Development of an integrated ultrasonic membrane anaerobic system (IUMAS) for palm oil mill effluent (POME) treatment

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Abstract— Biofouling is a critical issue in membrane water and wastewater treatment as it greatly compromises the efficiency of the treatment processes. It is difficult to control, and significant economic resources have been dedicated to the development of effective biofouling monitoring and control strategies. This manuscript introduces and investigates the potentials of an integrated ultrasonic membrane anaerobic system (IUMAS) as a single reactor unit to overcome membrane biofouling and retain the methane gas, CH_4 in Pam oil mill effluent (POME) wastewater treatment. Six steady states were attained as a part of a kinetic study that considered concentration ranges of 11,760 to 18,400 mg/L for mixed liquor suspended solids (MLSS) and the mixed liquor volatile suspended solids (MLVSS) ranges from 9,000 to 16,008 mg/L. Steady state influent chemical oxygen demand, COD concentrations increased from 67,800 mg/L in the first steady to 82,700 mg/L in the sixth steady state. Kinetic equations from Monod, Contois, and Chen and Hashimoto were employed to describe the kinetics of POME treatment at organic loading rates ranging from 3 to 13 kg COD/m^3/day. The chemical oxygen demand, COD removal efficiency was from 94% to 97% with hydraulic retention times, HRTs from 750 to 10 days. The methane gas yield production rate was between 0.21 and 0.55 l/g COD/day. The complete treatment reduced the COD content to 4,962 mg/L equivalent to a reduction of 94%.

Keywords: POME; UMAS; methane; kinetics; COD; BOD

1. INTRODUCTION

Oil palm, scientifically known as Elaeis guineensis is one of the potential sources of biomass. Crude palm oil (CPO), produced from oil palm, has become an important commodity in the world, mainly dominated by Indonesia and Malaysia in terms of its production and exportation. Malaysia contributes about 30% of production and 37% of world exports contributing to the growth of gross domestic product (GDP) [1]. Processing fresh fruit bunches (FFBs) from palm trees for palm oil production generates several types of waste. Oil extraction, washing, and cleaning processes generate liquid waste, it calls palm oil mill effluent (POME). In the oil extraction process, three major operations generate the bulk of POME:

1. Sterilizing fresh fruit bunches
2. Clarifying extracted crude palm oil: pressing station, separation, clarification
3. FFB pressing for every ton of fresh fruit bunches processed, the mill discharges from 0.7–1 m^3 of POME. Fresh POME is (temperature 60–80°C), acidic (pH of 3.3–4.6), thick, brownish liquid with high solids, oil and grease, COD, and Biological Oxygen Demand (BOD) values.

Palm oil has risen to become the most produced and consumed vegetable oil in the world, widely used in food, cosmetic and hygienic products due to its affordable price, efficient production and high oxidative stability [2,3,4]. As reported by Hansen, et al. [5] and MPOB [6], Palm oil is the most produced vegetable oil in the world with a global production of almost 60 million tons and a global vegetable oil market share of more than 35% by weight in 2015.

POME is a highly polluting wastewater with high chemical oxygen demand (COD), total suspended solids (TSS), and biochemical oxygen demand (BOD) which can cause serve pollution to the environment, typically pollution to water resources [4, 7].

In Malaysia, palm oil industry is identified as one of the agricultural industries that generates the highest pollution load into rivers throughout the country [8]. Although POME is a non-toxic liquid waste with unpleasant smell, its COD and BOD values are high enough to cause serious pollution and environmental problem to the rivers. One of the biggest challenges in the palm oil industry is the disposal of its major waste products such as oil palm empty fruit bunch (OPEFB) and palm oil mill effluent (POME). Yearly, an estimated 60 million tons of POME and 9.9 million tons of OPEFB are generated from palm oil industry in Malaysia [9]. The current practice of burning the OPEFB for power generation has been discouraged due to the production of carbon dioxide, nitrous oxide and nitrogen dioxide and smoke which caused air and environmental pollution problems [10, 4]. Annually, an estimated 11,570 tons of POME anaerobic sludge is produced from 207,000 tons of fresh POME in a typical mill [11].

Membrane separation techniques have proven to be an effective method for separating biomass solids from digester suspensions and recycling them to the digester [12]. Several studies using membrane anaerobic processes to treat a variety of wastewaters [13, 14, 15, 16, 17] found that membrane anaerobic system (MAS) processes retained and due to long solids retention times liquefied and decomposed all particulate matter. To accurately and precisely design bioreactor, it is important to have values for the relevant kinetic parameters. These parameters depend on the substrate type, microorganisms and temperature. The three widely used kinetic models considered in this study are shown in Table 1. The purposes of the present work are to study the performance of (IUMAS) in treating POME and producing methane and to determine the kinetic parameters of the process, based on three known models; Monod, Contois and Chen & Hashimoto.

Table 1. Mathematical expressions of specifics substrate utilization rates for known kinetic models

odel	Equation 1	Equation 2
	$U = \frac{k\,S}{k_s + S}$	$\frac{1}{U} = \frac{K_s}{K}(\frac{1}{S}) + \frac{1}{k}$
	$U = \frac{U_{\max} \times S}{Y(B \times X + S)}$	$\frac{1}{U} = \frac{a \times X}{\mu_{\max} \times S} + \frac{Y(1+a)}{\mu_{\max}}$
ashimoto	$U = \frac{\mu_{\max} \times S}{Y\,K\,S_o + (1-K)\,S\,Y}$	$\frac{1}{U} = \frac{Y\,K\,S_o}{\mu_{\max}\,S} + \frac{Y(1-K)}{\mu_{\max}}$

2. MATERIALS AND METHODS

A. Raw POME Wastewater Preparation

The raw POME was collected from a near local palm oil mill in Lebah Hillier, Kuantan, Malaysia. The raw POME was stored in a cold room at 4 ^{o}C before use. Different dilutions of POME were prepared using tap water. The pH of the feed was adjusted to 7.0 using a 6 N NaOH solution.

B. UMAS Bioreactor Operation and Experimental Set-Up

A laboratory scale, IUMAS reactor with an effective 100-Litre volume Figure 1 was used in this study. The IUMAS reactor was consists of a cross-flow ultra-filtration membrane apparatus, a centrifugal pump and an anaerobic reactor. The total volume of the reactor was 100 Litre and the working volume was 75 Litre. Six multi frequency ultrasonic transducers, operated at 25 KHz, are bonded to two-sides of the tank chamber and connected to a Crest Genesis

Generator (250W, 25 KHz; Crest Ultrasonic, Trenton, NJ, USA). The maximum operating pressure on the membrane was 55 bars at 70 WC, and the pH ranged from 2 to 12.

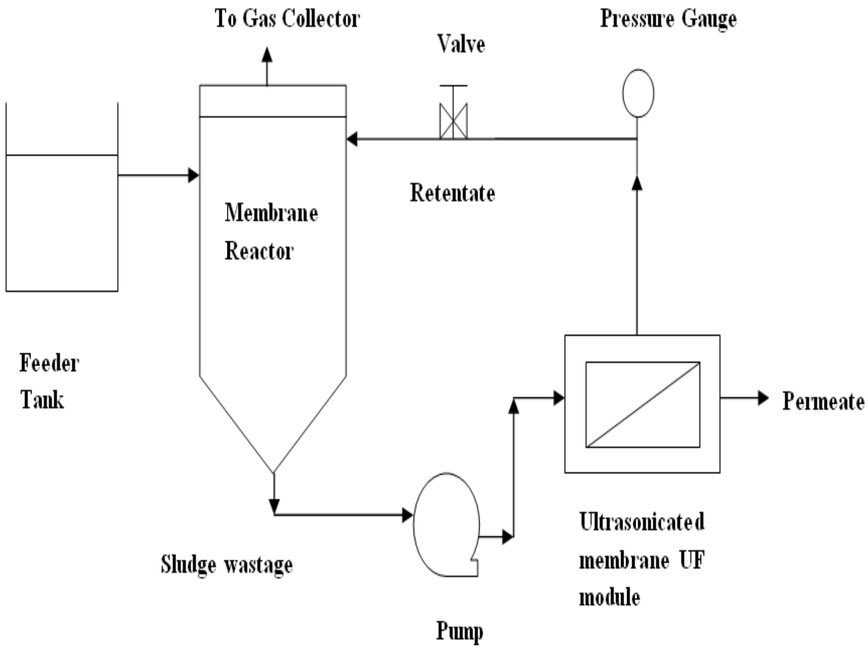

Figure 1: Configuration and start-up operational conditions of 100 Liter bioreactor

C. Analytical methods

The following parameters were analyzed: COD, BOD, pH, VSS, and TSS.

Methane gas was determined by gas chromatography with a stainless steel column (200 x 0.3 cm) packed with active carbon (30-60 mesh) using thermal conductivity detection). For TSS, VSS, volatile fatty acids and alkalinity were determined according to the Standard Methods. The COD was measured using a Hach colorimetric digestion method (Method # 8000, Hach Company, and Loveland, CO, USA). The MLSS and MLVSS were determined by drying the sample at 105 ºC and 550 ºC.

D. Bioreactor operation

The integrated ultrasonic membrane anaerobic system, IUMAS performance was evaluated under six steady states with different influent COD concentrations ranging from (67,800-82,700 mg/l), hydraulic retention time, HRTs (300.6-16.8 days) and OLR of (1.6-11.6 kg COD/m^3/d), as shown in Table 2. The system in this study was considered to have achieved steady state when the operating and control parameters were within ± 10% of the average value. To measure the daily gas volume, a 20 Liter displacement bottle was used to measure methane gas, CH_4 volume. The produced biogas contained only CO_2 and CH_4, so the addition of sodium hydroxide solution (NaOH) to absorb CO_2 effectively isolated methane gas (CH_4). Table 2 summarizes IUMAS performance at six steady states, that were established at different influent COD concentrations and HRTs. The kinetic coefficients of the selected models were derived from Eq. (2) in Table 1 using a linear relationship; the coefficients are summarized in Table 3.

Table 2. Summary of results (SS: steady state)

(SS)	1	2	3	4	5	6
g/L	67800	70500	73400	76800	80600	82700
e, mg/L	2034	2468	2936	3302	4352	4962
n (L/d)	240	310	325	350	375	391
d, L/g COD/d	0.29	0.34	0.47	0.68	0.73	0.80
	72	71.5	69.4	72.8	70.1	68.8
COD/d	0.21	0.24	0.33	0.50	0.51	0.55
	11760	12900	15380	16800	17200	18400
L	9000	10250	12250	13950	14940	16008
	76.53	79.46	79.64	83.04	86.86	87.00
	750.0	243.0	84.0	29.0	15.0	10.0
	900	300	150	50	21.0	14.0

)/m³/d	3	5	7	9	11	13
D/kg VSS/d	0.195	0.253	0.264	0.272	0.278	0.291
)/m³/d	0.0346	0.8454	3.3028	5.6657	7.7753	9.4528
removal	97.0	96.5	96.0	95.7	94.6	94.0

Table 3. Results of the application of three known substrate utilization models

	Equation	R^2(%)
	$U^{-1} = 2025\ S^{-1} + 3.61$ $K_s = 498$ $K = 0.350$ $\mu_{Max} = 0.259$	99.3
	$U^{-1} = 0.306\ X\ S^{-1} + 2.78$ $B = 0.111$ $u_{Max} = 0.344$ $a = 0.115$ $\mu_{Max} = 0.384$ $K = 0.519$	98.1
imoto	$U^{-1} = 0.0190\ S_o\ S^{-1} + 3.77$ $K = 0.006$ $a = 0.006$ $\mu_{Max} = 0.277$ $K = 0.374$	99.6

3. RESULTS AND DISCUSSION

The obtained performance results of IUMAS at six steady states were summarized in Table 2. The kinetic coefficients of the three selected models were derived from Eq. (2) in Table 1. by using a linear relationship and the coefficients were summarized in Table 3. At steady state conditions with influent COD concentration of 67,800-82,700 mg/L, the IUMAS performed well and pH in the reactor remained within the optimal working range for anaerobic digesters (6.7-7.8). At the first steady state, the MLSS concentration was 11,760 mg/L whereas the MLVSS concentration was 9,000 mg/L, equivalent to 76.53% of the MLSS. This low result can be attributed to the high suspended solids contents in the POME. However, at the six steady state, the volatile suspended (VSS) fraction in the reactor increased to 87% of the MLSS. This indicates that the long solid retention times, SRT of IUMAS facilitated the decomposition of the suspended solids and their subsequent conversion to methane gas (CH_4); this conclusion supported by [4, 15]. The highest influent COD was recorded at the sixth steady state (82,700 mg/L) and corresponded to an organic loading rate, OLR of 13 kg COD/m³/day, at this OLR, the IUMAS achieved 94% COD removal and an effluent COD of 4962 mg/L. This value is better than those reported by [18, 19] on anaerobic POME digestion. The three kinetic models demonstrated a good relationship ($R^2 > 94$ %) for the membrane anaerobic system treating POME as depicted in Figs. 2-4. The Monod and Chin and Hashimoto models demonstrated better, implying that the digester performance should consider organic loading rates. Results of these two models suggested that the predicted permeate COD concentration (S) is a function of influent COD concentration (S_o). the excellent fit of the three models ($R^2 > 94\%$) in this study suggested that the IUMAS process is capable of handling sustained organic loads between 3 and 13 kg COD/m³/day.

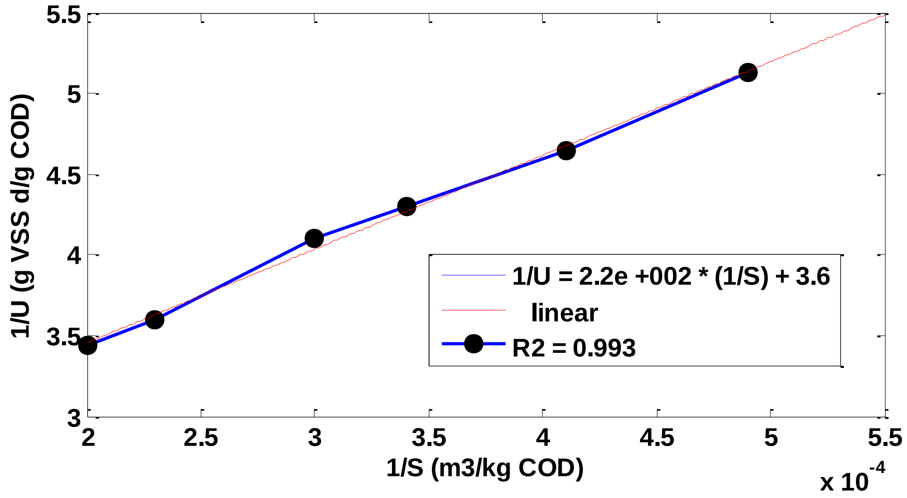

Figure 2: The Monod model.

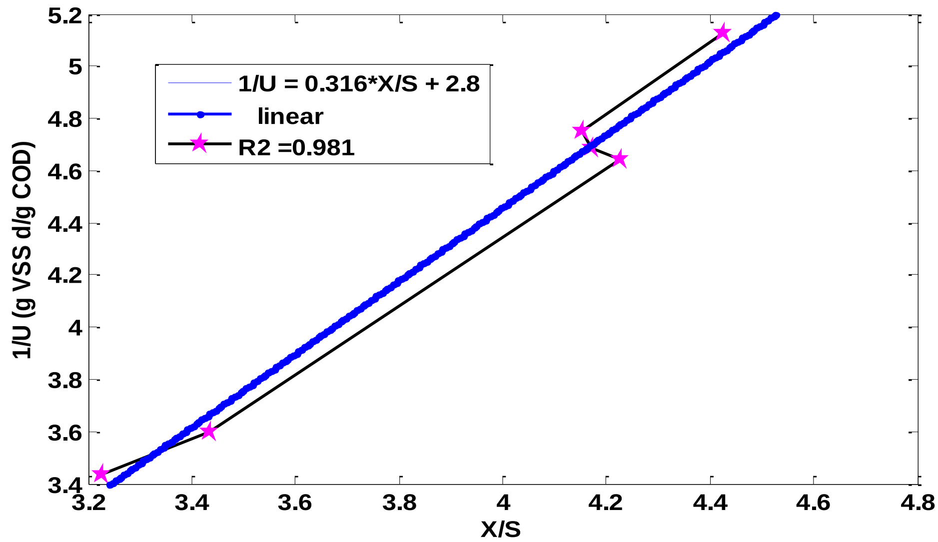

Figure 3: The Contois model.

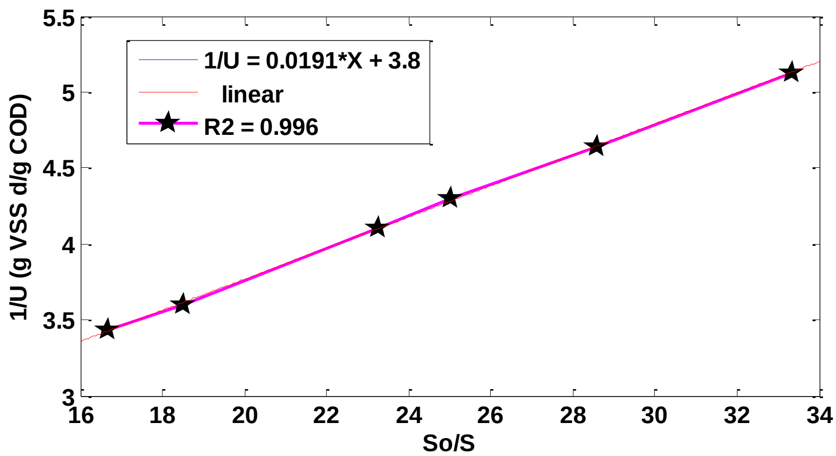

Figure 4: The Chen and Hashimoto model.

4. GAS PRODUCTION AND COMPOSITION

A. *IUMAS Treatment Efficiency*

The treatment efficiency of the IUMAS is demonstrated in Fig. 5. The average percentage of COD removal for the six steady states was 99.0%. The highest influent COD recorded was 82,700 mg/L at the sixth steady states, corresponding to an OLR of 11 kg COD/m^3/day. at this OLR, the IUMAS achieved a 94.0% COD removal and an effluent COD of 4,962 mg/L. Results were shown that at low organic loading rates, the system was able to digest all the influent COD, however, the COD removal efficiency decreased with increasing OLR. During the six steady states, the MLSS increased from 11,760 mg/L to 18,400 mg/L and a proportional increase of the MLVSS from 9,000 mg/L to 16,008 mg/L. Fig. 6 shows the gas production rate and methane content of the biogas. The methane content generally declined with increasing OLRs. Methane gas contents ranged from 68.8 % to 72.8 % and methane yield ranged from 0.21 to 0.55 L/g COD/d. Biogas production increased with increasing OLRs from 0.29 L/g COD/day at 3 kg COD/m^3/day to 0.80 L/g COD/day at 13 kg COD/m^3/day. The decline in methane gas content may be attributed to the higher OLRs, which favours the growth of acid forming bacteria over methanogenic bacteria.

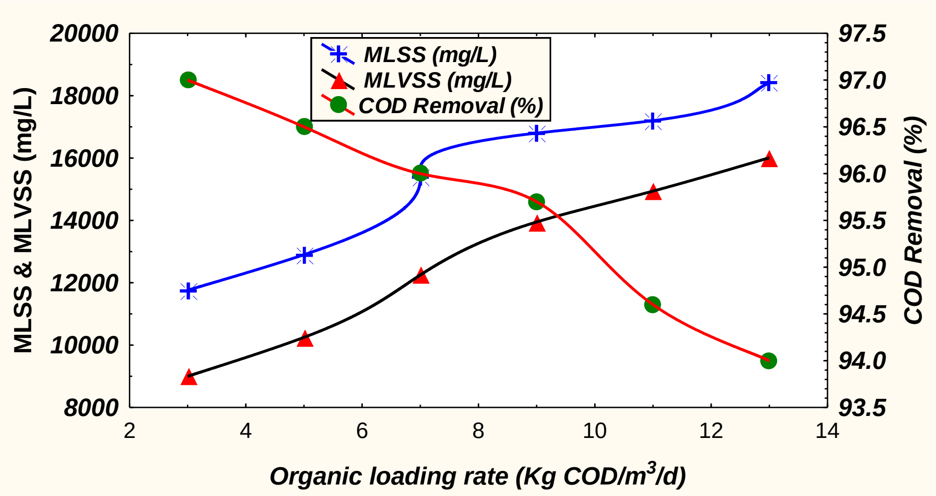

Figure 5: IUMAS treatment efficiency

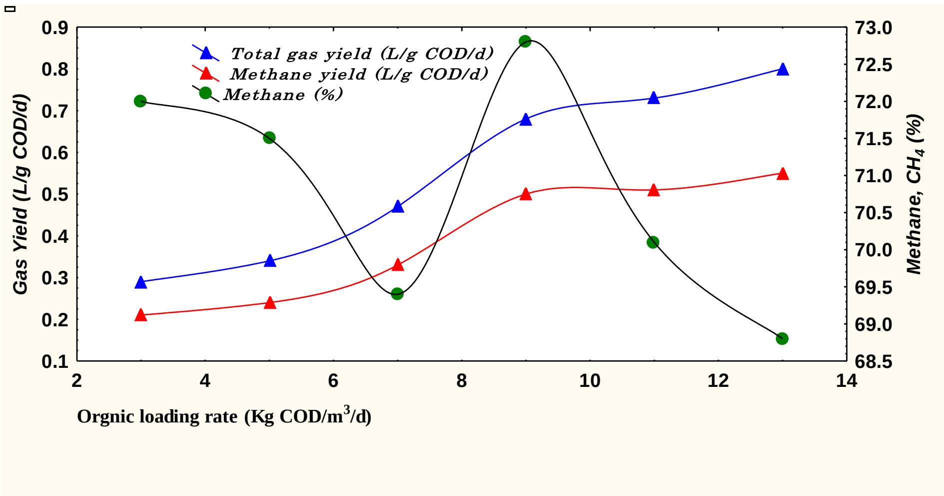

Figure 6: Organic loading rate (kg COD/m^3/day)

Fig. 7 shows the percentage of COD removal by IUMAS at various hydraulic retention times, HRTs, COD removal efficiency increased as HRTs increased from 10 days to 750 days and was in the range 94%-97%. This result was higher than the 85% COD removal observed for POME treatment using anaerobic fluidized bed reactors [20] and the 91.7%-94.2% removal observed for POME treatment using membrane anaerobic system, MAS [21].

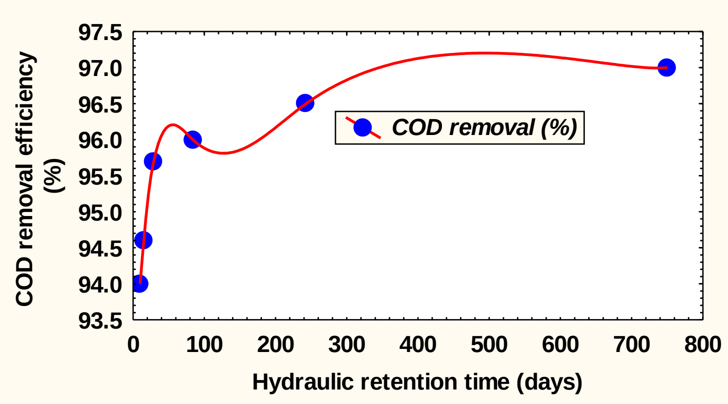

Figure 7: COD removal efficiency of IUMAS under steady state conditions with various hydraulic retention times

5. CONCLUSIONS

The laboratory semi-continuous integrated ultrasonic membrane anaerobic system, IUMAS showed a good performance for the treatment of palm oil mill effluent by achieving considerable removal of chemical oxygen demand (COD) in a short period of time (94%-97%). The proposed kinetic equations were found to be applicable to the anaerobic treatment of POME. IUMA was able to operate at a high solid retention time, SRT and was tolerant of variations in influent COD loadings. Therefore, IUMAS can be an alternative and cost effective for treating high strength wastewaters, and retain methane for energy would be an additional valuable result of the process.

Appendix A. Nomenclature

COD: chemical oxygen demand (mg/l)
OLR: organic loading rate (kg/m^3/d)
CUF: cross flow ultra-filtration membrane
SS: steady state
SUR: substrate utilization rate (kg/m^3/d)
TSS: total suspended solid (mg/l)
MLSS: mixed liquid suspended solid (mg/l)
HRT: hydraulic retention time (day)
SRT: solids retention time (day)
SSUR: Specific substrate utilization rate (kg COD/kg VSS/d)
MAS: Membrane an aerobic System
MLVSS: mixed liquid volatile suspended Solid (mg/l)
VSS: volatile suspended solids (mg/l)
MWCO: molecular weight Cut-Off
BLR: biological loading rate
U = specific substrate utilization rate (SSUR) (g COD/G VSS/d)
S = effluent substrate concentration (mg/l)
S_o = influent substrate concentration (mg/l)
X = micro-organism concentration (mg/l)

μ_{max} : Maximum specific growth rate (day^{-1})
K: Maximum substrate utilization rate (COD/g/VSS.day)

K_s : Half velocity coefficient (mg COD/l)
X: Micro-organism concentration (mg/l)
b = specific microorganism decay rate (day^{-1})
Y = growth yield coefficient (gm VSS/gm COD)
T: time

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