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Fundamentals of Biological Wastewater Treatment

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Preface

Clean water is an essential nutrient for humans, animals and plants. Because of its limited resources, especially in countries with low rainfall, little surface water, deep ground water levels and relatively high temperatures, careful use and frequent reuse after appropriate treatment are requirements for healthy life. This awareness is relatively new, because it was not until the late 19th century that the population of larger industrialized cities learned that wastewater must be treated to prevent disease. The reuse of treated water is still a topic of controversial discussions. However, the authors of this book are convinced both that we must learn to develop and continue to promote water recycling systems and also that biological wastewater treatment processes play a highly important role.

The modern concept of industrial wastewater treatment is moving away from the classic "end-of-pipe" technology towards "decentralized effluent treatment processes", "process integrated water management" and ultimately in a number of cases being as close as possible to "fresh water-free processes". The central concept is to save water. In the classic concept, the groups producing intermediate or finished products are relatively isolated from the group which treats the wastewater, frequently treating several different effluents mixed together. This situation characterizes the first period of industrial wastewater treatment. After sampling, the water quality is determined and compared with regulations and the treated water is discharged into surface water. In all but a few exceptional cases, municipal wastewater treatment is performed in this same manner. Frequently, it is more favorable and economical to treat some industrial effluents by using specialized processes ("decentralized effluent treatment"), giving a water quality which makes it possible to reuse one or more water streams and to save fresh water. The next phase of development is to combine production processes and wastewater treatment, often called "process-integrated water management" (sustainable water use, industrial water use, cleaner production, etc.).

Typically, the improvement comes about through a complete change of the production process paradigm to reduce water and energy consumption, as well as waste production. Here, productional and environmental engineers need to cooperate and build one team. In this book, the fundamentals are discussed which are needed to better understand the processes taking place in "end-of-pipe" and "decentralized effluent treatment" plants. In the last chapter, examples of "process-integrated water management" and "decentralized treatment" are presented.

Two different wastewater treatment concepts can be followed: either the separation of impurities from water, or the partial or complete mineralization of impurities. Separation processes are based on fluid mechanics (sedimentation, centrifugation, filtration and flotation) or on synthetic membranes (micro-, ultra- and nanofiltration, as well as reverse osmosis). Additionally, physical–chemical processes can be used – like adsorption and coagulation – to separate dissolved or emulsified compounds from water. Impurities can be mineralized by biological and chemical processes (advanced oxidation with ozone, H_2O_2, UV, etc.). We want to concentrate our attention on biological processes. Other ones, such as sedimentation or membranes, will be discussed in connection with the activated sludge process and membrane bioreactors.

The main advantages of biological processes in comparison with chemical oxidation are: no need to separate colloids and dispersed solid particles before treatment, lower energy consumption, the use of open reactors, resulting in lower costs, and no need for waste gas treatment.

The advantages of chemical oxidation over biological processes are: no sludge production, mineralization of non-biodegradable compounds and smaller reactor volumes. If it is necessary to remove very large amounts of organics, both processes should be coupled if possible, first the biological step and then the chemical step. We will concentrate our discussion on the fundamentals of biodegradation.

Because of the early development of wastewater technology in industrialized countries, we frequently find "end-of-pipe" treatment plants in industry which simultaneously treat municipal wastewater and vice versa. "Decentralized effluent treatment" plants are initiated only if a large plant would be overloaded or the process would be negatively influenced by hazardous compounds. The main aim is then to optimize the treatment process by using process controls and thereby to reduce the cost of aeration and pumping.

In countries with rapidly growing industries and no municipal treatment plants, the construction and operation of a "decentralized effluent treatment" plant frequently has to be tested for each factory and realized as necessary. An appropriate treatment method should be applied rigorously to enable water reuse in regions with water scarceness or high water prices, for irrigation in agriculture, or as cooling water for power stations or industry. In addition, it is often very important to protect natural water systems used for drinking water supplies, recreation and conservation. Compared with "end-of-pipe" treatment, "decentralized treatment" is often the more economical process.

A better understanding is needed of the biological, physical, ecological, social and economical interactions surrounding water and wastewater. We cannot consider all these aspects, but this book provides important information about the fundamentals and engineering aspects of biological wastewater treatment. The methods used to describe and solve the problems presented are those used by biochemical engineers developing models based on mass balances which are valid for specific systems. The authors made every effort to present mathematical derivations so comprehensively that at least graduate students can follow. The target group also includes all engineers, biologists and chemists working in the field of wastewater treatment who are interested in learning more about its fundamentals.

After a survey of the historical development of microbiology and wastewater treatment, we give a brief introduction to wastewater characteristics and relevant legislation as well as microbial metabolism and stoichiometry, which is of fundamental importance for mass balances with biological reactions. Gas/liquid oxygen transfer is discussed in detail because of its high importance for all aerobic processes in wastewater treatment. Anaerobic substrate degradation is discussed afterwards as a very interesting alternative for the treatment of high-load effluents. Persistent, industrially produced compounds are not easily treated in biological processes. Therefore, the results of several recent studies are summarized and discussed here. The great significance of nitrogen and phosphorus removal has led us to report about their stoichiometric and kinetic backgrounds individually. In the past two decades, discussions about modelling of the activated sludge process have increased. To gain a better understanding of activated sludge model number 1 (ASM 1) and its description of nitrogen removal, we give detailed explanations. We have dealt with the use of membranes in place of secondary clarifiers to emphasize that new possibilities exist for reusing and recycling water in the future. Therefore, they may be suitable in tandem with the topic of the previous chapters which discuss production-integrated water management and decentralized effluent treatment.

Mrs. Christine Heimerl-Rötsch transcribed our texts several times, as they were updated numerous times. She deserves our high recognition for her thoroughness and punctuality. Dr.-Ing. Gregory Morgan corrected our English. Although we made every effort to compose the text faultlessly, there was still need for improvement. We express our thanks to him.

It would not have been possible to write this book without the numerous discussions with students, graduate students, scientific and chemotechnical co-workers as well as assistants. Thank you all very much for your cooperation!

We realize that not all parts of this book are easy to read, because it was necessary to use a large number of different variables and complicated indices. It was our conviction, however, that this was necessary to avoid misunderstanding and confusion.

Over the past 25 years, many new processes have been tested successfully, a lot of them have gone into operation and a great number of papers have been published in this field. We hope that this book will help provide a better understanding and orientation in the important and interesting field of "Biological Wastewater Treatment".

The Authors

List of Symbols and Abbreviations

Symbol	Explanation	Unit (example)	Basic unit
A	Surface	m^2	L^2
A	Membrane area	m^2	L^2
A	Membrane constant	$m\ h^{-1}\ bar^{-1}$	$L^2\ M^{-1}$
A^*	Membrane constant	$g\ m^{-2}\ h^{-1}\ bar^{-1}$	L^{-1}
a	Volume specific surface	$m^2\ m^{-3}$	$L^2\ L^{-3}$
a	Activity	–	–
a	Coefficient	–	–
a_1, a_2, a_3	Constants	–	–
B	Membrane constant	$m\ h^{-1}$	$L\ T^{-1}$
Bi	Biot number	–	
B_v	Loading per volume	$g\ m^{-3}\ d^{-1}$	$M\ L^3\ T^{-1}$
C	Dimensionless concentration	–	–
C	Integration constant		
C^*	Dimensionless dissolved concentration in equilibrium with gas concentration	–	–
C'	Dimensionless dissolved oxygen concentration	–	–
c	Concentration of special gas components in air	$g\ m^{-3}$	$M\ L^{-3}$
c'	Dissolved concentration	$g\ m^{-3}$	$M\ L^{-3}$
c^*	Dissolved concentration in equilibrium with gas concentration	$g\ m^{-3}$	$M\ L^{-3}$
D	Dilution rate	h^{-1}	T^{-1}
D_c	Critical dilution rate	h^{-1}	T^{-1}
D	Diameter	m	L
D	Diffusion coefficient	$m^2\ h^{-1}$	$L^2\ T^{-1}$
DC	Desorption capacity	$g\ m^{-3}\ h^{-1}$	$M\ L^{-3}\ T^{-1}$
D_x	Dispersion coefficient in x direction	$m^2\ h^{-1}$	$L^3\ T^{-1}$

Symbol	Explanation	Unit (example)	Basic unit
Da_{II}	Damköhler number II (= $\mu_{max} t_v$)	–	
d	Diameter	m	L
d_h	Hydraulic diameter	m	–
E	Efficiency	kg $(kWh)^{-1}$ O_2	L^{-2} T^2
E	Density of residence time	–	
E^*	Dimensionless efficiency	–	–
e_A	Energy of activation	kJ mol^{-1}	M L^2 T^{-2} N^{-1}
F	Residence time distribution	–	
F_{O_2}	Power of resistence of oxygen molecules	–	
f_i	Portion of inert biomass related to the total biomass	–	
f_p	Portion of particulate products related to biomass	–	–
ΔG^0	Difference of free reaction enthalpy	kJ mol^{-1}	M L^2 T^{-2} N^{-1}
g	Earth acceleration	m s^{-2}	L T^{-2}
h	Distance of the stirrer from the bottom	m	
ΔH^0	Difference of enthalpy	kJ mol^{-1}	M L^2 T^{-2} N^{-1}
H′	Henry coefficient	g L^{-1} bar^{-1}	M L^{-1} T^{-2}
H	Henry coefficient	–	
H_g	Henry coefficient	atm $(mol/l)^{-1}$	N L^{-2} M^{-1} L^{-3}
H	“Height” of deep tanks		
H	Height	m	L
I	Strength of a electric current	A	S
i	Strength of electric carrent	A	
i_{XB}	Nitrogen in bacteria related to mass of bacteria and slowly biod. susbstrate	–	–
i_{XP}	Nitrogen in bacteria related to particular inert organic matter	–	–
J	Specific mass transfer rate (volume flux)	g m^{-2} s^{-1} mol m^{-2} s^{-1}	M L^{-2} T^{-1} N L^{-2} T^{-1}
J_D	Diffusion flux	g m^{-2} s^{-1}	M L^{-2} T^{-1}
J_{D+C}	Flux for diffusion and convection	g m^{-2} s^{-1}	M L^{-2} T^{-1}
J_o	Standard volume flux	L m^{-2} bar^{-1} s^{-1}	M T^{-3}
K	Total mass transfer coefficient	h^{-1}	T^{-1}
K	Bolzmann constant	1.38×10^{-23} J K^{-1}	M L^2 T^{-2} θ
K′	Saturation coefficient for oxygen	mg L^{-1}	M L^{-3}
K_D	Dissoziation constant	–	–

Symbol	Explanation	Unit (example)	Basic unit
K_e	Equilibrium constant	–	–
K'_e	Equilibrium constant	$L\ mg^{-1}$	$L^3\ M^{-1}$
K_{iH}, K_i	Coefficients for excess substrate inhibition	$mg\ L^{-1}$	$M\ L^{-3}$
K_{iN}	Coefficient of non-competitive inhibition	$mg\ L^{-1}$	$M\ L^{-3}$
K_L	Overall mass transfer coefficient	$m\ h^{-1}$	$L\ T^{-1}$
K_La	Specific overall mass transfer coefficient	h^{-1}	T^{-1}
K_m	Michaelis–Menten coefficient	$mol\ L^{-1}$	$N\ L^{-3}$
K_m	Equilibrium constant	–	–
K_{OH}	Saturation coefficient for hydrolysis	$mg\ L^{-1}$	$M\ L^{-3}$
K_P	Henry coefficient	$bar\ L\ g^{-1}$	$M\ T\ L^{-1}$
K_S	Saturation coefficient for substrate	$mg\ L^{-1}$	$M\ L^{-3}$
K_{SH}	Saturation coefficient	–	–
k	Coefficient for dry air (= 0.2857)	–	–
k	Coefficient of reaction rate	h^{-1}	T^{-1}
k_o	Theoretical maximal value of reaction rate for $T \to \infty$	–	–
k_L	Mass transfer coefficient for liquid boundary	$m\ h^{-1}$	$L\ T^{-1}$
k_La	Specific mass transfer coefficient for liquid boundary	h^{-1}	T^{-1}
k_G	Mass transfer coefficient for gaseous boundary	$m\ h^{-1}$	$L\ T^{-1}$
k_Ga	Specific mass transfer coefficient for gaseous boundary	h^{-1}	T^{-1}
k_d	Decay coefficient	h^{-1}	T^{-1}
k_s	Coefficient of bacteria dying	h^{-1}	T^{-1}
k_e	Coefficient of endogeneous respiration	h^{-1}	T^{-1}
L	Length	m	L
L	Biofilm thickness	m	L
LD_{50}	Mass of a compound per mass of living test organism, fatal to one-half of population if delivered rapidly	$mg\ kg^{-1}$	–
M	Molmass	$g\ mol^{-1}$	$M\ N^{-1}$
m	Mass	g	M
N	Amount of moles	mol	N

Symbol	Explanation	Unit (example)	Basic unit
n	Speed of a stirrer	s^{-1}	T^{-1}
n_i	Number of droplets	–	–
n_R	Recycle ratio	–	–
n_E	Thickening degree	–	–
n_{PHB}	Fraction of PHB inside of bacteria		
n	Number of stages of a cascade	–	–
OC	Specific oxygenation capacity	$mol\ L^{-1}\ h^{-1}$	$N\ L^{-3}\ T^{-1}$
OTR	Oxygen transfer rate	$g\ O_2\ L^{-1}\ h^{-1}$	$M\ L^{-3}\ T^{-1}$
OTE	Oxygen transfer efficiency	–	–
P	Power demand	kW	$M\ L^2\ T^{-3}$
p	Pressure	bar	$M\ L^{-1}\ T^{-2}$
Q	Flow rate	$m^3\ h^{-1}$	$L^{-3}\ T^{-1}$
R	Radius	m	L
R	Gas constant [= 8.314 J $(mol\ K)^{-1}$]	J $(mol\ K)^{-1}$	$M\ L^2\ T^{-2}\ N^{-1}\ \theta^{-1}$
R	Resistance	m^{-1}	L^{-1}
R	Retention coefficient	%	
R_t	True retention coeffcient	%	
r	Reaction rate	$mg\ L^{-1}\ h^{-1}$	$M\ L^{-3}\ T^{-1}$ $N\ L^{-3}\ T^{-1}$
r'	Respiration rate	$g\ L^{-1}\ h^{-1}$	$M\ L^{-3}\ T^{-1}$
r_x	Growth rate of bacteria	$g\ L^{-1} d^{-1}$ MLSS	$M\ L^{-3}\ T^{-1}$
S	Concentration of substrates	$mg\ L^{-1}$[1], $mol\ L^{-1}$	$M\ L^{-3}$, NL^{-3}
SOTR	Standardized oxygen transfer rate	$mg\ L^{-1}\ h^{-1}$	$M\ L^{-3}\ T^{-1}$
S^*	Dimensionless dissolved oxygen concentration (= S'/K')	–	–
S	Selectivity	–	–
T	Temperature	K, °C	θ
t	Time	h	T
t_R	Mean retention time	h	T
t_{RC}	Critical mean retention time	h	T
t_{RX}	Mean retention time of bacteria (= sludge age)	h	T
t_{RXC}	Critical sludge age	h	T
U	Voltage	V	$M\ L^2\ T\ A^{-1}$
V	Volume	m^3	L^3
v	Velocity	$m\ s^{-1}$	$L\ T^{-1}$
w	Flow rate	$m\ s^{-1}$	$L\ T^{-1}$

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[1] BOD_5, COD, DOC etc.

Symbol	Explanation	Unit (example)	Basic unit
$\bar{w}$	Gaging void velocity		
$\bar{w}$	Mean velocity	$m\ s^{-1}$	$L\ T^{-1}$
X	Concentration of bacteria	$g\ L^{-1}$ MLSS	$M\ L^{-3}$
X^*	Dimensionless bacteria concentration ($= X/K'$)	–	–
x	Local coordinate	m	L
x	Mole fraction	–	–
y	Mole fraction	–	–
$y_{X\text{-}0/X\text{-}C}$	Mole fraction oxygen/carbon in bacteria	–	–
Y	Yield coefficient	–	–
$Y^o_{X/S}$	True yield coefficient growth of bacteria/used substrate	g MLSS (g COD)$^{-1}$	–
$Y^o_{XC/SC}$	True yield coefficient growth of bacteria carbon/used substrate	g C (g DOC)$^{-1}$	
$Y_{X/S}$	Apparent yield coefficient growth of bacteria/used substrate	g MLSS (g COD)$^{-1}$	–
Z	Dimensionless local coordinate	–	–
z	Local coordinate	m	L
Bi	Biot number	$(= w\ d\ D^{-1})$	
Da	Damköhler number	$(\equiv \mu_{max}\ t_R)$	
Da_{II}	Damköhler number II	$(\equiv \mu_{max}\ R^2\ D^{-1})$	
Fr	Froude number	$(\equiv n^2\ d\ g^{-1})$	
Mo	Monod number	$(\equiv S_o\ K_S{}^{-1})$	
Mo′	Modified Monod number	$(\equiv c^*\ k'^{-1})$	
Ne	Newton number	$(\equiv P\ d^{-5}\ n^{-3}\ g^{-1})$	
Pe	Peclet number	$(\equiv w\ d\ D^{-1})$	
Pe′	Modified Peclet number	$(\equiv \bar{w}\ L\ D_x^{-1})$	
Re	Reynolds number	$(\equiv \bar{w}\ d\ \nu^{-1})$	
Sc	Schmidt number	$(\equiv \nu\ D^{-1})$	
Sh	Sherwood number	$(\equiv k_L\ d\ D^{-1})$	
Sm	Semenov number	$(\equiv k_L a\ \mu_{max}^{-1})$	
Y	Oxygen transfer number	$\left(\equiv \frac{K_L a\, V}{d^3}\left(\frac{\nu}{g^2}\right)^{1/3}\right)$	

Symbol	Explanation		
Greek Symbols			
α	Conversion, removal ratio	–	–
α_w	Relation of specific mass transfer coefficient wastewater/clean water	–	–
β	Separation coefficient of a settler	–	–
β	Osmotic coefficient	–	–
β_w	Relation dissolved oxygen concentration at 20 °C wastewater/clean water	–	–
γ	Activity coefficient	–	–
γ_w	$\alpha_w \beta_w$ relation maximal oxygen mass transfer rate at 20 °C wastewater/clean water	–	–
δ	Boundary layer thickness	m	L
ε	Porosity	–	–
η	Rate of hydrolosis by anoxic bacteria related to rate of hydrolosis by aerobic bacteria	–	–
η	Efficiency coefficient	–	–
η	Dynamic viscosity	$g\ m^{-1}\ s^{-1}$	$M\ L^{-1}\ T^{-1}$
θ	Coefficient, describing an influence of temperature	–	–
μ	Specific growth rate	d^{-1}	T^{-1}
μ	Tortousity	–	–
μ_{O_2}	Velocity of diffusing oxygen molecules	$m\ s^{-1}$	$L\ T^{-1}$
ν	Kinematic viscosity	$m^2\ s^{-1}$	$L^2\ T^{-1}$
ξ	Resistance coefficient	–	–
π	Number in analysis of dimensions	–	–
π	Osmotic pressure	bar	$M\ L^{-1}\ T^{-2}$
ρ	Density	$g\ m^{-3}$	$M\ L^{-3}$
Σ	Sum	–	–
σ	Surface tension	$N\ m^{-1}$	$M\ T^{-2}$
σ	Dimensionless variance	–	–
σ^*	Dimensionless surface tension	–	–
σ_t	Variance according time	s	T
τ	Dimensionless time	–	–
φ	Phase angle of electric current	–	–

Symbol	Explanation
Indices	
arith	Arithmetic mean value
A	Active autotrophs
A	Air
Alk	Alkaline
a	Adsorption
a	Behind reactor
a	Air
ae	Aerobic
an	Anaerobic
ap	Apparent
ax	Anoxic
b	Back
b	Blower
c	Cake
cat	Catalyst
cf	Cross flow
C	Convective
CO_2-O	CO_2-oxygen
CO_2-C	CO_2-carbon
CO_2-C/S-C	CO_2-C/substrate-carbon
CO_2-O/S-O	CO_2-O/substrate-oxygen
CO_2-N	CO_2 needed for neutralisation of H^+ formed by NH_4-N oxidation
Σ	Summary
d	Daily
d	Decay
d	Diameter
d	Dissolved
D	Denitrifyers
D	Diffusion
DO	Dodecan
D+C	Diffusion and convection
e	Effluent
e	Endogenous
eff	Effective
ex	Excess
E	Enzyme
ES	Enzyme–substrate complex
ET5	Emulgin ET5

Symbol	Explanation
f	Fouling
f	Foreign
f	Free of oxygen
g	Gear
G	Gas
G	Generation
H	Active heterotrophs
H	Hydrolysis
i	Impuls
i	Inert
i	Inhibitor
i,j	Component
L	Liquid
max	Maximal
m	Membrane
m	Motor
M	After mixure
M	Mixing point
ML	Mixed liquid
MLSS	Mixed liquid suspended solids
N	Nitrogen
N	secondary materials
NB	*Nitrobacter*
ND	dissolved organic nitrogen
NH	Dissolved NH_3 and NH_4
NH_4-O_2	Oxygen used for NH_4 oxydation
NH_4-N	Nitrogen in ammonia
NS	*Nitrosomonas*
NO	Nitrate and nitrite nitrogen
NO_2	Nitrite
NO_3	Nitrate
NS	Nitrosomonas
o Influent	Standardized to $c' = 0$ mg L^{-1}
org.P	Dissolved organic phosphorous
oTS	Organic dry matter
O_2	Oxygen
p	Permeate
p	Particulate product
po	Pore
pw	Process water
P	Phosphorus

Symbol	Explanation
PM	Primary materials
PO4	Orthophosphate
P-P	Dissolved inorganic polyphosphate
rt	Rapid test
R	Reactor
R	Recycle
s	Substrate
spec	Specific
S	Sewage
SC	Substrate-carbon
SO	Substrate-oxygen
SS	Readily biodegradable substrate
St	Standard test
t	Total
th	Theoretical
T	Temperature
v	Related to volume
VOC	Volatile organic carbon
w	Water
XA	Biomass of autotrophs
XH	Biomass of heterotrophs
X	Local coordinate
XC	Bacteria mass-carbon
XO	Bacteria mass-oxygen
XC/XO	Carbon in bacteria mass/oxygen in bacteria mass
XC/SC	Carbon in bacteria mass/carbon in substrate
X/O_2	Bacteria mass/oxygen
X/S	Bacteria mass/substrate
z	Local coordinate
0	Influent

Numbers as Indices

20	Temperature of 20 °C
*	Saturation
–	Mean value
20	Applied to 20 °C
20,0	Applied to 20 °C and $c' = 0$ mg O_2 L^{-1} dissolved oxygen

Symbol	Explanation
Abbreviations	
AAO	Anaerobic Anoxic Oxic
ADP	Adenosin diphosphate
AO	Anaerobic Oxic
ASM	Activated sludge model
ASCE	American Society of Civil Engineers
ATP	Adenosine triphosphate
ATV	Abwasser Technische Vereinigung
BOD	Biological oxygen demand
BWB	Berliner Wasserbetreiber
CA	Cellulose acetate
CFD	Computational fluid dynamics
COD	Chemical oxygen demand
CSTR	Completely stirred tank reactor
DNA	Deoxyribonucleic acid
DMSO	Dimethylsulfonoxide
DOC	Dissolved organic carbon
DWA	Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V.
DVWK	Deutscher Verband für Wasserwirtschaft und Kulturbau e.V.
EDS	Endocrine disrupting substances
EPA	Environmental Protection Agency
EPS	Extracellular polymer substances
FM	Ratio of feed to biomass
LDS	Lignin degradation system
MAP	Magnesium ammonium phosphate
MBR	Membrane bioreactor
MLSS	Mixed liquor suspended solid
MLVSS	Mixed liquor volatile suspended solid
NDSA	Naphtalene disulfonic acid
NSA	Naphtalene sulfonic acid
PA	Polyamide
PAN	Polyacrylnitrile acid
PAO	Phosphate-accumulating organism
PES	Polyethensulphone
PFU	Plug-forming unit
PHB	Polyhydroxybutyrate
PP	Polypropylen
PSU	Polysulphone
PUDF	Polyvinylidenfluoride

Symbol	Explanation
RB5	Reactive black 5
RDR	Rotating disc reactor
RNA	Ribonucleic acid
SCP	Single-cell protein
SRB	Sulfur-reducing bacteria
SS	Suspended solid
UASB	Upflow anaerobic sludge blanket
VFA	Volatile fatty acid
VOC	Volatile organic compound
WWTP	Wastewater treatment plant