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Treatment of poultry slaughterhouse wastewater using a membrane process, water reuse, and economic analysis

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ABSTRACT

Poultry slaughterhouse wastewater, which represents one of the most important pollutants in Turkey, is generally treated with conventional biological processes in Turkey and around the world. In this study, poultry slaughterhouse wastewater was treated using laboratory-scale membrane processes, which were substituted for conventional processes. The performances of the membrane processes were investigated in terms of chemical oxygen demand (COD), conductivity, and membrane fluxes. Economic analyses were conducted for several membrane system alternatives. In addition, the alternatives were compared with each other and with conventional economic analysis of the data obtained in this study and data from several previous studies. The membranes used for the membrane processes were AG for reverse osmosis (RO), DK for nanofiltration (NF), and ER for ultrafiltration (UF). The highest COD removal efficiencies were 90% for NF and 97.4% for RO, and the conductivities decreased by 51.7% for NF and 96.6% for RO. When the (UF) was not used, the long-term membrane fluxes of the RO and (NF) sharply decreased, which increased the operation costs of these processes. Therefore, RO and NF without pre-treatment and with UF were not effective for this wastewater. According to the economic analysis results, the operational costs of the RO and NF after UF, the UF alone, and the conventional treatment process were 0.66, 0.70, 0.79, and 1.66 $/m^3$, respectively. Because the operational cost of the conventional treatment process was 2.5 times greater than RO after pre-treatment with UF, it was deduced that this membrane process combination was a suitable treatment alternative for treating poultry slaughterhouse wastewater.

Keywords: Poultry slaughterhouse wastewater; Ultrafiltration; Nanofiltration; Reverse osmosis; Economic analysis

1. Introduction

Poultry production is an extremely important industry in Turkey. In 2005, approximately one million tons of poultry meat was produced in Turkey, and 81 million tons was produced worldwide. The total capacity of slaughterhouses in Turkey is approximately 4.5 thousand tons per day and approximately 1.4 million tons annually [1]. The poultry industry requires a high volume of water for cleaning and

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plucking the birds. The water remaining after the cleaning processes is termed poultry slaughterhouse wastewater and contains high amounts of protein and fats. Although poultry slaughterhouse wastewater is discharged into the environment or sewer systems after treatment, the solid matter and fats obtained during the treatment process are converted to poultry feed after the rendering process.

The wastewater volume is related to the slaughter process and could differ at each plant [1]. According to a study performed in Portugal, the average wastewater volume from eight poultry plants was between 8.3 and 13.8 m^3/bird [2]. However, another study reported an average volume of 26.5 L/bird [3]. The percent distributions of water use at poultry slaughterhouses are 5% at the ice plant, 62% during the production process, 2% for boilers, 9% for industrial cleaning, 6% for washing the boxes, 3% for washing the cages, 8% for the cooling towers, 1% for freezing the cooling tunnel and storage chambers, and 4% for personal hygiene [4].

Poultry slaughterhouse wastewater is a medium-strength wastewater because of its high chemical oxygen demand (COD) and high protein and fat contents. In addition, the wastewater characteristics and volume are related to the slaughter process and might differ for each plant. Poultry slaughterhouse wastewater is treated using a conventional biological-activated sludge process after the dissolved air flotation (DAF) process [2]. The same treatment combination is used in Turkey. However, different treatment alternatives have been used to treat poultry slaughterhouse wastewater and are reported in the literature. Several authors have studied poultry slaughterhouse wastewater treatment using electrocoagulation [5–9], anaerobic treatment [10–17], ultrafiltration (UF) [3], and DAF processes [18].

Additionally, studies have been conducted regarding different issues resulting from wastewater treatment, including hydrogen production from poultry slaughterhouse wastewater through biological [19] and microwave [20] processes, which were used to obtain the flocculation [21] and growth of *Rubrivivax gelatinosus* [22].

This study aimed to examine a new and economic alternative that can be used rather than conventional treatment processes for treating poultry slaughterhouse wastewater. Thus, the UF was implemented using the ER membrane nanofiltration (NF) process with a DK membrane and the reverse osmosis process (RO) with an AG membrane to treat poultry slaughterhouse wastewater. The centrifuge process was applied as a pre-treatment before all of the membrane experiments. After the centrifuge process, the NF and RO experiments were performed in two ways (i.e. with and without pre-treatment and with UF). An economic analysis was performed using the data from six different alternatives, the conventional UF-only, NF-only, RO-only, UF + NF, and UF + RO treatment processes.

2. Materials and methods

2.1. Analyses

The wastewater sample was obtained from a large slaughterhouse in Sakarya, Turkey, and stored at 4°C in a refrigerator. The COD, total suspended solids (TSS), volatile suspended solids (VSS), pH, and conductivity analyses were measured to characterize the wastewater. All of the analyses were carried out according to the standard methods [23]. The characterization of the poultry slaughterhouse wastewater is shown in Table 1.

2.2. Pre-treatment studies

All of the samples were centrifuged for 10 min at 3,750 rpm as a pre-treatment step before the membrane experiments using an Allegra X12 centrifuge (Beckman Coulter, Inc., Brea, CA, USA). The COD and TSS concentrations in the wastewater after centrifuging were approximately 1,200 and 200 mg/L, respectively. Some experiments using NF and RO were performed after UF in addition to the centrifuging process. When the COD concentration of the wastewater decreased to approximately 260 mg/L, the TSS were completely removed from the wastewater by the UF. The specifications of the UF membrane (ER) used in this study are shown in Table 2.

2.3. Working plan

In this study, the RO and NF membranes were both used in two different ways (i.e. with and without the UF process). Consequently, four different alternatives were performed, the NF-only process, the RO-only process, the NF process after UF, and the RO

Table 1
Wastewater characteristics

Parameter	Value	Unit
COD	7.97 ± 0.14	g/L
TSS	2.76 ± 0.70	g/L
VSS	2.41 ± 0.60	g/L
Conductivity	2.75 ± 0.10	mS/cm
pH	6.6 ± 0.1	

Table 2
Membrane specifications

Membrane	Membrane type	Polymer	MWCO[a]	Salt rejection efficiency, %
ER	Ultrafiltration (UF)	Polysulfone	30,000	–
DK	Nanofiltration (NF)	TF (Thin film)	150–300	98.0[b]
AG	Reverse osmosis (RO)	Polyamide	0	99.5[c]

[a]Molecular weight cutoff.
[b]Mg_2SO_4 removal efficiency.
[c]NaCl removal efficiency.

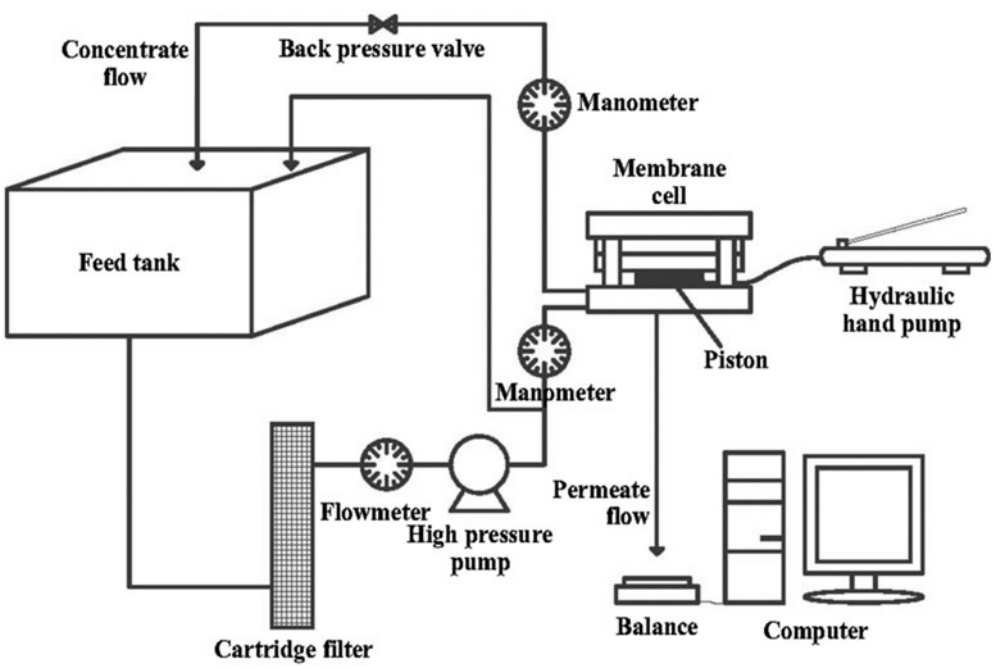

Fig. 1. Schematic view of the membrane system [24].

after UF. In addition, six alternatives were considered: the four alternatives listed above and the conventional and UF-only processes. The AG membrane was used for the RO process, and the DK membrane was used for the NF process (GE Osmonics). The specifications of these membranes are shown in Table 2. The membrane system used in the study was the GE Sepa™ CF2 membrane cell, which was produced by Osmonics. A schematic view of the laboratory-scale membrane system is shown in Fig. 1 [24]. The membranes were used once, and chemical cleaning and backwashing were not performed. In all experiments, the permeate flux was returned to the influent tank to avoid increasing the influent concentrations. Transmembrane pressures (TMP) of 5, 10, 15, 20, and 25 bars were used in the RO and NF processes. The COD removal efficiencies and conductivity decreases were measured for all TMPs. In addition, the membrane fluxes were measured for each TMP, and the optimum TMP was determined. Long-term studies were performed to determine the practical membrane fluxes obtained using these TMPs.

3. Results and discussion

3.1. Membrane performances

The COD and conductivity parameters were used to specify the membrane performances. The COD concentration decreased to 1,200 mg/L after the centrifuging process and to 260 mg/L after UF. Therefore, while the influent COD concentration was 1,200 mg/L for the UF-only, NF-only, and RO-only processes, it was 260 mg/L for the NF and RO processes after the

UF process. The COD removal efficiencies obtained using membrane processes are shown in Fig. 2.

The COD removal efficiencies increased in parallel with the TMPs. Using the UF process generally improved the removal efficiencies for NF and in all of the TMPs for the RO process. When the TMP increased from 5 to 10 bars, the removal efficiencies in all but the UF + NF quickly improved and became more stable. The highest removal efficiencies were obtained using the RO process after UF. The highest removal efficiency was 96.8% for the RO process, and the effluent COD concentration was below 10 mg/L. The highest total COD removal efficiency for the UF and RO processes was greater than 99%.

The conductivity parameter is important for membrane processes because it refers to the dissolved solids concentration of the sample. Significant changes in the conductivity parameter did not occur after centrifuging and UF. This observation is normal because the centrifuging and UF are conducted to remove suspended solids. The COD removal efficiencies obtained with the membrane processes are shown in Fig. 3.

The “decreasing” term was substituted for the “removal efficiency” term because the conductivity parameter is not a direct pollution parameter. The conductivities decreased more with the TMPs, similar to the COD removal efficiencies. The use of the UF process improved the removal efficiencies of the NF and RO processes. In addition, the decreases in the conductivity were low for the NF process and very high for the RO process. The highest decrease was 51.7% for the NF process and 96.6% for the RO process. Although the NF process failed to adequately remove dissolved solids from this wastewater, high removal efficiencies were obtained for the RO process.

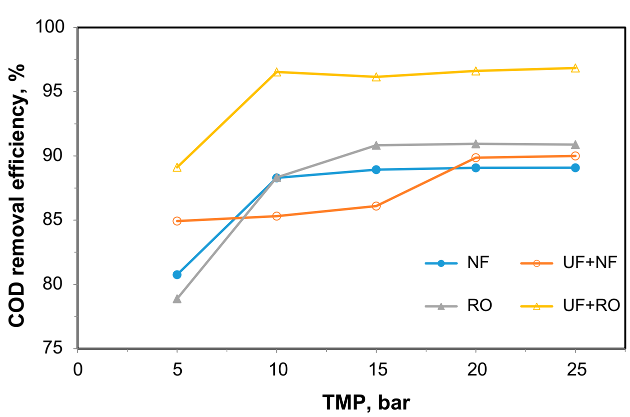

Fig. 2. COD removal efficiencies vs. TMP.

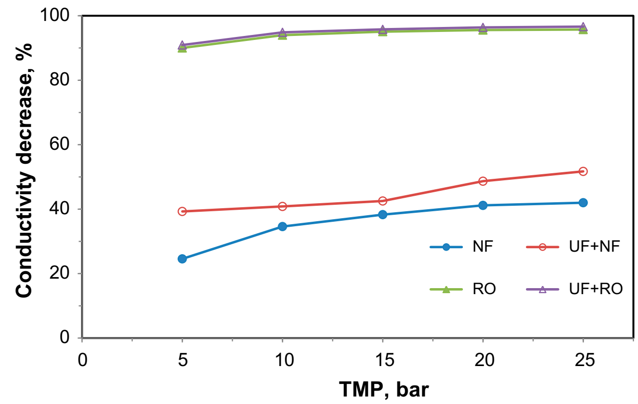

Fig. 3. Conductivity decreases vs. TMP.

3.2. Membrane fluxes

The fluctuations in the membrane processes generally decreased sharply at the beginning of operation and then become more stable. Thus, these fluxes must be considered in economic analyses. Long-term experiments were conducted to determine practical membrane fluxes in this study and are shown in Fig. 4.

Using the UF process before the NF and RO processes as an additional pre-treatment process did not result in significant changes in the COD and conductivity results. Instead, this situation was important for membrane fluxes. When only the centrifuge process was used for pre-treatment, the membrane fluxes quickly decreased. However, this decline in the fluxes was not firm for the combination of the UF process when using centrifuge pre-treatment with the NF and RO processes. Therefore, the final membrane flux in the situation that used the UF and RO processes was 5.7 times greater than the situation that did not use the UF process, and the ratio for the combination

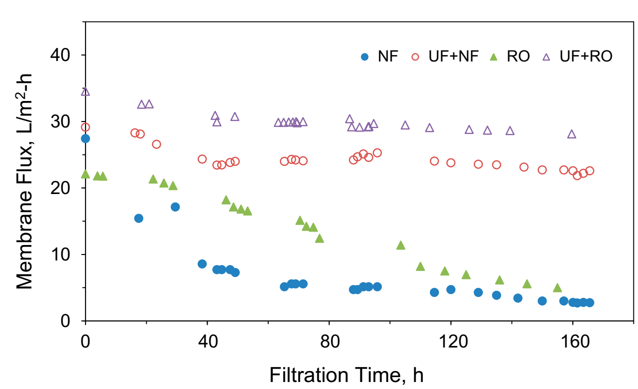

Fig. 4. Long-term membrane fluxes.

involving the NF process was 8.1 times higher. It was observed that the role of the UF process before the NF and RO processes was important.

3.3. Economic analysis

3.3.1. Economic analysis methods

A conventional poultry slaughterhouse wastewater treatment plant includes a DAF unit for pre-treatment and a conventional activated sludge process. The DAF system functions similar to the centrifuge pre-treatment process. Therefore, the unit costs of the pre-treatment process were not included in the economic analysis.

The poultry industry has high water use costs because water consumption is significant in its processes. Consequently, the first cost item is the cost that results from the use of raw water. Because treated water cannot be reused in the poultry process, it is discharged to the sewer system or the receiving bodies after the conventional treatment process, and the water needs are met using the raw water. However, some treated water can be reused in the process, and the remaining total water needs are only met for the raw water using the treatment alternatives that were analyzed in this study. Thus, the cost for water consumption would be lower because the raw water use would decrease. When the water consumption costs are calculated, the price of well water for the supplier in the province from which the wastewater sample is obtained is $0.90/m^3.

Another cost item was the unit cost of the treatment processes. Regarding the treatment unit cost calculations, the pilot-scale studies provide more precise results than the laboratory-scale studies. For example, in a previous study, the unit cost for using a membrane process to treat municipal wastewater was $0.433/m^3 for a 9-m^3 reactor and $0.306/m^3 for a 1,150-m^3 reactor [25]. Therefore, several unit cost values were obtained from studies of pilot-scale plants presented in the literature. Because this study is one of the few studies regarding poultry slaughterhouse wastewater treatment using membrane processes, several studies regarding the treatment of municipal wastewater with the same characteristics as the pre-treated poultry slaughterhouse wastewater used in this study were cited.

Slaughter operations represent 84% of the water consumption in a poultry slaughterhouse, with other operations using the remaining 16% [4]. The water consumption in slaughter operations can be divided as follows: 0.19 L/bird for killing, 0.95 L/bird for scalding, 1.14 L/bird for de-feathering, 3.03 L/bird for final bird washing, 2.12 L/bird for chilling, 7.57 L/bird for eviscerating, 1.32 L/bird for whole bird washing, 3.03 L/bird for cutup/deboning, and 1.14 L/bird for pack-out, resulting in 20.49 L/bird [3]. Accordingly, the water consumption for the other operations was calculated as 0.73 L/bird for washing the cages, 1.94 L/bird for the cooling towers, 0.24 L/bird for freezing the cooling tunnel and storage chambers, and 0.94 L/bird for personal hygiene, resulting in 3.94 L/bird. Thus, the total water consumption for all of these processes is 24.39 L/bird. The sample plant capacity for the economic analysis was 50,000 birds/d, which is an average slaughter capacity in Turkey. Therefore, the total water consumption was 1,220 m^3/d.

Six different alternatives were considered for the economic analysis, excluding the unit cost for the pre-treatment process because it would be the same for all alternatives. These alternatives include the conventional activated sludge process (Alt.1), the UF-only process (Alt.2), the NF-only process (Alt.3), the RO-only process (Alt.4), the UF + NF process (Alt.5), and the UF + RO process (Alt.6) (Fig. 5). The raw water consumption, the unit costs, and the total costs of each process are shown in Table 3.

3.3.2 Raw water use costs

The permeate flows of the NF and RO can be used in the stages that precede bird washing in the slaughter process, along with all other processes.

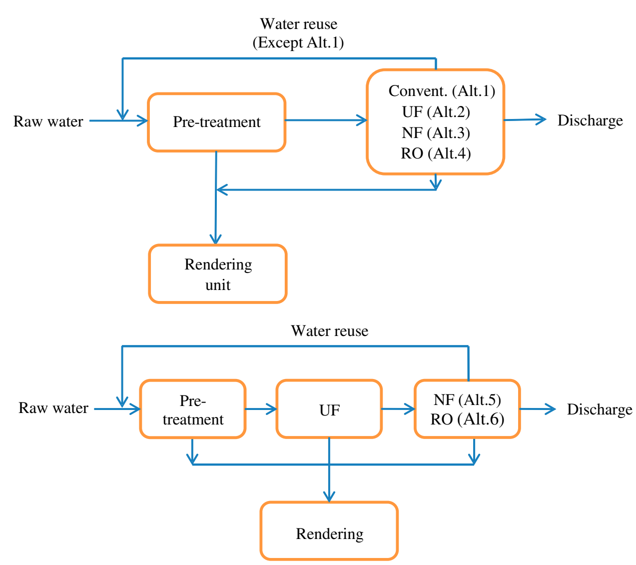

Fig. 5. Schematic view of the treatment alternatives.

Table 3
Economic analysis summary

Alternative number	Process	Water consumption, L/bird: Slaughter operation	Water consumption, L/bird: Other operations	Available volume, L/bird	Permeate production, L/bird	Added raw water, L/bird	Raw water consumption, m^3/d	Unit costs: Water using cost, $/year	Unit costs: Treatment unit cost, $/year	Unit costs: Total unit cost, $/year	Unit costs: Total unit, $/$m^3$
Alt.1	Conventional	–	–	–	–	24.39	1.220	402,500	336,000	738,600	1.66
Alt.2	UF	2.31	2.93	5.24	21.95	19.16	958	316,100	36,500	352,600	0.79
Alt.3	NF	15.00	3.90	18.90	18.29	6.10	305	100,600	1,182,900	1,283,500	2.88
Alt.4	RO	15.00	3.90	18.90	18.29	6.10	305	100,600	731,800	832,400	1.87
Alt.5	UF + NF	15.00	3.90	18.90	16.47	7.93	396	130,800	183,000	313,900	0.70
Alt.6	UF + RO	15.00	3.90	18.90	16.47	7.93	396	130,800	164,900	295,700	0.66

However, the UF permeate flows can be used in the chilling stages of the slaughter process and in all of the stages except personal hygiene among the other processes. Therefore, the NF and RO permeates can compose part of the slaughter process at 15 L/bird, and all of the other processes at 3.90 L/bird, resulting in 18.90 L/bird. The UF permeate can be used in part of the slaughter process at 2.31 L/bird and in all of the other processes at 2.93 L/bird, resulting in 5.24 L/bird.

The recovery rate (permeate flow rate/feed flow rate) was expected to equal 75% for the NF and RO processes [26] and 90% for the UF process. Accordingly, the permeate production was 21.95 L/bird for Alt.2, 18.29 L/bird for Alt.3 and Alt.4, and 16.47 L/bird for both Alt.5 and Alt.6 (Table 3). Therefore, although all the permeate that was produced could be used for the NF and RO processes, only some of the permeate could be used for the UF process. Thus, all of the water consumption needs for the conventional treatment could be met using 1,220 m^3/d of raw water. The raw water consumption was 958 m^3/d with Alt.2, 305 m^3/d with Alt.3 and Alt.4, and 396 m^3/d with Alt.5 and Alt.6. Therefore, the most economical alternatives regarding raw water consumption were Alt.3 and Alt.4, which had a water usage cost of $100,600/year.

3.3.3. Treatment process unit costs

The unit costs for the treatment of municipal wastewater using the conventional process are specified as $0.4/$m^3$ [25] and $0.33/$m^3$ [27]. Thus, a unit cost of $0.365/$m^3$ was used in this study. The total unit cost for the sample plant that used the conventional treatment process was $336,000/year. The unit cost for the UF process was calculated by Qin et al. [28]. Accordingly, the unit costs for Alt.2 were $0.082/$m^3$ and $36,500/year.

The unit costs for treating municipal wastewater using the membrane process are $0.306/$m^3$ for the RO process [25], $0.243/$m^3$ for the RO process and $0.198/$m^3$ for the NF process [26]. The unit costs obtained from the literature were used in this study. Thus, the difference between the fluxes calculated in previous studies and in this study was considered. The unit costs of the NF and RO processes without the UF process were high because the fluxes for these experiments were quite low. The most economical alternative was Alt.6 because it resulted in the highest flux. The unit cost for Alt.6 was $164,900/year, but that of Alt.4 (RO only) was only $731,800/year.

3.3.4. Total unit costs

All of the stages in the economic analysis are shown in Table 3. Accordingly, the expense increased as follows: Alt.6, Alt.5, Alt.2, Alt.1, Alt.4, and Alt.3. The most economical alternative was the RO process, followed by the UF process. The total unit costs for this process were \$295,700/year and \$0.66/m^3. The total unit costs for the NF process following the UF process were \$313,900/year and \$0.70/m^3. The RO and NF processes without the UF process were not economical alternatives to the conventional process. The total unit costs for the conventional process were \$738,600/year and \$1.66/m^3 when the raw water use costs were considered.

4. Conclusions

The treatment of poultry slaughterhouse wastewater using membrane processes was investigated, which is not frequently investigated in the literature. The treatment performances and membrane fluxes were determined, and an economic analysis of the different alternatives was performed. An economic analysis was conducted using the data in this study and the data from several other studies from the literature. Overall, the following results were obtained:

(1) Approximately 80% COD removal and more than 90% TSS removal when using the centrifuge process.
(2) The decrease in conductivity was low in the NF process, in contrast with the RO process with a decrease of more than 96%. The COD removal efficiencies were approximately 90% for the NF process and 97% for the RO process.
(3) Using the UF process resulted in greater final fluxes for the NF and RO membranes. The ratios between the fluxes with and without the UF process were 8 for the NF process and 5.7 for the RO process. The use of the UF pretreatment process was necessary for both the NF and RO processes.
(4) An economic analysis of the six alternatives was performed. The best alternative was the RO process, which followed the UF process. The total unit costs for the treatment and raw water use for the UF + RO, UF + NF, UF-only, and the conventional treatment processes were \$0.66, \$0.70, \$0.79, and \$1.66/m^3, respectively.
(5) The total unit costs for the RO and NF processes were high when the UF process was not used as a pre-treatment.
(6) Because the total unit cost for the conventional treatment process was 2.5 times greater than the RO process following the UF process, this combination was a better alternative than the conventional process.
(7) In the future, a pilot study regarding the treatment of poultry slaughterhouse wastewater using membrane processes should be performed with an economic analysis to obtain precise results.

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