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Development of Natural and Ecological Wastewater Treatment System for Decentralized Regions and Rural Communities

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The feasibility of the Natural and Ecological Wastewater treatment System (NEWS) was examined for rural wastewater treatment in Korea. The intermittent trickling biofilter with high hydrophilic filter media was used for pretreatment for suspended solids and organic pollutants. The subsequent constructed wetland with porous granule materials was used for promoting nutrient removal. The results show that the removal efficiencies of the system were high with respect to the water quality parameters except COD. Even if the effluent from the biofilter did not meet the guidelines for wastewater treatment plant effluent in Korea in terms of BOD_5 and TN, the final effluent of the system meets the guidelines due to good performance of the constructed wetland. The regression analysis between pollutant loading rate and removal rate indicated that the system could have stable removal for SS, BOD_5, TN, and TP in the given influent ranges. The analysis in the winter period indicated that the wetland covered with transparent polycarbonate glass had the stable performance during the winter period due to increase of temperature inside the wetland without any heating system. With the stable performance, effective pollutant removal, low maintenance, and cost-effectiveness, the NEWS could be considered as an alternative treatment system for decentralized regions and rural communities in Korea.

Key words : wastewater treatment, trickling biofilter, constructed wetland, decentralized wastewater treatment system

INTRODUCTION

Wastewater discharged into the aquatic environment can contaminate surface and ground water, degrading the quality of drinking water supplies. The conventional wastewater treatment plants can be applied to treat wastewater in densely populated urban areas while decentralized wastewater treatment system can be used to treat relatively small volume of wastewater generated from rural dwellings. Decentralized wastewater treatment systems are individual on-site or clustered wastewater systems used to treat wastewater from individual dwellings or small communities. Among the systems, the septic system is most commonly used to treat sewage and wastewater. In the septic system, a raw sewage is treated biologically in the septic tank under the anaerobic condition and subsequently discharged to leaching field or tile bed for further aerobic treatment (Butler and Payne, 1995). De-

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centralized wastewater treatment systems are recognized as potentially viable, low-cost, and long-term methods for wastewater treatment under appropriate design and operation. Recently, optimization of the onsite systems attracts considerable attention after recognition of their impacts on water quality.

In wastewater treatment, biological treatment processes are considered to be more efficient and less expensive than physical and/or chemical processes (Cohen, 2001). In biofiltration, wastewater can be treated while flowing through filter medium where microorganisms are immobilized. The treatment of wastewater with biofiltration has been studied by many researchers under various conditions (Yap *et al*., 1992; Diab *et al*., 1993; Hu *et al*., 1993; Lowengart *et al*., 1993; Le Bihan and Lessard, 1998; Kwun *et al*., 2000; Villaverde *et al*., 2000), including treatment of septic tank effluent using a horizontal subsurface biofilter (Netter *et al*., 1993), development of biofilter system with wheat straw for irrigation water treatment (Avnimelech *et al*., 1993), application of submerged aerated biofilter to treat hazardous landfill leachate in a bench scale (Smith, 1995), development of a peat-based biofilter for on-site wastewater treatment (Talbot *et al*., 1996), dynamic simulation of submerged biofilters using a mathematical model (Jacob *et al*., 1997), treatment of flushed swine wastes with upflow aerated biofilters (Westerman *et al*., 2000), biofilter treatment of an eel culture pond water for reuse (Yang *et al*., 2001), and biological treatment of domestic wastewater with floating filter media (Xie *et al*., 2004).

In this study, a natural and ecological wastewater treatment system (NEWS) was developed using up- and down-flow type constructed wetland for decentralized wastewater treatment in Korea.

MATERIALS AND METHODS

1. Treatment system

The NEWS was developed by combining the high-hydrophilic biofilter and the constructed wetland into the wastewater treatment system (Fig. 1). The biofilter was made of polyethylene and had a dimension of 1.49 m in diameter and 2.00 m in height. The biofilter was packed by porous materials with the packing height of 1.20 m. The porous material used in the biofilter was melamin resin foam with a dimension of 4.0 cm × 4.0 cm × 4.0 cm. The constructed wetland had a total capacity of 15.75 m^3 (dimension of 10.5 m in length, 1.5 m in width, and 1.0 m in depth) and a hydraulic retention time (HRT) of 12 hr. The porous materials used as the wetland media was a volcanic tuff and yellow Russian iris (*Iris pseudoacoru* L.) was planted. The diameters of the porous materials ranged from 5 to 10 mm with the porosity of about 0.595, which is higher than those of sands and gravels (0.3-0.4). Iris pseudoacorus was planted at the total area of 12.75 m^2 with 25 individuals per unit area.

2. Operation of treatment system

The NEWS was operated at the Rural Research Institute located in Ansan, Korea with an operation capacity of 30 m^3 day^{-1}. High strength wastewater obtained from the animal wastewater treatment plant near the study area was diluted and applied into the biofilter as influent with intermittent injection mode (supply: 1-3 min; pause: 10-25 min). The hydraulic loading rate in the biofilter ranged from 4.31-8.62 m^3 m^{-2} day^{-1}. In the biofilter tank, an aerobic condition was maintained by circulating air for 24 hr using a ventilation fan (25 w hr^{-1}). The wastewater treated in the biofilter was discharged as influent into the constructed wetland. In the wetland, the dynamic flow was designed to move up and down repeatedly to obtain the maximum removal efficiency per unit area (Fig. 1).

The operation of the treatment system was performed for 11 months between September, 2004 and July, 2005. The effluents at the biofilter and constructed wetland were monitored seventeen times during the operation. The water samples were analyzed with the Standard Methods (APHA, 1998).

3. Regression analysis

The regression analysis was performed for the observed data using SPSS (Version 12). In the regression analysis, the method of least squares was applied to minimize difference between the observed and predicted values. In the analysis, the coefficient of determination (R^2) was calculated and then F distribution was analyzed to asses the adequacy of the regression line.

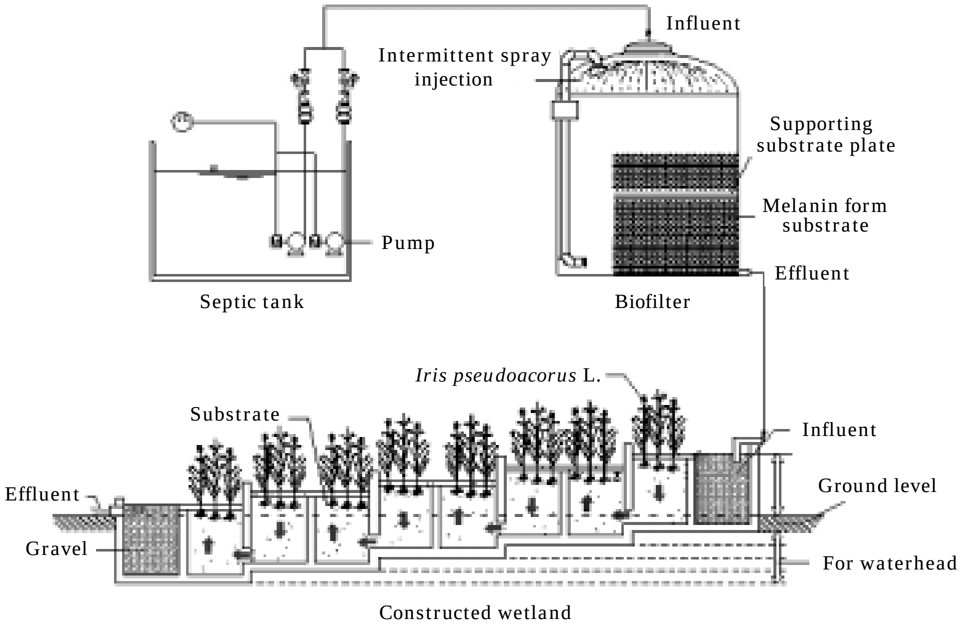

Fig. 1. Schematic diagram of the NEWS.

Table 1. Removal efficiencies of SS, BOD_5, COD, TN, and TP in the NEWS.

Parameter	Influent Conc.±SD	Biofilter effluent (mg L^{-1})		Wetland effluent (mg L^{-1})		Total removal (%)	Guideline for effluent*
		Conc.±SD	Removal (%)	Conc.±SD	Removal (%)		
SS	86.7±56.1	9.5±5.2	88.5	2.2±5.9	78.3	97.5	10/20
BOD_5	121.2±49.6	20.8±16.3	82.9	5.2±17.7	75.8	95.7	10/20
COD	28.9±12.2	30.9±16.6	−6.6	12.0±14.8	59.3	58.5	40/40
TN	42.1±12.1	26.2±12.0	37.8	7.5±3.5	71.4	91.8	20/60
NH_4-N	31.5±9.22	17.7±14.3	43.8	1.0±1.7	94.4	94.8	−
NO_2-N	0.5±0.5	1.8±2.5	−295.0	0.5±1.4	70.0	−214.2	−
NO_3-N	2.9±5.0	17.1±14.3	−490.4	6.2±5.3	63.6	−81.3	−
PO_4-P	1.3±0.5	1.3±0.5	6.0	0.3±0.2	82.6	80.7	−
TP	3.1±1.7	1.7±0.8	45.1	0.4±0.3	73.8	90.1	2/8

*: Guidelines for wastewater treatment plant effluent at special regions (4 major rivers)/other regions in Korea

RESULTS AND DISCUSSION

1. System performance

The removal efficiencies of SS, BOD_5, COD, TN, and TP in the treatment system were presented in Table 1. The total removal efficiency of SS in the NEWS was 97.5%. In case of BOD_5 and COD, the removal efficiencies were 95.7 and 58.5 %, respectively. In addition, the removal efficiencies of TN and TP were 91.8 and 90.1%, respectively. The removal efficiencies of the treatment system were high with respect to the water quality parameters except COD. The low COD removal might be attributed to the high refractory organic compounds in the livestock waste, and higher removal rate is expected in municipal wastewater treatment. The effluent from the biofilter did not yet meet the guidelines for wastewater treatment plant effluent in Korea in terms of BOD_5 and TN. In overall, however, the final effluent of the NEWS system met the guidelines stably due to a good of the constructed wetland.

In the biofilter, the mean influent and effluent concentrations of SS were 86.7 and 9.5 mg L^{-1}, respectively, with the averaged percent removal efficiency of 88.5%. The removal efficiency of BOD_5 was 82.9% with the influent and effluent concentrations of 121.2 and 20.8 mg L^{-1}, respectively. In case of COD, the mean effluent concentration in the biofilter (30.9 mg L^{-1}) was even higher than that of the influent (28.9 mg L^{-1}), indicating the negative removal efficiency (−6.6 %). The influent and effluent concentrations of TN were 42.1 and 26.2 mg L^{-1}, respectively, with the removal efficiency of 37.8%. In case of TP, the removal efficiency was 1.7% with the influent and effluent concentrations of 42.1 and 26.2 mg L^{-1}, respectively. It indicated that the biofilter had high removal efficiencies in SS and BOD_5 but low efficiencies in TN and TP. In addition, the biofilter was not effective in the removal of COD.

In the constructed wetland, the influent concentrations were equivalent to the effluent concentrations of the biofilter. The mean effluent concentration of SS in the wetland was 2.2 mg L^{-1} with the removal efficiency of 78.3%. The removal efficiency of BOD_5 was 75.8% with the effluent concentrations of 5.2 mg L^{-1}. In case of COD, the effluent concentration was 12.0 mg L^{-1} with the removal efficiency of 59.3%. It should be noted that the wetland could remove COD considerably whereas the biofilter had negative removal efficiency. The effluent concentrations of TN and TP were 7.5 and 0.4 mg L^{-1} with the removal efficiencies of 71.4 and 73.8%, respectively. It indicated that the constructed wetland had relatively high removal efficiencies for the water quality parameters.

2. Removal of nutrients

In the treatment system, the total removal efficiency of TN was high. However, the removal efficiencies of the nitrogen components including NH_4-N, NO_2-N, and NO_3-N varied in the system (Table 1). In the biofilter, the mean influent and effluent concentrations of NH_4-N were 31.5 and 17.7 mg L^{-1}, respectively, with the averaged percent removal efficiency of 43.8%. In case of NO_2-N, the mean effluent concentration in the biofilter (1.8 mg L^{-1}) was higher than that of the influent (0.5 mg L^{-1}) with the negative removal efficiency (−295.0%). In the biofilter, NO_3-N also had the negative removal efficiency (−490.4%) with the influent and effluent concentrations of 2.9 and 17.1 mg L^{-1}, respectively. It indicated

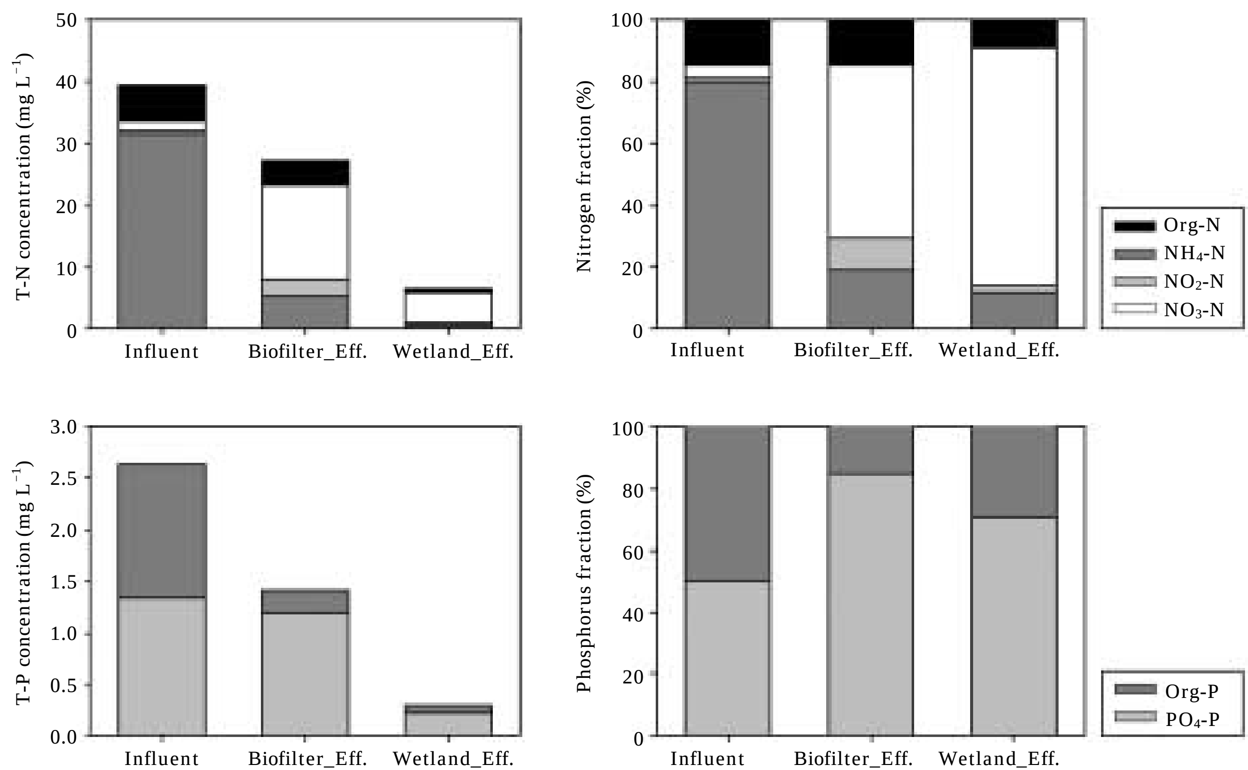

Fig. 2. Concentrations of nutrients in the treatment system.

that the concentration of NH_4-N decreased in the biofilter due to volatilization along with nitrification to NO_2-N and NO_3-N.

In the wetland, the influent concentrations of the nitrogen components were equivalent to the effluent concentrations of the biofilter. The effluent concentration of NH_4-N was 1.0 mg L^{-1} with the removal efficiency of 94.4%. The removal efficiency of NO_2-N was 70.0% with the effluent concentrations of 0.5 mg L^{-1}. In case of NO_3-N, the effluent concentration was 6.2 mg L^{-1} with the removal efficiency of 63.6%. In overall, the removal efficiency of NH_4-N was high in the treatment system with 94.8%, but the efficiencies of NO_2-N and NO_3-N were negative (−214.2 and −81.3%, respectively).

The variation of the nitrogen components in the treatment system was depicted in Fig. 2. The composition ratio of Org-N decreased slightly from 15.0% to 14.6% in the biofilter and down to 8.8% in the constructed wetland. In case of NH_4-N, the ratio decreased sharply from 79.8% to 18.9% in the biofilter and down to 11.5% in the wetland. The ratio of NO_2-N increased about 10 times from 1.0 to 10.2% in the biofilter but decreased down to 2.6% in the wetland. The ratio of NO_3-N increased sharply from 4.2 to 56.3% in the biofilter and continuously up to 77.1% in the

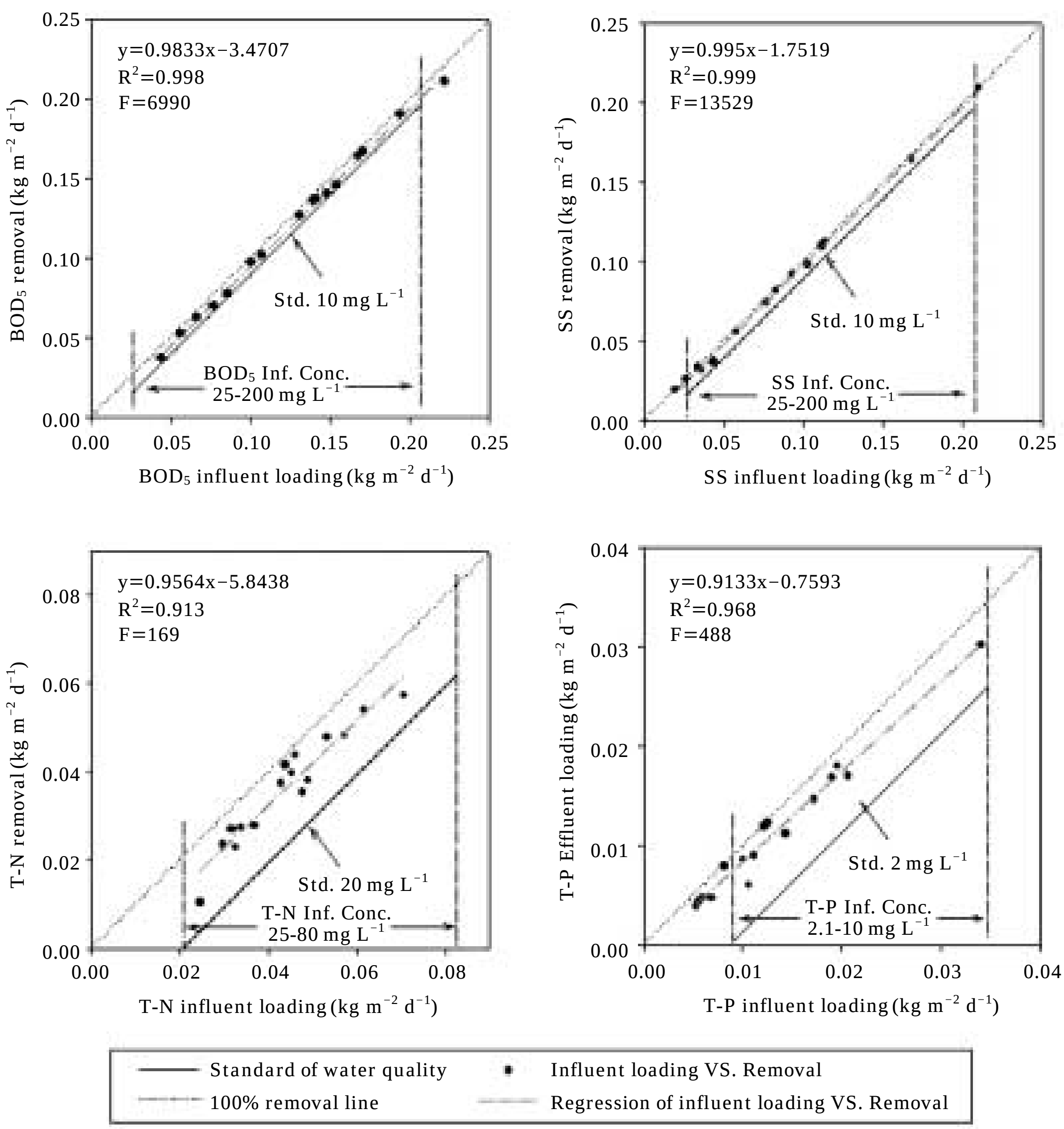

Fig. 3. Regression analysis between pollutant loading and removal rate.

wetland.

The variation of the phosphorus components in the treatment system was also shown in Fig. 2. The composition ratio of Org-P decreased sharply from 49.6% to 15.3% in the biofilter but increased to 29.0% in the constructed wetland. In case of PO_4-P, the ratio increased from 50.4% to 84.7 % in the biofilter but decreased to 71.0% in the wetland. It indicated that Org-P (particulate type P) was filtered out in the biofilter whereas PO_4-P (dissolved type P) was removed in the wetland. As presented in Table 1, the overall removal efficiency of PO_4-P in the treatment system was 80.7 % with 6.0% in the biofilter and 82.6% in the wetland.

3. Regression between pollutant loading rate and removal rate

The regression analysis between pollutant loading rate and removal rate was given in Fig. 3. The influent and effluent concentrations were converted into pollutant loading rate and removal rate, respectively and presented along with the water quality standard in the figure. The 100 % removal line indicated the ideal condition that all the pollutants loaded in the treatment system were removed. For SS, BOD_5, TN, and TP, the coefficient of determination (R^2) was over 0.9 and F-value over 150, indicating that the regression models could be used to predict the effluent concentration. The regression analysis indicated that BOD_5 had R^2 of 0.998 and F of 6990 and could be removed stably in 25-200 mg L^{-1} of influent concentration. SS had R^2 and F of 0.999 and 13529, respectively, and could be removed stably in 25-200 mg L^{-1}. TN had R^2 of 0.913 with F of 169, and the system could have stable removal of TN in 20-80 mg L^{-1} of influent concentration. TP had R^2 of 0.968 with F of 1488 and the system could have stable removal of TP in 2.1-10 mg L^{-1}.

4. Performance in winter period

In the winter period between December 2003 and February 2004, the constructed wetland was covered with transparent polycarbonate glass to increase temperature inside the wetland without any heating system and so to solve the low performance of the wetland due to cold weather. The variation of the temperature in the winter period was presented in Fig. 4. The inner temperature of the wetland was higher than the outer temperature with the maximum difference of 20°C. As presented in Table 2, the wetland had the stable performance during the winter period.

In the winter period, the mean influent concentration of SS into the NEWS system was 35.9 mg L^{-1} and the effluent concentration from the wetland was 2.8 mg L^{-1} with the averaged removal efficiency of 95.2%. In other seasons, the influent and effluent concentrations of SS were 42.3 and 1.9 mg L^{-1}, respectively, with the removal efficiency of 96.8%. In case of BOD_5, the influent and effluent concentrations were 130.7 and 6.5 mg L^{-1} with the removal efficiency of

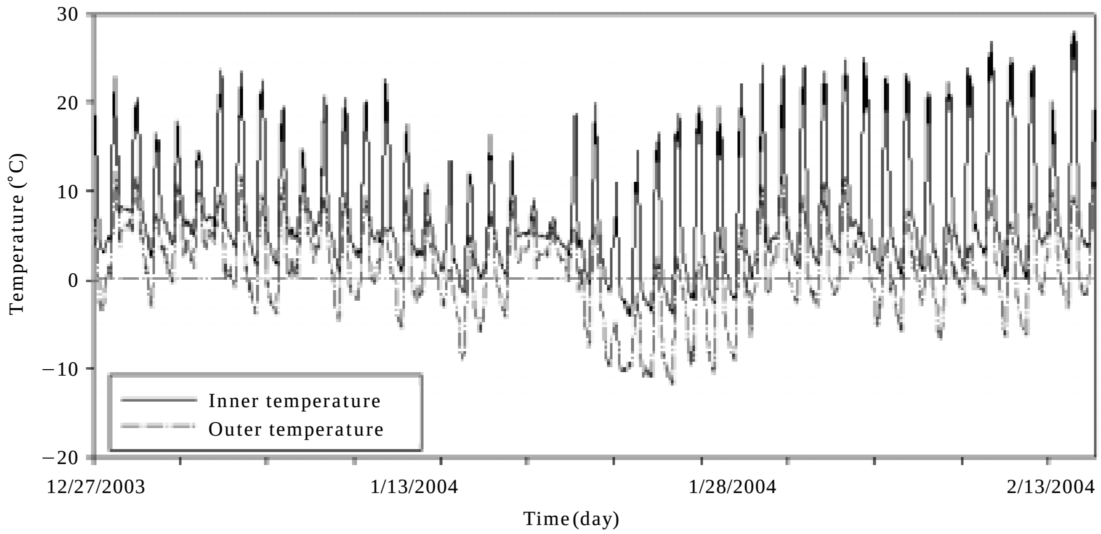

Fig. 4. Inner and outer temperatures of the constructed wetland.

Table 2. Removal efficiencies of SS, BOD_5, COD, TN, and TP at the wetland in winter versus other seasons.

Parameter	Winter			Other seasons		
	Influent Conc.±SD	Wetland effluent (mg L^{-1})		Influent Conc.±SD	Wetland effluent (mg L^{-1})	
		Conc.±SD	Removal (%)		Conc.±SD	Removal (%)
SS	35.9±9.0	2.8±2.6	95.2	42.3±11.7	1.9±1.4	96.8
BOD_5	130.7±20.0	6.5±1.4	95.0	118.1±56.7	5.3±2.4	94.2
COD	68.9±28.1	12.1±4.9	81.3	119.1±70.3	12.0±6.9	89.1
TN	41.7±14.2	9.8±3.5	72.9	40.6±10.5	6.5±3.1	84.0
TP	3.9±2.6	0.6±0.3	81.4	2.7±1.1	0.4±0.3	84.8

95.0% in the winter while they were 118.1 and 5.3 mg L^{-1}, respectively, with the removal efficiency of 94.2% in other seasons. For COD, the removal efficiency was 81.3% in the winter with the influent and effluent concentrations of 68.9 and 1.9 mg L^{-1}, respectively, while it was 89.1% in other seasons with the influent and effluent concentrations of 119.1 and 12.0 mg L^{-1}, respectively.

In case of nutrients, the influent concentration of TN into the system was 41.7 mg L^{-1} and the effluent concentration from the wetland was 9.8 mg L^{-1} with the removal efficiency of 72.9%. In other seasons, the influent and effluent concentrations of TN were 40.6 and 6.5 mg L^{-1}, respectively, with the removal efficiency of 84.0%. For TP, the removal efficiency was 81.4% in the winter with the influent and effluent concentrations of 3.9 and 0.6 mg L^{-1}, respectively, while it was 84.8% in other seasons with the influent and effluent concentrations of 2.7 and 0.4 mg L^{-1}, respectively.

CONCLUSIONS

In this study, the feasibility of the NEWS composed of the biofilter and constructed wetland was examined for rural wastewater treatment in Korea. The results show that the removal efficiencies of the system were high with respect to the water quality parameters except COD. Even if the effluent from the biofilter did not meet the guidelines for wastewater treatment plant effluent in Korea in terms of BOD_5 and TN, the final effluent of the NEWS system meets the guidelines due to good performance of the constructed wetland. The regression analysis between pollutant loading rate and removal rate indicated that the system could have stable removal for SS, BOD_5, TN, and TP in the given influent ranges. The analysis in the winter period indicated that the wetland covered with transparent polycarbonate glass had the stable performance during the winter period due to increase of temperature inside the wetland without any heating system. With the stable performance, effective pollutant removal, low maintenance, and cost-effectiveness, the NEWS could be considered as an alternative treatment system for decentralized regions and rural communities.

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LITERATURE CITED

American Public Health Association. 1995. Standard methods for the examination of water and wastewater (19^{th} ed.). APHA, Washington D.C.

Avnimelech, Y., S. Diab and M. Kochba. 1993. Development and evaluation of a biofilter for turbid and nitrogen-rich irrigation water. *Water Res.* **27**: 785-790.

Butler, D. and J. Payne. 1995. Septic tanks: problems and practice. *Build. Environ.* **30**: 419-425.

Cohen, Y. 2001. Biofiltration-the treatment of fluids by microorganisms immobilized into the filter bedding material: A review. *Bioresour. Technol.* **77**: 257-274.

Diab, S., M. Kochba and Y. Avnimelech. 1993. Development of a biofilter for turbid and nitrogen-rich irrigation water; B: removal of phosphorus, algae and clay. *Bioresour. Technol.* **44**: 137-140.

Hu, H.Y., K. Fujie and K. Urano. 1993. Dynamic behaviour of aerobic submerged biofilter. *Water Sci.*

Technol. **28**: 179-185.

Jacob, J., J.M. Le Lann, H. Pingaud and B. Capdeville. A generalized approach for dynamic modeling and simulation of biofilters: Application to waste-water denitrification. *Chem. Eng. J.* **65**: 133-143.

Kwun, S.K., C.G. Yoon and B. Kim. 2000. Performance of a small on-site wastewater treatment system using absorbent biofilter for Korean rural community. *J. Environ. Sci. Heal. A.* **35**: 1701-1717.

Le Bihan, Y. and P. Lessard. 1998. Microbiological study of a trickling biofiltration process: representativeness of washwaters and vertical distribution of heterotrophic aerobic bacteria. *Environ. Technol.* **19**: 555-566.

Lowengart, A., S. Diab, M. Kochba and Y. Avnimelech. 1993. Development of a biofilter for turbid and nitrogen-rich irrigation water; A: organic carbon degradation and nitrogen removal processes. *Bioresour. Technol.* **44**: 131-135.

Netter, R., E. Stübner, P.A. Wilderer and I. Sekoulov. 1993. Treatment of septic tank effluent in a subsurface biofilter. *Water Sci. Technol.* **28**: 117-124.

Smith, D.P. 1995. Oxygen flux limitation in aerobic fixed-film biotreatment of a hazardous landfill leachate. *J. Hazard. Mater.* **44**: 77-91.

Talbot, P., G. Bélanger, M. Pelletier, G. Laliberté and Y. Arcand. 1996. Development of a biofilter using an organic medium for on-site wastewater treatment. *Water Sci. Technol.* **34**: 435-441.

Villaverde, S., F. Fdz-Polanco and P.A. García. 2000. Nitrifying biofilm acclimation to free ammonia in submerged biofilters. Start-up influence. *Water Res.* **34**: 602-610.

Westerman, P.W., J.R. Bicudo and A. Kantardjieff. 2000. Upflow biological aerated filters for the treatment of flushed swine manure. *Bioresour. Technol.* **74**: 181-190.

Xie, W., Q. Wang, G. Song, M. Kondo, M. Teraoka, Y. Ohsumi and H.I. Ogawa. 2004. Upflow biological filtration with floating filter media. *Process Biochem.* **39**: 765-770.

Yang, L., L.S. Chou and W.K. Shieh. 2001. Biofilter treatment of aquaculture water for reuse applications. *Water Res.* **35**: 3097-3108.

Yap, M.G.S., W.J. Ng and H. Chua. 1992. Performance of an anaerobic biofilter for 2-ethylhexanoic acid degradation. *Bioresour. Technol.* **41**: 45-51.

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<국문적요>

분산지역 및 농촌마을 하수처리를 위한 자연정화 고도처리 공법 개발

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본 연구에서는 우리나라의 분산지역 및 농촌마을의 하수처리를 위해 자연정화 고도처리 공법인 NEWS (Natural and Ecological Wastewater treatment System)를 적용하였다. 고친수성 biofilter를 사용하여 고형물질과 유기물질을 제거하였으며, 인공습지를 이용하여 영양물질을 제거하였다. 장지적으로 안정성을 갖으며, 부지면적과 효율 면에서 기계적인 공법과 경쟁할 수 있는 자연정화 고도처리공법을 개발하고자 고친수성 biofilter와 상하흐름형 인공습지를 조합하여(NEWS)처리효과를 검토하였다. 본 처리시설을 적용한 결과 COD를 제외한 수질항목에서 높은 제거율을 나타내었다. Biofilter 유출수는 국내 수질기준을 만족시키지 못하였으나, 인공습지를 거쳐 처리된 최종 유출수는 수질기준을 만족시켰다. BOD, SS, TN, TP의 유입부하량과 제거량과의 관계를 회귀분석 한 결과 결정계수는 각각 0.998, 0.999, 0.919, 0.919로 매우 높은 상관성을 나타냈다. 동절기 효율저하의 문제점을 해결하기 위해 연구시설의 지붕을 투명 폴리카보네이트 글라스로 설치하여 난방을 하지 않는 온실을 도입하고, 12-2월 동안 겨울철 처리장 실내·외 온도차이를 측정한 결과 처리장 실내온도가 실외 온도보다 최고 20°C까지 높게 나타났다. 따라서 본 연구에서 개발한 자연생태학적 하수고도처리공법인 NEWS는 유기물질과 영양물질 처리공정을 분리하여 처리효율을 높일 수 있으며, 국내의 분산지역 및 농촌마을의 하수처리에 적용가능성이 높을 것으로 판단된다.