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Conceptual basis for the appropriate design of biological wastewater treatment systems: drawbacks of existing prescriptions

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ABSTRACT

The paper reviews and evaluates the basic steps in designing activated sludge systems based on process stoichiometry and mass balance. Appropriate system design requires the use of biodegradable COD as the main parameter, which sets a balance between substrate utilized, biomass generated and oxygen consumed. In practice, this balance is easily translated into excess sludge production and oxygen requirement. The evaluation first covers the necessary database for a rational design approach, with emphasis on relevant domestic wastewater characterization. Then it defines the excess sludge production, together with the daily oxygen demand. Principles outlined are illustrated in a numerical design example where the proposed rational approach is compared with the German Design Guidelines, A-131 for organic carbon removal.

Keywords: Activated sludge; Chemical oxygen demand; Endogenous decay; Mass balance; Process design; Stoichiometry; Yield coefficient

1. Introduction

The conceptual basis for the design of suspended growth, activated sludge-type wastewater treatment plants is very simple; it relies on electron balance between substrate utilized, biomass generated and dissolved oxygen consumed. This basis easily defines the backbone for the appropriate design of activated sludge systems provided that certain essential conditions are taken into account:

(i) Choice of substrate parameter—BOD, as recommended in some design prescriptions also utilized in Turkey cannot be a design parameter, simply because it reflects only a portion of substrate and therefore cannot accurately establish mass balance sludge generation and oxygen utilization. Therefore, appropriate design requires COD to be adopted as the major parameter;
(ii) COD fractionation—The conceptual basis becomes only applicable when the biodegradable fraction of the total COD is identified;
(iii) Reliable wastewater characterization—A reliable database is required to establish the design input, especially for unit pollution loads. These values differ as a function of community size and location and they are certainly markedly different from the levels adopted in Europe.

Aside from the above-mentioned issues, simple process stoichiometry is all that is needed for appropriate design. A sound background on major processes and process kinetics, especially for complicated process

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configurations for nutrient removal is also a prerequisite. Then, design expressions can simply be derived from mass balance [1–4]. The problem with major design prescriptions, such as the German guidelines given in this ATV-131 [3], is that they offer empirical expressions where certain parameters for local conditions are hidden; the values assigned for these parameters are often meaningless when transposed to local conditions and they cannot be easily identified.

This paper provides a brief overview of an appropriate design procedure derived from process stoichiometry and basic mass balance and presents the pitfalls of using the German Design Procedure ATV-131 [3] commonly adopted in Turkey on a real-case design exercise.

2. Conceptual design

2.1. Wastewater characterization

The determination of wastewater characteristics plays the most important role in sizing and selection of wastewater treatment configuration as well as treatment technologies to be applied to sludges generated during treatment process. The variation of wastewater amount and its characteristics are highly affected by many factors such as: (i) public welfare, (ii) the habit of water usage and waste characteristics, (iii) the climatic conditions (temperature, rain, etc.) and (iv) status of infrastructure systems (water distribution network; combined and/or separate sewer systems, pressurized or gravity sewer etc.). Table 1 summarizes the wastewater characteristics and ranges of pollutant parameters for touristic areas in Turkey during 5 month period (from May to October). The diluted characteristics of wastewaters especially for Fethiye and Marmaris regions were reported according to the analyses results [5,6].

Under dry weather conditions, the variation of wastewater characteristics with respect to COD, BOD_5 and TSS parameters are illustrated in Table 2 pertaining to the 5 largest cities of Turkey [6,7]. A statistical evaluation was provided in order to compare the average concentrations with 70% and 80% percentiles of related parameters. High variations in the pollutant parameters collected for different cities can be observed from Table 2 because of above mentioned factors influencing the influent wastewater characteristics. Another important issue is that the concentrations of each parameters exhibits considerable deviation from their average values. Considering the ratio of the difference between 80% percentile and the average to the average concentration, the variation ranges of COD and TSS parameters can be calculated as 0.15−0.38 and 0.22−0.31, respectively for the 5 largest cities of Turkey (Table 2). As expectedly, these conditions will directly influence not only the design but also the operation of wastewater treatment plants.

2.2. Design presciptions

A number of different methods have been proposed for the engineering design of activated sludge processes [2,3,8]. The traditional design of activated sludge system was initiated with organic carbon removal based on traditional BOD_5 parameter, basically describes the relationship between biomass production and organic carbon removal in relation with oxygen utilization [8]. Until 1980s, lots of experiences were accumulated on BOD-based design and operation of activated sludge systems in parallel to the construction of large number of wastewater treatment plants. Inherently, many BOD-based methods have been extended to a standard design procedure to be used in tendering of treatment plant designs [3,8]. Until recently, activated sludge technology necessitates detailed information on the fractionation of the organic matter (influent COD fractionation) in order to govern realistic relationship between substrate, biomass and electron acceptor conditions for biological nitrogen and phosphorus removal.

Table 1
Domestic wastewater characteristics at touristic areas in Turkey [5]

Parameter	Fethiye		Marmaris		Bodrum	
	Average mg/l	Range mg/l	Average mg/l	Range mg/l	Average mg/l	Range mg/l
Total COD	227	190–245	370	215–480	473	335–530
Filtered COD	52	30–145	96	60–125	128	85–140
TKN	26.8	20–37	37	31–42	45	32–57
NH_4–N	17.9	11.5–21	26	21–34	33	26–41
TP	5.4	3.3–9	7.7	5.6–9	8.8	7–11
TSS	150	100–270	194	170–265	227	140–310
VSS	136	90–235	177	160–230	199	120–290
Alkalinity	412	310–470	462	380–520	486	410–540

Table 2
Variation of urban wastewater characteristics in Turkey [6,7]

WWTP	COD (mg/l)			BOD$_5$ (mg/l)			TSS (mg/l)		
	Average	70%	80%	Average	70%	80%	Average	70%	80%
Istanbul*	665	732	766	330	–	–	455	465	559
Izmir	424	483	544	202	220	240	250	267	305
Ankara	305	336	362	158	185	190	147	169	184
Antalya	386	451	524	252	310	338	266	310	350
Adana	439	514	606	225	248	260	190	212	241

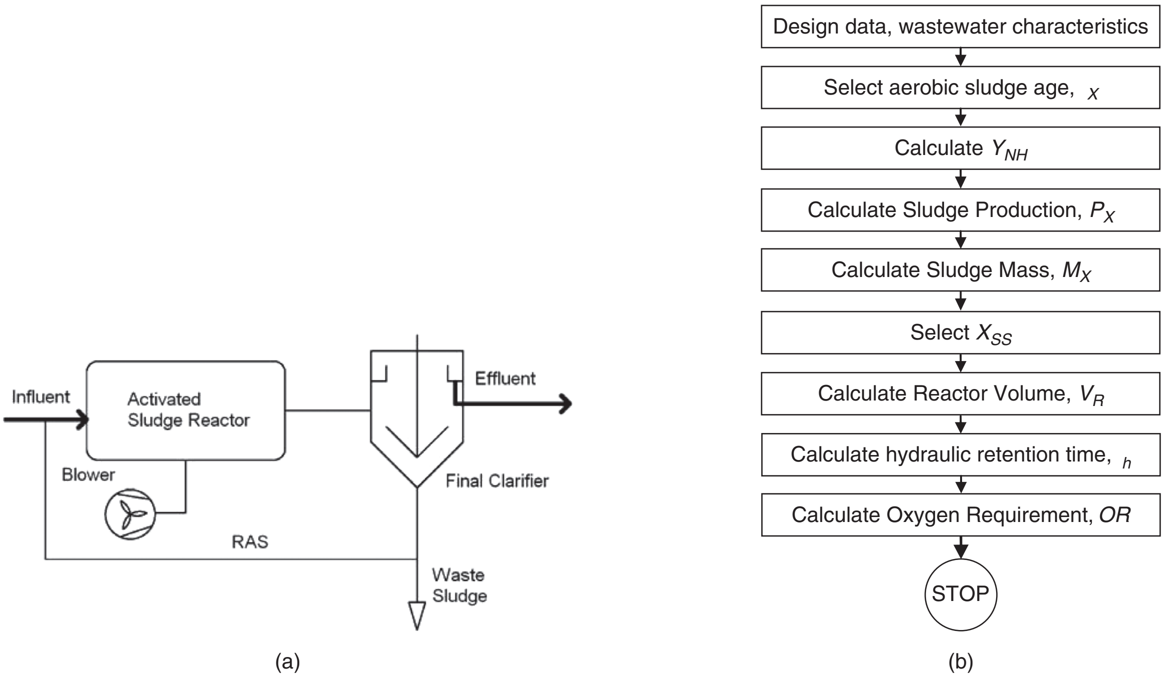
*Pasakoy WWTP [7].

As in traditional approach, the BOD only reflects only a portion (%40–60) of biodegradable organic matter which does not sufficiently mimic the real process conditions as stated in the introduction section. As a further step, the assessment of biodegradation characteristics of different organic fractions in raw waste waters had to be considered in design process. With the pioneering work of Dold et al. [9] and Ekama et al. [10], the Chemical Oxygen Demand (COD) is now accepted as the main parameter for the organic carbon removal [9,10]. In parallel to the vast developments in activated sludge technology and process modeling, the nutrient (N, P) removal processes have also been incorporated in design methodologies.

Currently, besides BOD-based methods, alternative COD–based design procedures have also been proposed within the same prescriptions [1,3,8]. The objective of this work is not to clarify each design versions but to highlight the main differences of fundamental BOD- and COD-based methods as given in the literature [2,3] with respect to sludge production and average oxygen requirement, which will serve as a reference point for further benchmarking study of different design methods for biological nitrogen removal systems. Here, it is attempted to underline the basic relationships between mass balance and design parameters used in excess sludge production and oxygen consumption by comparing the commonly used design procedures in Turkey.

2.2.1. Aerobic sludge age

The sludge age, (t_{ss} or θ_X) is the most vital parameter in the design and operation of the activated sludge systems (Fig. 1a). It is conveniently defined as the ratio



(a) (b)

Fig. 1. (a) Activated sludge system, (b) design procedure for aerobic activated sludge system.

of the total biomass in the reactor to the daily amount of total excess sludge that needs to be wasted in order to maintain the activated sludge reactor at steady state condition. However, the resulting sludge age is rate limiting and it is applicable to all microbial communities, i.e., nitrifiers, maintained in the biological reactor. In system operation, the sludge age reflects the mean solids retention time, SRT as given below:

$$\theta_x = \frac{V \cdot X_{SS}}{P_{XT}} \tag{1}$$

where, V: aerobic reactor volume (m^3); X_{SS}: total biomass concentration (kg/m^3) and P_{XT}: daily amount of excess sludge (kg/d). The first line given in Table 3 shows the calculation of required sludge age for stable nitrification and organic carbon processes, at once. The German ATV-131 [3] design enables the selection of minimum aerobic sludge age based on an empirical approach which corresponds to the inverse of the net growth rate as given in the method of Orhon and Artan [2]. Since the kinetic rates are dependent upon the process temperatures, an exponential correction function had to be included as a lump parameter in the expression of ATV-131. On the other hand, the temperature correction factor for the maximum autotrophic growth and endogenous decay rates are explicitly defined in the method of Orhon and Artan [2]. In both methods, a Safety Factor (SF) was included in sludge age calculation so as to render the negative impact of daily peak loadings. After the selection of the sludge age of the system, the assessment of activated sludge design includes a number of fundamental steps for appropriate design and operation of activated sludge systems, namely the (i) selection of appropriate sludge age, θ_X; (ii) excess biomass (sludge) generated, P_{XT}; (iii) effluent quality, S_{eff}; (iv) utilized oxygen.

Mass balance requires adoption of a mechanistic model for description and incorporation of different biochemical processes involved [2,11]. The *endogenous decay* model was selected for process evaluation. In essence, interpretation of specific system functions for design purposes requires only two major model parameters, the *heterotrophic net yield coefficient*, Y_{NH} and the *endogenous decay rate*, b_H together with the selected (aerobic) sludge age, θ_X. As one of the most important design parameter of sludge (biomass) production is calculated by using *heterotrophic net yield coefficient*, Y_{NH} which governs the stoichiometric equivalence of biomass generation when unit of substrate is biodegraded by the heterotrophic microbial community. The calculated biomass includes the active biomass (X_H) and endogenous residues due to decay (X_P) according to the formula as given in Table 3 [2]. In addition, the inert particulate organic matter (X_I) that could not be consumed by biomass together with the inert inorganic matters (i.e., sand, inorganic residues) formulized as the difference between Total Suspended Solids (TSS) and Volatile Suspended Solids (VSS) were added in total sludge production (P_{XT}). The parameter "*f*" is the transformation term of COD fraction to suspended solids unit in order to calculate the mass of real sludge generated. The summary of design procedure is given in Fig. 1b. The incorporation of overall sludge production (P_{XT}) in Eq. 1 allows to calculate the reactor volume by deciding the concentration of biomass in the reactor (X_{SS}). The overall mass maintained in the reactor can be calculated by multiplying daily sludge production (P_{XT}) and sludge age (θ_X). As a rule of thumb, the X_{SS} is generally selected in the range of 3–5 kgSS/m^3 in activated sludge reactor followed by secondary settling tank [8].

After the selection of aerobic sludge age, the sludge production calculation can be derived depending upon BOD and COD load, alternatively according to ATV-131 (Table 3). The expression for the sludge production has three different components. (a) the first component "0.75" governs the conversion of biomass due to organic carbon removal (b) second term of 0.6 X_{SS}/BOD$_5$ describes the remaining suspended solids after biodegradation process and (c) the final term defines the decayed biomass similar to the concept of net growth where biomass decay occurs during growth [2]. Alternatively, the sludge production based on COD is expressed with three different terms as (a) the net biomass growth, X_{BM} (b) decay based inert particulate matter generation, X_P and finally (c) the amount of fixed solids, X_F given as the difference between TSS and VSS parameters. The contribution of inert particulate organic matter (X_I) to the sludge generation was also explicitly defined according to German ATV-131 standard [3]. The effluent quality is then calculated as a fraction of soluble influent inert COD that by-passes the system without any subjection to biodegradation process (Fig. 1a).

2.2.2. Oxygen requirement

The oxygen requirement for organic carbon removal processes is defined with a simple process stoichiometry as the difference of substrate and the net yield of biomass generated $Y_H/[1+b_H \cdot \theta_X]$ as given in Table 3. The daily amount of oxygen can then be calculated by multiplying that term with influent flowrate (*Q*). The BOD-based calculation of ATV-131 method suggests a two transformation terms of (a) "0.56" that translates the oxygen consumption due to growth and (b) additional oxygen consumption due to endogenous decay. Alternatively, the COD-based method of ATV-131 can be derived by a mass balance as the difference of influent COD load and the total effluent COD loads from settling

Table 3

Calculation for Sludge Production (P_{XT}) and Oxygen Utilization (OU_C) for organic carbon removal

Design parameter	Units	This study*	ATV-131[3]	
			BOD$_5$-based	COD-based
Aerobic sludge age calculation	day	$\frac{1}{\theta_{XA}min} = \hat{\mu}_A(T) - b_A(T)$ $\theta_{XA} = SF * \theta_{XA}min$ $\hat{\mu}_A(T) = \hat{\mu}_A(20) * 1.103^{T-20}$ $b_A(T) = b_A(20) * 1.072^{T-20}$	$t_{ss} = SF * 3.4 * 1.103^{15-T}$	$t_{ss} = SF * 3.4 * 1.103^{15-T}$
Sludge production**	kgSS/d	$Y_{NH} = \frac{Y_H(1 + b_H * fE * \theta_{XA})}{1 + b_H * \theta_{XA}}$ $b_H(T) = b_H(20) * 1.072^{T-20}$ $P_{XH} + P_{XP} = Q * Y_{NH} C_{S1} \frac{1}{f}$ $P_{X1} = \frac{Q * X_1}{f}$ $P_{XF} = Q * (TSS - VSS)$ $P_{XT} = P_{XH} + P_{XP} + P_{X1} + P_{XF}$	$B_{d,BOD} = Q * C_{BODs}$ $SP_{d,C} = B_{d,BOD} \left[0.75 + 0.6 \frac{XSS}{C_{BOD}} - \frac{(1-0.2) \cdot 0.17 \cdot 0.75 \cdot t_{SS} \cdot F_T}{1 + 0.17 \cdot t_{SS} \cdot F_T} \right]$ $F_T = 1.072^{T-15}$	$S_{COD} = COD_{in} - 1.45\,(1 - 0.20)\,TSS$ $S_I = 0.05 \cdot S_{COD}$ $X_{BM} = \frac{Y_{obs \cdot H}}{1 + 0.17 \cdot t_{ss} \cdot P_T} C_{S1}$ $X_P = 0.20 \cdot [0.17 \cdot t_{ss} \cdot F_T] \cdot X_{BM}$ $X_{WAS} = X_{1COD} + X_{BM} + X_P$ $X_F = TSS - VSS$ $P_{XT} = Q_d \left[\frac{X_{WAS}}{0.8 \cdot 1.45} + X_F \right] \cdot \frac{1}{1000}$
Oxygen utilization, OU_C	kgO$_2$/d	$OR = \left[1 - \frac{Y}{1 + b_H \cdot \theta_{XA}} \right] Q * C_{S1}$	$OU_{d,c} = B_{d,BOD} \left[0.56 + \frac{0.15 \cdot t_{SS} F_T}{1 + 0.17 \cdot t_{SS} \cdot F_T} \right]$ $F_T = 1.072^{T-15}$	$OR = [COD - (S_I + X_{WAS})] \frac{1}{1000}$

* adapted from Orhon and Artan, 1994 [2];

***conversion parameters*: MLVSS/MLSS = 0.8; $COD/VSS = 1.45$; $f = 0.8\ 1.45 = 1.16$ gCOD/gTSS tank (S_I) and sludge wastage (X_{WAS}) as shown in Fig. 1a. It should be noted that the use of COD based method is recommended if the daily oxygen requirement (OR) difference is more than 5% compared to that of BOD-based method according to ATV-131 [3].

Table 4 summarizes 3 pre-selected different characterizations (WW1, WW2 and WW3) reflecting the urban wastewater characterization in Turkey. These characterizations will be further used with three design methods given in Table 3. It reflects relatively concentrated urban wastewater characteristics compared to the parameters given in Table 1 and Table 2 for crowded cities of Turkey. In addition, the process temperature was selected as 12 °C reflecting the measured values of the coldest 3 month climate period together with the selection of safety factor of $S_F = 1.45$. The same aerobic sludge ages were selected in order to compare the methods and also to secure nitrification process according to all design methods. In order to do so, the parameter of maximum autotrophic growth rate and decay rate were assigned to 0.70 d^{-1} and 0.17 d^{-1}, respectively for reference temperature of 20 °C (Table 5). It is important to note that the reference process temperature for ATV-131 was assigned as 15 °C. The aerobic sludge age can be calculated around 6.5 d at 12 °C process conditions.

Table 5 given below, summarizes the sludge production and the theoretical oxygen demand calculations (for carbon removal, OR_H) for the design of activated sludge systems using three different influent wastewater types in Turkey. In order to compare the results on the same basis, the model parameters were adjusted to yield the same sludge age of 6.6 d in all methods.

The BOD-based ATV-131 calculation yielded a sludge production of 8225 kg/d which is 15% higher than that of ATV-131 COD-based method for WW1. On the other hand, the sludge production (P_{XT}) calculated in this study was found to be closer to the BOD-based ATV-131 approach. The oxygen requirements obtained with the proposed approach always yielded the highest daily oxygen consumptions (OR_H) of 6704, 4137 and 3058 kgO_2/d for WW1, WW2 and WW3, respectively. In case of WW2 and WW3, the ranking of highest sludge generation was altered as follows: The calculation provided with proposed approach yielded the maximum level of sludge production (P_{XT}) pertaining to the wastewaters of WW2 and WW3.

The relative errors between the calculation of sludge production and oxygen requirements become more visible when high strenght wastewater is considered. However, the calculation results with respect to P_{XT} and OR_H were found to be much closer for the designs applied for wastewaters having diluted characteristics (Table 4, influent COD < 424 mg/l). Finally, all COD-based calculation methods facilitate the calculation of mixed liquor composition as: active biomass (X_{BH}) and inert microbial products (X_P), inert particulate organic matter (X_I) and the fixed solids (X_F). Again, the calculation of biomass fractions were found to be much closer for the diluted influent wastewater characteristics. The relative error between oxygen utilizations for BOD and COD based ATV-131 method decreased from 11% down to 3% by comparing the results obtained for a strong wastewater (WW1) with a relatively diluted sample (WW3).

Table 4
Different wastewater characterization (WW) and parameters used in design

Parameter	Units	Notation		WW1	WW2	WW3
		This study	ATV-131			
Total Suspended Solids (TSS)	mgSS/l	TSS	XSS	455	250	147
Chemical Oxygen Demand (COD)	mgO_2/l	C_T	COD_{in}	680	424	305
Biochemical Oxygen Demand (BOD_5)	mgO_2/l	BOD_5	C_{BOD}	330	212	150
Influent Soluble COD	mgO_2/l	S_T	S_{COD}	204	127	125
COD Fractions	–					
Soluble inert COD	mgO_2/l	S_I	S_I	35	21	15
Particulate inert COD	mgO_2/l	X_I	X_{ICOD}	86	58	35
Readily biodegradable COD	mgO_2/l	S_S	S_S	174	100	77
Slowly biodegradable COD	mgO_2/l	X_S	X_S	385	244	178
Total Kjeldahl Nitrogen (TKN)	mgN/l	TKN	TKN_{in}	52**	45**	40**
Design process temperature	°C	°C	°C	12	12	12
Design flowrate*	m^3/d	19,440	19,440	19,440	19,440	19,440

*Population equivalence= 100,000 PE;

**Ammonia nitrogen, NH_4–N=0.70 TKN.

Table 5
Calculation results for sludge production and oxygen demand for carbon removal

Parameter	Unit	WW1			WW2			WW3		
		This study	ATV-131		This study	ATV-131		This study	ATV-131	
			BOD_5	COD		BOD_5	COD		BOD5	COD
Autotrophic growth rate, $\hat{\mu}_A(20)$	d^{-1}	0.70	–	–	0.70	–	–	0.70	–	–
Autotrophic decay rate, $b_A(20)$	d^{-1}	0.17	–	–	0.17	–	–	0.17	–	–
Endogenous Decay rate, $b_H(20)$	d^{-1}	0.20	0.24*	0.24*	0.20	0.24*	0.24*	0.20	0.24*	0.24*
Arrhenius coefficient for , $\hat{\mu}_A$, θ	–	1.103	1.103	1.103	1.103	1.103	1.103	1.103	1.103	1.103
Arrhenius coefficient for b_A and b_H , θ	–	1.072			1.072			1.072		
Aerobic sludge age, (θ_X or t_{ss})	d	6.5	6.6	6.6	6.5	6.6	6.6	6.5	6.6	6.6
Sludge production, P_{XT}	kgDS/d	8007	8282	7535	4880	4827	4515	3287	3078	3214
Heterotrophic growth, X_H+X_P (X_{BM})	kgCOD/d	4630	–	3050	2858	–	2777	2112	–	2053
Particulate inert COD, X_I	kgCOD/d	1670	–	1440	1127	–	1153	680	–	830
Fixed solids, X_F	kgDS/d	2210	–	1439	1215	–	1120	720	–	690
Oxygen Requirement for X_H, OR_H	kgO_2/d	6704	6380	7135	4137	4043	4032	3058	2861	2890

*Endogenous decay rate of b_H = 0.17 d^{-1} at reference process temperature of T:15 °C

3. Conclusions

The activated sludge plant design for organic carbon and nitrogen removal can be derived from simple bioprocess stoichiometry and kinetics. In the last decades, the use of influent COD fractionation has started to become the commonly preferred approach since it directly reflects the amount of biodegradable organic matter available for biomass growth and oxygen utilization. The calculations applied to the different specific domestic wastewaters characteristics indicated that different sludge productions could be obtained with larger errors for the concentrated wastewaters. With the use of the same design conditions, the BOD-based method yielded the maximum amount of sludge produced and the minimum amount of oxygen consumed at higher COD levels. The COD-based methods led to comparable results, but they were found to be dependent upon selected parameters. In this respect, the appropriate design and operation of wastewater treatment plants require a thorough experimental determination of specific model parameters to be used in the calculation method. In order to do so, a regional design procedure should be developed to serve as an appropriate design manual.

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