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A Case Study on the Relationship between Conductivity and Dissolved Solids to Evaluate the Potential for Reuse of Reclaimed Industrial Wastewater

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Abstract

A case study was conducted to evaluate and identify the main materials and sources affecting the conductivity of reclaimed industrial wastewater for reuse. There were two suppliers (food production companies, S and M) and two users (pulp and paper making companies, P1 and P2). The user requirements for quality of the reclaimed water were conductivity <1,000 μS/cm and Volatile Suspended Solids (VSS) <10 mg/L. Conductivity of treated wastewater at M company varied from 872 to 1620 μS/cm, but the VSS was very stable over the year, with an average of 5 mg/L. According to the source tracking of M company, it was determined that the main materials affecting conductivity were TDS, Ca^{2+}, and Na^{+}. Electrical Conductivity (EC) measurement is sometimes the only practical method for the analysis of Total Dissolved Solids (TDS); therefore, developing this relationship would be helpful for company-to-company wastewater reuse. In this case study, the ratio of TDS to EC was in the range of 0.58-0.67, with a mean value of 0.64 and a very strong relationship at the effluent point. Even though the results were from only one industry, this conversion factor could be used to estimate TDS using EC measurements for similar industrial wastewater and could motivate further research for the direct use of treated industrial wastewater. This study is a first case study of company-to-company wastewater reuse.

Keywords: *conductivity, TDS (Total Dissolved Solids), reclaimed industrial wastewater, source tracking, cations*

1. Introduction

In the Banwol & Sihwa industrial complex, pulp and paper making industries consume 11.1% (over 2 million ton/year) of the total industrial process water used in the complex. The operating and maintenance costs in these industries are gradually increasing in relation to increasing potable water prices. To save costs, about 70% of the process water is recycled. However, there are several problems associated with this water reuse, including scales, clogging, deterioration of process water quality, and inorganic materials accumulated in the recycling system. Thus, the recycled water quality must be improved through the use of potable water or by enhancing the performance of the recycling system. Reuse of treated municipal and industrial wastewater with high water quality has been recommended. However, reclaimed municipal and industrial wastewater has been reused mainly as gray water, agricultural and golf course irrigation, groundwater and dried river recharging water, not as industrial process water. Recently, the Korean government has begun rearranging and improving the Environmental Law and other related laws to enhance reclaimed water and industrial solid wastes reuse. However, there are no specific guidelines for reusing reclaimed water according to sector (urban, industry, agriculture, and so on) and application.

The measurement of the Electrical Conductivity (EC) of liquids, which is generally determined by the ionic compounds dissolved in water, is important in many industries. EC measurement in any solution illustrates the presence of organic and inorganic materials in the solution. Using EC, direct relationships with the level of impurities present in specified solutions can be determined. In the U.S. and Australia, water reclamation practices are becoming very popular, and EC is known to be an important parameter of reclaimed water quality (EPA, 1999).

There have been several different studies conducted to determine the relationship between EC and Total Dissolved Solids (TDS) in surface water and ground water, but few studies have been performed on this relationship in the industrial sector. A past study established a relationship between TDS and EC in groundwater and concluded that the ratio of TDS and EC ranged from 0.527 to 0.597 for water with an EC of 106-2050 μS/cm (Day and Nightingale, 1984). In natural water case studies, a conversion factor range of 0.54-0.96 was established, with most falling between 0.55 and 0.75. Also, there is a direct relationship between EC and TDS when assuming that groundwater contains

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ions (Hem, 1985). It was demonstrated that, for the desalination industry, one factor alone was not suitable for determining the relationship between EC and TDS (US EPA, 2004). EC also showed a correlation with organics and soluble nutrients in liquid manure but did not show any relationship with phosphorus (Steven *et al.*, 1995).

Conductivity is a good surrogate for total cation and salinity estimations (APHA, 1995). A relationship between Total Dissolved Ions (TDI) and EC data of natural surface water samples from Queensland was found and used to establish a ratio between TDI and EC for future predictions (McNeil and Cox, 2000). They concluded that the most suitable range for the ratio was from 0.65-0.72 for EC values up to 800 μS/cm, while higher EC values resulted in ratios in the range of 0.58-0.64. EC is also used to estimate total ionic concentrations and ionic salinity (Zinabu *et al*., 2002). A previous study concluded that TDS was a geochemical parameter that established a relationship between bulk conductivity and microbial degradation of hydrocarbons in groundwater (Atekwana, 2004).

The US EPA recommended EC as an important factor for reclaimed water quality in different fields such as agriculture and industrial reuse (US EPA, 2004). Also, wastewater from different sources (municipal treatment plants and industrial treatment plants) has been shown to have high concentrations of ions, which increased the conductivity of the effluent samples, requiring additional treatment to maintain the parameters within the established limits (Kim, 2007). Some studies concluded that a regression line is helpful for converting EC data into nutrient levels (nitrogen and potassium) in animal slurry (Provolo and Suller, 2007). However, limited work has been conducted to determine the correlation between TDS and EC in industrial reclaimed wastewater. Every industry discharges different kinds of effluents with different concentrations of salts and ions, so TDS/EC ratios are different across industries.

The purpose of this study was to evaluate the quality of wastewater from a food production company in order to reuse it as process water according to the user requirements. Thus, source tracking was used to identify which factors affected wastewater quality. The other purpose of this study was to determine a relationship between EC and TDS of treated wastewater as a valid method for predicting solid concentrations in the treated wastewater by measuring the EC of a water sample.

2. Materials and Methods

2.1 Suppliers and Users of Reclaimed Industrial Wastewater

Two suppliers which manufacture bread and milk (S and M companies) and two users of pulp and paper (P1 and P2 companies) were investigated. Of the user process water, 30% is tap water and 70% is reused. According to increasing recirculation frequencies, the recycled process water quality was seriously deteriorated, and accumulated Suspended Solids (SS) and other various inorganic materials caused clogging in the filtering system and scale and slime in the water supply pipe lines. Therefore, the recycled process water quality should be improved by increasing the potable water amount or substituting with reclaimed water. P1 and P2 companies will use reclaimed industrial wastewater instead of potable water if the water quality satisfies the requirements. The reclaimed water qualities required by P1 and P2 companies were conductivity <1,000 μS/cm and Volatile Suspended Solids (VSS) <10 mg/L.

2.2 Sampling Points

M company was investigated as a case study because the treated wastewater from S company had excessively high levels of VSS and conductivity that disallowed its reuse as processing water (see section 3.1). M company has two plants, one old and one new, which were constructed in 1985 and 1993, respectively. In the old plant, there are 15 manholes, although only three were selected as sampling points because wastewater coming from these manholes was considered representative of the entire wastewater supply (Fig. 1). Wastewater flowing to manhole-1 (MH #1) came from the milk- and yogurt-making section, flow from manhole-2 (MH #2) came from milk processing, and flow from manhole-3 (MH #3) came from the cheese-making process. A point just before the mixing tank and the tank which held the wastewater from the new plant, subsequently referred to as “old plant,” was selected because it was the point at which the wastewater flowing from all 15 manholes collected. Other sampling points were at the mixing tank and at the wastewater effluent point. Relationships between EC and TDS were evaluated at all sampling points.

Wastewater effluents were obtained after they were treated in an oxidation ditch to remove contaminants. Samples were collected twice a day (11:00 AM and 3:00 PM) on a weekly basis

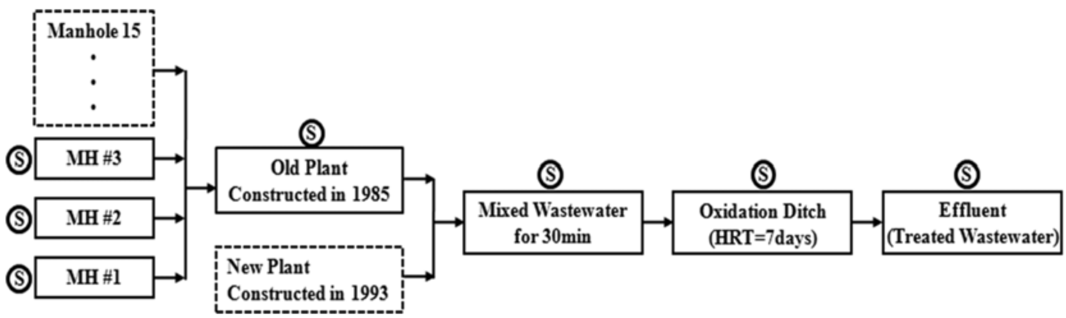

Fig. 1. Sampling Points for Source Tracking in M Company (S: Sampling point)

for one year. The times 11:00 AM and 3:00 PM were selected because the labor shift changes at this time and because the daily washing of different sections of the plant happens at this time, respectively.

2.3 Analytical Method

Two recycled process water sources, two treated wastewater sources, and all samples in M company were analyzed according to standard methods (APHA *et al*., 2005). Total solids, pH, and turbidity were measured. Conductivity was measured with a conductivity meter (Model No. 85/10 FT, YSI 85, USA), and cation concentrations (Ca^{2+}, Mg^{2+}, Fe^{2+}, and Na^{+}) were analyzed using ICP-MS.

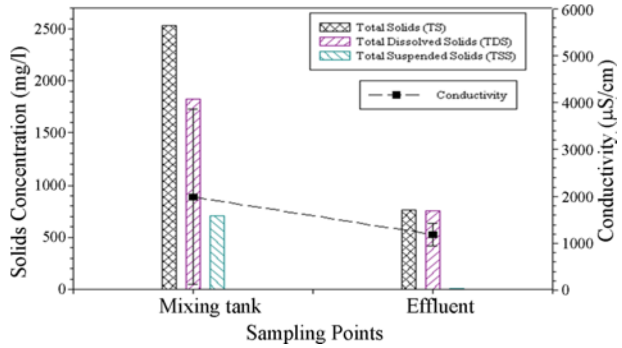

Fig. 2. Solids and Conductivity Change in M Company Wastewater Treatment Plant

3. Results and Discussion

3.1 Water Quality of Recycled and Treated Wastewater

The qualities of recycled process water of P1 and P2 companies and the treated wastewater of S and M companies are summarized in Table 1. P1 company wanted to reuse the treated wastewater from S company, but the VSS concentration (44 mg/L) was much higher than the concentration limit of 10.0 mg/L. The high VSS resulted from weak and unstable removal efficiency in the flotation process after chemical coagulation of the wastewater in S company. Therefore, this treated wastewater could not be used as a substitution for process water in P1 company. On the other hand, the water quality of the treated wastewater from M company was high and very stable. Thus, M company was selected as a case study for source tracking and estimation of the relationship between TDS and EC.

In the treatment plant of M company, there were fluctuations in the solids and conductivity data in the water before the mixing tank, while the data at the effluent points were quite stable (Fig. 2). At the mixing tank, almost 80% of the solids were dissolved solids, and the average EC was approximately 2000 µS/cm (Fig. 2). At the effluent point, over 90% of the solids concentration consisted of dissolved solids, and the average EC was approximately 1,200 µS/cm.

There was no uniformity in the wastewater coming from different source points until mixing tank. That's why the solids data were very fluctuating at each point while at the effluent point there was found stability in the conductivity as well as solids data. The average value of conductivity at mixing point was 1,700 µS/cm with high standard deviation (approx. ± 1100) while total solids and TDS were around >2,500 mg/l and 1,896 mg/l, respectively. Similarly the average conductivity at effluent point was 1,175 µS/cm with less standard deviation in data and total solids and TDS were 840 and 760 mg/l, respectively. The reason of stability in data at effluent point was because of application of equalization tank at the mixing point. At the effluent point the wastewater was containing about 90% of dissolved solids so no need to find other parameters relationships like suspended solids etc. so it was found that TDS was main material which affects conductivity directly at effluents discharged wastewater.

Wastewater discharged from different points fluctuated so much that diverse values of EC were observed in two samples collected within duration of 2-5 minutes. A reason for the high fluctuation in conductivity was due to insufficient equalization time (30 min). However, conductivity did not decrease throughout the biological treatment because of the inability to remove inorganic materials and cations. Conductivity might be improved by controlling and handling the main sources and materials, especially TDS (Atekwana, 2004).

3.2 Main Source Affecting Conductivity

There were variations in Ca^{2+} and Na^{+} in each source tracking point sample (Fig. 3). The sampling point with the highest concentrations of Ca^{2+} (167.6 mg/L) and Na^{+} (114.1 mg/L) was MH #3, which was connected to the NaCl-containing cheese-producing lines. The concentrations of other ions were very small compared to Ca^{2+} and Na^{+}. Sodium ions are well known for raising conductivity and decreasing soil permeability (Horneck *et al*., 2007, Harivandi, 2007, Christian, 1999). It was not recommended in reclaimed water reuse guidelines of the US EPA (US EPA, 2004). In addition, Ca^{2+} has been shown to increase conductivity and scale formation in pipelines supplying reclaimed water (US EPA, 2004). Therefore, based on the information in Figs. 2 and 3, it was determined that the major materials affecting con-

Table 1. Recycled and Treated Wastewater Qualities of Users and Suppliers (Average±standard deviation)

Wastewater	Conductivity (µS/cm)	Turbidity (NTU)	TS (mg/L)	TDS (mg/L)	TSS (mg/L)	VSS (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)
P1 (Recycled)	3295±957	166±54	2874±536	2782±517	93±21	78±32	397±64	20±2
P2 (Recycled)	5860±764	1544±904	7237±176	6700±54	537±231	393±194	1137±152	35±3
S (Treated)	2112±593	78±52	1440±191	1391±191	50±35	44±31	27±4	5±1
M (Treated)	1189±242	38±25	765±38	755±38	9±4	5±3	29±2	3±1

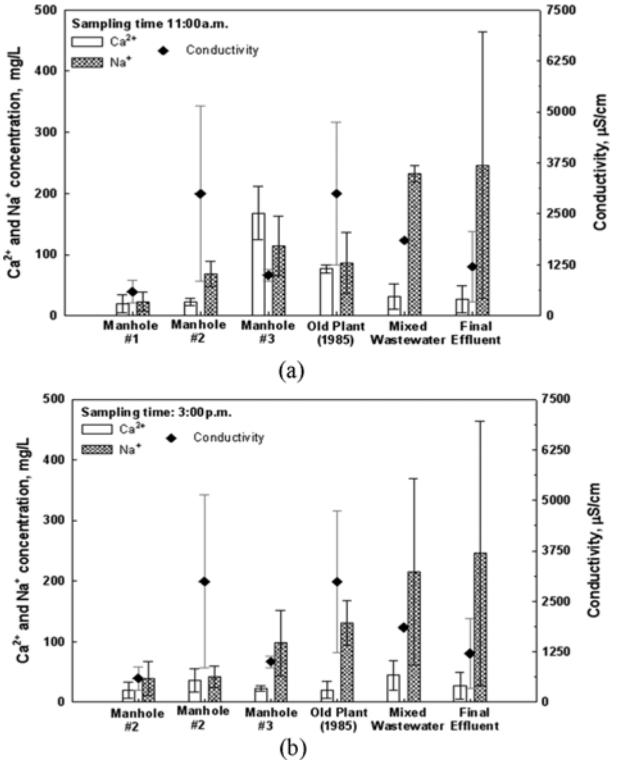

Fig. 3. Variations in Ca^{2+}, Na^{+}, and Conductivity at Each Source Tracking Sampling Point in M Company.

ductivity in the wastewater of M company were TDS, Ca^{2+} and Na^{+}. From the results in Fig. 3, it was determined that excess conductivity (based on a limit of 1,000 µS/cm) could be neutralized by controlling Na^{+} concentration. Such control could be adequately performed with water in a storage tank (for example, a pumping station for supplying reclaimed water to P2 company). According to the source tracking results, TDS, Ca^{2+}, and Na^{+} should be monitored and introduced as reclaimed water according to quality regulations in order to reuse the treated wastewater from other industries as recycled process water in the paper-making industry.

3.3 Relationship between Conductivity and Dissolved Solids

The equation below is used to estimate the TDS according to a measured conductivity (Aquarius Technologies, 2000).

$$\text{TDS (Total dissolved solids, mg/L)} = K \cdot \text{EC (Electrical conductivity, µS/cm)} \quad (1)$$

"K" is a factor called cell constant relates to the physical characteristics of the measuring cell and is affected by many measurements, such as temperature, etc. In simple sense, K shows the relationship between TDS/EC of any solution. The value of K is different for different waters (ground water, surface water, industrial water) depending upon concentrations of different ions in that water.

The TDS was determined at each sampling point by measuring the conductivity. After measuring the EC online at the effluent point, the result was multiplied by factor "K" to roughly estimate the concentration of dissolved solids in the treated reclaimed water. This case study gave "K" value for milk processing industry for TDS estimation.

Table 2 shows the ratio of TDS/conductivity at different sampling points in M company. The EC and TDS values for all wastewaters fluctuated significantly. At MH #1, a regression equation with a very low coefficient value (R^2= 0.034) was calculated, showing no clear relationship between EC and TDS. The mean value of 'K' at MH #1 was 2.01, although a wide range of variation was observed. At MH #1, wastewater was coming from the yogurt-manufacturing sections, which had a different production schedule and shift change time compared to those in the other sections, thus, no clear relationship was seen. At MH #2 and MH #3, the 'K' values were 0.41 and 1.81, respectively, due to the high concentration of organic matter coming from the curd-, butter-, and cheese-making sections. At MH #2 and MH #3, wastewaters from the butter- and cheese-making sections were arriving with different characteristics, so no clear relationship was observed at these points. At MH #2, a curvilinear relationship was found but had a very low regression coefficient (R2=0.009) (Fig. 4b). The old plant also showed fluctuating results even though it contained wastewater from all 15 manholes. There were changes in the EC and solids data because of changing production loads, washing of tanks, cleaning of different sections, and the use of different salts in the food production processes. This explains why the total dissolved solids, volatile dissolved solids, and fixed dissolved solids data were highly variable and why the ratios of TDS/EC were not constant for all sampling points.

Wastewater from MH #1 was from the milk-processing and curd-making sections, which had an EC range of 150-750 µS/cm (Fig. 4a). At MH #2, an inverse curvilinear equation showed that, as the conductivity value increased, the ratio decreased until an EC of 1,100 µS/cm, after which the ratio remained constant (Fig. 4b). However, at MH #3, a straight-line regression equation was obtained (Fig. 4c) with a regression coefficient of R^2=0.0008. The results showed that, at MH #3, more scattered data was common compared to that at other sampling points because cheese-manufacturing wastewater with high concentrations of TDS was entering into this location.

At the old plant, no clear relationship was found between EC and TDS; EC was very high, and TDS was variable, as shown in

Table 2. The Ratio of TDS/EC for the Various Wastewaters in M Company (Average±standard deviation)

Sampling point	Conductivity (µS/cm)	TDS (mg/L)	TDS/EC (mg·cm/µS·l)
MH #1	458±537	922±1227	2.01±1.95
MH #2	2276±3672	943±1217	0.41±1.26
MH #3	967±859	1750±2685	1.81±2.1
Old plant	2168±3763	1275±854	0.59±0.77
Mixing tank	2020±1859	1822±990	0.90±0.96
Effluent	1189±242	756±38	0.64±0.25

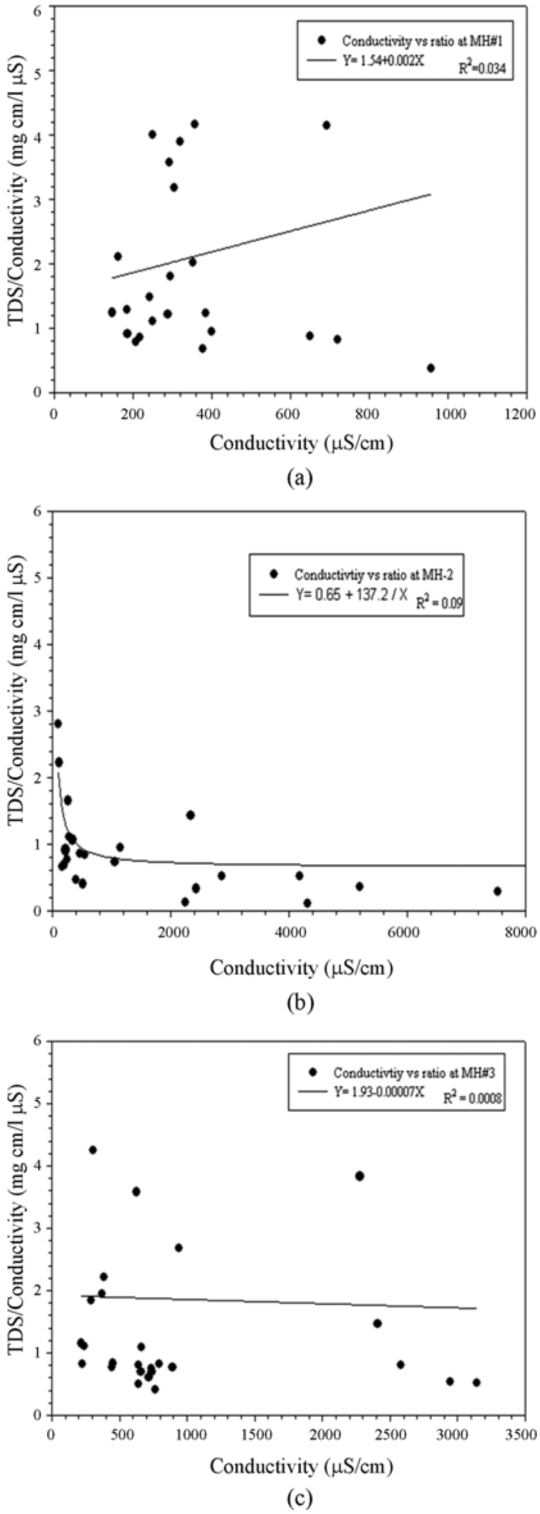

Fig. 4. Relationship between Conductivity and TDS/Conductivity at (a) MH #1, (b) MH #2, and (c) MH #3 in M Company

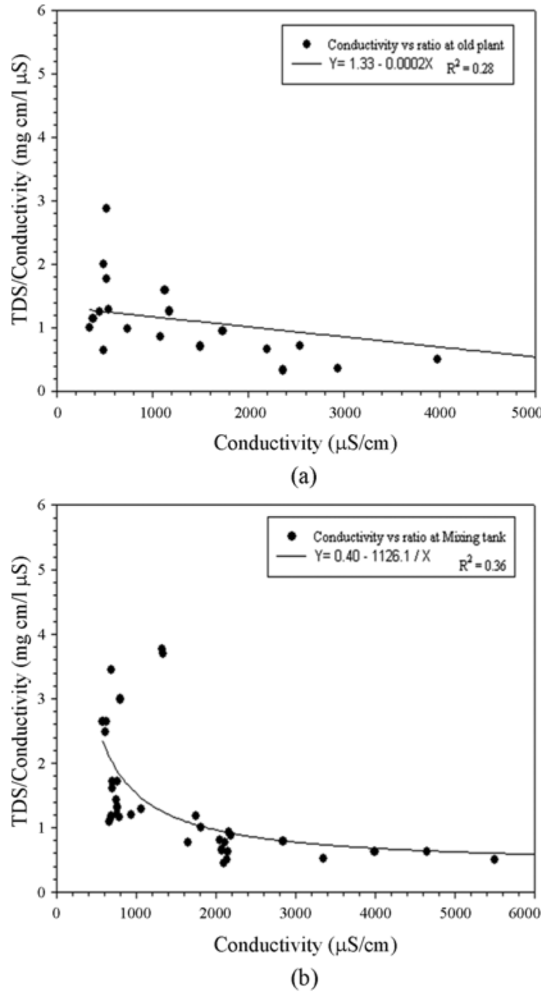

Fig. 5. Relationship between Conductivity and TDS/Conductivity at (a) the Old Plant and (b) the Mixing Tank in M Company

Fig. 5(a). At the mixing tank, although little stability was found in the TDS/EC ratios because the wastewater flowed in from all of the food-making plants, a slightly better curvilinear relationship (R^2=0.36) than that at the old plant (R^2=0.28) was seen (Fig. 5b).

At the effluent point, the EC ranged between 400-1600 μS/cm (Fig. 6). The ratio of TDS/conductivity was high (0.9-1.8) when EC was less than 800 μS/cm, but most of the sample ratios fell within the range of 0.58-0.66, with a median value of 0.605 and an average value of 0.64. Hem previously reviewed natural water case studies and reported that most conversion factors range between 0.55 and 0.75 (1985), similar to the range from the treated industrial wastewater in this study. Also, the ratios found in this study are similar to those from a previous study (McNeil and Cox, 2000) that concluded that the most suitable range for the TDS/EC ratio is 0.65-0.72. It has been reported that the total solid substances and ionized solids can be estimated when the EC of the water solution is multiplied by an empirical factor varying in the range of 0.55-0.99 depending on the nature of the dissolved solids and the temperature (APHA, 1985). The results of the regression in the present study show that there was not much variation (R^2= 0.982) in the EC data at the effluent discharge point.

In this case study, there were wide variations in flow rate and ion concentrations in milk-processing wastewater. The data were stable and uniform only at the effluent point after treatment. Since

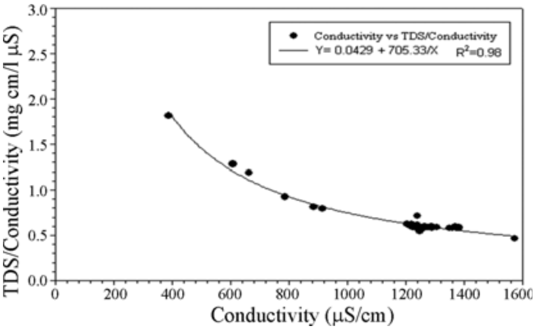

Fig. 6. Ratio of TDS/Conductivity at the Effluent Point in M Company

each specific industry discharges different qualities of effluents, the TDS/EC ratios are different across industries. The TDS/EC value (0.64) from this case study could be considered an average value for the milk-processing industry. Nevertheless, the conversion factor used in this study could be used to estimate TDS from EC measurements of similar industrial wastewater and to guide further research on the direct use of treated industrial wastewater as process water in other industries. This research was the first trial of company-to-company wastewater reuse.

4. Conclusions

Throughout the treated wastewater quality analysis, the recycled process water of P1 company was not able to be substituted with the treated wastewater of S company due to high VSS concentrations greater than 40 mg/L. However, the process water of P2 company could be substituted with the wastewater of M company after equalizing the conductivity. According to the source tracking in M company, the major materials that affect conductivity were identified as TDS, Ca^{2+} and Na^{+}. The relationships between EC and TDS were determined at the different sampling points. No clear relationship for any wastewater flowing into the wastewater treatment facility was found. Only the effluent after the wastewater treatment showed a strong relationship (R^2 = 0.98) between TDS/EC and conductivity. The regression equation Y= 0.0429 + 705.33/X was feasible for estimating the TDS/EC ratio (0.64 by average). The outcome and an innovative step of this study was an estimation of an appropriate conversion factor and a curve by which one can predict the dissolved solids concentration in a sample through the online measurement of conductivity in the milk-processing industry.

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