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Waste sludge reduction with a pilot-scale membrane bioreactor for point source pollution management

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ABSTRACT

It is an important subject to reduce the amount of waste sludge from small-/middle-scale wastewater facilities for the establishment of point source pollution management. In this work, we focused on the development of sludge decomposition system which did not increase organic loading ratio into wastewater treatment units. The excess sludge produced from wastewater treatment plant of a food factory was decomposed by an aerobic digestion technology with a membrane bioreactor (MBR) system. It was composed of digestion tank (500 L) and a membrane filtration unit (350 L). Sludge was decomposed under the following conditions: 25 g L^{-1} of MLSS, 36.9 d of HRT, average temperature 32.3°C, and 0.565 kg-SS m^{-3} d^{-1} of sludge loading rate. The system decomposed 77.2% of the fed sludge to inorganic carbon, and all of average TOC, COD_{Mn} and COD_{Cr} in the effluent were less than 50 mg L^{-1}. However, the effluent contained T–N and T–P at 200 mg N L^{-1} and 150 mg-P L^{-1}, respectively. The quinone profile analysis indicated that the consortia of sludge in the reactor were different from the fed sludge.

Keywords: Excess sludge; Aerobic digestion; Membrane bioreactor; Quinone profile

1. Introduction

In order to protect the water quality of watershed, the point source as well as nonpoint source control is inevitable. Among them, the disposal of waste sludge from the sewage treatment plant can be an important role in the water quality management.

As organic wastewater is generally treated by activated sludge process, and large amounts of excess

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sludge having solids contents of about 1–4% are also produced as by-product. As a result, excess sludge contains considerable volume of water with organic materials, which are causing economic problems of vast magnitude including transportation and final storage/disposal [1,2]. Disposing excess sludge is an important issue for the employment of biological treatment process.

Sewage system is too costly to be operated in Japanese rural area, and on-site small-/middle-scale wastewater biological treatment facility called as Johkasou system is being operated instead. The capacity of Johkasou is 5–1,000 $m^3 day^{-1}$, and it is able to be installed into a narrow space. A lot of Johkasou systems include nitrogen removal processes, and membrane bioreactor (MBR) for Johkasou is also being developed for the reason. The treatment of excess sludge is still difficult and important problem in Johkasou. Normally, the excess sludge of sewage system was treated by methane fermentation or composting, although they need large operation area. Excess sludge from Johkasou is treated by night soil treatment facilities, where the transportation energy is required, and it causes the reduction of night soil treatment facilities.

Sludge reduction processes for Johkasou have already been developed, and it can be categorized as follows: (a) mechanical methods such as milling [3] or ultrasonic [4]; (b) oxidation with ozone [5]; chlorine [6] or fenton oxidation [7]; (c) thermophilic aerobic bacteria [8]; and (d) enzyme decomposition [9]. These processes have to be combined into wastewater process. Excess sludge was dissolved into these processes, and dissolved excess sludge was returned to aerobic tank, where the problem such as high cost, frequent maintenance, and the increase of loading rate may be caused.

Sludge digestion process with continuous aeration is simple, and water quality of treated water is better than other sludge reduction processes enough to be released directly into the water environment.

MBR separates biomass satisfactorily from mixed liquors using microfiltration (MF) or ultrafiltration membrane, where slow growth rate of microorganism which treats persistent organic matters is able to be kept longer. In recent, thus, MBR is also of use to reduce excess sludge [10] because this system can reduce up to 28–68% depending on the SRT control [11]. Previous works reported the aerobic digestion for excess sludge decomposition system with high-performance separation unit. [11,12]. Aerobic sludge digestion for household size Johkasou (1–2 $m^2 day^{-1}$) was also reported [13].

In addition, the microbial approach for the analysis of MBR operation is being reported [14], and quinone profile is an analytical method for understanding microorganism community structure. It is able to perform quantitatively analysis method typified by activated sludge [15].

In this study, a pilot-scale MBR was employed for the reduction of excess sludge. This work focused on the following points: the sludge reduction ratio, water quality of effluent, sludge separation under high concentration of MLSS, and change of microbial community between retained sludge in MBR and fed sludge.

2. Materials and method

2.1. Reactor

The reactor was set up of two tanks, which are digestion tank and filtration (membrane) tank. The digestion tank is cylinder form (working volume: 500 L) and the filtration tank is cubic form (working volume: 350 L). MF membrane (pore size: 0.4 μm, working area: 0.8 m^2, structure: panel type, material: chlorinated polyethylene) which is made by Kubota was installed in the filtration tank. The reactor is shown in Fig. 1. The sludge in the digestion tank was pumped to the filtration tank, and the sludge in the filtration tank was returned to the digestion tank through the overflow tube. MF membrane was set sideways and was continuously washed by air bubble. The diffuser tube was installed at the bottom of the digestion tank. DO is kept more than 2 mg L^{-1} without period of aeration trouble. The filtration interval was intermittently controlled between 3 min on and 2 min off. Membrane was not flushed by chemicals during the experiment period, and pH of the reactor was not controlled.

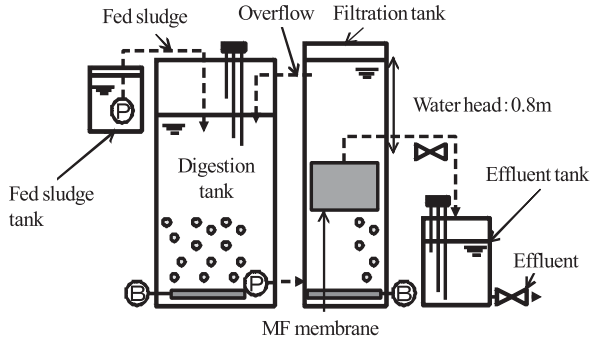

Fig. 1. Schematic of pilot-scale MBR.

Table 1
Experimental conditions of pilot-scale membrane bioreactor

Run	1	2	3
Operation period (d)	37 (0–36)	36 (51–86)	52 (93–144)
HRT (d)	36.9	33.0	39.8
Water temperature (℃)	32.3	38.1	29.9
Volumetric loading ratio ($kg\,m^{-3}\,d^{-1}$)	0.565	0.539	0.483
SS loading ratio ($kg\,kg^{-1}\,d^{-1}$)	0.020	0.019	0.016
Concentration of fed sludge ($g\,L^{-1}$)	18.2 (15.0–20.2)	15.7 (14.6–18.1)	15.1 (10.4–24.6)

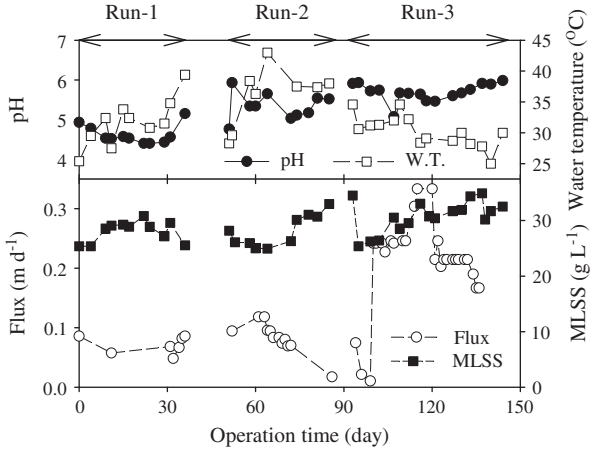

Fig. 2. Relationship between water flux and MLSS considering pH water temperature vs. operation time.

2.2. Sludge reduction performance

The excess sludge was obtained from food factory wastewater treatment plant (conventional activated sludge process), where the returned sludge was fed into the reactor directly. The fed sludge was high concentration of MLSS (15–22 $g\,L^{-1}$) and VSS/SS rate was also high (85–90%). The treatment of excess sludge was performed as following sequence: (1) aerobic digested sludge was inoculated into the digestion tank for the first time. (2) Fed sludge was added on the basis of total volume considering filtration volume and evaporation volume. (3) Filtration was performed by the water head difference of 0.8 m-H_2O between the water level in the filtration tank and the effluent port of membrane. (4) Total filtrate was withdrawn by water level in the effluent tank. Detailed operating conditions were summarized in Table 1. In 36th and 86th day, diffuser was blocked up. In the period from 37th to 50th day and 87th to 92nd day, experiment was stopped for the maintenance.

Water qualities of the effluent were analyzed by the JIS [16] and the US standard methods [17]. Quinone profile for the detection of microbial community structure was analyzed by SFE-CO_2 method, which was suggested by Irvan [18]. Phosphorus content ratio in biomass was detected by molybdenum blue method with potassium peroxydisulfate pretreatment. Carbon and nitrogen content ratio in biomass was detected by an element analyzer (EA-1108, FISONS).

3. Results and discussion

3.1. Filtration properties

Solid/liquid separation is the most important process for biological water treatment system. In this reactor, the separation was carried out through the sieving effect of MF membrane, and then, water flux was also influenced by the fouling of membrane surface. In a previous work, the pH in aerobic digestion bioreactor was decreased to a rather low value about 4.0 without pH control [11,12]. pH in the reactor affected the filtration performance, and low pH condition was better than neutral and alkali conditions in the view point of keeping stable water flux during the operation [11]. Water flux was also correlated with pH value for this work, and low pH may little inhibit the reduction of excess sludge. Water flux, MLSS, water temperature, and pH of the reactor were shown in Fig. 2. Water flux of Run-1 and Run-2 was about 0.08 $m\,d^{-1}$. Normally, water flux is 1.0 $m\,d^{-1}$ in MBR. Although it is a half filtration force, the water flux is too low. The reason was the location of MF membrane. In this study, MF membrane was installed sideway. The air was accumulated in the membrane. The part of air accumulation was not able to be filtered. In the 90th day, as the accumulated air in membrane was removed, and water flux was increased up to 0.2 $m\,d^{-1}$. It is expected that true water flux was better than the value of observed data.

pH in the reactor was increased 4.5–6.0 in Run-1. pH was increased during the period of aeration trouble. It was caused by the denitrification or sulfate reduction. Water temperature was high and ranged 25 to 40℃.

3.2. Sludge reduction

Profiles of MLSS concentration, VSS/SS ratio of reactor and fed sludge were shown in Fig. 3. The profiles of measured MLSS and calculated MLSS were

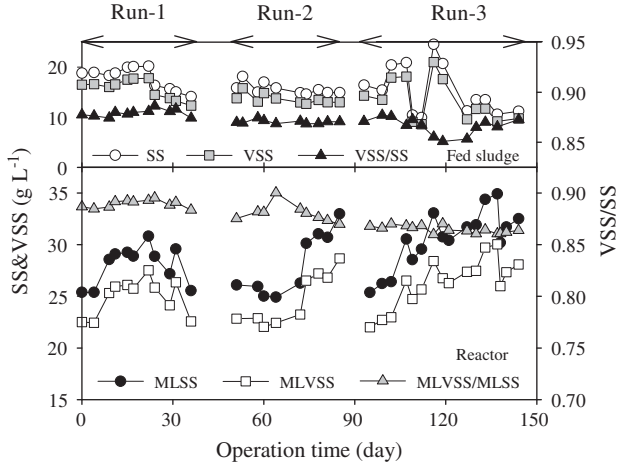

Fig. 3. Profiles of concentration of SS and VSS and VSS/SS ratio vs. operation time.

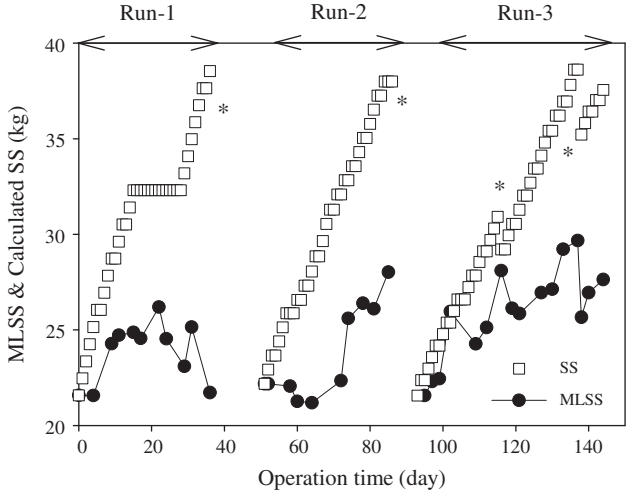

Fig. 4. Variation of sludge weight in the reactor and calculated SS vs. operation time.

shown in Fig. 4. Calculated MLSS was obtained on the basis of total sum of initial MLSS and fed sludge weight during the time. The excess sludge was drained at the proper time shown as the symbol (*) in Fig. 4. Since the excess sludge without pretreatment was directly provided from the treatment plant to be used as substrate at the digestion tank, the excess sludge cannot be separated from the digested sludge. Thus, SRT is hardly considered for this work.

It was operated at the same MLSS concentration range of previous work [11,12]. MLVSS/MLSS ratio and VSS/SS ratio of fed sludge were decreased, and they were influenced by fed sludge. It was operated with long HRT because the concentration of fed sludge was very high. It was considered that the microorganism with aerobic digestion was shown low growth rate. When the sludge of aerobic digestion was drained, the activity of sludge digestion was decreased and indicated that it had to be operated at an appropriate loading rate. During the period of 70th to 110th day, it showed the similar trend at both measured and calculated MLSS, and the sludge was not fully decomposed. From the period of 54th to 70th day, sludge reduction was stable, but after that it was deteriorated. It was the reason that water temperature was above 40˚C. It was influenced by the microbial community of aerobic digestion sludge with high water temperature. As it has been generally observed that temperature play an important role in the operation of aerobic digestion, sludge reduction was also influenced by the variation of temperature.

In Run-3, water temperature was decreased and became stable. In our previous works [11,12], the stabilization period of sludge reduction performance required about 1 to 2 month. The sludge reduction performance of Run-3 was not recovered in a short period, and it indicated the change of microbial community from water temperature.

The sludge reduction ratio was shown in Table 2. The sludge reduction (R_{SS}) ratio was calculated according to the following (see Tables 3–5):

$$R_{SS}\ (\%) = \left(\frac{SS_f - SS_a - SS_s - SS_w}{SS_f}\right) \times 100 \qquad (1)$$

"SS_a" is sludge accumulation weight in the reactor. "SS_s" is total sludge weight of sampling; the measurement of MLSS, Quinone profile and element analysis. "SS_w" is withdrawn sludge weight for MLSS control. "SS_f" is the fed sludge weight. In Run-1, the sludge reduction ratio was obtained 77.2% when the loading ratio was 0.565 kg-SS m^{-3} d^{-1}. In Run-2, the sludge reduction ratio dropped to 63.9% because of high water temperature in the reactor. The high water temperature in the reactor was influenced by sunlight and ambient temperature, which affected the wastewater treatment facility simultaneously because the facility treated wastewater with high temperature. It was shown that the excess sludge with this process was reduced effectively considering less than 50% with conventional aerobic sludge digestion process.

3.3. Effluent quality and material balance

Profiles of effluent TOC, COD_{Cr}, $COD_{Mn,}$ and colority were shown in Fig. 5. The reduced excess sludge became solved component once. COD_{Cr} of sludge is about 1,000 mg g^{-1}, but COD_{Cr} in the effluent was low.

Table 2
Monitoring of sludge contents in the reactor and summary of sludge reduction rate

Run	SS_f (kg)	SS_a (kg)	SS_s (kg)	SS_w (kg)	R_{SS} (%)
1	16.9	3.54	0.284	0	77.2
2	16.2	5.59	0.277	0	63.9
3	18.6	6.71	0.210	3.72	42.9

Table 3
Monitoring of sludge contents in the reactor and summary of carbon reduction rate

Run	C_f (g)	C_a (g)	C_s (g)	C_w (g)	C_e (g)	R_C (%)
1	7,009	1,514	120	0	20.2	76.4
2	6,781	2,459	123	0	17.3	61.7
3	7,545	2,847	198	1,595	17.6	38.3

Table 4
Monitoring of sludge contents in the reactor and summary of nitrogen reduction rate

Run	N_f (g)	N_a (g)	N_s (g)	N_w (g)	N_e (g)	R_N (%)
1	1,173	200	21.0	0	124	70.6
2	1,084	328	17.6	0	72.8	61.4
3	1,282	428	34.5	244	64.4	39.9

Table 5
Monitoring of sludge contents in the reactor and summary of phosphorus recovery rate

Run	P_f (g)	P_a (g)	P_s (g)	P_w (g)	P_e (g)	Re_P (%)
1	244	113	3.54	0	89	84.2
2	256	100	5.59	0	85	74.4
3	278	77	5.67	58.3	94	84.5

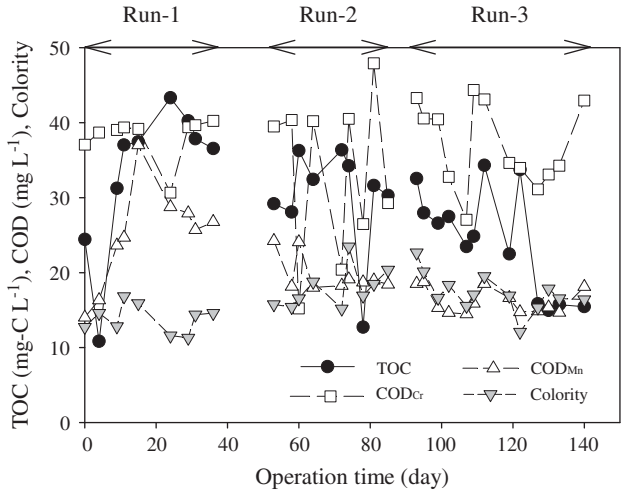

Fig. 5. Plots of TOC, COD, and colority of the effluent vs. operation time.

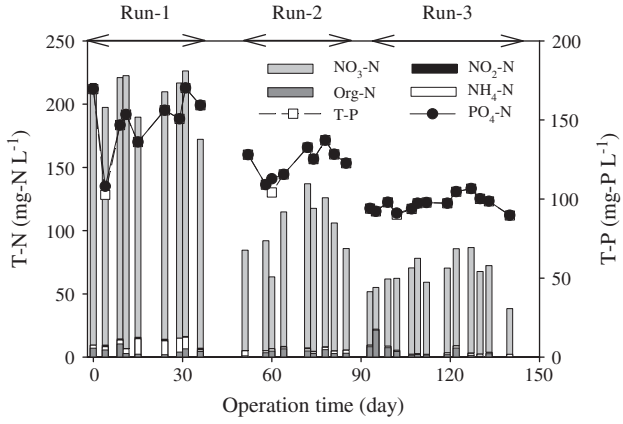

Fig. 6. Plots of T-N component and T-P of the effluent vs. operation time.

COD_{Cr} and COD_{Mn} showed the similar removal trend and indicated that the substance in the effluent was not persistent. The colority of the effluent was very low, and it was not detected by visual evaluation.

Profiles of total nitrogen (T-N) including organic nitrogen (Org-N), ammonium (NH_4-N), nitrite (NO_2-N) and nitrate (NO_3-N), and total phosphorus (T-P) of the effluent were shown in Fig. 6. Organic nitrogen and nitrite was detected little and NH_4-N was less than 5 mg L^{-1}, where NO_3-N accounted for a large fraction of T-N, and which indicated that nitrogen derived from decomposed sludge was effectively nitrified. From the experimental results, it can be concluded that MBR is an effective system for the reduction of sludge volume considering that the microbes are aerobically oxidized. NO_3-N in Run-1 was very high concentration (larger than 200 mg L^{-1}), but it was decreased in Run-2. It was the reason that denitrification was rapidly occurred in the period of aeration trouble with the absence of oxygen. T-P was high concentration in the all experimental periods (60–130 mg L^{-1}). Phosphate (PO_4-P) was almost equal to T-P. T-N and T-P were very high concentration. In order to discharge the effluent into water environment from this system, further treatment process is required.

Carbon reduction ratio (R_C) and nitrogen reduction ratio (R_N), phosphorus recovery ratio (Re_P) were calculated according to the following:

$$R_C\ (\%) = \left(\frac{C_f - C_a - C_s - C_w - C_e}{C_f}\right) \times 100 \quad (2)$$

$$R_N\ (\%) = \left(\frac{N_f - N_a - N_s - N_w - N_e}{N_f}\right) \times 100 \quad (3)$$

$$R_P\ (\%) = \left(\frac{P_f - P_a - P_s - P_w - P_e}{P_f}\right) \times 100 \quad (4)$$

Most terms were referred by Section 3.2. C_e and N_e, P_e are dissolved components in the effluent, and others were included both dissolved and suspended component.

Carbon reduction ratio was the same value as sludge reduction ratio. Carbon that was derived by decomposed sludge was mineralized. Nitrogen removal ratio was lower than carbon. Denitrification was limited by the lack of electron donor such as organic materials. Low phosphorus recovery ratio was caused by the circulation in this work, which was detected in the shortage of stirrer located in the bottom of reactor.

3.4. Microbial community structure

Since microbial respiratory quinines are components of bacterial respiratory chains as the electron transfer during the bacterial respiration, some works have reported [19,20] that the changes in a microbial community of microbes could be analyzed by the method of quinine profiles, and this study has also quantified the quinones.

Fig. 7 shows the profiles of the quinone content ratio, total amount of quinone and the dissimilarity index. Results were very different in each period. Analytical samples for quinone profile were collected in the end of each period. The dissimilarity index of sludge in the reactor was compared with fed sludge. Dissimilarity index (D) was calculated according to the follows [15]:

$$D(i,j) = \frac{1}{2}\sum_{k-1}^{p}(X_{ki} - X_{kj}) \quad (5)$$

Quinone profile of the fed sludge was constant, and the dissimilarity index of fed sludge in each period was low. In Run-1, total amount of quinone in the reactor and dissimilarity index were less than the others. It was shown that aerobic digestion microorganism was cultured in Run-1, and microbial structure was different between Run-1 and others.

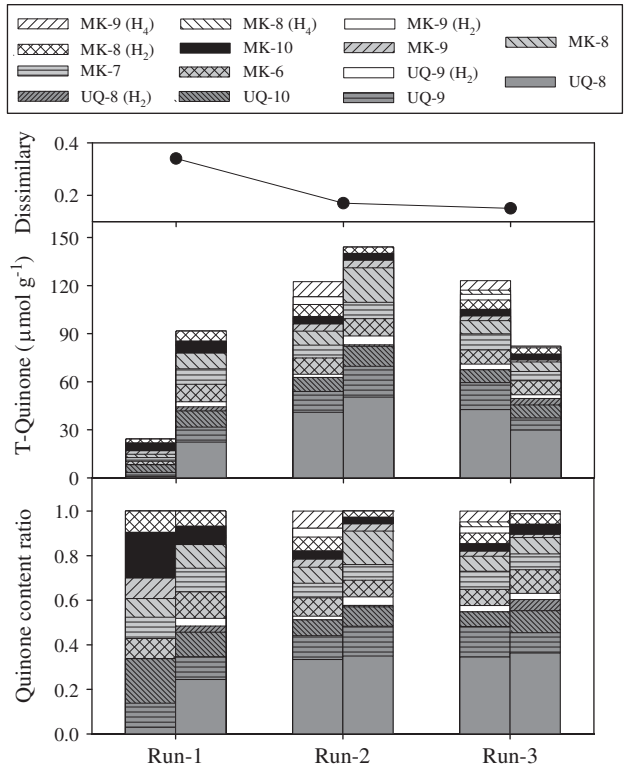

Fig. 7. The changes of quinone profiles and dissimilarity index (analytical samples for each period were collected at 36th day, 86th day, and 144th day, respectively).

In this study, MK/UQ ratio of aerobic digestion sludge was 0.74–1.96 and the proportion of menaquinone was higher than ubiquinone. Menaquinone contained anaerobic microorganism. For the experimental condition, MK is higher than UQ in the reactor, although the collected sludges were kept aerobic condition without trouble period. The neighborhood of microorganisms became anaerobic condition because it was kept high concentration of MLSS in the reactor. It was the reason that nitrogen was removed under continuous aeration condition.

4. Conclusions

Pilot-scale MBR was developed to reduce excess sludge. Fed sludge was decomposed approximately 77%, when the loading rate was $0.565\,kg\,m^{-3}\,d^{-1}$. The concentration of organic pollutants and colority was low, and sludge reduction rate was the same as the carbon reduction rate. Nitrogen from sludge decomposition was removed 90%, but nitrogen concentration was too high to be discharged into water environment directly. The phosphorus concentration was high, besides. The sludge decomposition performance was

not constant in our works, and quinone profile was changed in each period. It requires more efforts to find other factors for sludge reduction performance.

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