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Inorganic Particulate Sludge Production in Biological Processes

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The inorganic fractions of the biomass components produced in aerobic biological reactors were defined experimentally. Experiments were conducted on synthetic waste and filtered domestic sewage to represent directly the production of active biomass and the inert biomass; results were supported with modeling studies. The average TSS content of the sludge was estimated as 1.15 g TSS/g particulate COD for synthetic waste and 1.05 g TSS/g particulate COD for domestic sewage higher than the values reported in the literature

Keywords: Biological sludge, domestic wastewater, heterotrophic growth, inorganic fractions, modeling, sludge components.

1. Introduction

Correct assessment of the total sludge production in the aeration tank of an activated sludge system is an important asset as the amount of total sludge limits loading rate of the clarifier. A rational evaluation of biological sludge production should rely on a model for biological processes and necessitates the determination of all stoichiometric relationships between the related model components.

In the modeling and design of activated sludge systems, sludge is generally calculated by means of VSS (Volatile Suspended Solids) or TSS (Total Suspended Solids). VSS reflects all particular organic matters entrapped in the activated sludge flocs, whereas TSS is an indicator of total biomass in the biological reactor representing both organic and inorganic fractions. In the classical design approach the VSS/TSS ratio in the activated sludge system is assumed as 0.8 or 1 for the total sludge without considering the sludge components [1]. New models, on the other hand, rely on the differentiation of the sludge components and definition of various stoichiometric conversion factors for the calculation of total sludge amount in the system [2, 3].

The objective of this study may be defined as the assessment of the inorganic fraction of the produced sludge in an activated sludge system. For this purpose, experimental studies were conducted on synthetic waste of readily biodegradable nature and domestic sewage. Data obtained with the measurement of total and soluble COD utilization versus TSS and VSS production were evaluated with modeling studies to identify the relevant conversion factors (i_{SSXH}, i_{SSXE}) representing the inorganic contents of the produced biological sludge.

2. Conceptual Basis

Total sludge expressed as total suspended solids (P_{SS}) in an activated sludge system actually consists of two major components:

i. Solids of inorganic nature or fixed solids (P_{XFS}) in the influent accumulating in the reactor.

ii. Sludge generated in biological processes through the microbial activities, active biomass and its residue as a result of endogenous decay

$$P_{SS} = P_{XTSS} + P_{XFS} \tag{1}$$

where, P_{XFS}: influent fixed solids input, [M TSS T^{-1}], P_{XTSS}: total biological sludge produced in the reactor, [M TSS T^{-1}].

The amount of fixed solids exits the system can be expressed as:

$$P_{XFS} = Q.X_{FS1} = f_{XFS}.Q.X_{TSS1}. \tag{2}$$

The influent concentration of fixed solids (X_{FS1}) is actually the difference between TSS and VSS in the influent and can be defined as a fraction of influent TSS concentration, (f_{XFS}). The magnitude of f_{XFS} and X_{FS1} depends strictly on the pretreatment scheme of the wastewater.

Biological sludge (P_{XT}) on the other hand, is the sum of three major components with the assumption that all the influent biodegradable organic matter is consumed during the biological process. So the biological sludge produced in the reactor may be expressed as:

$$P_{XT} = P_{XH} + P_{XE} + P_{XI} \quad (3)$$

where, P_{XH}: viable heterotrophic biomass, [M COD T^{-1}], P_{XE}: inert biomass produced in the system, [M COD T^{-1}], P_{XI}: inert particular organic biomass from influent, [M COD T^{-1}].

Substituting the correct expressions yields;

$$P_{XT} = Y_{NH}.f_S.Q.C_{T1} + Y_{NH}.f_{EX}.b_H.f_S.Q.C_{T1}.\theta_X + f_{XI}.Q.C_{T1} \quad (4)$$

where, C_{T1}: influent total COD, [M COD L^{-3}], f_{EX}: fraction of endogenous mass converted into inert products [-], f_S: biodegradable fraction of the influent total COD [-], f_{XI}: particulate non-biodegradable fraction of the influent total COD [-], Y_{NH}: net yield coefficient for heterotrophic growth, [M COD (M COD)$^{-1}$].

Formulating this equation on the basis of TSS,

$$P_{XTSS} = P_{XHSS} + P_{XESS} + P_{XISS} \quad (5)$$

necessitates conversion factors indicating the inorganic content of specific related parameters. Consequently, total solids production may be expressed as :

$$P_{SS} = i_{SSXH}.P_{XH} + i_{SSXE}.P_{XE} + i_{SSXI}.P_{XI} + f_{XFS}.Q.X_{TSS1} \quad (6)$$

where, i_{SSXH}: TSS ratio to COD for X_H, [M TSS (M COD)$^{-1}$], i_{SSXE}: TSS ratio to COD for X_E, [M TSS (M COD)$^{-1}$], i_{SSXI}: TSS ratio to COD for X_I, [M TSS (M COD)$^{-1}$].

Using the definition of yield coefficient,

$$Y_N = P_{XT}/QC_{T1} \quad (7)$$

a Y_N expression on TSS basis may be derived as:

$$Y_{N(TSS)} = i_{SSXH}.Y_{NH}.f_S + i_{SSXE}.Y_{NH}.f_{EX}.b_H.f_S.\theta_X + i_{SSXI}.f_{XI} + f_{XFS}.\frac{X_{XTSS1}}{C_{T1}} \quad (8)$$

3. Materials and Methods

Experimental studies to identify the inorganic fractions of the produced sludge were conducted in 2 liter aerated batch reactors under single and multiple feeding conditions using synthetic waste and domestic wastewater. The biomass was obtained from the mixed liquor of a 4 liter fill and draw aerobic reactor operated at a sludge age of 2 days to maintain a significant level of active heterotrophic biomass (X_H) in the reactor. Acclimation in fill and draw reactors was first performed using synthetic mixture (1250 mgCODl^{-1}) of simple organic compounds [4] in form of readily biodegradable substrate. Necessary nutrients were added in sufficient amounts [5]. Secondly, experiments were conducted on domestic sewage taken from Atakoy/Istanbul. The acclimation to domestic wastewater was completed approximately in 15 days.

In single feeding system, the batch reactor was fed once with the samples investigated, whereas the reactor representing the multiple feeding was fed every day with a pre-selected amount of substrate for a 3 days period. Total and soluble COD utilization together with TSS and VSS production versus time were observed in the batch reactors. The reactors were initially fed with the wastewater sample and seeded with appropriate biomass to start with a suitable S_{T1}/X_{T1} (F/M) ratio. Batch tests were conducted on filtered sample for domestic sewage to avoid the particular components in the wastewater. Similar experiments at steady state were also carried out in the fill and draw reactors for performance tests. Reactors were constantly aerated to maintain a dissolved oxygen concentration of 6-8 mg litre^{-1}.

The data collected from the batch reactors were tested with the modeling studies in order to assess the conversion factors for X_H and X_E separately. The model based on the endogenous decay model [6] was performed using the AQUASIM program developed by Reichert [7].

Model simulations were carried out for different sludge ages, in view of the fact that the X_E/X_H ratio is a function of the sludge age. The sludge age of the fill and draw reactor was first increased to 8 and then to 20 days to investigate the possible effect of the X_E/X_H ratio on the sludge production and on the conversion factors.

All analyses for conventional characterization were performed as defined in Standard Meth-

Table 1
Experimental results for synthetic waste

Experiments	S_{T1}/X_{T1} *	S_{T1}mgCODl^{-1}	gVSS(gTSS)$^{-1}$		gTSS(gCOD)$^{-1}$		gVSS(gCOD)$^{-1}$	
			Average	Range	Average	Range	Average	Range
θ_X=2 days								
FDR	1.75	1250	0.69	0.68-0.70	1.38	1.37-1.39	0.95	0.93-0.97
R1	10	550	0.73	0.70-0.75	1.26	1.16-1.33	0.92	0.86-0.96
R2	5	500	0.74	0.70-0.75	1.16	1.15-1.30	0.88	0.85-0.95
R3	7	1000	0.69	0.68-0.71	1.34	1.33-1.39	0.93	0.92-0.97
R4	7	850	0.72	0.70-0.74	1.20	1.18-1.30	0.84	0.84-0.93
R5	8	800	0.72	0.70-0.73	1.19	1.16-1.22	0.85	0.84-0.87
R6	10	1000	0.73	0.69-0.73	1.18	1.15-1.32	0.85	0.84-0.91
R7	10	1000	0.72	0.69-0.74	1.18	1.15-1.30	0.85	0.85-0.87
θ_X=8 days								
FDR	0.75	800	0.73	0.72-0.75	1.16	1.12-1.20	0.85	0.83-0.86
θ_X=20 days								
FDR	0.25	500	0.71	0.69-0.73	1.20	1.19-1.27	0.86	0.85-0.88
R8	5	775	0.73	0.71-0.73	1.19	1.15-1.21	0.86	0.84-0.87

FDR: Fill and Draw Reactor
R: Batch Reactor

* S_{T1}/X_{T1} for FDR : mgCOD(mgVSS.day)$^{-1}$
S_{T1}/X_{T1} for R : mgCOD(mgVSS)$^{-1}$

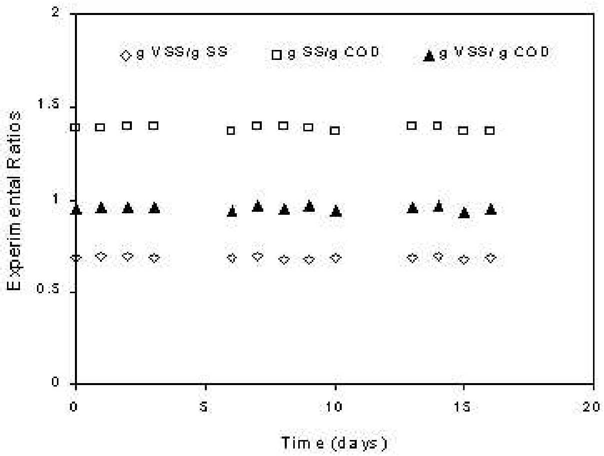

Figure 1. Results of fill and draw reactor for synthetic waste

ods [8] except COD, which was accomplished by ISO 6060 method [9]. Filtrates of samples subjected to vacuum filtration by means of Millipore membrane filters with a pore size of 0.45 μm were defined as soluble fractions. The Millipore membrane filters (0.45 μm) were also used for total suspended solids (TSS) and volatile suspended solids (VSS) measurements.

4. Experimental Results

The batch experiments for the assessment of the inorganic sludge production were carried out under moderately high initial F/M ratios to maintain unlimited growth conditions in the reactors. The experimental scheme was based on the measurement of total and soluble COD utilization together with TSS and VSS production versus time. Fill and draw reactors operated at steady state conditions were also observed to check the results of the batch tests.

4.1. Synthetic Waste

The data obtained from the fill and draw reactor operated at a sludge age of θ_X=2 days were evaluated on the basis of different ratios as illustrated in Fig. 1 and in Table 1. Inspection of the data reveals that the ratios are rather constant in the observation period. Average values were calculated as 1.39 for TSS/COD, 0.96 for VSS/COD and 0.69 for VSS/TSS.

Table 2
Characterization of the domestic sewage (Okutman, 2001)

Parameter	Unit	Value	Parameter	Unit	Value
Influent COD			Other Parameters		
Total COD	mgl^{-1}	520	TSS	mgl^{-1}	325
Soluble COD	mgl^{-1}	130	VSS	mgl^{-1}	275
Particulate COD	mgl^{-1}	390	Total TKN	mgl^{-1}	42
COD Components			Soluble TKN	mgl^{-1}	32
Readily biodegradable COD	mgl^{-1}	30	NH_3-N	mgl^{-1}	26
Soluble slowly biodeg. COD	mgl^{-1}	70	TP	mgl^{-1}	10
Particulate slowly biodeg. COD	mgl-1	300	pH	-	7.2
Soluble inert COD	mgl^{-1}	30	Alkalinity	mgl^{-1}	255
Particulate inert COD	mgl^{-1}	90	Chloride	mgl^{-1}	450

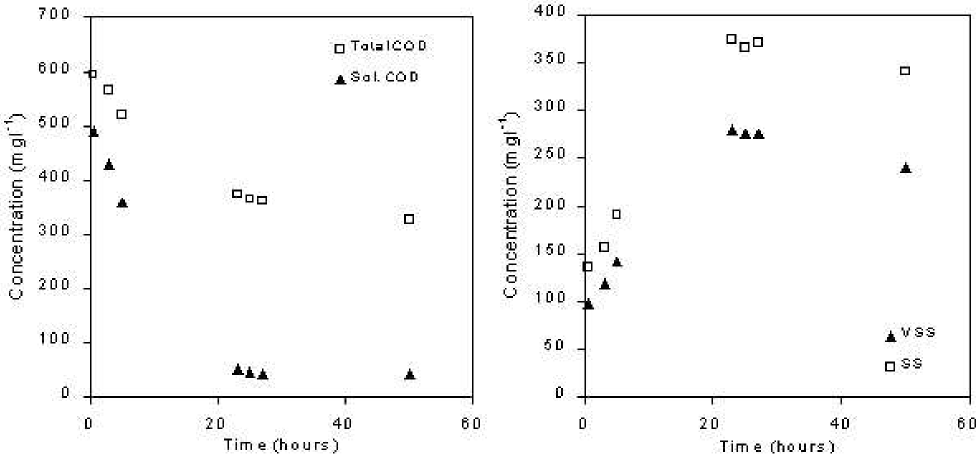

Figure 2. Experimental results of the single feeding batch reactor R2 for synthetic waste (a) Total COD and soluble COD utilization (b) VSS and TSS production

Experimental results on batch reactors conducted at different initial S_{T1}/X_{T1} ratios are also summarized in Table 1. Data obtained from the batch reactors represent only the sum of the X_H and X_E productions in the system since the soluble synthetic waste does not cover the particulate inert organic substrate and particulate inorganic solids as expressed in Eq. 6. The tests R1, R2 and R3 were run applying the single feeding method whereas the others represent the multiple feeding results.

Significant point of interest in the first group of the batch tests (θ_X=2 days), as summarized in Table 1, is the observation that the runs yielded quite reproducible results for different S_{T1}/X_{T1} ratios. The ratios of TSS/COD and VSS/COD were observed to vary in a range of 1.15-1.39 and 0.84-0.97 for all the samples tested, respectively, resulting an overall average VSS/TSS ratio of 0.72.

For testing the possible effect of X_E/X_H ratios on the sludge production and mainly on the conversion factors, additional tests were run at different sludge ages (θ_X=8 and 20 days). It can be noted that comparable results in batch and fill and draw reactors were obtained for the different sludge ages as outlined in the table. The average values for TSS/COD and VSS/COD ratios were found as 1.16 and 0.85 for θ_X=8 days, as 1.19 and 0.86 for θ_X=20 days, respectively. The average VSS/TSS ratio remained unchanged for both experiments conducted at different sludge ages.

Results of R2 were outlined in Fig. 2 as an example, to represent the sensitivity of the single feeding method in the experiments. As seen from the figure, the data collected from this reac-

Table 3
Experimental results for synthetic waste

Experiments	S_{T1}/X_{T1} *	S_{T1}mgCODl^{-1}	gVSS(gTSS)$^{-1}$		gTSS(gCOD)$^{-1}$		gVSS(gCOD)$^{-1}$	
			Average	Range	Average	Range	Average	Range
θ_X=2 days								
FDR	1	200	0.81	0.80-0.82	1.05	1.02-1.08	0.85	0.84-0.87
R9	6	120	0.80	0.78-0.82	1.06	1.04-1.09	0.85	0.82-0.87
θ_X=20 days								
FDR	0.2	200	0.79	0.78-0.80	1.08	1.05-1.11	0.85	0.83-0.87
R10	5	130	0.79	0.78-0.82	1.08	1.05-1.12	0.86	0.83-0.88

FDR: Fill and Draw Reactor * S_{T1}/X_{T1} for FDR : mgCOD(mgVSS.day)$^{-1}$
R: Batch Reactor S_{T1}/X_{T1} for R : mgCOD(mgVSS)$^{-1}$

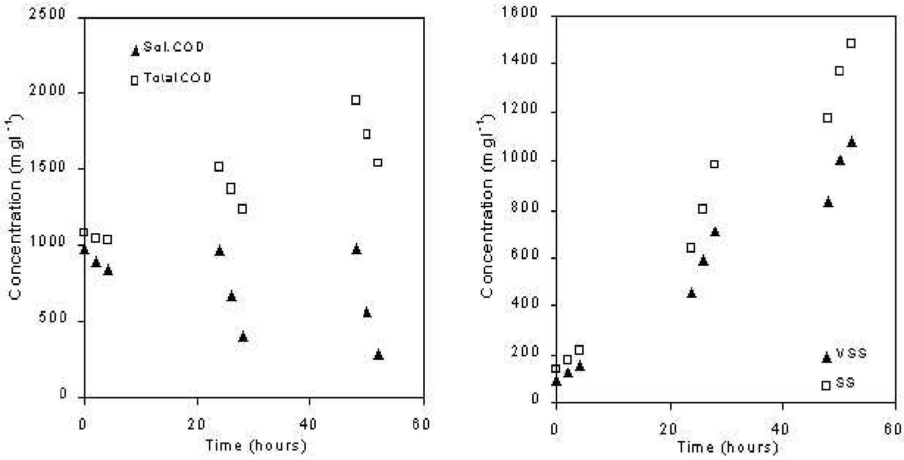

Figure 3. Experimental results of the multiple feeding batch reactor R6 for synthetic waste (a) Total COD and soluble COD utilization (b) VSS and TSS production

tor exhibit a significant substrate limitation after 24 hours, approximately corresponding the 4^{th} sample. The remaining data appear to be very limited to make a statistically valid experimental evaluation. Thus, in further analysis, the multiple feeding approach was preferred in order to improve the sensitivity by increasing the number of the data needed for the evaluation (Fig. 3). All data measured in the experiment period can be used for the assessment of the sludge production since no substrate limitation was represented in the multiple fed reactor.

4.2. Domestic Sewage

The same batch experimental approach relying on multiple feeding was performed for domestic sewage to assess the production of X_H and X_E in the system. The sewage was filtered to avoid the interference of particulate components in the influent. Fill and draw reactors were also observed for performance testing.

The domestic sewage previously taken from Atakoy/Istanbul was experimentally surveyed in terms of conventional parameters and COD fractions over a period of more than 6 months [10]. Results of the characterization study summarized in Table 2 revealed that the soluble organic COD was 130 mgl^{-1} accounting for only 25% of the total COD. The soluble part of the wastewater mainly covered the readily biodegradable substrate (23 %), slowly biodegradable substrate (54%) and inert organic matter (23 %). The study outlines that the particulate slowly biodegradable substrate fraction corresponding to approximately 58 % of the total COD, is lower than the values reported for domestic sewage [11, 12].

Experimental data obtained for two different sludge ages at 2 and 20 days show that the mag-

Table 4
Evaluation of the results for synthetic waste and domestic sewage

	$gVSS(gTSS)^{-1}$		$gTSS(gCOD)^{-1}$		$gVSS(gCOD)^{-1}$	
	Average	Range	Average	Range	Average	Range
Synthetic waste	0.72	0.68-0.75	1.22	1.12-1.39	0.88	0.83-0.97
Domestic sewage	0.80	0.78-0.82	1.07	1.02-1.12	0.85	0.82-0.88

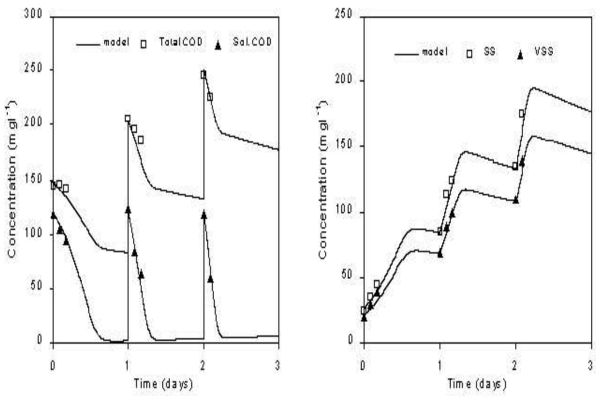

Figure 4. Modeling results for domestic sewage (R9) (a) Total COD and soluble COD utilization (b) VSS and TSS production

Table 5
Evaluation of the conversion factors for domestic sewage

Conversion Factor	Unit	Value	Reference
Domestic sewage			
i_{SSXH}	$gTSS(gCOD)^{-1}$	0.9	[2]
		0.83	[3]
		1.05	This study
i_{SSXE}	$gTSS(gCOD)^{-1}$	0.75	[2]
		0.83	[3]
		0.75	This study
i_{VSSXH}	$gVSS(gCOD)^{-1}$	0.75	[2]
		0.85	This study
i_{VSSXE}	$gVSS(gCOD)^{-1}$	0.75	[3]
		0.75	This study

nitudes of TSS/COD, VSS/COD and VSS/TSS ratios were practically the same for all of the samples tested, as listed in Table 3. The mean value for TSS/COD ratio was 1.05 and varied within a narrow range of 1.02-1.08 and the VSS/COD ratio was found to be varied in a range of 0.84-0.87 with a mean of 0.85 for the fill and draw reactor operated at θ_X=2 days. Similar ratios were calculated using the data measured in batch experiments. Comparable results were also obtained in the tests conducted at θ_X=20 days; average TSS/COD and VSS/COD ratios were estimated as 1.08 (1.05-1.12) and 0.86 (0.83-0.88) in the batch reactor, respectively.

5. Modeling and Evaluation of Results

The evaluation of the results obtained for synthetic waste and domestic sewage leads to the conclusion that the inorganic particulate sludge production in terms of TSS/COD is not affected by the sludge age. A general evaluation representing the overall average values for different ratios are summarized in Table 4. Similar results were obtained for VSS/COD ratios for both samples, but TSS/COD value for synthetic waste was found slightly higher than that obtained for domestic sewage, which can be explained by the possible precipitation of chemicals present in buffer solutions.

The second part of the study covers the modeling studies with the purpose of the assessment of conversion factors for X_H and X_E. In the adopted endogenous decay model [6], applied to batch reactors, evaluation was performed for both synthetic waste and domestic sewage using the following basic data: Y_H = 0.45 gVSS $(gCOD)^{-1}$, $\hat{\mu}_H$= 3 day^{-1}, b_H= 0.15 day^{-1}, K_S=20 $mgCODl^{-1}$, f_{ES}=0.1 and f_{EX}=0.15. The differential equations for model components were solved for unknown conversion factors yielding best fit with the experimentally determined total COD, soluble COD, TSS and VSS profiles. The conversion factors may be defined in terms of mass balance on X_H and X_E on the basis of VSS and TSS using the expression (6). This equation can be converted to expressions (9) and (10) for the investigated study:

$$X_{VSS} = i_{VSSXH}X_H + i_{VSSXE}X_E \quad (9)$$

$$X_{TSS} = i_{SSXH} X_H + i_{SSXE} X_E \quad (10)$$

Simulation study conducted on R9 for domestic sewage was illustrated in Fig. 4 as an example, reflecting a perfect fit with the experimental data for the i_{SSXH} value of 1.05 gTSS(gCOD)$^{-1}$ and i_{SSXE} value of 0.75 gTSS(gCOD)$^{-1}$ as summarized in Table 5. An important feature of the simulation results is that the conversion factors for active biomass on the basis of TSS and VSS were determined higher than the values reported in the literature. Conversion factor for inert biomass on TSS basis was found to be the same as stated by Gujer *et al.* [3], whereas a slight difference was noticed from the data given by Gujer and Kayser [2]. The conversion factors calculated on the basis of VSS for both active and inert biomass (0.85 gVSS(gCOD)$^{-1}$ and 0.75 gVSS(gCOD)$^{-1}$) were determined to be higher than the commonly accepted value of 0.70 gVSS(gCOD)$^{-1}$.

Similar methodology carried out on synthetic waste resulted in comparatively higher value for i_{SSXH}, 1.15 gTSS(gCOD)$^{-1}$ and the same value of i_{SSXE} was obtained for domestic sewage.

6. Conclusion

In the modeling and design of activated sludge systems, one of the key steps is the correct assessment of the total sludge production in the aeration tank. The total sludge amount on the basis of TSS is an important parameter for design as it controls the performance of the clarifier. The correct assessment necessitates the determination of appropriate conversion factors. The conversion factor for active biomass obtained in this study is higher than the values stated in the literature, leading to the higher sludge production deviates from reported counterparts. Further investigation on the assessment of inorganic particulate sludge production is highly necessary for the appropriate design of the activated sludge systems.

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