep points were stable, and did not exceed 0.4 mg/L throughout the operation cycle. This result suggests that, despite the intensive mixing caused by the prolonged recirculation period, the anoxic condition was continuously created at the bottom of the reactor. As mentioned previously, as well as in Run 1, T-N was effectively removed in Run 2 (Table 2). These results suggest that, although the volume of anoxic zone suitable for denitrification in Run 2 was greatly reduced compared with that in Run 1, the B-MBR still had a sufficient capacity to promote denitrification. Therefore, it can be said that effective removal of nitrogen by the B-MBR can be achieved in a relatively wide range of fraction of recirculation time.
Figure 4 | DO profile measured in Run 1. Values of lengths provided in legends indicate depth from top of baffles.

Figure 5 | DO profile measured in Run 2. Values of lengths provided in legends indicate depth from top of baffles.
Because the exterior zone of the baffle is utilized for denitrification, excess introduction of DO should be avoided. Therefore, the increase in DO concentration in the exterior zone during the recirculation period is not desirable, and would be a heavy burden from the viewpoints of both denitrification and cost associated with aeration; the introduction of DO into the exterior zone results in undesirable consumptions of BOD to be used for denitrification and the DO itself to be used for nitrification. Indeed, the rate of biology aeration required for achieving comparable treated water quality was apparently higher in Run 2 (Table 1). Based on our brief estimation on electrical power consumption assuming a hypothetical full-scale wastewater treatment plant with a treatment capacity of 7,000 m³/d (the effective water depth in this treatment plant was set at 5 m), it is suggested that the operating conditions adopted in Run 2 result in approximately 0.1 kWh/m³ higher specific energy consumption than those in Run 1. In this estimation, we assumed that the masses of oxygen required for a unit of BOD determined in the two runs of the pilot-scale experiment are fixed in the hypothetical full-scale treatment plant, and the energy consumptions in each operation were evaluated based on calculating shaft power. Taking the nitrogen removal efficiency in Run 1 (approximately 88.9%) into consideration, the operating conditions of the B-MBR in Run 1 correspond to the recirculation ratio of 6 in the MLE process, even though the fraction of recirculation time is smaller in this run. The results of tracer testing in the MLE process, even though the fraction of recirculation time is approximately 4 minutes after the initiation of recirculation. Therefore, it is suggested that complete mixing of the B-MBR tank was achieved during the recirculation period in both runs. This information is thought to be important for further optimization of the operating conditions of the B-MBR.

CONCLUSION

In this study, we investigated the effect of recirculation and separation durations on the removal of BOD, nitrogen, and phosphorus by a B-MBR. A pilot-scale B-MBR was operated under different fraction of recirculation time. The results of the pilot-scale testing revealed that the BOD was well removed irrespective of the fraction of recirculation time. With regard to the nitrogen removal, although a tiny decrease in removal efficiency was seen by increasing fraction of recirculation time, T-N concentration in the treated water of the B-MBR satisfied the requirement for the recirculated MBR, irrespective of operating conditions. Phosphorus was also well removed by the B-MBR, but did not satisfy the requirement for recirculated MBR with coagulation addition, when the B-MBR was operated under long time fraction of recirculation. The results obtained in this study indicate that appropriate selection of recirculation is important for efficient use of a B-MBR.

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