



Denitrification potential enhancement by addition of external carbon sources in a pre-denitrification process

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Abstract

The aim of this study is to investigate the denitrification potential enhancement by addition of external carbon sources and to estimate the denitrification potential for the predenitrification system using nitrate utilization rate (NUR) batch tests. It is shown that the denitrification potential can be substantially increased with the addition of three external carbon sources, i.e. methanol, ethanol, and acetate, and the denitrification rates of ethanol, acetate, and methanol reached up to 9.6, 12, and 3.2 mgN/(g VSS·h), respectively, while that of starch wastewater was only 0.74 mgN/(g VSS·h). By comparison, ethanol was found to be the best external carbon source. NUR batch tests with starch wastewater and waste ethanol were carried out. The denitrification potential increased from 5.6 to 16.5 mg NO₃-N/L owing to waste ethanol addition. By means of NUR tests, the wastewater characteristics and kinetic parameters can be estimated, which are used to determine the denitrification potential of wastewater, to calculate the denitrification potential of the plant and to predict the nitrate effluent quality, as well as provide information for developing carbon dosage control strategy.

Key words: predenitrification process; external carbon addition; ethanol; denitrification potential

Introduction

More stringent effluent requirements in combination with increasing loads and limiting plant volumes in many wastewater treatment plants call for more efficient processes. The planning and upgrading of the wastewater treatment plant (WWTP) are increasingly concerned with the biological nutrient removal (BNR) approaches. Nitrogen removal is often incomplete because of low organic loading in sewers. In particular, the denitrification potential of wastewater is primarily a function of the available organic carbon, which is usually expressed as the COD/N or the BOD/N ratio. Many studies report a wide range of COD/N ratios required for satisfactory denitrification or complete denitrification processes between 4 and 15 g COD/gN. If the influent wastewater COD/N ratio is not sufficient, an external carbon source is required for a satisfactory denitrification step. Methanol, ethanol, and hydrolysate from fermentation of primary sludge have been the main external carbon sources used for denitrification (Christensson *et al.*, 1994; Hallin *et al.*, 1996; Hallin, 1998; Isaacs *et al.*, 1994; Nyberg *et al.*, 1996; Bolzonella *et al.*, 2001). These are either added to the anoxic zone

of a single-sludge system (pre- or post-denitrification) as supplement to the influent COD, or to the denitrification tank of a two-sludge post-denitrification system.

The choice of ethanol as the carbon source is an interesting alternative to the more commonly used methanol both with respect to economy and process flexibility. Pure methanol is now more expensive than pure ethanol, and ethanol can be obtained as an inexpensive waste product from chemical and pharmaceutical industries. Full scale experiments with ethanol added to a pre-denitrification process showed that the nitrogen removal efficiency was approximately proportional to the COD/N ratio and a specified anoxic zone fraction as long as nitrate was not limiting for denitrification (Plaza *et al.*, 1990). Full-scale experiments with methanol in the post-denitrification process demonstrated a lag period before an increase of the denitrification rates and nitrogen removal (Nyberg *et al.*, 1992). Methanol has been shown to select for a highly specialized denitrifying population consisting of facultative methylotrophs (Claus and Kutzner, 1985; Timmermans and van Haute, 1983). Ethanol, on the other hand, is converted by the bacterial cell to acetyl-ScoA, similar to acetate, before entering the tricarboxylic acid cycle. Acetate may account for 5%–10% of the total COD (chemical oxygen demand) in sewage (Henze *et al.*, 1994). Suitable denitrifying populations with the appropriate enzymes for ethanol degradation must therefore already exist in activated sludge. Acetate is known as an easily degradable

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carbon compound for many bacteria. Isaacs *et al.* (1994) showed that nitrogen removal was enhanced immediately after acetate addition (Isaacs and Henze, 1995).

In this article, ethanol, methanol, and acetate were compared with their performance as carbon sources for denitrification, because the denitrification activity and operational costs are clearly influenced by the choice of the carbon source. In addition, experimental procedures to determine the denitrification potential of raw wastewater and the denitrification potential enhancement after waste ethanol addition were also investigated. To optimize the denitrification of the existing WWTP, anoxic batch tests were studied to determine the denitrification rates and the denitrification potential on soluble COD (Ss), particulate COD (Xs) and endogenous material, and further estimate the overall denitrification potential of the plant.

1 Materials and methods

The activated sludge used for batch tests was taken from a BNR pilot-plant (Fig.1) working at a sludge organic loading of 0.1–0.15 kg COD/(kg MLSS-d) with working volume of 300 L. The wastewater provided to the plant and used in the tests was starch wastewater with the TN (total nitrogen) concentration of 40–80 mg/L and the influent COD of 150–350 mg/L; the average COD/TN ratio of influent wastewater was 4.5. In view of the low COD/N ratio, the waste ethanol (from the alcoholic drinks production industry, consisting of about 30% ethanol and only small concentrations of starch, which was easily available and has low cost) was added to starch wastewater to increase the system denitrification potential. Table 1 summarizes the characteristics of the starch wastewater with (one milliliter waste ethanol dosage into one liter starch wastewater) and without waste ethanol addition. The plant was operated indoors at a temperature of 20–22°C.

Nitrates utilization rate (NUR) tests were carried out in five parallel SBR (sequencing batch reactor) reactors (Fig.2) in pulse mode and the stirred MLSS (mixed liquor

suspended solid) concentration in the vessels was about 2400 mg/L with MLVSS (mixed liquor volatile suspended solid)/MLSS equal to 0.80. The working volume of the reactors was 10 L. The solids retention time (SRT) was set to about 15 d. The influent pH was controlled at 7–7.5. Three SBR reactors were used to compare the performances of ethanol, methanol, and acetate as carbon sources for denitrification; the dosing carbon sources were excessive and pure cultures were used (with pure culture mixed with tap water). As for the remaining two SBR reactors, one was used with starch wastewater, and the other was used the starch wastewater with the addition of waste ethanol, to determine the denitrification potential. On the basis of the typical operational conditions of the pilot pre-denitrification process, a wastewater/activated sludge ratio (f_{ww}) of 0.25 was used in the SBR reactors, and when dissolved oxygen (DO) in the bulk dropped to low values (<0.1 mg O₂/L), wastewater was added in the pulse mode. Samples were usually collected at every 30 min; the samples were then filtered immediately through a paper filter, and the concentrations of nitrate, nitrite, and other analytical parameters were determined according to APHA (1995).

2 Results and discussion

2.1 Comparison of ethanol, methanol, and acetate as carbon sources for denitrification

Based on the NUR test, the experiments were carried out, and the results obtained using the different carbon sources (ethanol, methanol, and acetate) are illustrated in Table 2.

As shown in Table 2, the observed sludge yield was about 0.4 g MLSS/g COD for methanol and ethanol, which is considerably less than that experienced from the operation with a pre-denitrification system (Nyberg *et al.*, 1996), whereas the sludge yield for acetate is high. The three carbon sources function very differently regarding the specific nitrate utilization rate; very high specific nitrate

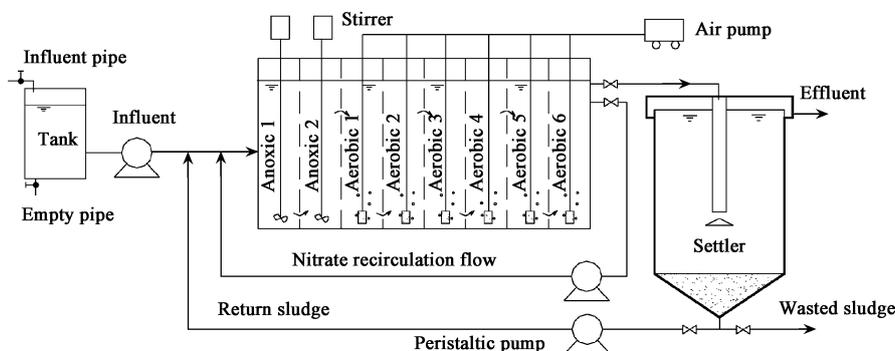


Fig. 1 Schematic diagram of the pilot pre-denitrification process.

Table 1 Wastewater characteristics with and without the addition of waste ethanol (mg/L)

Parameter	TSS	COD	BOD	NH ₄ -N	NO ₂ -N	NO ₃ -N
Starch wastewater	50±10	200±10	68±5	53±3	0.10±0.1	0.78±0.5
Wastewater + waste ethanol	60±10	296±10	145±5	55±3	0.10±0.1	0.78±0.5

Table 2 Comparison of methanol, ethanol, and acetate as carbon sources for denitrification

Carbon sources	Denitrification rate (mg NO ₃ -N/(g VSS·h))	Sludge yield (g MLSS/g COD)	Adaptation time	Response time	Price
Methanol	3.2 (relatively low)	0.40	Long (about 40 d)	Slowly (several days)	Low
Ethanol	9.6 (relatively high)	0.42	Short	Quickly (several hours)	Low
Acetate	12 (relatively high)	0.65	Short	Quickly (several hours)	High

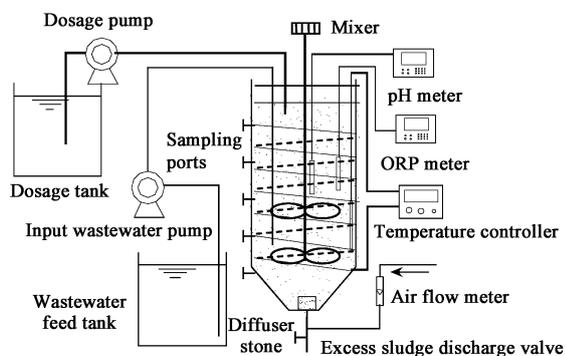


Fig. 2 Schematic diagram of the SBR reactor.

utilization rate were measured in the system with the use of external carbon sources, and the denitrification rates of ethanol, acetate, and methanol reached as high as 9.6, 12, and 3.2 mg NO₃-N/(g VSS·h), respectively at 20°C. The denitrification activity and the ratio of consumed COD to removed nitrate-N measured in NUR tests under different temperatures are shown in Fig.3. A significant difference can be seen between the denitrification activity of ethanol and methanol, the denitrification activity of ethanol was about three times as that of methanol; hence, denitrification with the external of ethanol and acetate requires a considerably smaller volume. The denitrification activity and the consumed COD to removed nitrate-N ratio are influenced by temperature, and therefore temperature correction must be introduced. The consumed COD to removed nitrate-N ratio for ethanol was lower than that of methanol. This may be explained by the ethanol enrichment bacteria exhibiting a high degree of endogenous respiration, resulting in a considerably lower growth yield, and thereby lower consumed COD to removed nitrate-N ratio.

The carbon source is used as the energy source and substrate for further growth of bacteria, and therefore the microbiology of the sludge will change when external carbon source is added. The average denitrification rate

was increased to a maximum value in about 40 d with methanol as the external carbon source. The adaptation time for the denitrifying biomass was short for ethanol and acetate (Table 2). The experiments studied the response of the secondary effluent nitrogen concentration when the three carbon sources were respectively added to the pre-denitrification system. The results show that effluent nitrogen concentration did not respond immediately while adding methanol, whereas when ethanol and acetate were added, the response was almost immediate (Table 2).

It is suggested that the volume for denitrification be made three times smaller if ethanol is utilized instead of methanol for the same amount of COD required and the same sludge yield as well. During winter, at especially low temperature, ethanol must be used as the carbon source, to obtain good performance of nitrification and denitrification under limited reactor volumes. With respect to the process conditions as available volume for denitrification and to economical aspects as price and availability, the comparison shown in Table 2 suggests that ethanol is the best external carbon source in application. However, it has been shown that the nitrogen standards of 10 mgN/L in the effluent can be met with the three external carbon sources.

2.2 Denitrification rate without or with the waste ethanol addition

During the denitrification step using a typical wastewater as the carbon source, three different rates can be generally recognized: the first and the highest, is firstly determined by the soluble readily degradable COD availability, the second by the particulate slow biodegradable COD, and the lowest in endogenous conditions (Kujawa and Klapwijk, 1999). In domestic wastewaters, the readily biodegradable COD fraction (S_s) generally accounts for only 10%–20% of the total COD and its contribution in the overall denitrification rate is not prevailing (Henze *et al.*, 1994); therefore the particulate COD fraction (X_s) determines the overall denitrification potential of a wastewater. Since only low weight organic molecular

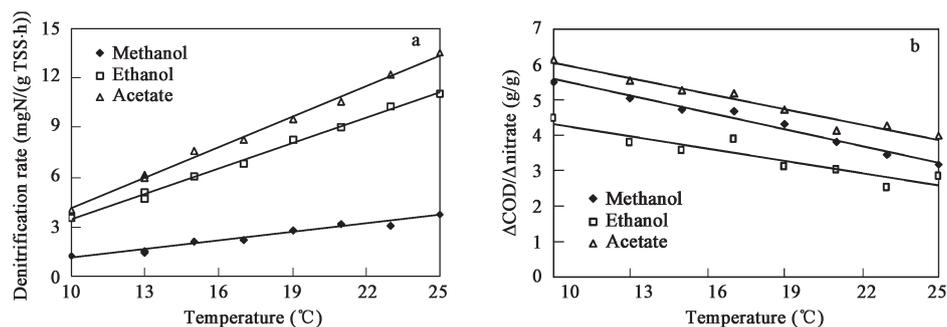


Fig. 3 Denitrification rates (a) and the consumed COD to nitrate-N ratio (b) for different carbon sources.

compounds are readily used in the denitrification step, the denitrification rate on Xs is determined by the hydrolytic and fermentation phenomena occurring in the anoxic step of a BNR system by which the conversion of Xs into Ss is carried out.

In general, the total denitrification rate of starch wastewater allows a typical value of 0.74 mgN/(g MLVSS·h) (at 20°C), which is the result of two different denitrification rates, i.e. one depending on the particulate COD and the other on the endogenous respiration. The typical denitrification rates observed during NUR tests are shown in Table 3. Fig.4a depicts the typical nitrates profile during a NUR test after the addition of the starch wastewater. The denitrification step depending on soluble COD is not present. In this case, no real contribution is made by the readily biodegradable COD fraction, and therefore only the particulate COD and the endogenous activity determine the overall denitrification potential of this wastewater. Thus the hydrolysis rate is the limiting step, since it is the only way to increase the Ss availability. As a result, no satisfactory nitrogen removal can be achieved under these conditions. To increase the denitrification rate and to enhance the nitrate removal, external COD was added. When the waste ethanol was added to the starch wastewater, an entirely different nitrate trend was observed as shown in Fig.4b. The total denitrification rate is about 2.11 mgN/(g

MLVSS·h), increased by 3 times as against wastewater containing only starch. This value is the combination of three different rates: the first, which is the highest, is because of the ethanol addition and depends on the Ss larger availability. With the waste ethanol addition, the maximum denitrification rate is characteristically close to 9 mgN/(g MLVSS·h) and is similar to the result obtained using pure ethanol carbon sources. The second relies on Xs, this value is higher than that obtained exclusively with wastewater as the electron donor. The third, endogenous denitrification rate is the same as for the wastewater experiment.

2.3 Denitrification potential without or with the waste ethanol addition

According to Kujawa and Klapwijk (1999), the denitrification potential (DP) of a wastewater can be described as the amount of nitrate, expressed as mg NO₃-N/L, which can be denitrified on the COD fractions Ss and Xs:

$$DP_{Ss} = \frac{\Delta(\text{NO}_3\text{-N} + 0.6\text{NO}_2\text{-N})}{f_{ww}} \tag{1}$$

$$DP_{Xs} = \frac{\Delta(\text{NO}_3\text{-N} + 0.6\text{NO}_2\text{-N})}{f_{ww}} \tag{2}$$

where, f_{ww} is the wastewater/activated sludge ratio and 0.6 is the conversion factor from nitrites to nitrate nitrogen. The denitrification potential of the wastewater fractions does not rely on the mixed liquor biomass concentration. Even with different MLSS levels, the amount of nitrate that can be denitrified on the subsequent wastewater fractions, Ss and Xs, is always the same and only the reduction rate changes. If the Ss and Xs fractions are not adequate for the denitrification process, endogenous denitrification is also required to accomplish the effluent standards for total nitrogen. The denitrification potential for endogenous conditions depends on the total denitrification volume and is given by:

$$DP_{end} = \frac{r_{d,end} V_d}{Q_{in}} \tag{3}$$

where, V_d represents the denitrification step volume and Q_{in} represents the wastewater inflow rate; thus, this ratio is, in other words, the hydraulic retention time (HRT) of the anoxic zone. If the biomass concentration in the denitrification step varies, the specific endogenous denitrification potential is to be used:

$$DP_{end,spec} = \frac{r_{d,end} V_d}{Q_{in} X_v} = \frac{k_{d,end} V_d}{Q_{in}} \tag{4}$$

where, X_v is the biomass concentration (mg/L) in the anoxic step. Ultimately, the total denitrification potential of the system depends, firstly, on the wastewater characteristics and, secondly, on the basic denitrifying activity of the sludge:

$$\sum DP = DP_{Ss} + DP_{Xs} + DP_{end,spec} \times X_v(V_d) \tag{5}$$

Table 4 summarizes the denitrification potential of the starch wastewater with and without the waste ethanol

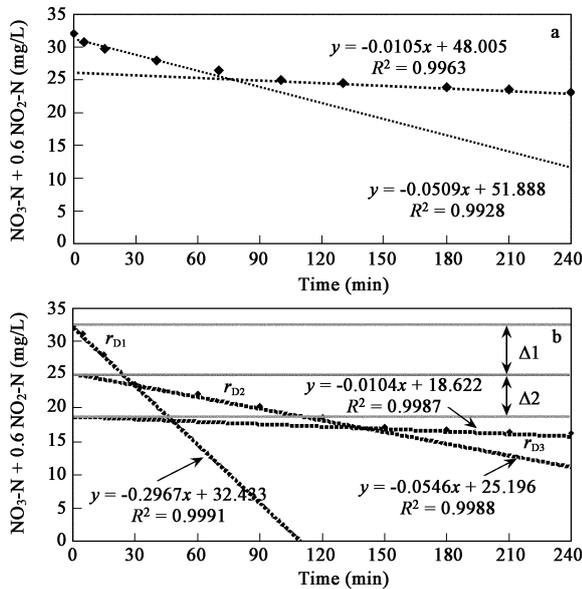


Fig. 4 Typical trend of the nitrate of starch wastewater without (a) and with (b) the waste ethanol addition.

Table 3 Typical denitrification rates observed during NUR tests (mgN/(g MLVSS·h))

Denitrification rate	Starch wastewater	Waste ethanol +starch wastewater
r_{D1}	–	8.9
r_{D2}	1.53	1.97
r_{D3}	0.30	0.34
r_D observed	0.74	2.11

r_{D1} is the denitrification rate on Ss, Xs, and endogenous respiration, r_{D2} is the denitrification rate on Xs and endogenous respiration, r_{D3} is the denitrification rate on endogenous respiration.

Table 4 Denitrification potential

Denitrification potential	Starch wastewater	Starch wastewater +waste ethanol
DP_{Ss} (mg $\text{NO}_3\text{-N/L}$)	0	9.1
DP_{Xs} (mg $\text{NO}_3\text{-N/L}$)	5.4	7.2
DP_{end} (mg $\text{NO}_3\text{-N/L}$)	0.2	0.2
$\sum DP$ (mg $\text{NO}_3\text{-N/L}$)	5.6	16.5

addition. As seen, the denitrification potential of the latter is nearly three times as great as the former's because of the increase of the Ss and Xs COD fractions with the addition of the waste ethanol, whereas the denitrification potential on the endogenous activity is the same.

The effluent nitrate concentration from a WWTP where COD is used exclusively for denitrification can be predicted by:

$$\text{NO}_3\text{-N}_{\text{eff, theory}} = \text{TKN} - \text{NH}_4\text{-N}_{\text{eff}} - \text{N}_{\text{org, eff}} - \frac{i_N \times P_x}{Q_{\text{in}}} - \sum DP \quad (6)$$

where, i_N is a fraction of N in biomass, mgN/g MLSS; P_x is the daily removal of surplus sludge, mg MLSS/d; $\text{N}_{\text{org, eff}}$ represents the effluent organic nitrogen. To use Equation (6) for predicting the nitrate effluent quality, it must be ensured that Ss and Xs are utilized exclusively in the predenitrification volume and are not transported into the aeration volume.

However, in fact, one part of Ss and Xs will enter the aerobic volume. To correctly predict the effluent nitrate concentration, the required denitrification volume for Ss (V_{Ss}) and Xs (V_{Xs}) completely utilized must be calculated:

$$V_{Ss} = C_{Ss, \text{in}} \times Q_{\text{in}} / r_{Ss}, V_{Xs} = C_{Xs, \text{in}} \times Q_{\text{in}} / r_{Xs}$$

where, $C_{Ss, \text{in}}$ is the influent Ss concentration, $C_{Xs, \text{in}}$ is the influent Xs concentration, r_{Ss} and r_{Xs} are the anoxic substrate utilization rates for Ss and Xs, respectively, calculated based on Equations (10) and (11).

Thus, Equation (6) is modified to:

$$(\text{NO}_3\text{-N})_{\text{eff, theory}} = \text{TKN} - (\text{NH}_4\text{-N})_{\text{eff}} - \text{N}_{\text{org, eff}} - \frac{i_N \times P_x}{Q_{\text{in}}} - \left(\frac{V_{\text{anoxic}}}{V_{Ss}} DP_{Ss} + \frac{V_{\text{anoxic}}}{V_{Xs}} DP_{Xs} + DP_{\text{end}} \right) \quad (7)$$

where, V_{anoxic} is the anoxic volume.

When the wastewater characteristics, the anoxic substrate utilization rates, and the endogenous denitrification rate are known, the part of wastewater COD that takes part in the denitrification process can be estimated. Based on the batch NUR tests, a series of denitrification potentials was obtained with average values of 12.9 mgN/L. These values characterized the settled domestic wastewater with an average total COD of 250 mg/L and TN of 55 mgN/L; Equation (7) was implemented to predict the denitrification potential of the fully nitrifying pilot plant, fed with the same wastewater (starch wastewater without waste ethanol addition) as examined in the batch tests. Since the activated sludge of the plant was the same as used for the tests,

all data could be transferred. The predicted effluent nitrate quality was 20.3 mg $\text{NO}_3\text{-N/L}$, which was in accordance with the average results from the pilot plant.

2.4 Nitrates utilization rate (NUR) tests of wastewater characteristics

Batch NUR tests with a pulse dose of wastewater enable to characterize the wastewater for Ss and Xs (mg COD/L); the biodegradable fractions of the wastewater and the anoxic substrate utilization rate (r (mg COD/(g MLVSS·h)) for Ss and Xs can be calculated from Fig.3 using the following equations:

$$C_{Ss} = \frac{2.86\Delta(\text{NO}_3\text{-N} + 0.6\text{NO}_2\text{-N})_1}{1 - Y_H} \times \frac{1}{f_{\text{ww}}} \quad (8)$$

$$C_{Xs} = \frac{2.86\Delta(\text{NO}_3\text{-N} + 0.6\text{NO}_2\text{-N})_2}{1 - Y_H} \times \frac{1}{f_{\text{ww}}} \quad (9)$$

$$r_{C_{Ss}} = \frac{2.86(r_{d1} - r_{d2})}{1 - Y_H} \quad (10)$$

$$r_{C_{Xs}} = \frac{2.86(r_{d2} - r_{d3})}{1 - Y_H} \quad (11)$$

When the wastewater characteristics and the kinetic parameters are known, the relation between the overall denitrification rate and the applied anoxic sludge loading rate of the predenitrification volume can be modeled. This relation provides information for optimizing the denitrification by increasing the COD/N-ratio with respect to Ss and Xs, and this can be useful in decision-making for enhancing the process with an external carbon source.

For the pre-denitrification system, it has been found that controlling the nitrate concentration at the end of the anoxic zone at a low set-point (1–2 mg/L) minimizes the amount of external carbon required while maintaining the long-term average effluent nitrate nitrogen concentration at a pre-specified level. With the NUR tests, the required external carbon dosage can be obtained to maintain the nitrate concentration at the end of the anoxic zone at the pre-specified set point.

3 Conclusions

The investigation described in this article has conveyed some important information about the advantages of using external carbon sources, on the basis of the denitrification potential evaluation.

The results showed that methanol, ethanol, and acetate as carbon sources for denitrification all functioned well, but on the basis of the denitrification potential, the sludge yield, the adaptation time, the response time, and the price, ethanol was found to be the best carbon source for denitrification.

To increase the denitrification rate and the denitrification potential, the waste ethanol was added into starch wastewater; it was found that there is a significant difference between the denitrification activity using starch wastewater and the external carbon sources. A real denitrification enhancement can be accomplished by the addition of the waste ethanol: nearly 3 times increase (from 5.6 to 16.5 mg $\text{NO}_3\text{-N/L}$) of this value was observed.

The anoxic NUR batch tests were used to evaluate the kinetics of the denitrification process, which included determining the wastewater characterization, the denitrification rate, the anoxic substrate utilization rate of Ss and Xs, as well as the denitrification potential of the wastewater, and estimating the overall denitrification potential of the plant.

By determining the denitrification potential and the wastewater characteristic, more precise information is gained about the process efficiency than the COD/N ratio, which is used for design purposes, and the required external carbon dosage can be obtained to maintain the nitrate concentration at the end of the anoxic zone at the pre-specified set point.

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