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SCENARIO-BASED SIMULATION OF TREATMENT PROCESSES FOR MINIMIZATION OF SLUDGE PRODUCTION FROM AL-SAAD WASTEWATER TREATMENT PLANT

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Water Resources

Under the Supervision of Dr. Mohamed Hamouda

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Declaration of Original Work

I am Omar Gamil Abdelmajeed Hussien, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Scenario-Based Simulation of Treatment Processes for Minimization of Sludge Production from Al-Saad Wastewater Treatment Plant*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Dr. Mohamed Hamouda, in the College of Engineering at UAEU. This work has not previously been presented or published or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

The biological activated sludge treatment process is the most widely used approach to treat domestic wastewater. It involves the transformation of soluble and particulate organic matter to gases and large amounts of settleable biomass (produced sludge). This sludge is considered one of the most pressing management challenges since its treatment represents approximately 50 to 60% of the total operational cost of a wastewater treatment plant (WWTP). The traditional management of excess sludge is by disposal to landfills, incineration, or agriculture reuse in the form of fertilizers but due to energy and environmental concerns, many jurisdictions developed strict policies and regulations for managing excess sludge. Therefore, this calls for the investigation of novel approaches to reduce the amount of generated sludge as the benefits would then be two-fold, environmental as well as economic. Sludge can be reduced through two main approaches which are post-treatment of produced sludge or in-situ activated sludge reduction. Post-treatment is an approach where treatment will take place after sludge is produced in the plant. Whereas in-situ activated sludge reduction will reduce the amount of produced sludge from the source itself. In this thesis, the in-situ activated sludge reduction without effluent quality deterioration is investigated for an existing full-scale WWTP which generates approximately 15 tons of sludge each day (Al Saad WWTP in Al Ain, UAE).

The complex combination of WWTP processes makes the investigation of their performance and interactions on bench and pilot scales technically challenging and costly. This is exacerbated when the scope of investigation attempts to experiment with different operating parameters and/or unit processes. Therefore, a simulation approach was adopted in this study using BioWin™ V.6 software. The challenge with the simulation approach is that it requires model calibration. Calibration entails the adaptation of some model parameters until the model prediction matches specific observed data of the plant stream quality characteristics. There are four different model calibration protocols proposed in the literature, the water environmental research foundation (WERF) is the one applied in this study. Routine historical data about the Al-Saad WWTP was gathered but were not enough to develop the model; therefore, a sampling campaign was conducted for further parameters characterization, particularly for determining the fractions of chemical oxygen demand (COD) and total Kjeldahl nitrogen (TKN). After the model of Al-Saad WWTP was developed and calibrated, several scenarios were structured to represent the application of variations of the oxic-settling-anaerobic (OSA) process which appears in literature as a sludge reduction retrofit. The OSA process was modeled by inserting a sludge holding tank (SHT) on the recirculation activated sludge stream between the secondary settling tank and the aeration tank. The results revealed that the percentage reduction in the amount of produced sludge increased from 4.04% to 5.76% when the hydraulic retention time (HRT) of the OSA tank increased from 2 to 12 hours. Selecting the optimum HRT is governed by the available area, the initial cost of SHT, and sludge treatment cost. This reduction was attributed to the stressful conditions that recycled biomass from secondary settling tank faces inside the OSA process resulting in an increase in the sludge anaerobic decay coefficient. This result is consistent with previous studies that investigated anaerobic side stream reactor (a process similar to OSA) on a full-scale WWTP. This study concluded that the OSA process is a simple adjustment in existing/new WWTPs that can potentially reduce the amount of excess sludge without deteriorating the effluent quality. The contribution of this study lies in detailing the model calibration process; and demonstrating the use of the calibrated model in examining the performance of plant retrofit alternatives. Further research is required to identify the mechanism behind the OSA process and to define the design principles for OSA.

Keywords: Wastewater Simulation, OSA, ASM, Activated Sludge, Al Saad Wastewater Treatment Plant, Model Calibration, Sludge Reduction, BioWin.

Title and Abstract (in Arabic)

نمذجة بعض عمليات المعالجة للتقليل من كميات الحمأة الناتجة من محطة الساد لمعالجة مياه الصرف الصحي

الملخص

تعتبر عملية معالجة الحمأة المنشطة بيولوجيًا هي الطريقة الأكثر استخدامًا لمعالجة مياه الصرف الصحي المنزلية. تتضمن العملية تحويل المواد العضوية الذائبة والمعلقة إلى غازات وكميات كبيرة من الكتلة الحيوية القابلة للترسيب (الحمأة المنتجة). تمثل هذه الحمأة أكثر التحديات صعوبة نظرًا لأن معالجتها تمثل حوالي 50 إلى 60٪ من إجمالي التكلفة التشغيلية لمحطة معالجة مياه الصرف الصحي. تتم الإدارة التقليدية للحمأة الزائدة عن طريق التخلص من الحمأة الزائدة في مدافن النفايات أو الحرق أو إعادة الاستخدام الزراعي في شكل أسمدة ولكن نظرًا للمشاكل المتعلقة بالطاقة والبيئة، طورت العديد من الجهات المسئولة سياسات وأنظمة صارمة لإدارة الحمأة الزائدة. لذلك فإن هذا يستدعي التحقيق في الأساليب الجديدة لتقليل كمية الحمأة المتولدة حيث ستكون الفوائد عندئذ ذات بعدين بيئي واقتصادي. يمكن تقليل الحمأة من خلال نهجين رئيسيين هما المعالجة اللاحقة للحمأة الناتجة أو تقليل الحمأة المنشطة في الموقع. المعالجة اللاحقة هي طريقة تتم فيها المعالجة بعد إنتاج الحمأة في المحطة. في حين أن تقليل الحمأة المنشطة في الموقع سيقلل من كمية الحمأة الناتجة من المصدر نفسه. في هذه الأطروحة، تم التحقيق في تقليل الحمأة المنشطة في الموقع دون تدهور جودة المياه المعالجة لمحطة معالجة مياه الصرف الصحي والتي تولد ما يقرب من 18 طنًا من الحمأة يوميًا (محطة الساد لمعالجة مياه الصرف الصحي في العين، الإمارات العربية المتحدة).

إن التركيبة المعقدة من عمليات معالجة مياه الصرف الصحي تجعل التحقيق في أدائها وتفاعلاتها على المقياس التجريبي أمرًا صعبًا ومكلفًا من الناحية الفنية. يتفاقم هذا عندما يحاول نطاق التحقيق تجربة معاملات تشغيل مختلفة و / أو عمليات عدة. لذلك تم اعتماد نهج المحاكاة في هذه الدراسة باستخدام برنامج BioWin ™ 6.0. التحدي في استخدام نهج المحاكاة هو أنه يتطلب معايرة النموذج المستخدم. تستلزم المعايرة تكييف بعض معاملات النموذج حتى يتطابق توقع النموذج مع البيانات المحددة المرصودة لخصائص جودة وحدات المعالجة. هناك أربع بروتوكولات معايرة نموذجية مختلفة مقترحة في الأبحاث السابقة ولكن نهج مؤسسة أبحاث المياه البيئية (WERF) هو الذي تم تطبيقه في هذه الدراسة. تم جمع البيانات التاريخية الروتينية لمحطة

الساد لمعالجة مياه الصرف الصحي ولكنها لم تكن كافية لتطوير النموذج؛ لذلك، تم أخذ عينات لمزيد من التوصيف خاصة لتحديد كسور الطلب على الأكسجين الكيميائي (COD) وإجمالي نيتروجين (TKN) Kjeldahl. بعد تطوير ومعايرة نموذج محطة الساد لمعالجة مياه الصرف الصحي، كانت هناك عدة سيناريوهات لتمثيل الاختلافات في عملية ترسيب الأكسدة اللاهوائية (OSA) والتي تظهر في الأبحاث كإجراء حديث للحد من الحمأة. تم تصميم عملية OSA عن طريق إدخال خزان احتجاز الحمأة اللاهوائية في دورة معالجة مياه الصرف الصحي بين خزان الترسيب الثانوي وخزان التهوية. أظهرت النتائج زيادة في نسبة انخفاض الحمأة المنتجة تراوحت بين 4.04 - 5.76٪ عندما كان زمن الاحتفاظ الهيدروليكي في خزان OSA زاد من 2 إلي 12 ساعة. تعزى هذه الزيادة في نسبة الانخفاض إلى الظروف المجهدة التي تشهدها الكتلة الحيوية من خزان الترسيب الثانوي في خزان OSA مما أدى إلى زيادة معامل التحلل اللاهوائي للحمأة. تتوافق هذه النتيجة مع الدراسات السابقة التي بحثت في مفاعل التيار الجانبي اللاهوائي (شكل من أشكال OSA) في محطة معالجة مياه الصرف الصحي. خلصت هذه الدراسة إلى أن عملية OSA هي تعديل بسيط في محطات معالجة مياه الصرف الصحي الحالية / الجديدة التي يمكن أن تقلل كمية الحمأة الزائدة دون تدهور جودة المياه المعالجة. تكمن مساهمة هذه الدراسة في تفصيل عملية معايرة النموذج؛ وشرح استخدام النموذج المعاير في فحص أداء بدائل التعديل للمحطة. مطلوب مزيد من البحث لتحديد الآلية الكامنة وراء عملية OSA ولتحديد مبادئ تصميم OSA.

مفاهيم البحث الرئيسية: محطة الساد، محاكاة محطات الصرف الصحي، معايرة نماذج محطات الصرف، التقليل من الحمأة باستخدام الخزان اللاهوائي.

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Dedication

To my beloved parents and family

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List of Abbreviations

ADSSC	Abu Dhabi Sewage Services Company
AS + ASSR	Activated Sludge - Anaerobic Side Stream Reactor
ASDM	Activated Sludge/Anaerobic Digestion
ASM 1	Activated Sludge Model 1
ASM 2	Activated Sludge Model 2
ASM 3	Activated Sludge Model 3
ASSR	Anaerobic Side Stream Reactor
AT	Aeration Tank
ATP	Adenosine Triphosphate
BOD_5	Biochemical Oxygen Demand
CAS-OSA	Conventional Activated Sludge-Oxic-Settling- Anaerobic
CAS	Conventional Activated Sludge
COD	Chemical Oxygen Demand
COD_T	Total COD
dNP	Dinitrophenol
DO	Dissolved Oxygen
EDCs	Endocrine Disrupting Chemicals
EPS	Extracellular Polymeric Substances
F_{cel}	Cellulose Fraction of Non-biodegradable Particulate
ffCOD	Flocculated Filtered COD
F_{na}	Ammonia
F_{nus}	Soluble Non-biodegradable TKN

F_{NXI}	Fraction of Non-biodegradable Particulate Organic Nitrogen
FP	Filter Paper
F_{po4}	Phosphate
F_{SI}	Fraction of Total Influent COD which is Soluble Non-biodegradable
F_{us}	Non-biodegradable Soluble [g COD /g of Total COD]
F_{XI}	Fraction of Total Influent COD which is Particulate Non-biodegradable
F_{XNB}	Fraction of Non-biodegradable Soluble Organic Nitrogen
F_{xsp}	Non-Colloidal Slowly Biodegradable
GF	Glass Fiber
HRT	Hydraulic Retention Time
HSG	Hochschulgruppe
IAWPCR	International Association on Water Pollution Control and Research
IPCC	Intergovernmental Panel for Climate Change
IWA	International Water Association
MBR – OSA	Membrane Biological Reactor- Oxic-Settling- Anaerobic
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
N_2O	Nitrous Oxide
OHO	Ordinary Heterotrophic Organisms
ORP	Oxidation Reduction Potential
OSA	Oxic-Settling-Anaerobic

PAOs	Phosphorus Accumulating Organisms
PHA	Poly-Hydroxyalkanoate
pNP	Para-Nitrophenol
PPCPs	Pharmaceuticals, Personal Care Products
PST	Primary Settling Tank
RAS	Return Activated Sludge
RBCOD	Readily Biodegradable COD
SA	Surface Aerator
SBCOD	Slowly Biodegradable COD
SHT	Sludge Holding Tank
S_I	Non-biodegradable Soluble
S_{ij}	Normalized Sensitivity Coefficient
SMP	Soluble Microbial Products
S_{NB}	Soluble Biodegradable Organic TKN
S_{NH}	Free and Saline Ammonia
S_{NI}	Soluble Non-biodegradable Organic TKN
SRT	Solids Retention Time
S_S	Readily Biodegradable COD
SST	Secondary Settling Tank
STOWA	Stichting Toegepat Onderzoek Waterbeheer
TCP	Trichlorophenol
TCS	Tetrachlorosalicylanilide
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen

TP	Total Phosphorus
TSS	Total Suspended Solids
UAE	United Arab Emirates
VFA	Volatile Fatty Acids
VSS	Volatile Suspended Solids
WAS	Waste Activated Sludge
WERF	Water Environmental Research Foundation
WWTPs	Wastewater Treatment Plants
X_I	Non-biodegradable Particulate
X_i	Input
X_{NB}	Particulate Biodegradable Organic TKN
X_{NI}	Particulate Non-biodegradable Organic TKN
X_{sc}	BOD Calculation Rate Constant for SBCOD Colloidal
X_{sp}	BOD Calculation Rate Constant for SBCOD Particulate
Y_i	Output
Y_{obs}	Observed Sludge Yield
ΔX_i	Change in Input
ΔY_i	Change in Output

Chapter 1: Introduction

1.1 Overview

Wastewater received by centralized wastewater treatment plants (WWTPs) originate from different sources such as residential, commercial, and industrial (after on-site treatment); and is typically collected through public sewage networks. The purpose of wastewater treatment plants is to treat and manage the collected wastewater and the byproducts of the treatment process (e.g., sludge). In a wastewater treatment plant, collected wastewater firstly passes through pre-treatment units to remove grits, grease, and oil. Then wastewater flows into the first stage of treatment which is primary sedimentation where suspended solids (organic and inorganic) removal takes place. Soluble organics in wastewater will be consumed by microorganisms in the secondary stage of treatment through biological processes (aerobic and / or anaerobic). Secondary treatment units can be in the form of different processes such as activated sludge, trickling filters, rotating biological reactor and oxidation ditch. The purpose of tertiary treatment is to polish the effluent before discharge or reuse, and it includes removal of nutrients, toxic compounds, and microorganisms. Membrane filtration (e.g., micro, ultra, nano, and reverse osmosis), activated carbon and disinfection (e.g., chlorination, ultraviolet) are examples of tertiary treatment units. Sludge treatment units such as thickening, dewatering, and stabilization are responsible for effectively reducing the water content, biochemical oxygen demand, pathogens and bad odors in the sludge (Drechsel et al., 2015). Wastewater treatment process design is based on the raw wastewater characteristics, limitation of receiving water body (or ultimate disposal), water reuse purpose, energy production, capital cost and operation cost (Haandel & Lubbe, 2012). Wastewater treatment is a combination of processes that could rely on three different technologies: physical, biological, and chemical; with each being responsible for removal of specific contaminants (Henze et al., 2015).

Wastewater is considered as a source of water supply and energy when it passes through the treatment facility. Ideally, the objectives of the WWTP are to reuse the treated water, recover and use some of the minerals in the water, and produce biogas from anaerobic processes for energy self-sufficiency. WWTPs produce sludge that contains the generated bacterial biomass from aerobic processes, and the settled suspended solids. Sludge could be used in land application as fertilizer since it includes viable nutrients (e.g., nitrogen and phosphorus). Also, sludge could be used as a soil conditioner due to its organic carbon content which improves the soil structure. Moreover, sludge can be anaerobically digested to produce energy represented in biogas (Drechsel et al., 2015).

The growth of world population and rise of urbanization has increased the volumes of domestic wastewater received by WWTPs worldwide. The estimated volume of wastewater and produced sludge generated in different countries are illustrated in Tables 1 and 2, respectively (AQUASTAT 2021; Drechsel et al., 2015) . The increasing volume of generated wastewater represents a burden on municipalities. This consequently increased the volume of sludge produced from WWTPs.

Table 1: Estimated Volume of Domestic Wastewater Generated in Different Countries (AQUASTAT, 2021)

Generated Wastewater in Different Countries (km^3/year)					
Country / Period	**1993-1997**	**1998-2002**	**2003-2007**	**2008-2012**	**2013-2017**
US	-	-	-	60.41	60.41
Canada	-	-	6.148	6.152	6.074
Australia	1.538	1.825	1.828	2.094	2.094
Austria	-	1.05	1.054	1.054	1.054
France	-	3.465	3.73	4	4
Chile	-	1.077	1.096	1.112	1.112
Egypt	3.632	4.12	5.92	7.078	7.078
Morocco	0.4054	-0.65	0.6438	0.7	0.7
Iraq	-	-	-	0.58	0.85
Japan	-	-	14.98	16.93	16.93
Kuwait	0.179	0.2332	0.252	0.292	0.292
Saudi Arabia	-	0.9852	1.336	1.546	1.546
Sweden	-	-	-	0.7807	1
Turkey	2.358	2.497	3.314	3.314	4.647

Table 2: Estimated Annual Amount of Produced Sludge (Drechsel et al., 2015)

Country	**Produced Sludge (tons)**	**Year**
USA	6,514,000	2004
China	2,966,000	2006
Japan	2,000,000	2006
South Korea	1,900,000	-
Iran	650,000	2008
Jordan	300,000	2008
Turkey	580,000	2004
Canada	550,000	2008
Brazil	372,000	2005
Australia and New Zeeland	360,000	2008
Norway	87,000	2008

Similarly, the United Arab Emirates (UAE) has treated domestic wastewater in centralized treatment facilities since 1973. There are currently 86 WWTPs across the UAE with a total capacity of 0.871 km^3/year (Table 3). Wastewater reuse applications play an integral role in meeting water demands in the UAE. Wastewater reuse for landscape irrigation in particular is widely practiced in the country as a water management strategy to alleviate the country's water scarcity and promote environmental sustainability and protection (ACWUA, 2010; Ahmad, 2017; Semerjian et al., 2018). Abu Dhabi identified as a priority the efficient and integrated management and conservation of all water resources in the Emirate. To achieve this, Abu Dhabi aims to maximize the use of recycled water to reach 100% in 2030 (Ahmad, 2017; Environment Agency- Abu Dhabi, 2013). In addition, the international center for bio-saline agriculture is investigating the possibility of transferring all the produced sewage sludge in UAE (104,319 tons/year) into valuable materials that can be recycled as a soil conditioner and nutrient source for plant growth (Alshankiti et al., 2016).

Table 3: Status of Wastewater Flow and Treatment in UAE (Bayanat, 2017)

Emirate	Inflow Volume (km^3/year)	Number of WWTPs	WWTP Design capacity (km^3/year)
Abu Dhabi	0.3356	39	0.4737
Dubai	0.2757	10	0.2472
Sharjah	0.0997	11	0.0993
Ajman	0.0315	1	0.0315
Ras Al-Khaimah	0.0147	23	0.0134
Fujairah	0.0072	2	0.0063
Total	0.7464	86	0.8714

1.2 Wastewater Treatment Plant Challenges

There are several challenges that face WWTPs. One main challenge stem from the fact that traditional designs of WWTPs have a main objective of treating water to an acceptable level with little regard for energy consumption. This resulted in WWTPs being classified as one of the most energy consuming infrastructure facilities. Current research focuses on optimizing WWTPs design and operation to achieve target water quality with minimal energy consumption (Gu et al., 2017). Another challenge is the increase in gas emissions from treatment processes and energy consumption in the WWTP. Most of WWTPs include nitrification and denitrification processes where removal of ammonium takes place by certain types of microorganisms producing nitrous oxide (N_2O) to the environment which is one of the biggest contributors to global warming. As a result, the Intergovernmental Panel for Climate Change (IPCC) has classified wastewater treatment to be one of the sectors that contributes to global artificial emission of N_2O (Thakur & Medhi, 2019). Another challenge which highly received attention lately is the presence of micro pollutants such as pharmaceuticals, personal care products (PPCPs) and endocrine disrupting chemicals (EDCs) in surface water and soil. Therefore, research has focused on the persistence of these micro pollutants in the WWTP and their concentration in the environment as they pose considerable environmental risks. WWTPs are considered as last line of defense against the introduction of these micro pollutant in the environment. Previous studies revealed that some of the micro pollutants in wastewater could end up in discharged effluent and the disposed sludge (Ben et al., 2018).

One of the major challenges is that WWTPs produce excess volumes of sludge (Yang et al., 2018). Activated sludge is the most widely used biological process applied all over the world, but it has a disadvantage of producing large volumes of sludge. Management of this excessive sludge represents a high percentage (approximately 50 – 60%) of the total operational cost of the WWTP (Campos et al., 2009). Therefore, management of waste activated sludge has now become one of the most challenging issues in biological wastewater treatment. Moreover, due to environmental concerns, many countries in the world developed strict policies and regulations for managing excess sludge (Guo et al., 2013). The traditional management of excess sludge was by disposal to landfills, incineration, or agriculture reuse in the form of fertilizers. Landfilling is becoming more challenging because it requires a huge space in addition to the strict regulations on landfilling operation. Incineration is a good solution since it can reduce the sludge volume by 95% but it requires expensive machinery to process, consumes non-renewable resource, and has its own negative impact on public health and the environment. In addition, using produced sludge as a fertilizer or soil conditioner is costly since it requires additional treatment because it may contain heavy metals or trace elements that can be toxic (Semblante et al., 2014). This calls for the investigation of approaches to reduce the amount of generated sludge as the benefits would be then two-fold, in terms of environmental as well as economic impact. In the literature, sludge can be reduced through two main approaches which are post-treatment and in-situ activated sludge. Post-treatment is an approach where treatment will take place after sludge is produced in the plant. Whereas, the in-situ activated sludge approach will reduce the amount of produced sludge from the source itself (Guo et al., 2013).

The complex combination of WWTP processes makes the investigation of their performance and interactions on the bench and pilot scales technically challenging and costly. This is exacerbated when the scope of investigation attempts to experiment with different changes in operating parameters and/or units. In addition, the dynamic nature of several operating and water quality factors and their impact on process performance becomes particularly difficult to investigate. With the development of mathematical models and design tools, computer-based simulation tools have now become beneficial in simulating the performance of complex treatment plants (Henze et al., 2015; Kazadi Mbamba et al., 2016; Meijer et al., 2002; Saagi et al., 2017). Such tools can be used to test the effectiveness of proposed solutions to the common challenges faced by WWTPs (Henze et al., 2015).

1.3 Statement of the Problem

Al-Saad WWTP is an existing plant, located in Al-Ain City, Abu Dhabi in the UAE (Figure 1). The plant is designed to serve a community discharging a flow of up to 92,000 cubic meters every day. The generated wastewater flow passes through a pretreatment stage where big particles, sand, and grease are filtered through physical treatment (e.g. sand and grease trap, screens). Then flows to primary sedimentation tanks (PST) where BOD and TSS partially decrease. PST overflow is forwarded to an activated sludge reactors which are divided into an aerobic zone and an anoxic zone for the purpose of nitrification and denitrification. Secondary settling tanks (SST) receive the flow from the activated sludge reactors for solid-liquid separation. The overflow of the SST is then forwarded to disinfection units; whereas 93% of the underflow is recirculated to the activated sludge reactor. The recirculated flow is partially split and waste activated sludge (WAS) flows to the sludge treatment units through anaerobic digesters. The plant currently produces sludge at a rate of 15 tons per day which represents a challenge to the feasible operation of the WWTP. Appendix A presents a schematic layout, and physical and operational data of Al-Saad WWTP.

The operators of the WWTP were interested in investigating the potential alternatives for reducing the generated sludge. This research aims to investigate the different feasible alternatives for reducing sludge produced at the Al-Saad WWTP. A modelling approach is followed to simulate the Al-Saad WWTP plant using BioWin™ software V.6. After developing and calibrating the model, it was used for investigating the impact of an in-situ activated sludge approach (Oxic-Settling-Anaerobic (OSA) process) on reducing the amount of produced sludge. The simulation focused on the main processes (particularly activated sludge) that produce excessive sludge.

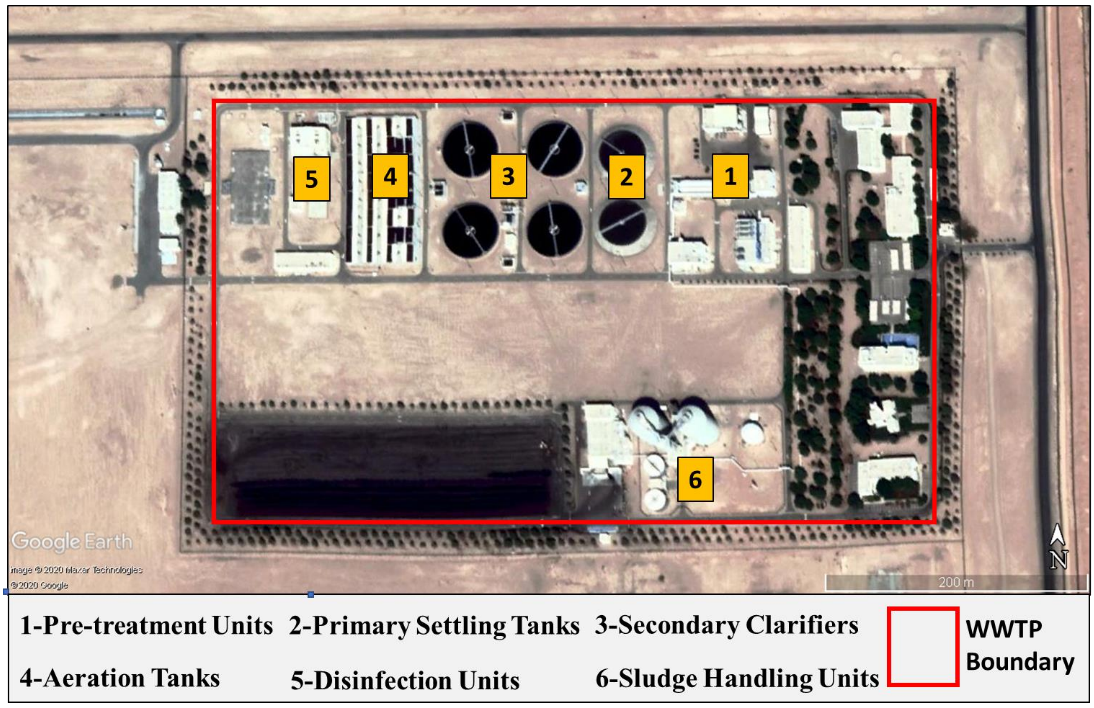

Figure 1: Al-Saad WWTP Aerial Image

1.4 Research Questions

This research has two main questions as follows:

1) Which parameters (e.g. kinetic and stoichiometric) are most influential in the outputs (sludge produced and effluent quality) of a WWTP model?
2) How much reduction in sludge could be achieved if OSA process is used in Al-Saad WWTP?

- The specific objectives of this research include:

1. To provide a state-of-the-art review of technologies and approaches for sludge reduction from WWTPs.
2. To review modeling strategies to incorporate modification on WWTP processes into BioWin software.

3. To develop a steady state model for Al Saad WWTP.
4. To do sensitivity analysis on the software's parameters.
5. To calibrate the model according to standards.
6. To simulate the impact of implementing sludge reduction approaches on the sludge produced by the WWTP.

1.5 Thesis Structure

Thesis structure is composed of 5 chapters, Chapter 1 (this chapter) introduced the wastewater sources, treatment technology, WWTP challenges, project description and objectives.

Chapter 2 reviews the literature pertaining to produced sludge minimization approaches, model calibration and validation protocols, activated sludge models (ASM), and wastewater characterization.

Chapter 3 describes the methodology of data acquisition, sampling campaign and laboratory analysis, Al-Saad WWTP model development, sensitivity analysis, Al-Saad WWTP model calibration and validation and model scenarios.

Chapter 4 presents and discusses the results of laboratory analysis, sensitivity analysis, model calibration and validation and scenarios generated for sludge reduction.

Chapter 5 provides the conclusions reached, limitations of the study, and outlines recommendations for further research.

Chapter 2: Literature Review

2.1 Wastewater Treatment Plant Simulation

Investigating wastewater treatment processes is a difficult endeavor since it is challenging to consider all the variables influencing the performance of each process and their interactive effect. Simulation of wastewater treatment processes is a viable tool to analyze the influence of a combination of factors on the performance of wastewater treatment processes.

A model can be defined as purposeful representation or description of a system of interest (Wentzel & Ekama, 1997). Therefore, it does not mean a model can exactly reflect the reality of treatment system response. It is impossible to develop a model that can fully describe a behavior of a system. Nonetheless, building a model and creating simulation is intended to be a simplified representation for part of the system that enables an acceptable prediction of the system response. Processes can be simulated in different states called frozen, steady, and dynamic. Models are usually used to simulate a dynamic state which is happening. A dynamic state describes the variation in respect time (Henze et al., 2015).

A simulator is a computer software that helps users to create a process model of an existing or newly designed WWTP to design, operate and analyze the relation between different units included in the process such as aerobic reactor and sedimentation reactors and visualize the performance of the plant in terms of specific operational parameter and influent load (Henze et al., 2015; Melcer, 2003; Water Environment Federation, 2014). In addition to supplemental models that are included in the software that go beyond the activated sludge process to include chemical precipitation, anaerobic digester, and sludge thickening. Each unit process integrates one mathematical model or more. Once the treatment process model has been created graphically incorporating all required data for the influent characteristics, the simulator could be utilized to solve the system and generate numerical and graphical results. Therefore, a simulator is a very powerful tool allowing users (engineers/researchers … etc.) somehow easily understand the complexity of the activated sludge mechanism and can answer the question what if controllable parameters changes and predict the response of the system (Melcer, 2003).

A survey has been conducted in 2001 for the available software in the market that include activated sludge modeling. There were seven software available as illustrated in Table 4 (Melcer, 2003).

Table 4: Available Software in the Market (Melcer, 2003)

Simulator	**Vendor**	**Location**	**Website**
ASIM	EAWAG	Switzerland	www.eawag.ch
Bio Win	EnviroSim Associate Limited	Canada	www.envirosim.com
EFOR	DHI, Inc	Denmark	www.dhi.com
GPS-X	Hydromaints, Inc	Canada	www.hydromaints.com
SIMBA	IFAC-System GmbH	Germany	www.ifac-system.com
STOAT	WRc Group	United Kingdom	www.wrcplc.co.uk
WSET	Hemmis N.V.	Belgium	www.hemmis.com

All softwares were developed in the period between 1988 and 1998. BioWin, EFOR, GPS-X, and STOAT are the most used software by consultant firms for the purpose of designing/retrofitting new/existing WWTPs (Makinia & Zaborowska, 2020; Melcer, 2003). GPS-X offers all IWA models in addition to a model attributed to Barker and Dold that has been modified by Hydromantis, In (Barker & Dold, 1997;

Melcer, 2003). BioWin is based on an extension of the 1997 Barker and Dold general model which can be substituted by IWA Models ASM1-3 (Barker & Dold, 1997; Melcer, 2003). BioWin software was selected to be the simulation software to build the model in this study because it is often used in literature, available at affordable cost, and training was available in the UAE.

2.2 Model Calibration

Model calibration is adaptation of some model parameters until model prediction match some specific observed data of the plant. Therefore, the objective is to reduce as much as possible the error between the model prediction and observed data. Differences between model predictions and observed data in steady-state simulation are acceptable in the range of 5 to 20 percent whereas in dynamic simulation should be within a range of 10 to 40 percent according to (Melcer, 2003).

Calibration procedures should be initiated before developing a model for an existing WWTP. These procedures include data collection (physical and operation parameters) and wastewater sampling for influent characteristics over a period of time. After that, the results should be transferred into the activated sludge model parameters to adjust the carbonaceous fractions, nitrogenous fractions, kinetic and stoichiometric parameters (Sin et al., 2005). There are four different model calibration protocols that have been proposed as follows (Sin et al., 2005):

1. The BIOMATH calibration protocol.
2. The Dutch Foundation for Applied Water Research (STOWA) calibration protocol.
3. The Hochschulgruppe (HSG) guidelines.

4. The WERF protocol for model calibration.

2.2.1 The BIOMATH Calibration Protocol

This protocol was proposed by Vanrolleghem in 2003 (Vanrolleghem et al., 2003) which is a standardized method for model calibration, and it is composed of four stages as shown in Figure 2. The first stage is defining the goals that should be achieved and determining the information required to reach a certain level of calibration. The second stage includes a comprehensive survey of the WWTP represented in physical parameters, operational parameters, sampling campaign for influent, biological and hydraulic characteristics. The third stage concerns the calibration of the hydraulic, aeration and settling models of the WWTP. A sensitivity analysis is conducted to reduce the effort and time of the calibration process. The fourth and final stage includes running a dynamic model to predict the variations in the performance of the WWTP due to the fluctuation in influent characteristics and operating parameters (Vanrolleghem et al., 2003).

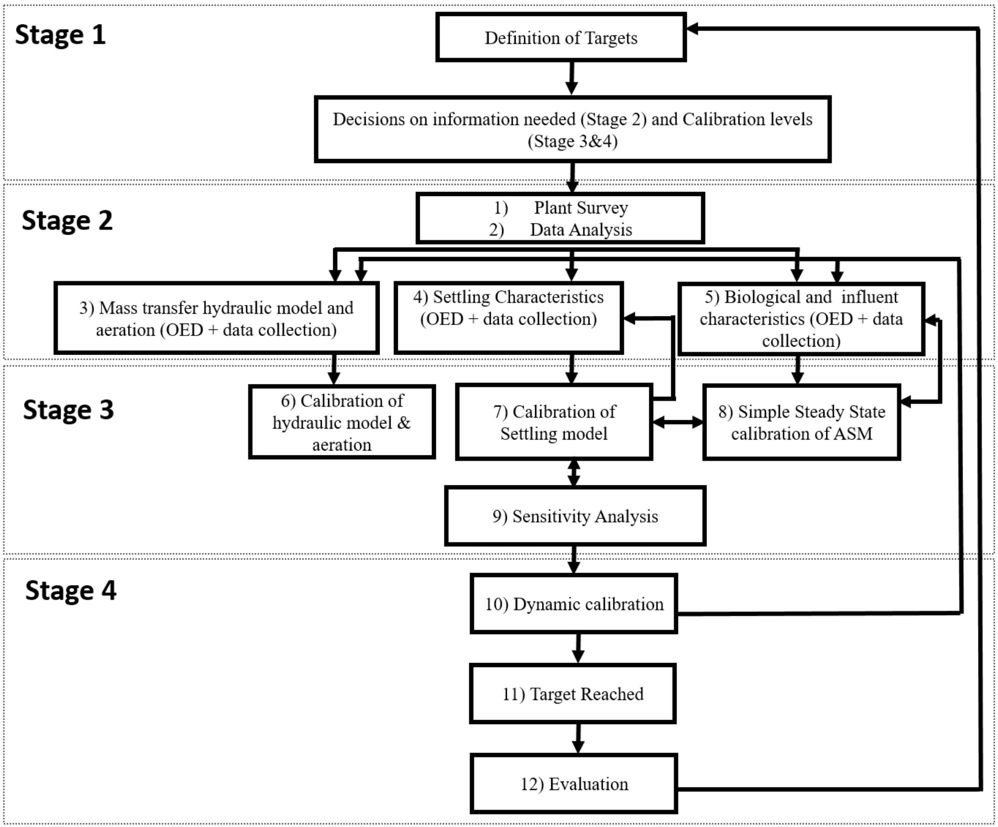

Figure 2: BIOMATH Calibration Protocol (Sin et al., 2005)

2.2.2 The STOWA Calibration Protocol

Practicing of almost 100 WWTPs simulation in the Netherland came out with STOWA protocol which is composed of eight steps for model calibration as illustrates in Figure 3. Step 1 is the same as in BIOMATH protocol which is defining goals. The second step is to describe the processes that are included in the WWTP. Third and fourth steps are concerned with data collection (physical and operational parameters) and model structure layout. The fifth step includes the characterization of influent, effluent, and intra-processes flows. Steps 6 to 9 include the calibration and validation processes leading to a final model serving the purpose of the study (Hulsbeek et al., 2002).

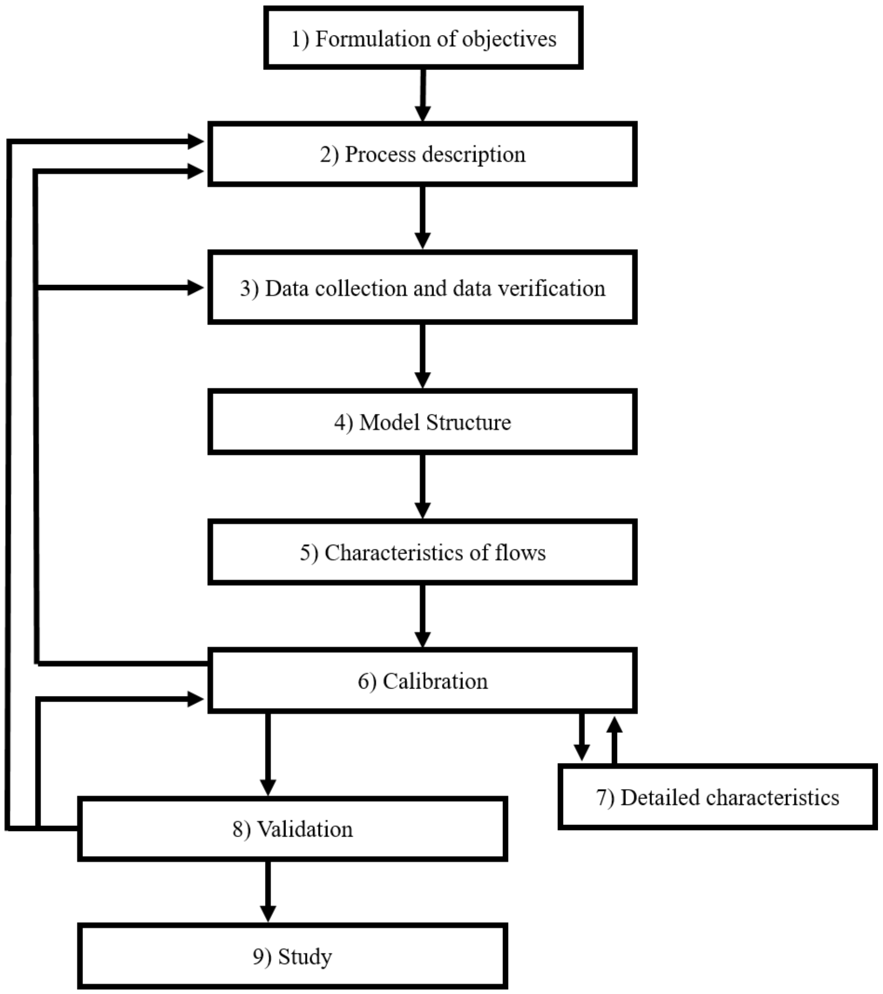

Figure 3: STOWA Model Calibration Procedures (Sin et al., 2005)

2.2.3 The Hochschulgruppe (HSG) Guidelines

Academic institutes from Germany, Austria and Switzerland working on activated sludge model's simulation came out with HSG guidelines for model calibration. The HSG protocol is divided into seven phases as illustrated in Figure 4 (Langergraber et al., 2004). The first phase is defining the objectives which is similar to STOWA and BIOMATH protocols. The second phase consists of: 1) Collecting routine data (operational and layout) from the plant operator; 2) Defining boundaries and selecting model to develop a preliminary model. The third phase is concerned with data analysis and evaluation to determine any additional data missing from the collected routine data. The hydraulic model evaluation is the concern of the fourth phase and it done through pre-simulation and comparing the simulated and measured values, then setting up a sampling campaign to close the gaps in the routine data. The Fifth phase is analyzing the sampling campaign results and transferring them into the final model. The sixth phase is the calibration and validation processes; and the seventh phase is the final step where scenarios can be studied and evaluated.

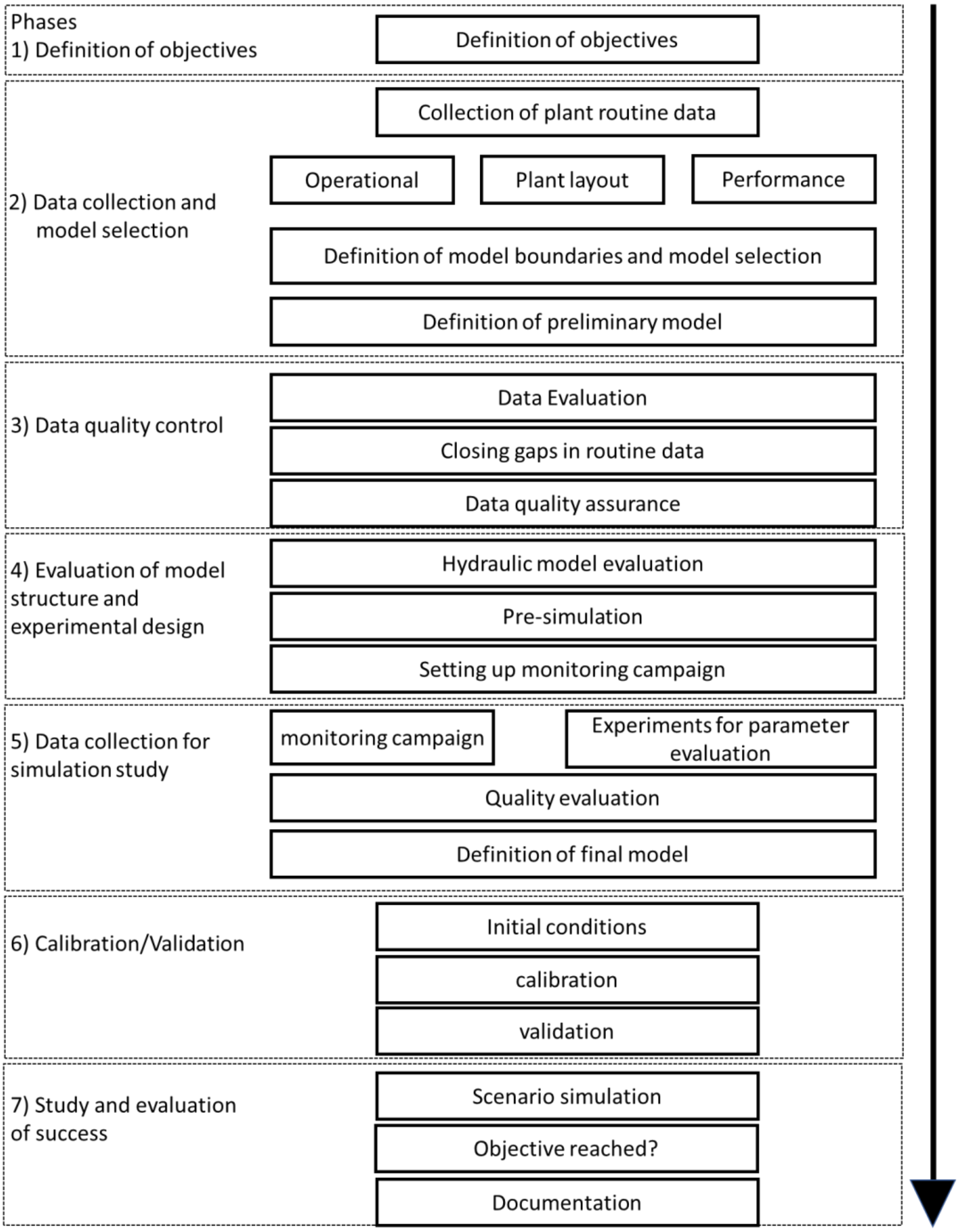

Figure 4: HSG Guidelines for Model Calibration (Sin et al., 2005)

2.2.4 The WERF Protocol for Model Calibration

Water Environmental Research Foundation (WERF) is another calibration protocol that could be used to build and calibrate a model to simulate an existing / new wastewater treatment plant (Melcer, 2003). It consists of four different types of data that can be classified as follows:

1) Physical plant data: aeration and clarifiers reactors dimension.
2) Plant operational data: Dissolved oxygen concentration, return activated sludge (RAS) and waste activated sludge (WAS) flow.
3) Influent loading flow: Wastewater characterization (mainly COD fractionation).
4) Kinetic and stoichiometric model parameters.

To sum up, the four calibration protocol have similarities as well as differences. The similarities can be summarized in defining clear goals, data collection and analysis, and the calibration and validation processes. On the other hand, differences are represented in: 1) sampling campaign design (sampling duration, frequency, sampling locations); 2) Methods for determining influent characteristics, kinetics and stoichiometric parameters; and 3) The calibration procedures (Sin et al., 2005).

The WERF calibration protocol was selected to be used for the case study in this research for the following reasons:

- Proper explanation of carbonaceous and nitrogenous fractionation.
- Comprehensive details of methods for determining the influent characterization.
- Tiered-approach for the calibration procedures.
- Several case studies exist in the literature were the procedures were implemented.

Published literature on model calibration illustrates that each calibration approach has its own methods for determining the type of lab experiments to characterize the influent, kinetic/stoichiometric parameter, hydraulic and settling characterization. This variation in model calibration methods negatively influences the ability to compare different models and model results. Therefore, different model calibration standards should be introduced to unify model calibration which will lead to a robust model that can predict the response of a treatment system (Sin et al., 2005).

Activated Sludge Models published by IWA and simulation software's make researchers and engineers understand the behavior of a treatment system better than before. As mentioned previously, wastewater plant simulation does not reflect the reality of a plant response, but it predicts part of the reality. Therefore, developing models to reach to actual response made researchers and engineers to think for a more robust model by characterizing the wastewater intensively (Roeleveld & van Loosdrecht, 2002).

2.3 Activated Sludge Models

Biological treatment is the most important stage through a long chain of wastewater treatment reactions since it is responsible for the removal of carbonaceous, nitrogenous and phosphorus content. When wastewater enters any biological reactor, many reactions occur which can be described by a set of mathematical equations. Tchobanoglous et al. (2014) have introduced the basic equations that describe the reactions in a biological reactor.

The International Association on Water Pollution Control and Research (IAWPCR) established a task group in 1982 to develop mathematical models for activated sludge process for the purpose of design and operation. Activated Sludge Model 1 (ASM1) was the first generated model for nitrogen removal purpose. Then, in 1995, Activated Sludge Model 2 (ASM2) was published for the purpose of biological phosphors removal followed by ASM2d to include the fundamentals of denitrification process. Finally, the task group established the most updated model in 1999 which is ASM3 that includes a 2-step model nitrification-denitrification (Rathore, 2018).

2.3.1 ASM1

ASM1 is the first generation of ASM model's series which involves carbon and nitrogen removal. The model is based on Monod kinetic for describing organism growth and decay. Chemical oxygen demand (COD) is used for oxygen balance. COD fractionation is divided into biodegradable, non-biodegradable, particulate and soluble. The model assumes that particulate substrate is hydrolyzed and transformed to soluble component. The model further assumes that organisms grow on soluble substrates under either aerobic or anoxic conditions. Death-regeneration is the approach used for the purpose of modelling organism decay assuming that part of decayed organisms will be transformed into inert component and the other part will be converted into particulate substrate then into soluble substrate that can be utilized by active organisms (Water Environment Federation, 2014).

2.3.2 ASM2

ASM2 is the second generation of ASM model series. It is the same as ASM1 with addition of biological phosphorus removal. Phosphorus accumulating organisms (PAOs) metabolism is represented in terms of internal storage products referred to poly-hydroxyalkanoate (PHA). PAOs growth is considered under aerobic environment only and does not incorporate the denitrification of PAOs. Particulate nitrogen and phosphorus are determined as a ratio of particulate COD state variables. Regardless, ASM2 is not used any more (Water Environment Federation, 2014).

2.3.3 ASM2d

ASM2d was developed in 1999 to include denitrifying metabolism of PAOs and the growth of PAOs under anoxic condition which is described by assuming one population of PAOs can grow at reduced rate. It is commonly used nowadays (Water Environment Federation, 2014).

2.3.4 ASM3

The purpose of ASM3 is similar to that of ASM1, which is related to carbon and nitrogen removal but with different principle for carbon removal. The bacteria growth metabolism is based on internal storage of carbon. Particulate substrate is hydrolyzed (transformed into soluble substrate) and then stored as an internal product by the heterotrophic bacteria. Bacterial growth is based on the stored substrate only. Therefore, separation should be considered between primary and secondary hydrolysis (wastewater particulate substrate and decayed biomass). An endogenous respiration approach is used for bacterial decay. This approach assumed a fraction of active biomass will be converted to inert material and additional oxygen demand will be assumed (Water Environment Federation, 2014).

The above-mentioned activated sludge models have been introduced into many simulator software's such as GPS-X, BioWin and SIMBA. Each company has selected a model as a basic model and it developed its own model by adding more processes that can describe the reactions occurred in each treatment stage in the plant which leads to a better prediction of the plant working performance.

2.4 BioWin™ Software

BioWin™ has IWA models which are ASM1, ASM2d, ASM3 and its own models which consist of six models as follows (EnviroSim Associates Ltd, 2020):

1) Biological/Chemical Models.
2) Aeration and Gas Transfer Model.
3) Solid-Liquid Separation / Clarifier Models.
4) Modeling Fixed Film Processes.
5) Modeling Side Stream Treatment Processes (Additional nutrient load in terms of nitrogen).
6) Modeling Granular Sludge Sequencing Tanks.

Only three of these models (1-3) are relevant to this study. For the first set of models, biological/chemical models, BioWin has its own model referred to as activated sludge/anaerobic digestion (ASDM) which consists of fifty state variables and more than eighty process expression. The overall model integrates these processes to describe the occurring reactions. These parts are activated sludge processes, anaerobic digestion processes, chemical precipitation reaction, pH and alkalinity and general parameters (EnviroSim Associates Ltd, 2020).

The Aeration and Gas Transfer Model allows users to model the transfer processes of gas-liquid mass of oxygen, carbon dioxide, methane, nitrogen, ammonia, hydrogen, and nitrous oxide. There are two different methods of aeration which are diffused aeration and surface aeration, and both can be modeled in the software (EnviroSim Associates Ltd, 2020).

The Solid-Liquid Separation / Clarifier Models are considered in the two different parts in the plant through the simulation, firstly in the primary sedimentation and secondly in the secondary clarifier. There are three different types of clarifier models which are point separation, ideal separation and flux-based models (EnviroSim Associates Ltd, 2020).

2.5 Wastewater Characterization

Wastewater characterization is one of the most important factors that influence the design, operation, and optimization of a treatment plant. Analysis methods play a vital role in characterizing wastewater (Melcer, 2003). Chemical oxygen demand (COD) and 5-day biochemical oxygen demand (BOD_5) are the routine tests for the design and operation of a treatment system (Melcer, 2003). Nutrient removal is affected by the relation of BOD/COD to nitrogen and phosphorus (Roeleveld & van Loosdrecht, 2002).

COD fractions are traditionally classified based on solubility and degradation. Literature categorized COD fractions into two groups (Henze et al., 2015; Melcer, 2003; Roeleveld & van Loosdrecht, 2002):

1. Biodegradable COD fractions determination.
2. Non-biodegradable (Inert) COD determination.

Even though, in literature, a third fraction of COD represents the quantity of heterotroph organisms in wastewater, there was a consensus that since their growth rate is high and wash-out will never occur there is no need to consider their biomass fraction in wastewater characterization (Roeleveld & van Loosdrecht, 2002). On the other hand, autotrophs and phosphate accumulating organisms (PAO) should be considered in the WWTP influent characterization due to their low growth rate and they can be washed out. However, these fractions are very small compared to the total COD and they can also be neglected (Roeleveld & van Loosdrecht, 2002).

2.5.1 Organic Material

COD is usually used as the key to wastewater characterization in the WWTP modelling approach since it can better quantify the strength of the waste stream as compared to BOD_5. Biodegradable COD is sub-divided into readily biodegradable and slowly biodegradable, whereas non-biodegradable COD is sub-divided into soluble and particulate substance (Melcer, 2003).

The biodegradable organic material in wastewater consists of readily biodegradable COD (RBCOD) and slowly biodegradable COD (SBCOD). RBCOD consists of two different forms which are complex and volatile fatty acids (VFA). Both forms are consumed readily by microorganisms for energy and synthesis, whereas the SBCOD is divided into particulate and colloidal material that requires much more time than RBCOD for utilization. On the other hand, the non-biodegradable material which is divided into particulate and soluble will not be affected by the biological process in the system. The non-biodegradable particulate (X_I) will accumulate in the sludge whereas the non-biodegradable soluble matter (S_I) leaves the system at a value equal to the influent concentration. Figure 5 and 6 illustrate the fractionations of the COD and its physical separation (Melcer, 2003).

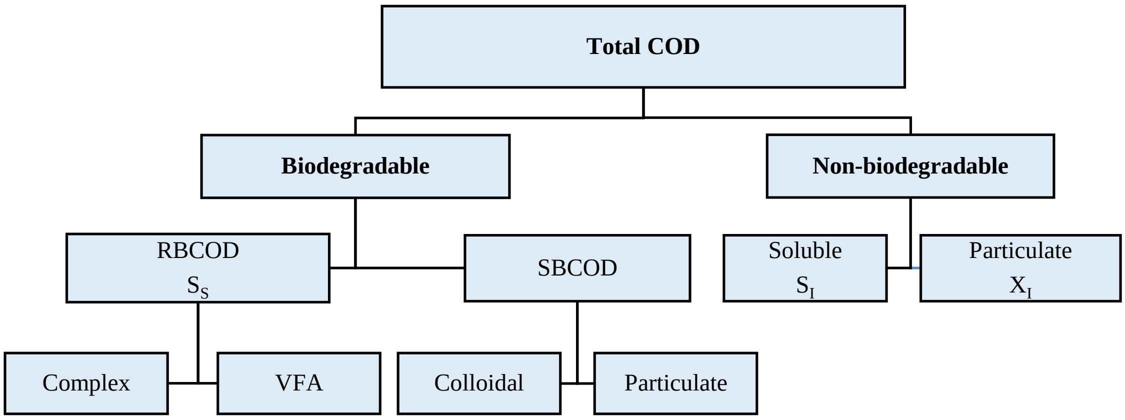

Figure 5: COD Fractionations (Melcer, 2003)

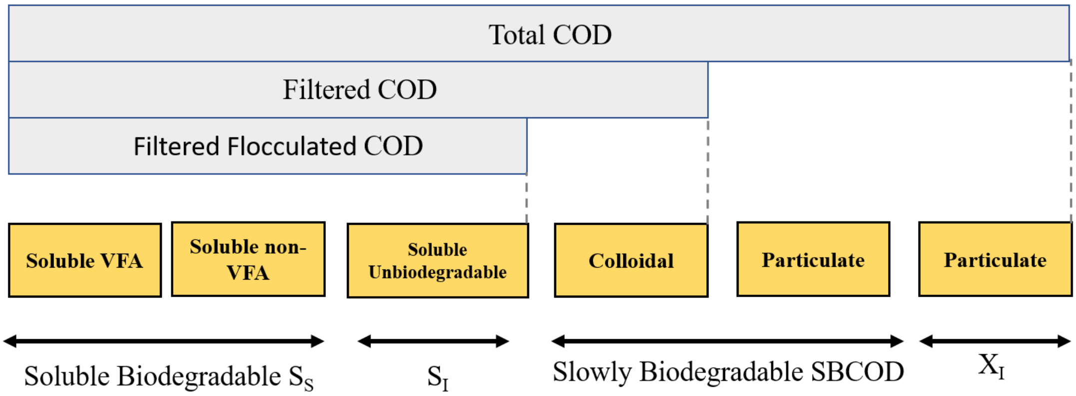

Figure 6: Physical Separation for Determination of COD Fractions (Melcer, 2003)

2.5.2 Nitrogenous Material

Total nitrogen (TN) is the sum of nitrate, nitrite and total Kjeldahl nitrogen (TKN). TKN is subdivided into free and saline ammonia and organically bound TKN. The organically bound TKN is divided into biodegradable and non-biodegradable. Furthermore, biodegradable and non-biodegradable fractions are further classified into soluble and particulate. Figure 7 illustrates the fractionations of the TN (Melcer, 2003).

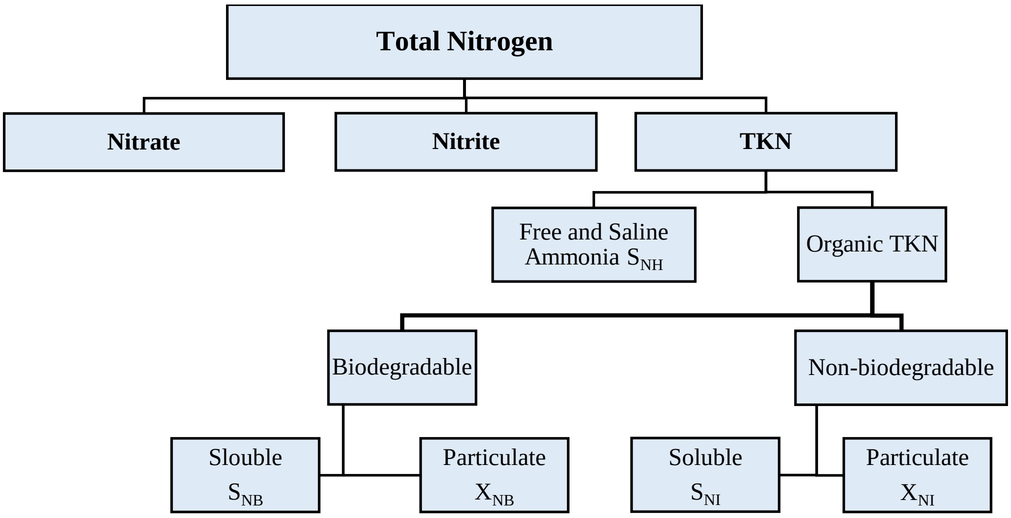

Figure 7: Total Nitrogen Fractionations (Melcer, 2003)

2.6 Sludge Reduction Approaches and Technologies

As mentioned previously, sludge reduction can be classified into two categories which are post treatment and in-situ activated sludge. The post treatment approach takes place after the sludge is produced from the treatment process whereas in-situ sludge treatment reduces sludge by modifying the process itself so that sludge generation is reduced at the source. Post-treatment includes three different treatment technologies: 1) Heat Treatment; 2) Chemical Oxidation; and 3) Sludge Digestion. Figure 8 illustrates the alternative application of each technology. Post treatment requires high energy compared to in-situ treatment (Mahmood & Elliott, 2006). In-situ sludge treatment three different mechanisms as illustrated in Table 5 and discussed in the next sections. However, selecting the in-situ sludge reduction approach should be considered without deterioration of effluent quality especially nutrient removal (Guo et al., 2013).

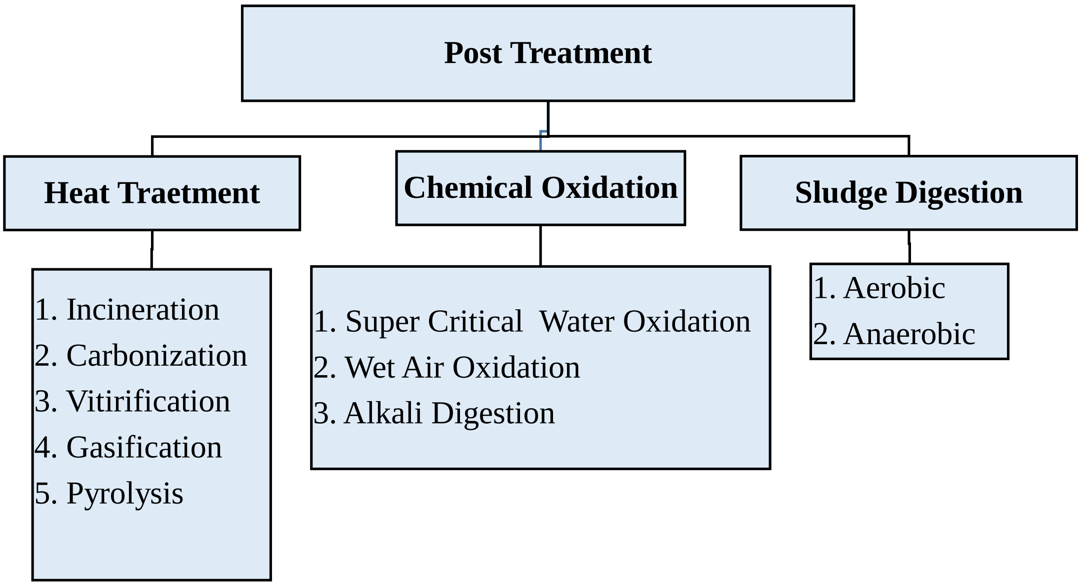

Figure 8: Sludge Post Treatment Technologies (Mahmood & Elliott, 2006)

Table 5: In-Situ Activated Sludge Reduction Processes (Guo et al., 2013)

In-Situ Activated Sludge Reduction Processes		
Lysis-Cryptic Growth	**Uncoupling Metabolism**	**Worm's Predation**
Chemical Treatment	OSA Process	Two-Stage Sludge Predation System
Physical Treatment	Repeatedly Coupling of Aerobic/Anaerobic Treatment	Oligochaeta Addition
	Uncoupler-Induced Sludge Reduction	New Reactor Concept for Sludge Reduction

2.6.1 Lysis-Cryptic Growth Process

Lysis-Cryptic growth process (illustrated in Figure 9) occurs when bacterial cells are disintegrated. The microorganism cell content is released into the liquid and these organics autochthonous substrates are reused by living microorganisms for metabolism (Chu et al., 2009). Sludge disintegration technologies, such as ozonation, chlorine dioxide, ultrasound treatments, have been developed and are now commonly applied for in-situ activated sludge reduction (Cui & Jahng, 2004; Gallard & von Gunten, 2002; He et al., 2006).

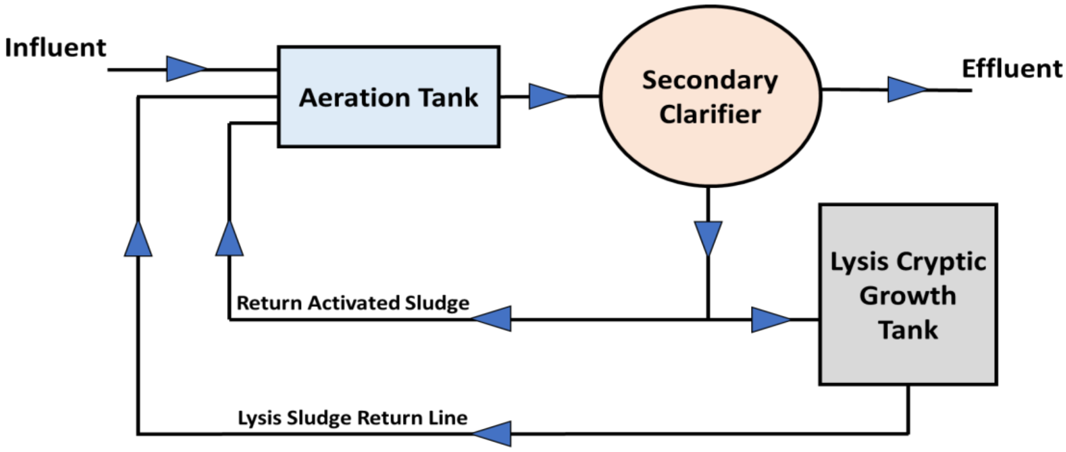

Figure 9: Lysis Cryptic Growth Technique (Guo et al., 2013)

2.6.1.1 Activated Sludge Process Combined with Chemical Oxidation

In ozonation lysis-cryptic growth process, microorganisms are inactivated and they release organic substances that are oxidized during sludge ozonation (Cui & Jahng, 2004). Sludge ozonation treatment improves sludge biodegradability, sludge bulking and scrumming (Chu et al., 2009). Sludge ozonation has been considered the most efficient technique in sludge disintegration process. Ozone, as a strong oxidant, reacts with the organic substances which could reduce the oxidation efficiency of the activated sludge resulting in high-cost operation since more required ozone should be added to the system. Other alternative oxidants that reduce produced sludge include chlorine (Cl_2), chlorine dioxide (ClO_2) and hydrogen peroxide (H_2O_2), but their effectiveness compared to ozone is less. (Huysmans et al., 2001) studied the ozone as the oxidant for the sequence batch reactor process and 50% reduction was achieved in the sludge yield. (Lee et al., 2005) investigated conventional activated sludge process with ozonation process and results revealed zero sludge production. Other oxidant such as chlorination (Cl_2) was investigated by (Saby et al., 2002) and 65% sludge reduction was reported. The disadvantage of chemical oxidants used for sludge reduction is that the return stream could destruct the bioactivity in the aerobic rector (Guo et al., 2013). In addition, by-products such as trihalomethanes are formed which are of health concern when released into the environment (Gallard & von Gunten, 2002).

2.6.1.2 Activated Sludge Process Combined with Ultrasound

Waste activated sludge could be subjected to ultrasonic energy to breakdown the cell walls. The process improves sludge biodegradability, dewaterability and biosolids quality (Khanal et al., 2007). Moreover, combining the ultrasound method with a chemical process such as ozonation could enhance sludge disintegration which minimizes the net amount of produced sludge (Zawieja et al., 2008). Mohammadi et al. (2011) studied the impact of ultrasonic waves into SBR process, with 30% of lysed sludge achieved 78% reduction in the sludge yield. However, effluent quality was deteriorated. Ultrasonic waves and chlorination processes combined together were studied by (Lin et al., 2012) on SBR system and results revealed 55% in sludge reduction but an increase in TP and TN concentration was observed in the effluent.

2.6.2 Sludge Reduction by Uncoupling Metabolism

Microbial metabolism involves catabolic and anabolic reactions which leads to biochemical transformation. Catabolism and anabolism reactions are coupled together due to the transfer of energy generated under normal conditions (Aragón et al., 2009). Uncoupling metabolism occurs when the energy coupling between catabolism and anabolism is separated and leads to inhibition of adenosine triphosphate (ATP) synthesis. Therefore, the energy generated from organic substrate oxidation is used partially for anabolism and this results in a decrease in microbial synthesis. Moreover, ATP is produced during a catabolism reaction which is a substrate oxidation process, and the microorganisms partially use the produced ATP as a source of energy to build new cells (biomass synthesis reaction). Metabolism uncoupling of catabolism and anabolism reactions occurs when the microorganisms are exposed to a different cycle of oxic, anaerobic and anoxic environment where there is a limitation of oxygen supplied and substrate, then when microorganisms are recycled back to the aerobic environment, they start rebuild their energy reserves at the expense of growth (Guo et al., 2013).

2.6.2.1 Oxic-Settling-Anaerobic Process

Oxic-Settling-Anaerobic (OSA) is a modification to activated sludge process through constructing anaerobic reactor on the sludge return line which is alternating environment condition for the microorganisms (Figure 10). This process is based on anaerobic and aerobic conditions which causes fasting/feasting condition that significantly achieves reduction in microorganism biosynthesis (Westgarth & Sulzzer, 1964). Chudoba et al. (1991) recognized that OSA process can achieve 20-65% reduction in sludge production in addition to sludge settleability improvement. An offered explanation of the OSA process is that when the microorganisms stay in oxygen environment and then feasted, cell energy (ATP or food storage) may be depleted (Dawes & Sutherland, 1992). Therefore, microorganisms re-synthesize the required energy reserve before biosynthesis when the microorganisms return back to aerobic conditions (Chudoba et al., 1991).

Chudoba et al. (1991) proposed OSA process which is represented in introducing anaerobic side stream reactor on the return activated sludge while microorganisms were fasted in the secondary settling reactor. Sludge reduction in the OSA process can be illustrated by sludge decay where low oxidation-reduction potential (ORP) takes place (Saby et al., 2003). In addition, short retention time can catalyst uncoupling microbial metabolism and decrease solids accumulated in the tank (Ye et al., 2008). Moreover, it has been noticed that sludge accumulates in the aerobic tank when the solids retention time (SRT) increases by adding an anaerobic reactor. Therefore, sludge production may be significantly reduced when exposing the RAS to a different environment of a sudden aerobic conditions in addition to reaching to the optimal SRT that affects biological nutrient removal. Different ORP values modified by changing the hydraulic retention time (HRT) have been utilized to study the effect on the produced sludge and it was concluded that neither anaerobic nor completely aerobic environment reduce produced sludge (Coma et al., 2013).

Recent work found that OSA can reduce the sludge yield up to 55% (Semblante et al., 2014). Therefore, OSA process is the most effective approach to minimize excess produced sludge and it can be easily applied for retrofitting an existing plant as well as for new design. However, there is a lack of contention in the literature on the mechanism behind biological sludge reduction and the influence of key operating parameters including SRT, ORP and temperature on the performance of the OSA (Semblante et al., 2014).

Observed sludge yield is the ratio of biomass formed to the substrate utilized. The kinetic of biomass growth can be described by Equation 1 (Semblante et al., 2014). Table 6 presents the typical values of maximum sludge yield.

$$\frac{1}{Y_{obs}} = \frac{1}{Y_{max}} + \frac{SRT \times K_d}{Y_{max}} \qquad (1)$$

Where Y_{obs} is the observed sludge yield, Y_{max} is the maximum sludge yield, SRT is the solids retention time, and K_d is the decay coefficient,

Table 6: Typical Values of Maximum Sludge Yield (Semblante et al., 2014)

Environment Condition	**Maximum Sludge Yield (VSS / COD)**
Aerobic	0.4
Anoxic	0.3
Anaerobic	0.1

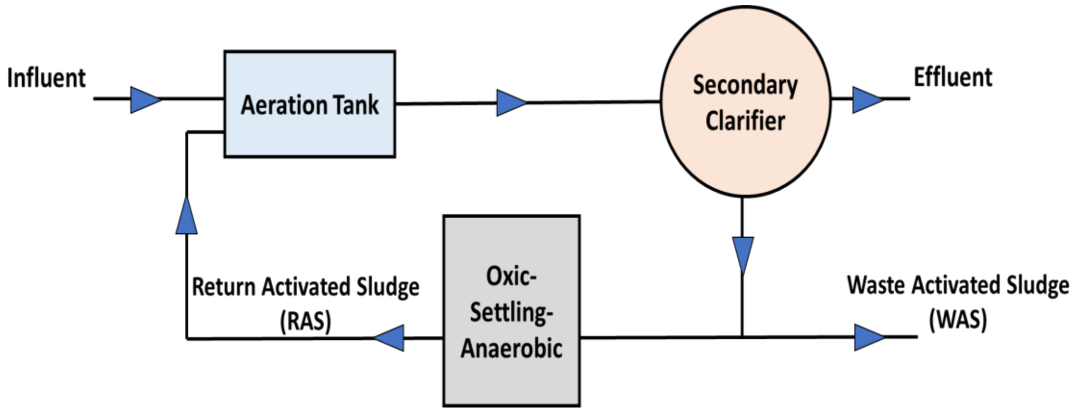

Figure 10: Integration of CAS and OSA (Semblante et al., 2014)

Several studies investigated the OSA process to know the main reason for sludge reduction in terms of observed sludge yield Y_{obs} as compared to CAS process. Datta et al. (2009) and Novak et al. (2007) reported 60% decrease in the produced sludge. Chon et al. (2011) proposed four alternative scenarios to compare the sludge reduction as shown in Table 7. Although most of the studies showed a reduction in produced sludge mass, the OSA process mechanism remains unclear (Datta et al., 2009).

Table 7: Alternative Scenarios with Sludge Reduction Percentage (Yağcı et al., 2018)

Scenario	Sludge Reduction Percentage
AS + anaerobic side-steam reactor (ASSR)	39%
AS + aerobic digester	54%
AS + anaerobic digester	22%
AS with no wastage	-

Semblante et al. (2014) attributed sludge minimization to enhanced endogenous decay, destruction of Extracellular Polymeric Substances (EPS), biomass starvation, energy uncoupling, and slow growing bacteria and predation on bacteria occurred at different stages of biomass growth. However, the key mechanism behind sludge reduction is unknown (Yağcı et al., 2018).

Environmental changes between aerobic and anaerobic conditions create physical stress for bacterial growth which requires energy maintenance. This enhances endogenous decay process and leads to noteworthy reduction in sludge mass. Moreover, flow cycling between aerobic/anaerobic environment improves predator variety but still the contribution of the predators in the OSA process has not been verified (Yağcı et al., 2018).

Energy uncoupling metabolism occurs when energy coupling between catabolism and anabolism is separated. This leads to inhibition of adenosine triphosphate (ATP) synthesis. As such, energy generated from organic substrate oxidation will be used partially for anabolism and this will encourage a decrease in microbial synthesis (Guo et al., 2013). Therefore, microorganisms are forced to use their ATP as source of energy under anaerobic condition. Microorganisms will reserve their energy requirement as an ATP under the aerobic condition. ATP production in the anaerobic reactor is low because the substrate is almost absent, when biomass is returned to the aerobic reactor bacteria will use their stored ATP instead of building biomass new cells (Yağcı et al., 2018).

Under anaerobic condition, metabolic products released from flocs, protein and polysaccharides serve as secondary substrate and there is a relation between Fe concentration and volatile suspended solids (VSS) reduction in the anaerobic stage. Despite this, Chen et al. (2003a) concluded that there is not any relation between soluble microbial products and biomass growth.

2.6.2.2 Repeatedly Coupling of Aerobic/Anaerobic Process

Based on the energy uncoupling theory mentioned previously, sludge could be decreased by building a system of decoupling anabolism and catabolism as shown in Figure 11. Repeatedly coupling of aerobic and anaerobic system was proposed by Yu et al. (2006) and resulted in surplus sludge not accumulating in the reactor. Repeatedly coupling of aerobic and anaerobic process could achieve 30–50% reduction in the produced sludge compared to the CAS process (Xing et al., 2008). However, energy uncoupling was not the only reason for sludge minimization. Researchers predicted that sludge cryptic growth is a contributing factor. Reactor change from aerobic to anaerobic may solubilize sludge into low micro molecule compounds that will be utilized for the synthesize of new cell (Quan et al., 2012).

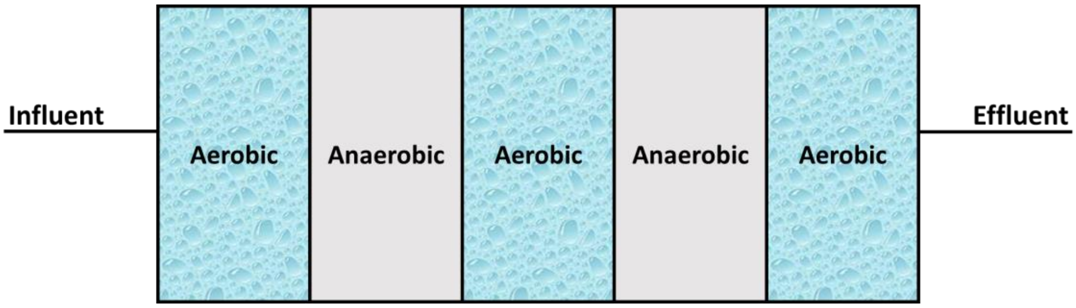

Figure 11: Repeatedly Coupling of Aerobic/Anaerobic Process (Guo et al., 2013)

2.6.2.3 Uncouplers-Induced Sludge Reduction

The mechanism is similar to OSA and repeatedly coupling of aerobic and anaerobic processes with the difference of adding a chemical metabolic uncoupler instead of creating stressful conditions (anoxic/anaerobic). Chemicals such as chlorophenol, 2.4-dinitrophenol (dNP), para-nitrophenol (pNP), pentachlorophenol, 3.3,4.5- tetrachlorosalicylanilide (TCS), 2,4,5-trichlorophenol (TCP), cresol, and aminophenol can be added to separate the coupling energy between catabolism and anabolism reactions. This uncoupling energy will result in limiting biomass synthesis due to lack of ATP which will reduce the generated sludge (Chen et al., 2002; Guo et al., 2013). Strand et al. (1999) investigated twelve metabolic uncoupler and TCP was found to be the most effective metabolic uncoupler for sludge reduction. The disadvantage of adding metabolic uncoupler such as TCP in more than 4 mg/L causes acute toxicity (Aragón et al., 2009). Qiao et al. (2011) achieved 78% reduction in produced sludge using 0.8 mg/L of TCS, which is reported to be the environmentally friendliest among the chemical uncoupler mentioned previously (Chen et al., 2002). Ye and Li (2005) achieved 30% sludge reduction by adding 40 mg/L TCS per day into CAS system. Ye and Li (2010) built a combination of OSA process and TCS chemical metabolic uncoupler which contributed to 56% reduction in sludge, but the effluent quality was deteriorated (Ye & Li, 2010).

2.6.3 Sludge Reduction by Worms' Predation

In this method for a sludge reduction, microfauna prey on the activated sludge microorganisms. This method is derived from the food chain theory which speculates sludge could be reduced by worm predation because of the required metabolic maintenance and the formation of higher living organisms. About 10% of the energy is transferred into the next level of nutrition and the predator consumes 90% of the energy in the conversion process when microfauna preyed on the microorganisms. Energy is lost when it is converted from bacteria to microfauna (Lee & Welander, 1996). Finally, sludge is reduced with worm’s predation method (Guo et al., 2013).

2.6.3.1 Two-Stage Sludge Predation Systems

Using worms as the predators in wastewater treatment system significantly reduces sludge yield but it requires a two-stage system since distribution of predators are uncontrollable in a biological treatment system (Khursheed & Kazmi, 2011). The first stage of the system is called bacterial stage which is responsible of growing bacteria, whereas the second stage is designed with a long SRT for the purpose of growing of protozoa and metazoan predator (Ratsak, 1994). Lee and Welander (1996) found that sludge yield was reduced in the second stage by 60–80% compared to the first stage. However, this system negatively affected the effluent parameters in terms of nitrate and phosphate since they were released (Lee and Welander, 1996).

2.6.3.2 Oligochaeta

In addition to protozoa and metazoan, the use of oligochaetes such as Nais, Aeolosoma, Tubificidae and Pristina have been investigated to assess their influence on sludge minimization (Liang et al., 2006). Liang et al. (2006) have used Aeolosomahemprichi in CAS system and a reduction of 39-65% in sludge yield was achieved in addition to the enhancement for sludge settleability and total phosphorus removal.

All in-situ activated sludge reduction approaches are capable of reducing the net amount of produced sludge as explained in the previous section (2.6). Selecting the optimum approach is governed by feasibility study to illustrate advantages and disadvantages of each approach as shown in Table 8. OSA system and repeatedly coupling of aerobic/anaerobic process have several advantages including being chemical free, allow for flexible operation, easy to implement in an existing plant, environmentally friendly, and inexpensive. However, their application at a full-scale treatment plant is quite rare. In addition, the impact of using these technologies on nutrient removal efficiency, for WWTPs that target nitrogen and phosphorus removal/recovery, should be further investigated and considered (Guo et al., 2013). Sludge reduction approach following in-situ activated sludge should be selected based on its benefits in terms of decrease in net amount of produced sludge in addition to the nutrient removal efficiency consistent with the international regulation and standards. Therefore, activated sludge mathematical models' developments and computer software will contribute to better understanding of the fate of organic matter (Guo et al., 2013).

Table 8: Comparison between In-situ Activated Sludge Reduction Approach (Guo et al., 2013)

Approaches / **Comparison**	**In-Situ Activated Sludge Reduction Processes**		
	Lysis-Cryptic Growth	**Uncoupling Metabolism**	**Worm's Predation**
Advantages	▪ Reduce the bulking ▪ Enhance biodegradability ▪ Short retention time ▪ Improve sludge settling and dewaterability	▪ OSA and Repeatedly coupling of oxic / anaerobic • Chemical free and no physical technology required • Improve sludge settling • Easy to operate • Environment friendly • Can be modeled in WWTP simulator software ▪ Uncoupler-induced • plant configuration as it is	▪ Low cost ▪ No release of by-product
Disadvantages	▪ High energy and Operation cost ▪ Reactor corrode ▪ Produce hazardous by-products ▪ Complicated process operation ▪ Optimization of chemical dose ▪ Deteriorate the effluent (TP and TN)	▪ OSA and Repeatedly coupling of oxic / anaerobic • Lack of practical application Uncoupler-induced • Fate of potential hazards is unknown • Application of single metabolic uncoupler might result in microbial acclimation • The selection and optimization of appropriate metabolic uncoupler are not easy • Effluent quality deterioration	▪ Difficult to control the predators species and quantities ▪ Risky to prey on some slow-growth microorganism ▪ Relation between operational controlled condition and worm growth is unknown ▪ Increase in concentration of nitrate and phosphate in the effluent

2.7 Oxic- Settling- Anaerobic (OSA) Process Mechanism Summary

Recent research investigated the performance of the OSA process through pilot-plant studies and full-scale application as illustrated in Table 9. The main goal was to evaluate the impact of different operating settings on the amount of produced sludge, effluent quality, and sludge characteristics (Coma et al., 2013; Saby et al., 2003; Velho et al., 2016; Ye et al., 2008). Results confirmed that the OSA process effectively reduced the amount of produced sludge. In addition, the effluent quality and sludge characteristics were improved.

Table 9: Summary of Studies Related to Sludge Reduction by OSA (Sarabia, 2016)

Reference	Configuration	OSA HRT (h)	ORP mV	Yield Reduction %
Chudoba et al. (1992)	CAS - OSA	3	-250	50
Saby et al. (2003)	MBR – OSA	11, 15 and 17	100, -100 and -250	28, 48 and 58
Wang et al (2008)	CAS - OSA	8 – 10.5	-250	40
Coma et al. (2013)	Biminex	34.5, 11.8 and 5.9	-150	18.31
Velho et al. (2016)	AS + ASSR	165.6 and 160.8	-250	20 and 10

Previous research theorized and proposed the mechanisms contributing to the effectiveness of the OSA process. The suggested mechanisms relate to the microbial activity in the OSA and include: 1) Spilling energy (uncoupling metabolism); 2) Domination of slow grower microbial population; 3) Soluble microbial products (SMP) that may be toxic to the microbes; 4) Acceleration of sludge decay in the sludge holding tank (SHT); and 5) Sludge predation by microorganisms (Chen et al., 2003b).

Semblante et al. (2014) concluded that the acceleration of sludge decay in the SHT under low ORP value could be the major contributing factor to explain the sludge reduction in the OSA process. ORP is a measure of presence of oxidizers in the reactor which determines the environmental condition whether aerobic, anoxic, or anaerobic. There is no universal ORP value for the reactor condition, however it was reported that more than 50 mV is associated with aerobic conditions, between 50 and -150 mV is anoxic condition, whereas below -150 mV is considered anaerobic (Semblante et al., 2014). The ORP is inversely proportional to HRT since oxidizers will be consumed with time in oxidizing organic matter. According to previous studies, maintaining a low ORP value in the OSA process will enhance the reduction of produced sludge and -250 mV ORP value was recommended to be maintained in the SHT (Semblante et al., 2014).

Several studies investigated the impact of ORP on sludge decay in the SHT. Saby et al. (2003) measured the sludge endogenous decay coefficient in the SHT for three different ORP values (100, -100 and -250 mV) and they were 0.068, 0.095 and 0.11 day^{-1}, respectively. Another study reported a value of 0.13 day^{-1} for the sludge endogenous decay coefficient in the SHT (An & Chen, 2008). According to Tchobanoglous et al. (2014), the anaerobic endogenous decay coefficient typically ranges from 0.02 to 0.04 per day^{-1}, which is much lower that the values achieved in the reviewed studies. Thus, this increase in the sludge decay coefficient was often considered the main contributor to the effectiveness of OSA in reducing sludge (An & Chen, 2008).

Chapter 3: Methodology

This research followed sequential stages after the proper definition of the statement of the problem (Figure 12). The first stage included a comprehensive review of literature that focused mainly on sludge generated from the process of activated sludge (AS) and the various approaches for simulating and calibrating computer-based simulation models of the AS process. The second stage entailed the development and calibration of Al-Saad WWTP model in BioWin™ V.6 software. This stage started with collecting and analyzing historical data for the plant and conducting sampling and laboratory analysis. These preliminary stages allowed for the effective development, calibration, validation, and sensitivity analysis of the WWTP model. Finally, the third stage involved running scenario-based simulations for in-situ sludge reduction approaches. Figure 10 illustrates the framework of the followed sequential procedure.

3.1 State-of-the-Art Review Literature

A comprehensive literature search has been carried out in Chapter 2 to summarize the available approaches for produced sludge minimization. OSA was selected to be included in the scenario-based simulation to illustrate the impact of process parameters on sludge reduction without compromising the quality of the effluent. The review also has covered the theory of activated sludge models and model calibration and validation protocols. Furthermore, wastewater fractionation methods were outlined from reliable literature sources (Melcer, 2003).

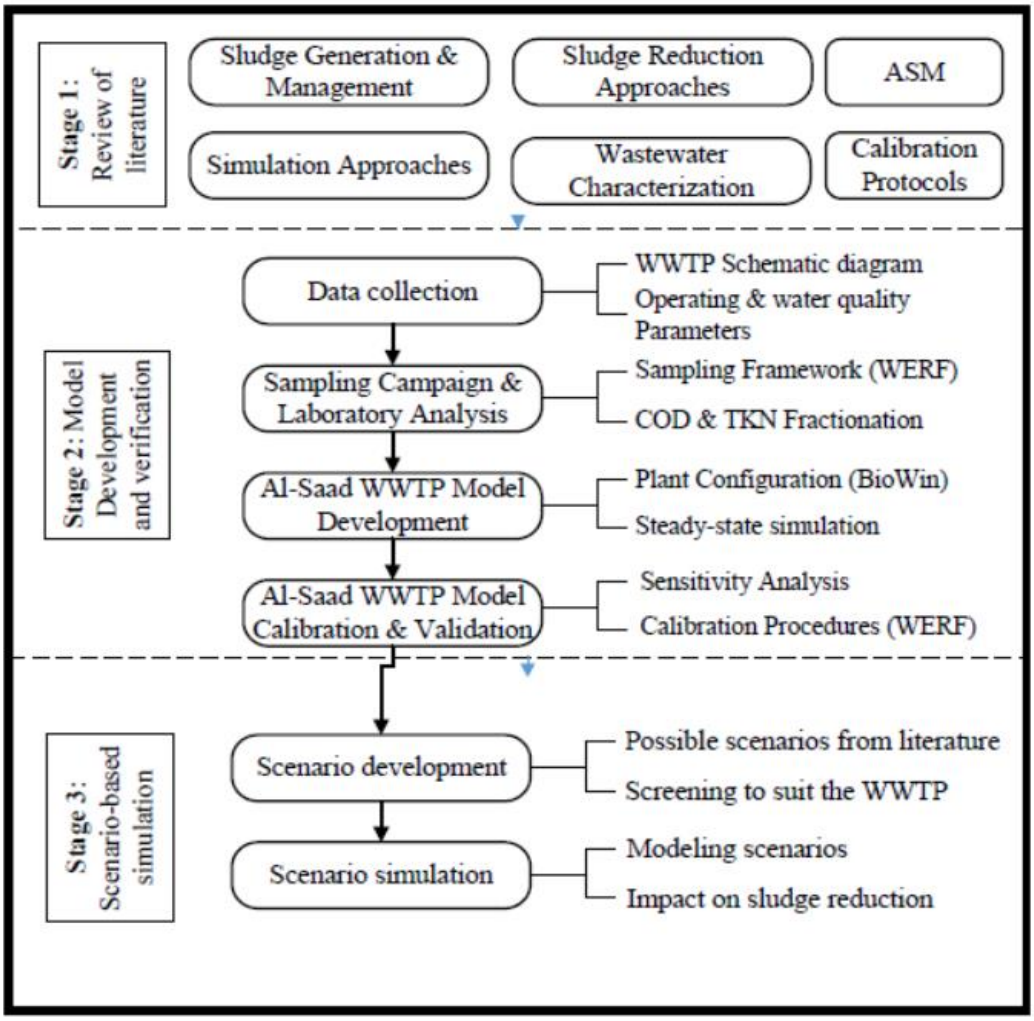

Figure 12: Methodology Applied in this Study

3.2 Data Acquisitions

An official letter was sent to the owner of Al-Saad WWTP (Abu Dhabi Sewage Services Company (ADSSC)) to provide all the required information about the WWTP. Such information included influent characteristics, physical and operational parameters related to primary and secondary settlement reactors, activated sludge reactor and effluent characteristics. Several site visits and meetings were conducted at the early stage of model development to verify the quality of the data collected.

The plant's operator (Kharafi National) collected samples on daily and weekly basis for water quality parameter analysis. The samples taken by the operator were composite and grab, collected from different locations in the plant. Samples were analyzed for COD, BOD_5, TKN, TSS, VSS, pH and alkalinity. Historical data was collected for a period of one and a quarter year starting January 1, 2017 until March 31, 2018 for the purpose of knowing the dynamic behavior of the plant throughout the four seasons of the year.

Based on the historical data collected, statistical analysis and screening was used to correlate the effect of influent variation to the plant response, remove outliers based on first and third quartiles, and to specify any data gaps required for the model development. The identified data gap prompted further sampling to quantify COD and TKN in the influent, in addition to their fractionations.

3.3 Sampling Campaign and Laboratory Analysis

WERF's "Methods for wastewater characterization in activated sludge modeling" (Melcer, 2003) was the main reference followed to establish the sampling campaign and wastewater characterization and fractionation calculations. A comprehensive sampling campaign framework was established to collect samples for 7-days in a period of two weeks from May 17, 2020 to August 04, 2020 covering different locations in the plant for the purpose of Al-Saad WWTP model calibration. Another 3 batch of samples were collected from November 19, 2020 to November 21, 2020 for the purpose of model validation. In addition to the wastewater sampling, operational data during the sampling period was collected for the model input, including: influent and effluent flow, temperature, WAS flow, RAS flow, underflow, amount of produced sludge.

The sample bottle was properly labeled describing the sampling location (e.g., influent tank, primary tank …etc.), date and time, temperature, pH, and sampling procedures (grab or composite). The samples type should be composite for influent, primary and secondary effluent and grab samples for aeration tank (aerobic zone) and RAS stream to catch the dynamic characterization at Al-Saad WWTP. However, taking composite samples for a period of seven days in a period of two weeks has logistical limitations. Therefore, only composite samples at the influent were taken every half an hour through the existing automatic sampler whereas grab samples were collected from all the remaining location. The bottles were properly preserved either by cleaning or adding H_2SO_4 for specific parameters tests. The collected sample bottles were stored in an ice box (temperature $\leq 6^{\circ}C$) and transferred to Al-Hoty-Stanger Laboratory to assist in carrying out wastewater quality analysis (Figure 13) according to Standard Methods of Examination of Water and Wastewater (Baird, 2017). The photos in Figure 14 were captured during sample collection.

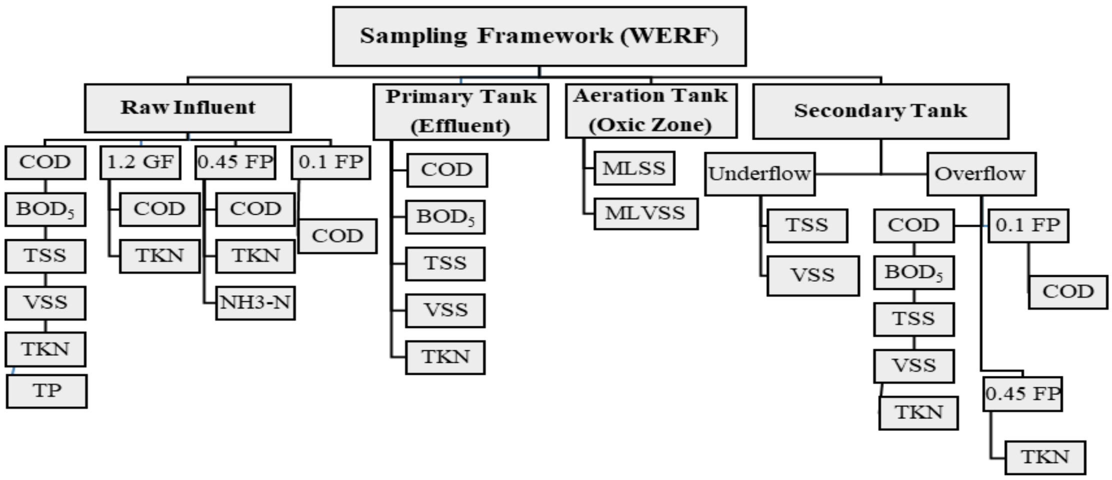

Figure 13: Sample Characterization Framework

Figure 14: Sample Collection

WERF's "Methods for wastewater characterization in activated sludge modeling" (Melcer, 2003) was the main reference followed in order to calculate the fractionation of COD and TKN. Table 10 presents a summary of all the fractions calculated in this study and refers to the calculation methods that are further explained later in the text.

Table 10: Summary of COD and TKN Fractionation Calculation

Symbol	**Fraction of**	**Description**	**Equation**
S_I	COD	Soluble non-biodegradable	(2)
S_S	COD	Readily biodegradable	(3)
X_I	COD	Particulate non-biodegradable	Assumption / Model
SBCOD	COD	Slowly biodegradable	(4)
S_{NH}	TKN	Free and saline ammonia	(5)
S_{NI}	TKN	Soluble non-biodegradable	Assumption of 3%
X_{NI}	TKN	Particulate non-biodegradable	Assumption of 10%
S_{NB}	TKN	Soluble biodegradable	(10)
X_{NB}	TKN	Particulate biodegradable	(9)

3.3.1 COD Fractions Calculations

The soluble non-biodegradable (S_I) COD concentration was determined directly as the concentration of filtered effluent COD as illustrated in Equation 2. The effluent was passed through a filter paper (FP) of pore size 0.1 micrometer instead of a flocculation step to retain colloidal material according to the recommendation of STOWA wastewater characterization guidelines. A correction factor (0.9) was applied to consider the residual biodegradable organics in the effluent. It was assumed that there was no generation of soluble non-biodegradable COD within the system (Melcer, 2003).

$$S_I = COD_{Effluent\ filtered} \qquad (2)$$

$$S_I = 0.9\ x\ COD_{Effluent\ filtered} \qquad (Low\ Loaded\ WWTPs)$$

Readily biodegradable COD (S_S) was determined using STOWA guidelines for wastewater characterization methods recommended to replace the flocculation step by using 0.1 micrometer pore size filter paper to separate the colloidal material. It should be emphasized that the previous method measures the soluble non-biodegradable (S_I). Equation 3 has been applied to calculate only the readily biodegradable COD (Melcer, 2003).

$$S_S = COD_{Filtered\ influent}\ (S_s + S_I) - COD_{filtered\ effluent}\ (S_I) \qquad (3)$$

To determine the particulate non-biodegradable COD (F_{xi}) portion, simulation by trial-and-error was used until the simulated MLSS in the aeration tank matched the measured value. Moreover, the colloidal fraction is non-settleable matter, therefore distinguishing between colloidal and particulate SBCOD is very important particularly for modelling of the primary settling tank. To determine the colloidal fraction of SBCOD, the raw influent was passed through 1.2 micrometer glass fiber filter (GF) to retain the biodegradable and non-biodegradable particulate fractions (Melcer, 2003).

Finally, slowly biodegradable COD (SBCOD) can be directly calculated by subtracting all other parameters (S_S, S_I and X_I) from the total COD (COD_T) as shown in Equation 4.

$$SBCOD = COD_T - S_S - S_I - X_I \qquad (4)$$

3.3.2 TKN Fractions Calculations

The free and saline ammonia (S_{NH}) which is a fraction of TKN was determined by Equation 5 (Melcer, 2003). Raw influent samples were analyzed for TKN concentration. Then, the raw influent sample was passed through 0.45 micrometer pore size filter paper to analyze for ammonia concentration.

$$S_{NH} = \frac{NH_3 - N_{\ Filtered\ influent}}{TKN_{Unfiltered\ influent}} \qquad (5)$$

Soluble biodegradable (S_{NB}) and soluble non-biodegradable organic nitrogen (S_{NI}) are generally determined based on the difference between the filtered effluent TKN and free and saline ammonia (S_{NH}). The previous description can be illustrated in Equation 6. Model application reported that the residual soluble concentration of biodegradable organic nitrogen in the effluent stream is typically about 0.4 mg N/L. Based on that, soluble non-biodegradable organic nitrogen (S_{NI}) could be calculated by subtracting the residual concentration of biodegradable organic nitrogen (0.4 mg N/L) and the fraction of free and saline ammonia (S_{NH}) from the filtered effluent TKN as illustrated Equation 7. This method, however, was found to be unsatisfactory, since it is difficult to distinguish between soluble biodegradable and non-biodegradable TKN and usually the soluble non-biodegradable (S_{NI}) represents a small fraction of less than 3% of total TKN. Therefore, this percentage was used instead of the equations (Melcer, 2003).

$$TKN_{Filtered\,effluent} - S_{NH} = S_{NB} + S_{NI} \quad (6)$$

$$S_{NI} = TKN_{Filtered\,effluent} - S_{NH} - 0.4 \quad (7)$$

Since the non-biodegradable particulate (X_{NI}) organic nitrogen will accumulate in the sludge, it is usually assumed that the nitrogen content of the non-biodegradable particulate of influent COD is the same as of the mixed liquor solids TKN. Raw influent passed through 1.2 micrometer GF filter to retain the biodegradable and non-biodegradable TKN. The fraction of non-biodegradable particulate organic nitrogen could be checked by Equation 8. Moreover, non-biodegradable particulate organic nitrogen is 10% of the total TKN, therefore this percentage was used instead of the equation 8 (Melcer, 2003).

$$f_{NXI} = \frac{TKN - TKN_{filtered}}{COD - COD_{filtered}} \quad (8)$$

To determine the soluble (S_{NB}) and particulate (X_{NB}) biodegradable organic nitrogen, raw influent samples have been collected, filtered (using 0.45 micrometer pore size filter paper), and analyzed for COD, TKN and ammonia. Equations 9, 10, and 11 have been used to determine the soluble and particulate biodegradable organic nitrogen parameters (Melcer, 2003).

$$TKN = S_{NH} + S_{NB} + S_{NI} + X_{NB} + X_{NI} \quad (9)$$

$$TKN_{filtered} = S_{NH} + S_{NB} + S_{NI} \quad (10)$$

$$f_{XNB} = \frac{X_{NB}}{S_{NB} + X_{NB}} \quad (11)$$

3.4 Al-Saad WWTP Model Development

A partial model was developed for Al-Saad WWTP. The model included only the processes that are pertinent to the production of sludge. The structure of the model included a primary tank, a secondary clarifier, and an activated sludge tank. The model was built using BioWin V.6 which employs ASDM model for the activated sludge process. The model was run under steady state conditions. Figure 15 illustrates all the data that was used to develop the model. The most important data to develop a robust model is the wastewater characterization in addition to COD and TKN fractionations.

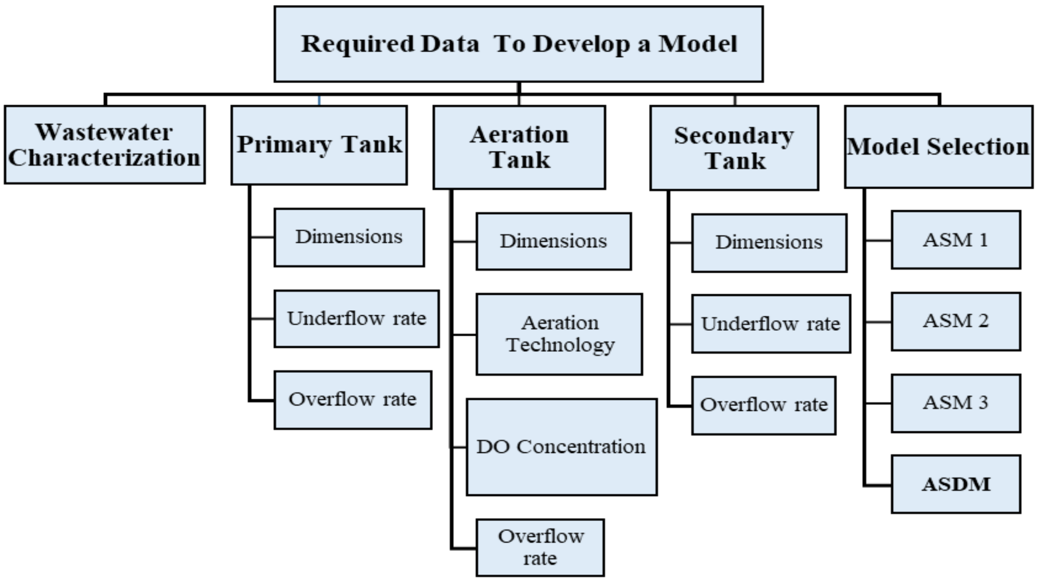

Figure 15: Required Data to Build a Model

3.5 Sensitivity Analysis

Many parameters are incorporated in BioWin™ software which are included in the model calculations, an extensive list of all parameters is available in the manual of BioWin™ (EnviroSim Associates Ltd, 2020). They are classified as follows: wastewater fractionation (Fxsp, Fus … etc.), kinetic parameters (maximum specific growth rate, aerobic decay, half saturation constant … etc.), and stochiometric parameters (Yield aerobic, yield anaerobic, COD: VSS ratio … etc.). Conducting sensitivity analysis will help to identify the most influential parameters to be used in model calibration to save time and effort. The normalized sensitivity coefficient (Sij) method was used for this analysis. It is defined as the change in output variable subject to a 1% change in input parameters (Linfield et al., 1987). If the sensitivity coefficient is equal to or more than 0.25, the parameter is believed to be influential. Therefore, more than 100 runs were conducted to illustrate the impact of each separate input parameter on specific output parameters for different stages in the plant. Equation 12 was used to calculate the sensitivity coefficient (Liwarska-Bizukojc et al., 2011).

$$S_{ij} = \left| \frac{\frac{\Delta \mathrm{Y}_i}{Y_i}}{\frac{\Delta \mathrm{X}_i}{X_i}} \right| \qquad (12)$$

Where $\Delta \mathrm{Y}_i$ is the change in the output, $\Delta \mathrm{X}_i$ is the change in the input, Y_i is the output value, and X_i is the input value.

3.6 Al-Saad WWTP Model Calibration and Validation

The plant model was calibrated using WERF protocol by matching a certain set of output parameters to the corresponding measured values. Results from the sensitivity analysis in addition to findings from previous research on WWTP simulation, helped reduce the number of input parameters to tune for the calibration purposes. WERF protocol provide well organized steps for model calibration as shown in Figure 16 (Melcer, 2003).

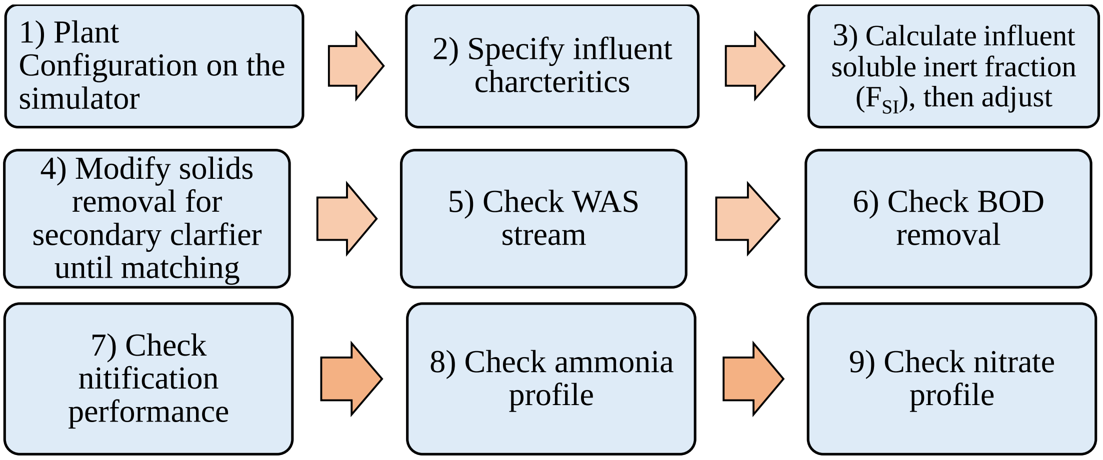

Figure 16: Model Calibration Steps

3.7 Scenarios Development for Sludge Reduction

This step drew on the results from the literature review on sludge reduction approaches and model structuring and developed scenarios to simulate in-situ activated sludge reduction processes. The OSA process was chosen as a representative process for in-situ sludge reduction since it is easy to implement in an existing WWTP and can effectively reduce the amount of produced sludge. It involves modifying the existing plant by inserting a sludge holding tank (SHT) on the recirculation activated sludge (RAS) stream between secondary settling and aerobic tanks. In addition, another sludge reduction process (i.e., anaerobic side stream reactor (ASSR)) similar to OSA process was simulated. ASSR process is represented by inserting side tank on the WAS stream between SST and activated sludge tank. The side tank should be maintained under anaerobic/anoxic conditions. Both OSA and ASSR processes are similar with the only difference of circulated flow rate percentage cycled to the side tank/SHT. As mentioned in Section 2.6, the key factor for OSA process is to maintain low levels of ORP in the SHT to create anoxic / anaerobic conditions. Therefore, a scenario-based simulation was formed (Table 11) involving different HRT for the SHT to simulate the impact of HRT on the reduction in produced sludge (kg TSS/day) and effluent water quality parameters (e.g., COD, BOD_5, NO_2 …). The scenarios were developed under a constraint that the footprint of the SHT can be accommodated in the available area inside Al Saad WWTP (10,560 m^2).

Table 11: Developed Scenarios to Test the Effectiveness of OSA in Sludge Reduction

Scenario #	HRT (h)	SHT Volume m^3	Footprint (m^2)
Base-Case	NA	-	-
1	2	5,932	1,318
2	3	8,899	1,977
3	4	11,865	2,636
4	5	14,831	3,295
5	6	17,797	3,954
6	7	20,763	4,614
7	8	23,730	5,273
8	9	26,696	5,932
9	10	29,662	6,591
10	11	32,628	7,250
11	12	35,595	7,910

Notes:
Base-case: Pre-anoxic Treatment System without the OSA Process

Chapter 4: Results and Discussion

4.1 Al-Saad WWTP Performance Analysis

Figure 17 presents the actual influent flow to the plant with time. The maximum flow occurred in May and recorded 85,876 m^3/day and registered minimum flow of 69,152 m^3/day in August and the calculated average flow is 76,587 m^3/day. Table 12 summarizes other influent characteristic parameters (BOD_5, TKN, ammonia, TSS. etc.) of Al-Saad WWTP. It is obvious that the influent quality to the plant significantly fluctuates during the year. Also, as shown in Figure 17, the flow rate in the first half of the year is higher than the second half and therefore other influent parameters are fluctuating. Figure 18 illustrates the amount of produced biomass. The maximum value reached 15,220 kg/d in December 2017, whereas the minimum value was recorded as 8,292 kg/d in January 2017.

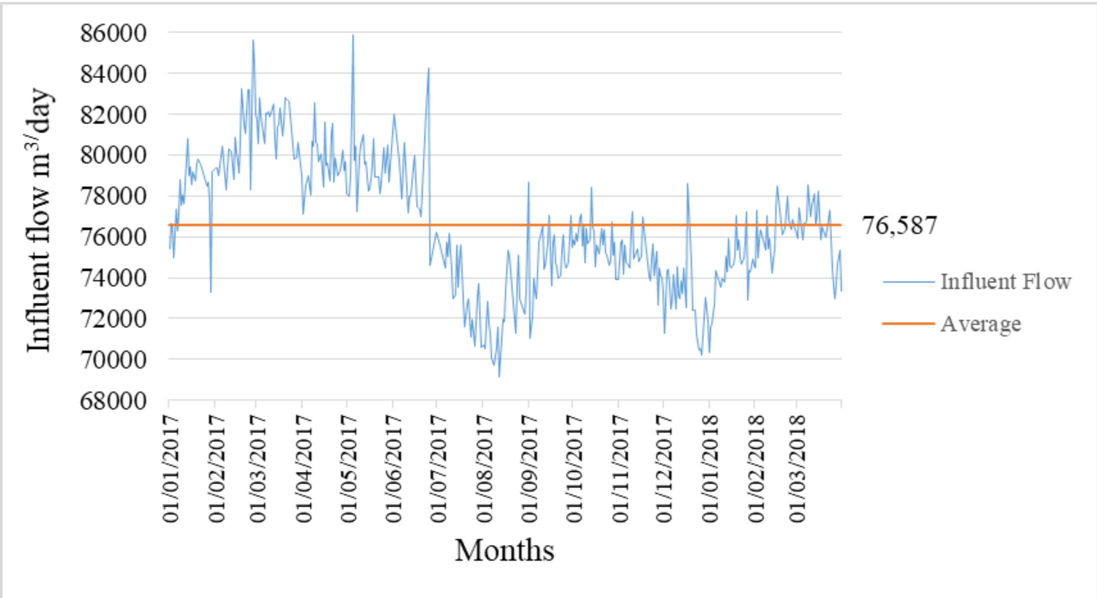

Figure 17: Actual Influent Flow at Al Saad WWTP

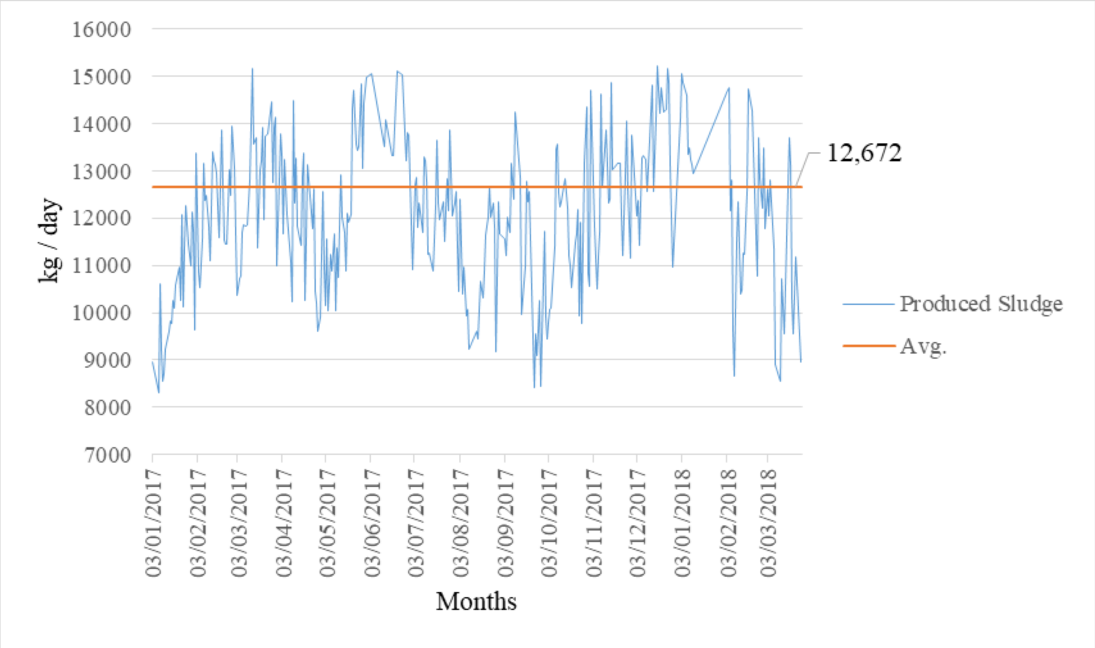

Figure 18: Produced Dewatered Sludge at Al Saad WWTP

Table 12: Al-Saad Wastewater Inflow Characteristics (2017-2018)

Parameter	Minimum	Maximum	Average	Standard Deviation
Flow (m^3/d)	69,152	85,876	76,587	3,204
COD (mg/L)	454.15	727.03	569.73	58.599
BOD_5 (mg/L)	201	386	273.81	28.235
TSS (mg/L)	150	338	231.55	35.053
VSS (mg/L)	132	252	189.73	27.917
TKN (mg/L)	35.06	45.04	39.16	2.129
NH_3(mg/L)	22.57	29.67	26.07	1.328
TP (mg/L)	3.4	5.3	4.35	0.335
pH @ 25°C	6.81	7.29	7.06	0.090
Alkalinity (mg/L) as $CaCO_3$	202.9	247.1	223.1	7.259

The full historical data collected from the operator for a period of one year and quarter as mentioned previously are shown in Appendix B. These data are classified into design and operational parameters. Design parameters such as number of reactors, their distribution, reactors dimension, dissolved oxygen concentration and temperature. Operational parameters include return activated sludge flow (RAS), waste activated sludge flow (WAS) and recirculation flow rate for anoxic chamber.

4.2 Results of Water Quality Sampling Campaign

Wastewater fractionation is one of the most important model calibration procedures. Proper wastewater fractionation will reduce the adjustment of kinetics and stochiometric parameters leading to a robust model for simulating WWTPs performance. Therefore, samples were collected from the plant during the period from July 23, 2020 to August 4, 2020. Results of the water quality analytics are tabulated in Table 13 and 14. The data were filtered based on first and third quartile percentile and confidence interval of 90% and the outliers were not considered. The measured values are quite close to each other from one day to another which leads to stable influent to the plant. Additional data for other measured parameters at different locations in the plant are presented in Appendix C.

Table 13: Raw Influent Characteristics

Parameters	23/07/20	25/07/20	27/07/20	29/07/20	31/07/20	2/8/2020	4/8/2020	Average
Flow (m^3/d)	80,036	81,292	79,133	81,699	86,646	78,957	77,167	79,239
COD (Total) (mg/L)	524	596	564	572	592	548	552	559
COD (1.2 µm GF) (mg/L)	208	212	216	224	196	208	216	216
COD (0.45µm) (mg/L)	180	192	184	188	176	192	176	185
COD (0.1µm) (mg/L)	156	168	164	152	168	220	164	175
BOD_5 (mg/L)	338	353	342	337	349	310	318	326.75
TKN (Total) (mg/L)	49	57	59	56	56	52	50.4	54.35
TKN (1.2 µm GF) (mg/L)	39.7	50.9	52.6	50.9	31	28	48	44.88
TKN (0.45µm) (mg/L)	24.6	22.6	21	22.6	27	26.3	23	23.23
NH_3 (0.45µm) (mg/L)	14.8	16.3	14.2	13.1	14.6	13.3	15.3	13.98
TN (mg/L)	53.7	66	67	63	60	57.4	59	61.6
NO_2 (mg/L)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
NO_3 (mg/L)	4.69	8.99	7.99	6.99	3.99	5.39	8.59	6.66
TSS (mg/L)	285	585	470	515	510	495	509	497.25

Table 13: Raw Influent Characteristics (Continued)

Parameters	23/07/20	25/07/20	27/07/20	29/07/20	31/07/20	2/8/2020	4/8/2020	Average
VSS (mg/L)	190	445	410	485	471	454	479	457
ISS (mg/L)	95	140	60	30	39	41	30	40.25
TP (mg/L)	5.2	5.8	5.4	5.3	5.3	5.5	5.9	5.53
Ca (mg/L)	58	55	54	53	60	49	51	51.75
Mg (mg/L)	4.86	5.3	5.83	5.4	7.3	6.8	6.3	6.08
pH @ 25°C	7.22	7.21	7.21	7.15	7.2	7.17	7.2	7.18
Alkalinity (mg/L) as $CaCO_3$	255	292	284	298	316	344	312	309.5

Table 14: Secondary Effluent Characteristics

Parameter	**23/07/20**	**25/07/20**	**27/07/20**	**29/07/20**	**31/07/20**	**2/8/2020**	**4/8/2020**	**Average**
COD (mg/L)	20	19.6	18	18.8	20	18	19	19.06
COD (0.1 µm) (mg/L)	7.6	7.2	7.2	7.6	8	9.6	8	7.89
BOD_5 (mg/L)	7	7	7	7	7	6	7	6.86
TKN (mg/L)	0.11	0.1	0.08	0.11	0.16	0.09	0.1	0.11
TKN (0.45 µm) (mg/L)	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.05
TSS (mg/L)	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
VSS (mg/L)	3	3	3	3	3	3	3	3
ISS (mg/L)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

4.3 Results of Sensitivity Analysis

The sensitivity analysis applied in this research resulted in 27 parameters which are the most influential on the model output. The 27 identified parameters included four which were previously identified in a similar study on Zgierz WWTP in Poland (Liwarska-Bizukojc et al., 2011). The 27 parameters are classified into fractional, kinetic, and stoichiometric. Figure 19, 20, and 21 is illustrating the impact of soluble non-biodegradable fraction, maximum specific growth rate of ordinary heterotrophic organism (OHO), and aerobic yield of OHO respectively on the output parameters (e.g. COD, BOD, NH_3, .Etc.) at different stages (Influent, primary tank overflow, aeration tank overflow, secondary clarifier overflow .Etc.) in Al-Saad WWTP. Soluble non-biodegradable fraction has only impacts on the COD and VSS removal in SST stage as illustrated in Figure 19. The full results of the sensitivity analysis are included in Appendix E.

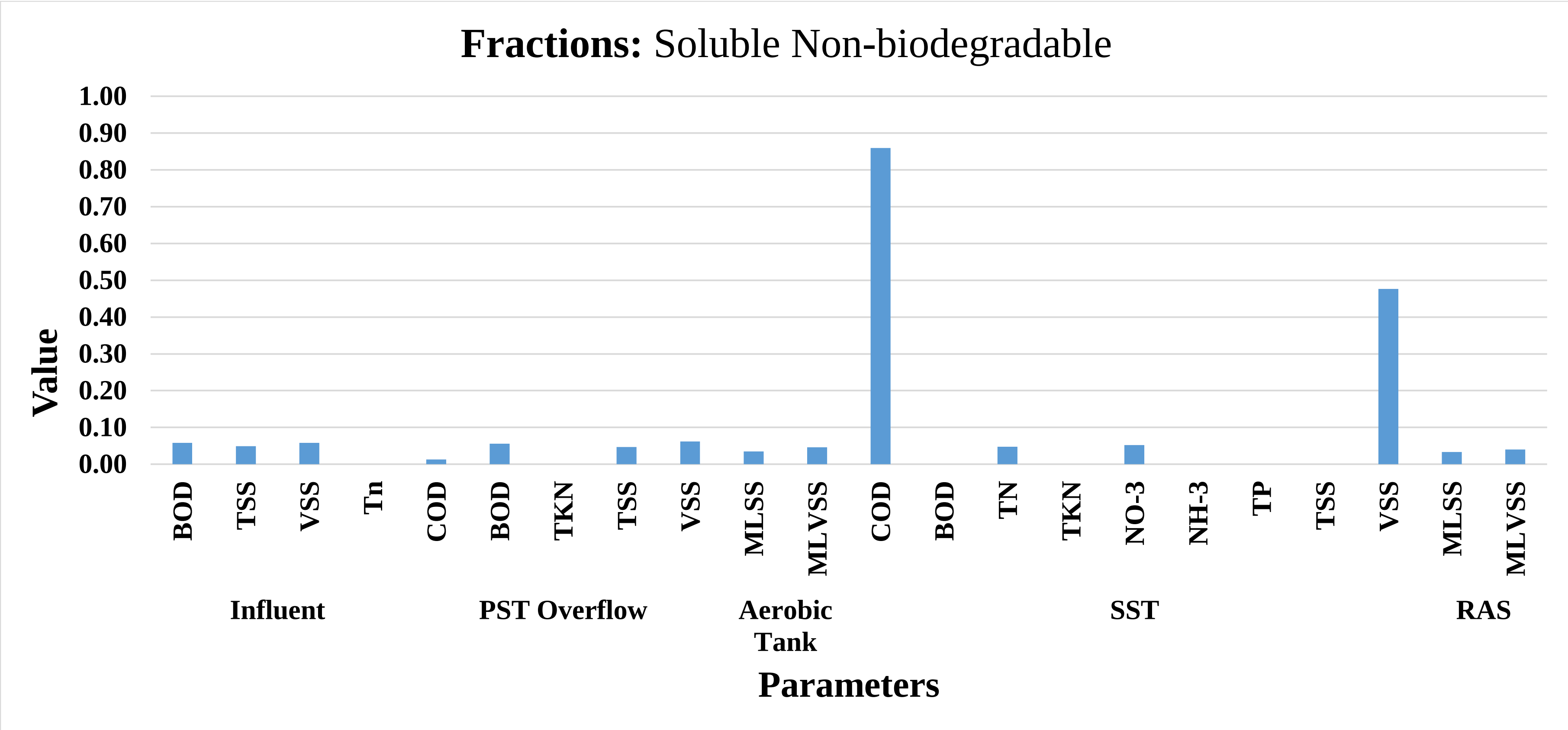

Figure 19: S_{ij} Value for F_{US} on Output Parameters at Different Stages

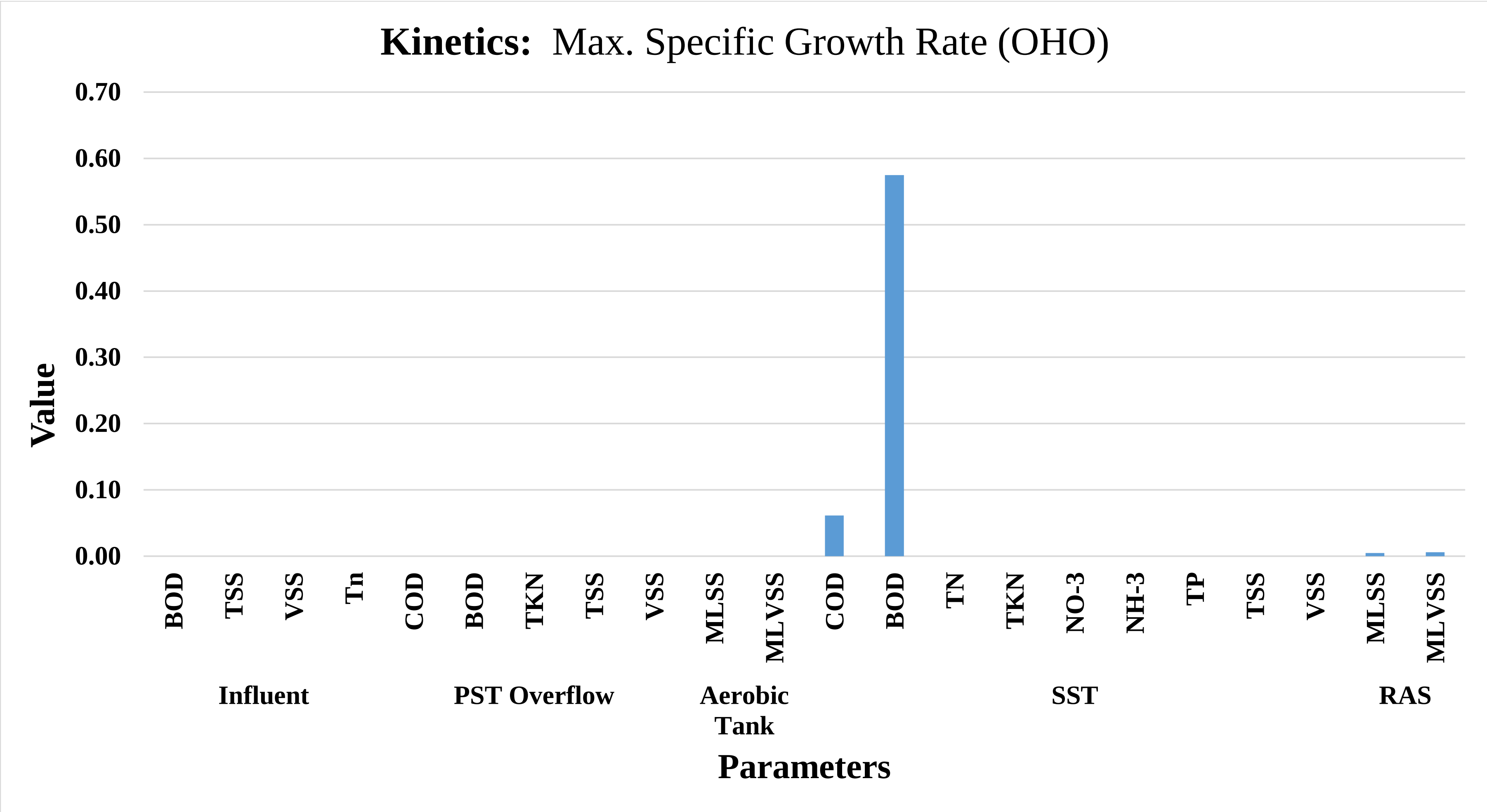

Figure 20: Sij Value for Maximum Specific Growth Rate on Output Parameters at Different Stages

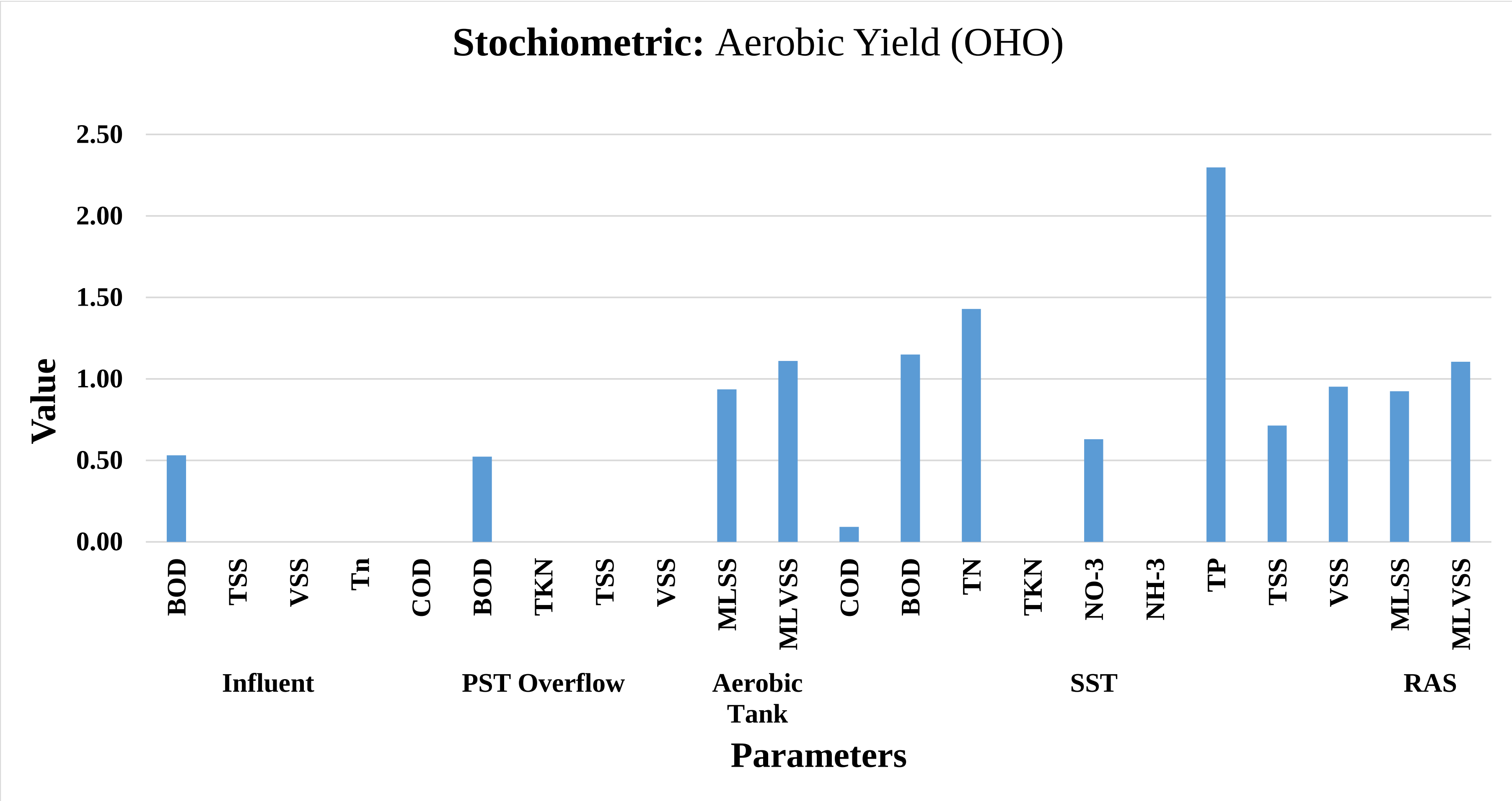

Figure 21: Sij Value for Aerobic Yield on Output Parameters at Different Stages

4.4 Al Saad WWTP Model Development and Calibration

A partial model was developed for Al-Saad WWTP (Figure 22). The structure of the model included: a primary tank, a secondary clarifier, and an activated sludge tank. There was a percentage of 5% recirculation for the aeration reactor effluent to the anoxic zone for the purpose of de-nitrification process. Appendix D presents the influent parameters which is the COD influent parameters of BioWin™ software. The model was developed using BioWin™ V 6.0 which employs ASDM model for the activated sludge process. The model was run under steady state conditions.

Wastewater fractions were calculated according to WERF standards, as described in Section 3.3, using water quality data from the sampling campaign (Table 18). For COD fractionation, RBCOD and particulate SBCOD values fall within the range according to WERF standards whereas soluble and particulate non-biodegradable values fall slightly outside the range. For TKN fractionation, ammonia fraction value was out of the standard range since the higher fraction of TKN was mainly represented in organic bound TKN. Therefore, the characteristics of Al Saad wastewater influent almost match the typical values particularly with the COD fractions with a minor deviations that could be due to dietary variations in different countries, or dilution factors from storm events and temperature (Melcer, 2003).

Table 15: Fractionation Calculated Values for Al-Saad WWTP

Parameters	**Symbol**	**Value**	**Typical Range** (Melcer, 2003)
RBCOD (g COD/ g COD_t)	F_{bs}	0.272	0.05 - 0.25
Particulate SBCOD (g COD/ g of slowly degradable)	F_{xsp}	0.749	0.4 - 0.8
Non-biodegradable Soluble (g COD/ g COD_t)	F_{us}	0.012	0.04 - 0.16
Non-biodegradable Particulate (g COD/ g COD_t)	F_{up}	0.3	0.07 - 0.22
Ammonia (g NH3-N/ g TKN)	F_{na}	0.26	0.5 - 0.75
Particulate organic nitrogen (g N/ g organic N)	F_{nox}	0.95	-
Soluble Non-biodegradable TKN (g N/ g TKN)	F_{nus}	0.03	0.07

Parameters in the BioWin™ software were adjusted from their default values based on the calculated fractions and ratios from the influent sampling results. In addition, other parameters were adapted from previous research concerning the calibration of WWTPs. Firstly, the inert particulate fraction of COD was assumed based on trials until good matching between the produced sludge and MLSS in the aeration tank occurs. Then, anoxic hydrolysis factor, ammonia oxidizing organism (AOO) substrate (NH_4) half increased from 0.28, 0.7 to 1 ,respectively, to match the effluent ammonia and nitrate concentration within the nitrification and denitrification processes with agreement with (Eidroos, 2015). Nitrogen content in biomass was increased from 0.07 to 0.12 to match the simulated value of ammonia and particulate organic nitrogen fraction was increased from 0.804 to 0.95 to closely match with the measured nitrate. Finally, COD and BOD effluent concentration were adjusted based on kinetics of ordinary heterotrophic represented in maximum specific growth rate, substrate half saturation and aerobic decay rate which are adjusted from the default value to 2.5, 14 and 0.9, respectively, in agreement with those reported by others (Elawwad et al., 2019; Liwarska-Bizukojc et al., 2011).

Furthermore, COD and BOD_5 effluent concentration still need to be closer to the measured and therefore the aerobic yield of ordinary heterotrophic organism's default value of 0.666 was adjusted to 0.8 in this research which is close to the value used by Liwarska-Bizukojc et al. (2011), who changed the default value to 0.74 to match their outputs to the measured values. All kinetic and stoichiometric parameters that have been adjusted in this study are summarized in Table 18 and 19.

Table 16: Stochiometric Calibrated and Calculated Values

Stochiometric	**Parameters**	**Value**	**Source**
Common	Particulate Substrate COD :VSS ratio (mg COD/ mg VSS)	0.756	Calculated
	Particulate Inert COD :VSS ratio (mg COD/ mg VSS)	0.756	Assumed
Ordinary Heterotrophic Organism (OHO)	Yield aerobic (day^{-1})	0.8	Liwarska-Bizukojc et al. (2011)
	N in biomass (mg N/ mg COD)	0.12	Trial
	COD : VSS ratio (mg COD/ mg VSS)	1.2285	Calculated
Other	BOD calculation rate constant for X_{sc} degradation (day^{-1})	1	Trial
	BOD calculation rate constant for X_{sp} degradation (day^{-1})	1	Trial

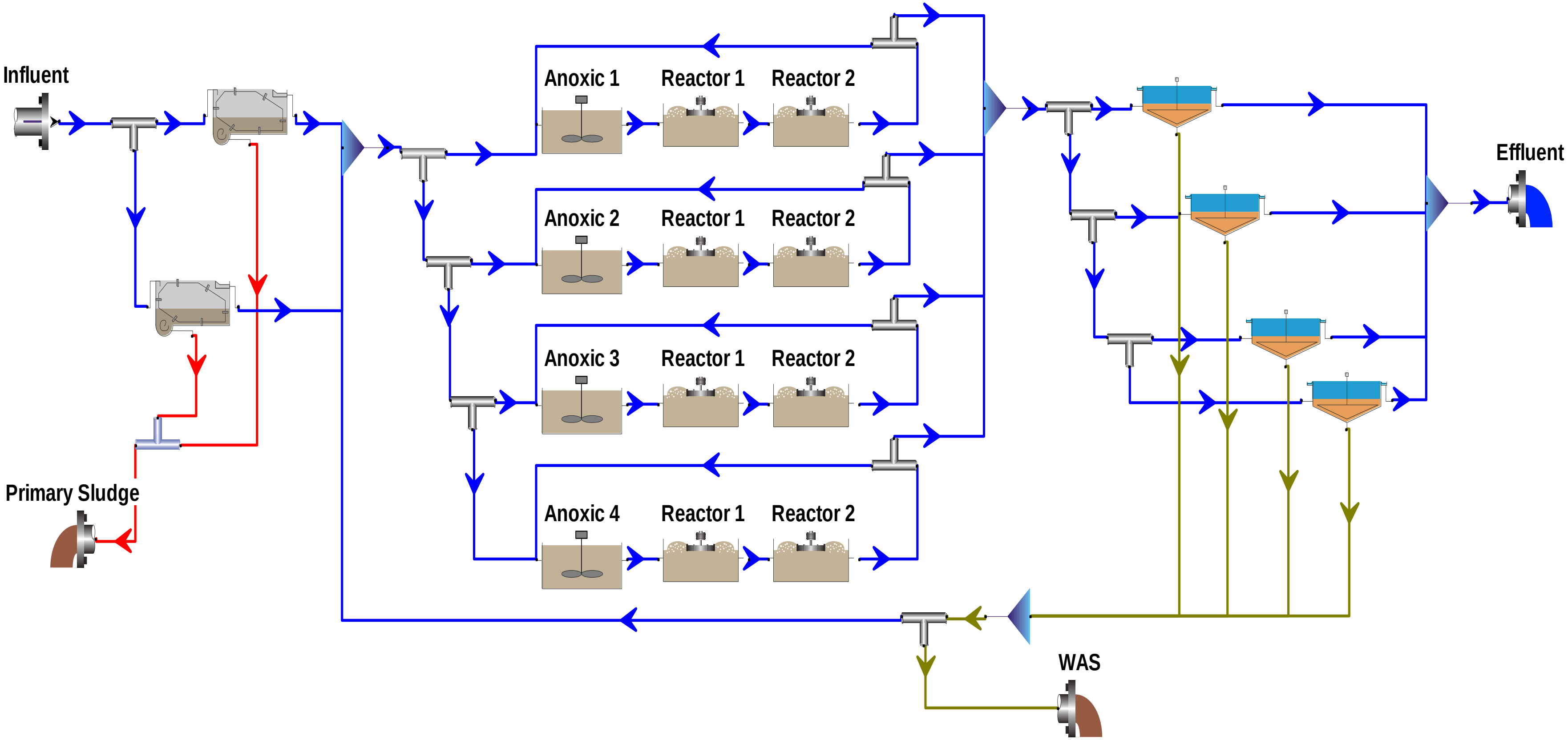

Figure 22: Model layout of Al-Saad WWTP

Table 17: Kinetics Calibrated Values

Kinetics	Parameters	Value	Source
Common	Anoxic hydrolysis factor	1	(Eidroos, 2015)
Ammonia oxidizing organism (AOO)	Substrate (NH_4) half	1	(Eidroos, 2015)
Ordinary Heterotrophic	Maximum specific growth rate	2.5	Elawwad et al. (2019), Liwarska-Bizukojc et al. (2011)
	Substrate half saturation	14	Elawwad et al. (2019), Liwarska-Bizukojc et al. (2011)
	Aerobic decay rate	0.9	Elawwad et al. (2019), Liwarska-Bizukojc et al. (2011)

Table 20 shows the measured and simulated values and the significant differences between them before the calibration. After the calibration procedures has been applied in the software, most of the significant differences between the measured and simulated were resolved as shown in Table 22. The only parameter that slightly exceed the limitation of Melcer, (2003) guidelines is the produced sludge and TSS in the WAS stream. More sampling could be taken from the plant for quality analysis which will improve the model predictivity but due to the limited budget of this research, we were not able to extend the number of samples.

Table 18: Differences between Measured and Simulated Values before Calibration

Stage	Parameter	Measured	Simulated	Difference %
SST	COD (mg/L)	18.90	32.29	-70
	BOD_5 (mg/L)	7.00	1.88	73
	TKN (mg/L)	0.11	1.89	-1700
	NH_3 (mg/L)	0.16	0.04	75
	NO_3 (mg/L)	5.50	30.59	-456
	TSS (mg/L)	3.80	2.43	36
	VSS (mg/L)	3.00	1.94	35
WAS	TSS (mg/L)	7670	3158.75	58
	Sludge Produced (kg/d)	18492	7615.74	58

Table 19: Differences between Measured and Simulated Values after Calibration

Stage	Parameter	Measured	Simulated	Difference %
SST	COD (mg/L)	18.90	18.08	4.34
	BOD_5 (mg/L)	7.00	5.42	22
	TKN (mg/L)	4.2	3.4	19
	NH_3 (mg/L)	0.16	0.19	-18
	NO_3 (mg/L)	5.50	6.07	-10
	TSS (mg/L)	3.80	3.9	-2.63
	VSS (mg/L)	3.00	3.33	-11
WAS	TSS (mg/L)	7670	5072.75	33
	Sludge Produced (kg/d)	18492	12230.4	33

4.5 Results of Model's Validation

Samples collected in this study covered two different operating periods. The first period which was from May 23, 2020 to August 04, 2020 for the purpose of model calibration whereas the second period of sampling was from November 19, 2020 to November 21, 2020 and used to validate the developed model. Previously determined kinetics and stoichiometric parameters used for calibration were used in the second run for validation and the results are illustrated Table 23.

There was a significant difference between the influent characteristics in the two different periods for all parameters. For example, the COD in the summer (first period) was 559 mg/L whereas in the winter (second period) it was 835 mg/L. Other parameters also fluctuate as shown Appendix C. Despite that, the model properly predicts the effluent COD, BOD_5, TKN, and ammonia but it did not match other parameters with the measured ones such as nitrate, TSS, MLSS and the amount of produced sludge. Since particulate matter is accumulating in the system for SRT duration and therefore affecting the sludge production, it is possible that the reason behind this mismatch is the assumption of particulate non-biodegradable COD which is the most important parameter in the calibration (Melcer, 2003) . This mismatch should not affect the impact of the OSA process on the sludge reduction percentage; however the predicted values of produced sludge from the different scenarios would not represent the reality in the field. Therefore, more sampling is required and another adjustment for the kinetics and stochiometric highly recommended for different load of the influent characteristics for robust predictions.

Table 20: Differences between Measured and Simulated Values for Validation Step

Stage	Parameter	Measured	Simulated	Difference %
SST	COD (mg/L)	24.93	26.71	-7.14
	BOD_5 (mg/L)	5.53	6.26	-13.2
	TKN (mg/L)	4.0	3.79	5.25
	NH_3 (mg/L)	0.17	0.17	0
	NO_3 (mg/L)	4.2	5.52	-31.43
	TSS (mg/L)	3.67	5.3	- 44.4
WAS	MLSS (mg/L)	5096	9270	-81.9
	Sludge Produced (kg/d)	10523.24	19142	-81.9

4.6 Results of OSA Retrofit Scenarios

The retrofit for Al-Saad WWTP which is represented by inserting SHT on the RAS stream between the secondary settling tank and the aeration tank was developed as shown in Figure 23. The results revealed a decrease in the produced sludge. The SHT volume was calculated based on the HRT and illustrated that the longer the HRT the better the reduction of sludge production. Most of the previous research revealed sludge reduction of about 30 to 50%, but with pilot-plants and synthetic wastewater which did not account for the inert particulate that affect the OSA efficiency on sludge reduction (Velho et al., 2016). The only application of anaerobic side stream reactor (ASSR) on full-scale was done by Velho et al. (2016). The authors revealed 6.7%

reduction in the amount of produced sludge (kg TSS), which is close to the value found in this study (5.76%) for the scenario of inserting SHT for 12 hours retention time although the capacity of the plant studied in this study was bigger than the one studied by Velho et al. (2016). In addition, Velho et al. (2016) retrofitted the plant by circulating 10% of the SST underflow to the ASSR for 6.7 days of retention time, whereas in this study 93% of SST underflow was recirculated to the SHT with only half day HRT. On the other hand, the ASSR process, investigated in this study, was simulated in BioWin™ under different flow rates and circulation percentages from SST underflow (Figure 24). The results indicated that this mode of simulation did not help in reducing sludge nor did it improve the effluent quality. The only difference between OSA process and ASSR is the ratio of recycled flow from the secondary settling tank into the anaerobic tank (Velho et al., 2016). Table 25 includes the SHT volumes along with the associated percent reduction of sludge.

Regarding the impact of OSA process on the other water quality parameters (COD, BOD. etc.) in the effluent, a small decrease in the removal efficiency was noticed as illustrated in Table 24.

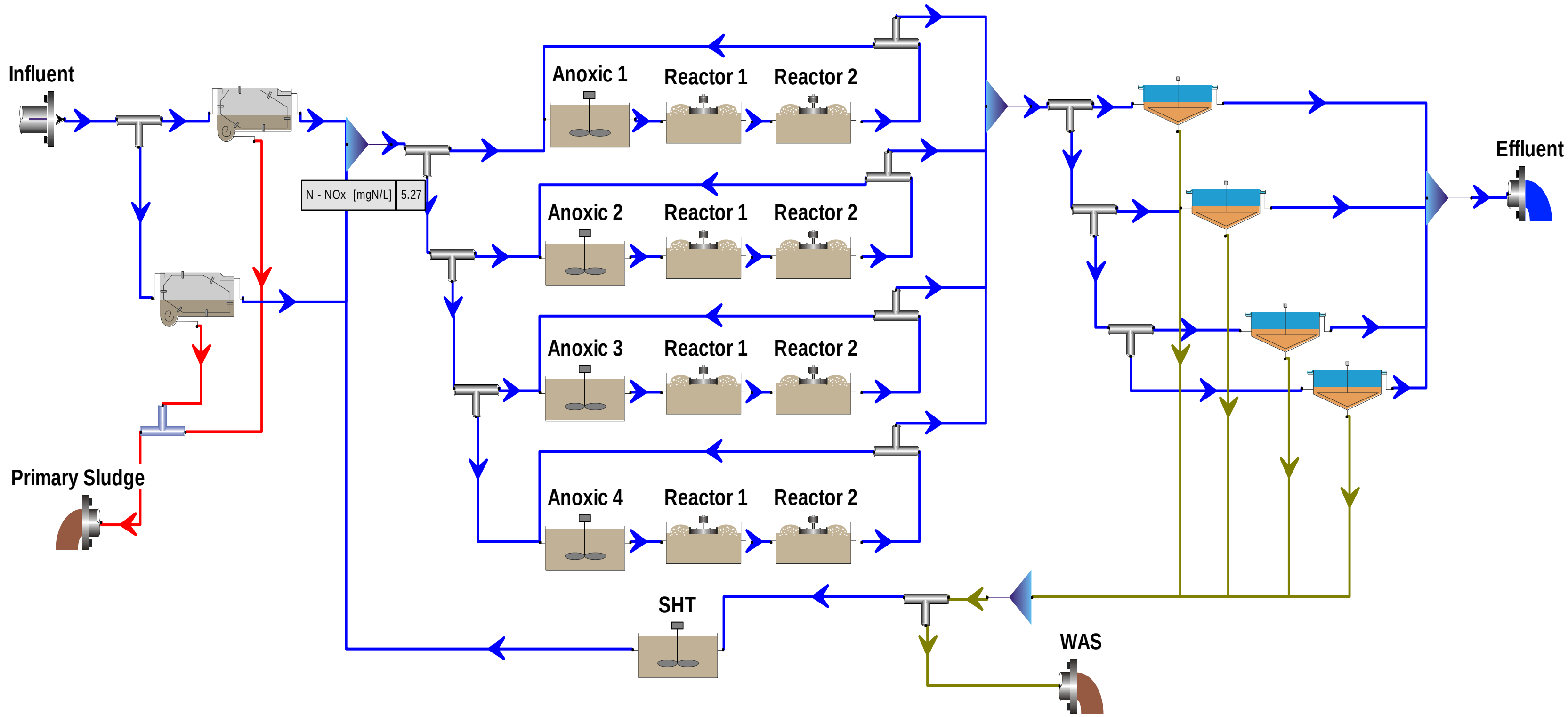

Figure 23: Model layout of Al-Saad WWTP with OSA Process

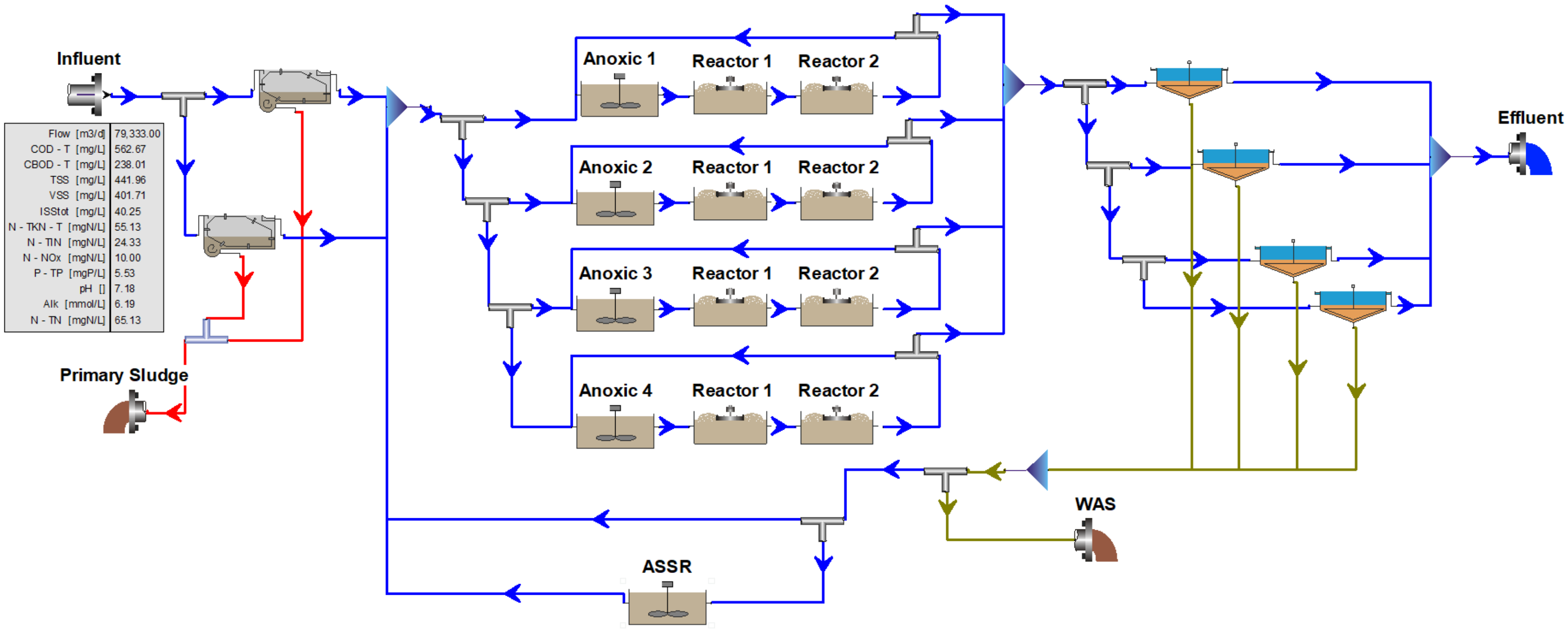

Figure 24: Model layout of Al-Saad WWTP with ASSR Process

Table 21: SHT Scenarios with Different HRT

Scenario	WAS	SST Effluent						
HRT (h)	TSS (mg/L)	COD (mg/L)	BOD_5 (mg/L)	TKN (mg/L)	NO_2 (mg/L)	NO_3 (mg/L)	NH_3 (mg/L)	TP (mg/L)
Base-Case	12230.4	18.08	5.42	3.4	6.07	0.04	0.19	0.21
2	11736	18.88	5.59	3.3	6.44	0.04	0.17	0.21
3	11691	19.13	5.68	3.31	6.5	0.04	0.18	0.21
4	11659	19.39	5.79	3.33	6.55	0.04	0.19	0.22
5	11636	19.65	5.91	3.35	6.58	0.05	0.2	0.22
6	11618	19.93	6.04	3.37	6.61	0.05	0.21	0.22
7	11603	20.21	6.18	3.4	6.64	0.06	0.22	0.22
8	11589	20.51	6.33	3.43	6.67	0.07	0.23	0.22
9	11577	20.82	6.49	3.45	6.69	0.08	0.25	0.22
10	11564	21.15	6.66	3.49	6.72	0.1	0.27	0.22
11	11549	21.49	6.84	3.52	6.75	0.11	0.29	0.22
12	11525	21.85	7.03	3.55	6.8	0.13	0.31	0.22

Notes:
Base-case: Pre-anoxic Treatment System without the OSA Process

Table 22: SHT Volume and Sludge Reduction Percentage

HRT (h)	SHT Volume (m^3)	Sludge Reduction (%)
Base-Case	-	-
2	5932	4.04
3	8899	4.41
4	11865	4.67
5	14831	4.86
6	17797	5.01
7	20763	5.13
8	23730	5.24
9	26696	5.35
10	29662	5.45
11	32628	5.57
12	35595	5.76

Notes:
Base-case: Pre-anoxic Treatment System without the OSA Process

Chapter 5: Conclusions and Recommendations

This study was concerned with the problem of sludge generated from the activated sludge process of a domestic WWTP. A state-of-the-art review of the different approaches for sludge reduction was provided. Of the reviewed approaches, the OSA process was often proposed to be the easiest to implement particularly for existing WWTPs. Further investigations in this study aimed to test the viability of in-situ activated sludge technology represented by oxic-settling-anaerobic (OSA) process as a potential solution for reducing sludge. Al-Saad WWTP was selected as a case study. The methodology applied in this research evaluated the potential for retrofitting Al-Saad WWTP with OSA process through simulation / modelling.

Modelling an existing WWTP requires calibration which entails the adaptation of some model parameters to match certain simulated values with actual measured values. Four different calibration protocols were reviewed and the WERF calibration procedure was followed in this research to calibrate the Al Saad WWTP model. Several site visits and meetings with Al-Saad WWTP operator were organized to understand the plant configuration and to collect design, operational, and the routine water quality data necessary for model construction. Al-Saad WWTP model was developed using BioWin™ version 6.0 software. A sampling framework was established to fractionate COD and TKN according to the WERF guidelines to aid in the calibration procedure and minimize model parameter adjustment. The developed model was calibrated successfully and a good match within the limitation of 20% difference between simulated and measured parameters was achieved. The calibration procedures came out with adjustment in stochiometric parameters (aerobic yield for OHO and N in biomass) and kinetics parameters (maximum specific growth rate, substrate half saturation and aerobic decay rate for OHO, NH_4 half saturation for AOO).

In addition, a sensitivity analysis was conducted on the model's input to reveal the most influential parameters that will significantly impact the output. Twenty-seven parameters were identified as significantly influential. Of these 27 parameters, certain stoichiometric and kinetic parameters were used for Al-Saad WWTP calibration.

The OSA process was applied to Al-Saad WWTP by inserting a sludge holding tank (SHT) on the RAS stream between the secondary settling tank and the aeration tank. Several scenarios were run for SHTs of different retention times. The scenario results of OSA process applied in the model revealed that the percentage reduction in the amount of produced sludge increased from 4.04% to 5.76% when the hydraulic retention time of the OSA tank increased from 2 to 12 hours. Selecting the optimum HRT is related to a feasibility study concern with the available area, the initial cost of SHT and sludge treatment cost. It is hypothesized that the reduction in sludge after including the OSA was because in the SHT a low oxidation-reduction-potential ORP levels were maintained and this could have created stressful conditions on the microorganisms resulting in an elevated sludge anaerobic decay rate.

The limitations of this research are summarized as follows:

- The historical data about Al-Saad WWTP was the routine data without fractionation.
- The developed model was run only for steady-state conditions which is not representing the reality of fluctuations occurring throughout the year.

It is thus recommended for further research to:

- Establish a clear unified model calibration protocol instead of different protocols.
- Define a detailed model calibration protocol procedure.
- Define a detailed sampling campaign required for wastewater fractionation and the laboratory methods involved.
- Investigate the models incorporated in simulation software and compare them to models generated by IWA.
- Establish a pilot-plant with a real wastewater for the purpose of knowing the secret behind the mechanism of OSA process to define other parameters other than sludge decay that can significantly reduce the excess sludge.
- Define the principal design of OSA process.

To my knowledge, this is the only work that investigates the impact of OSA process on a full-scale WWTP through a modeling approach. The mechanism behind the OSA process operation which is sludge anaerobic decay rate proposed in literature is confirmed in this research but does not significantly reduce the excess sludge as mentioned.

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Appendices

Appendix A: Al-Saad WWTP Schematic Layout and Operational Data

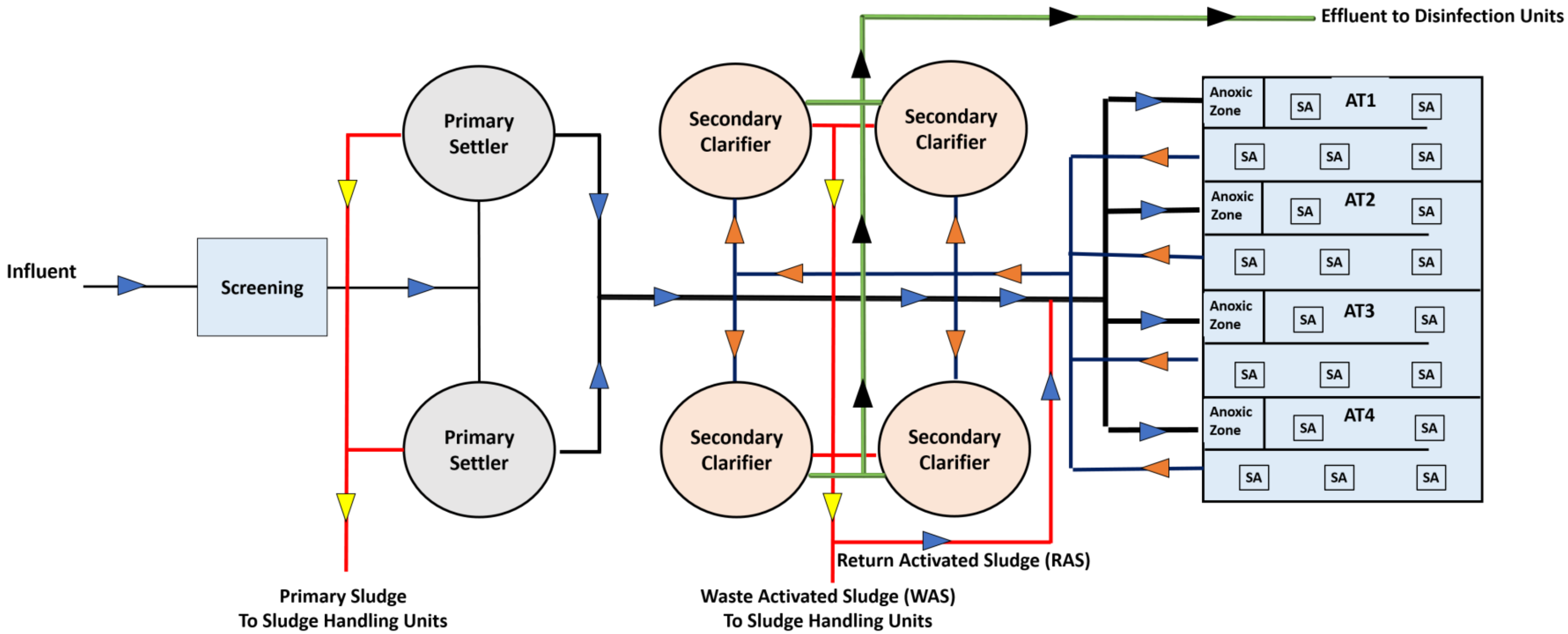

Figure A1: Al-Saad WWTP Schematic Diagram

Table A1: Primary Sedimentation Tank

Parameter	Primary tank 1	Primary tank 2
Volume (m^3)	2,540	2,540
Depth (m)	2.5	2.5
Area (m^2)	1017	1017

Table A2: Activated Sludge Tank

Parameter	Aerobic tank1	Aerobic tank2	Aerobic tank3	Aerobic tank4
Volume (m^3)	7,550	7,550	7,550	7,550
Depth (m)	5.5	5.5	5.5	5.5
Area (m^2)	1342	1342	1342	1342
Temperature (C°)	34	34	34	34
Number of Aerators	5 Surface aerators	5 Surface aerators	5 Surface aerators	5 Surface aerators

Table A3: Secondary Clarifier

Parameter	Secondary tank 1	Secondary tank 2	Secondary tank 3	Secondary tank 4
Volume (m^3)	5800	5800	5800	5800
Depth (m)	4.2	4.2	4.2	4.2
Area (m^2)	1378	1378	1378	1378

Appendix B: Historical Data

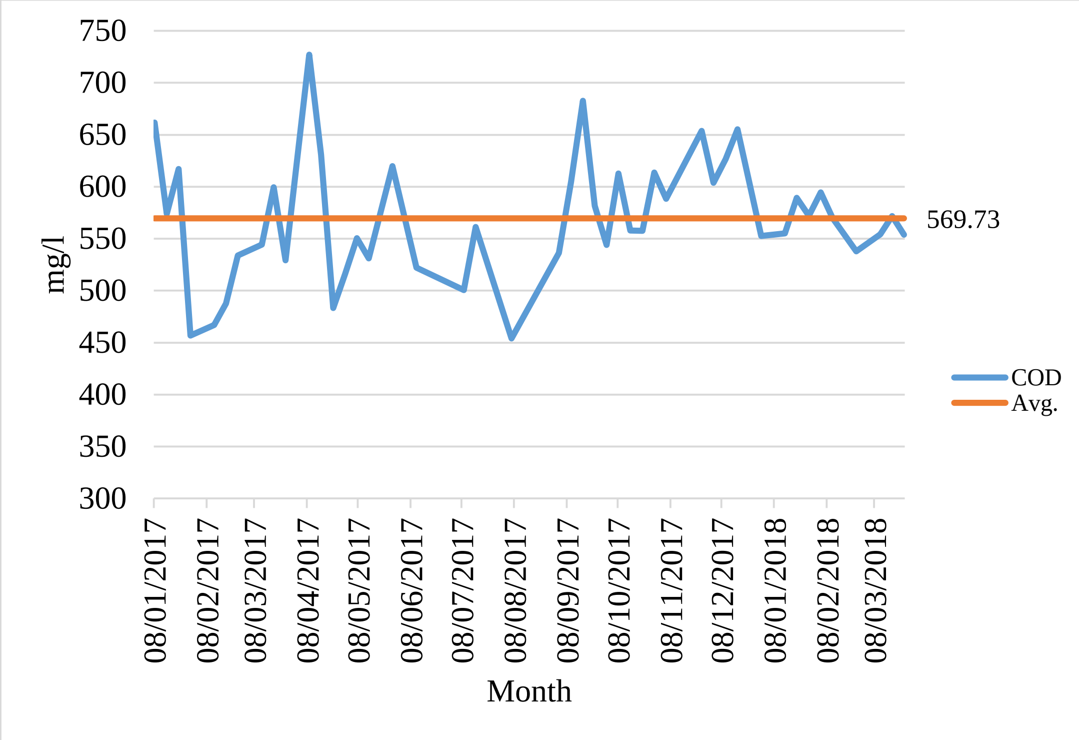

Figure B1: Influent COD at Al-Saad WWTP

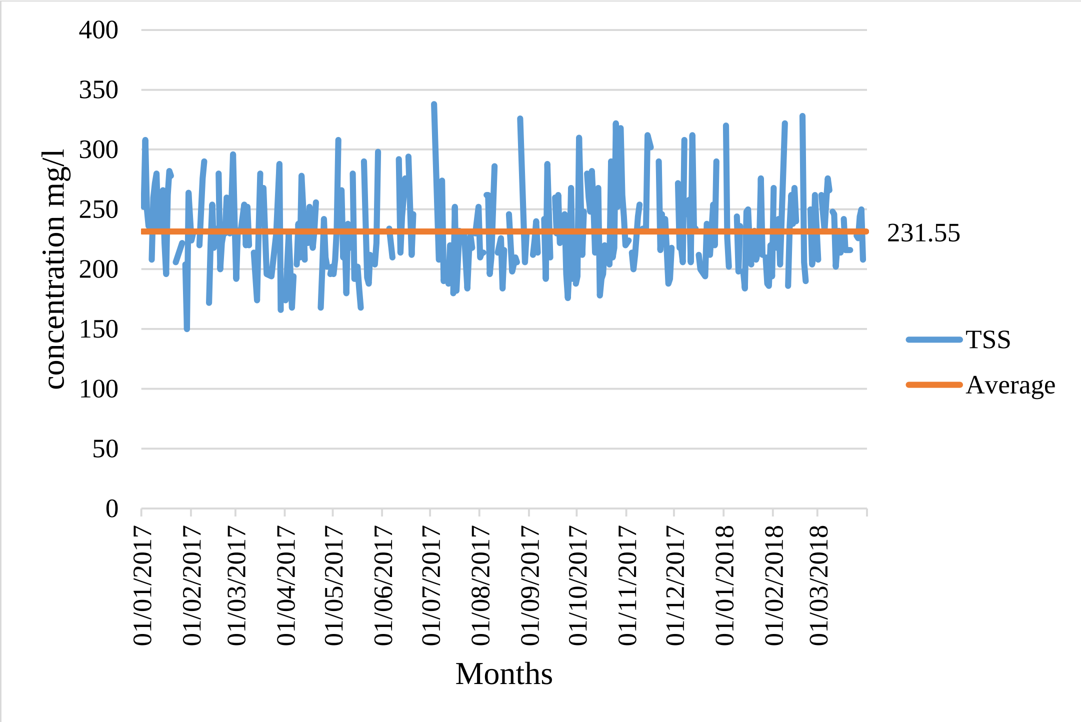

Figure B2: Influent TSS at Al-Saad WWTP

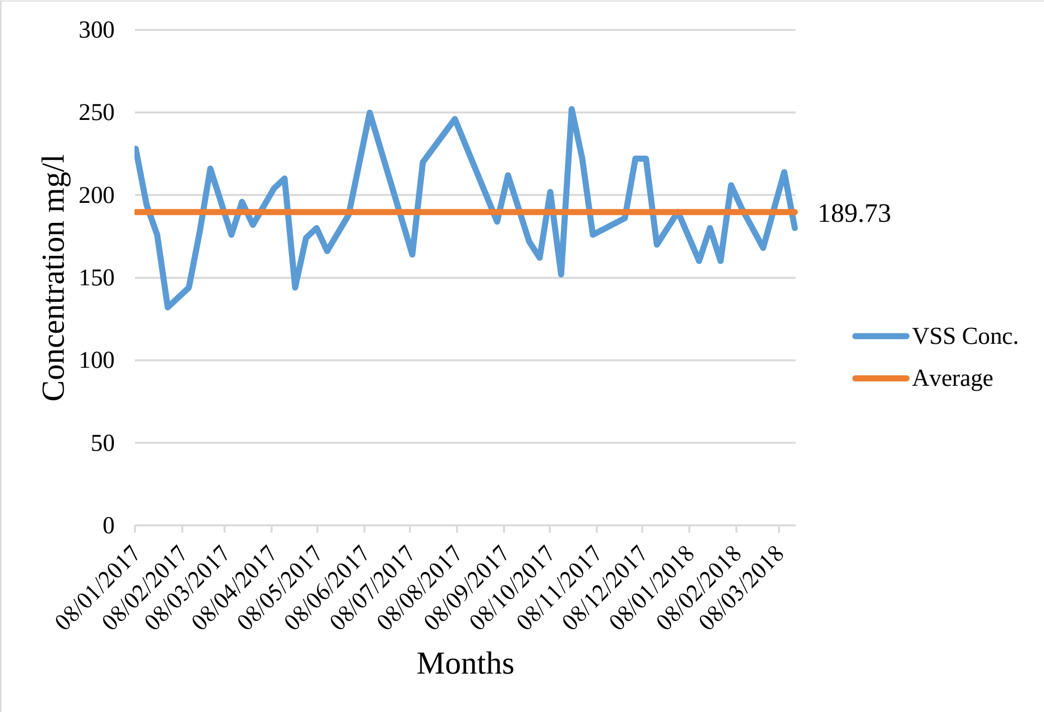

Figure B3: Influent VSS at Al-Saad WWTP

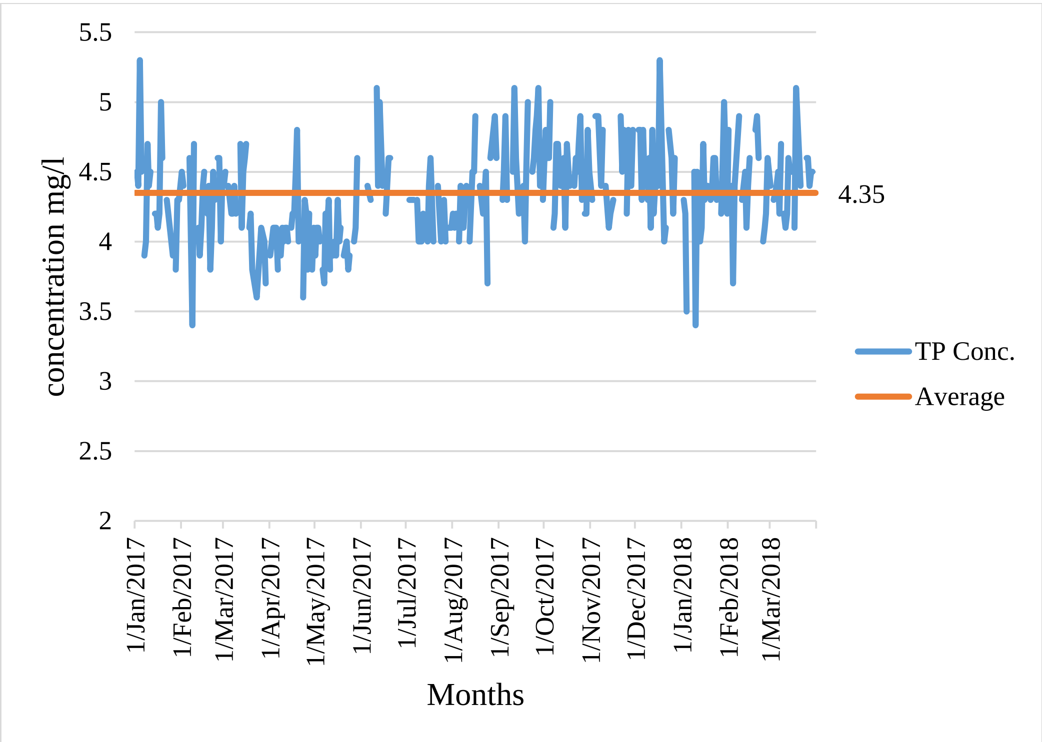

Figure B4: Influent total phosphorus at Al-Saad WWTP

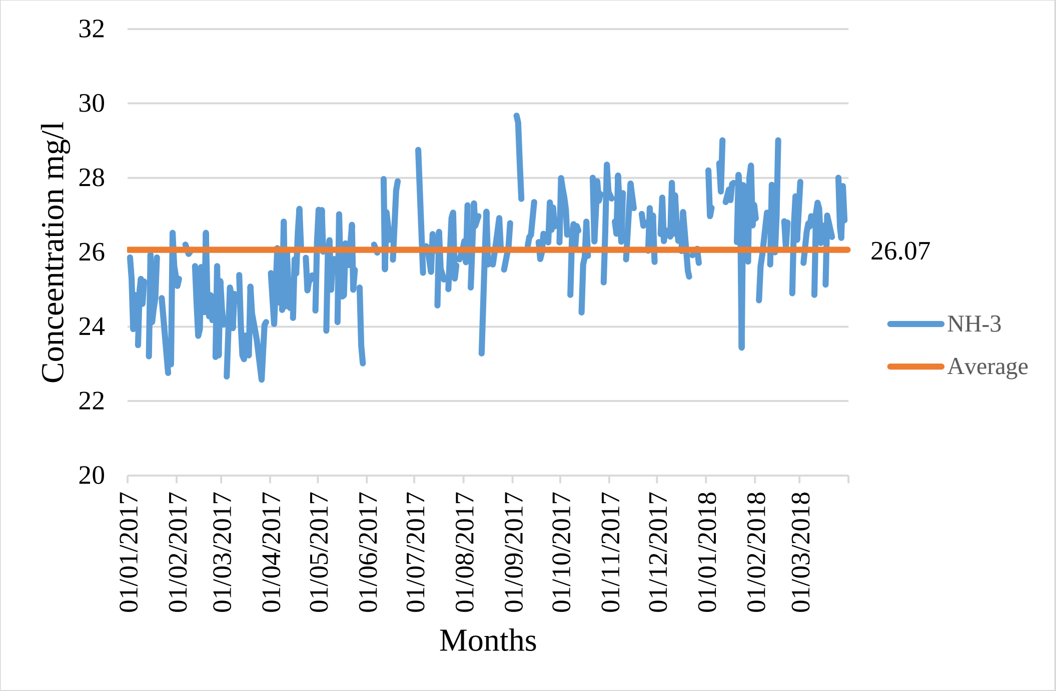

Figure B5: Influent ammonia at Al-Saad WWTP

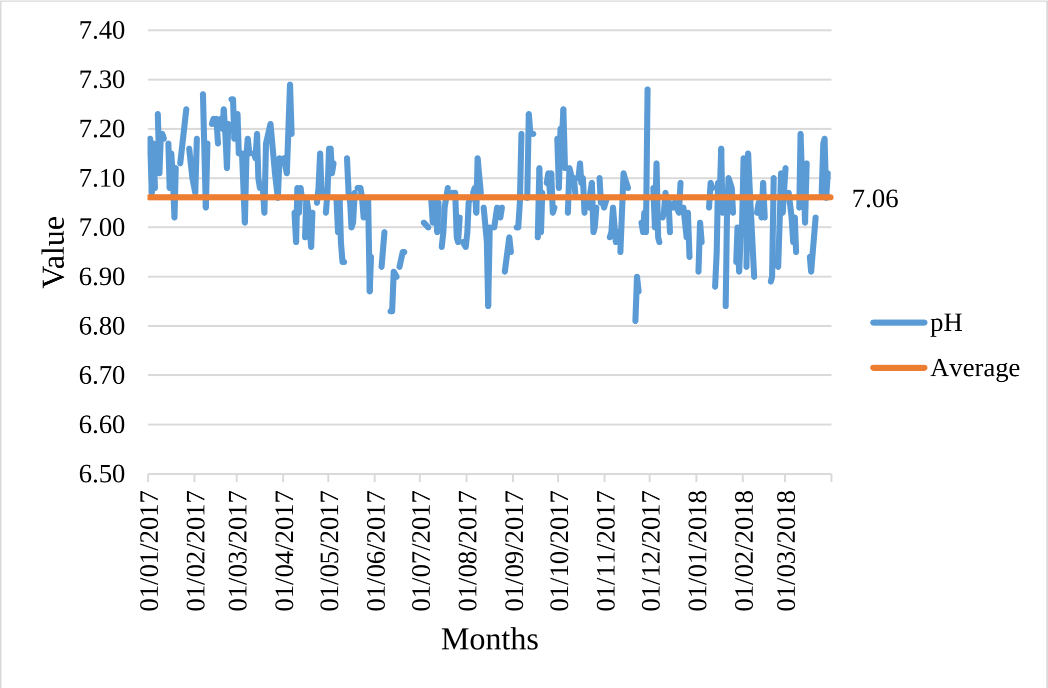

Figure B6: Influent pH at Al-Saad WWTP

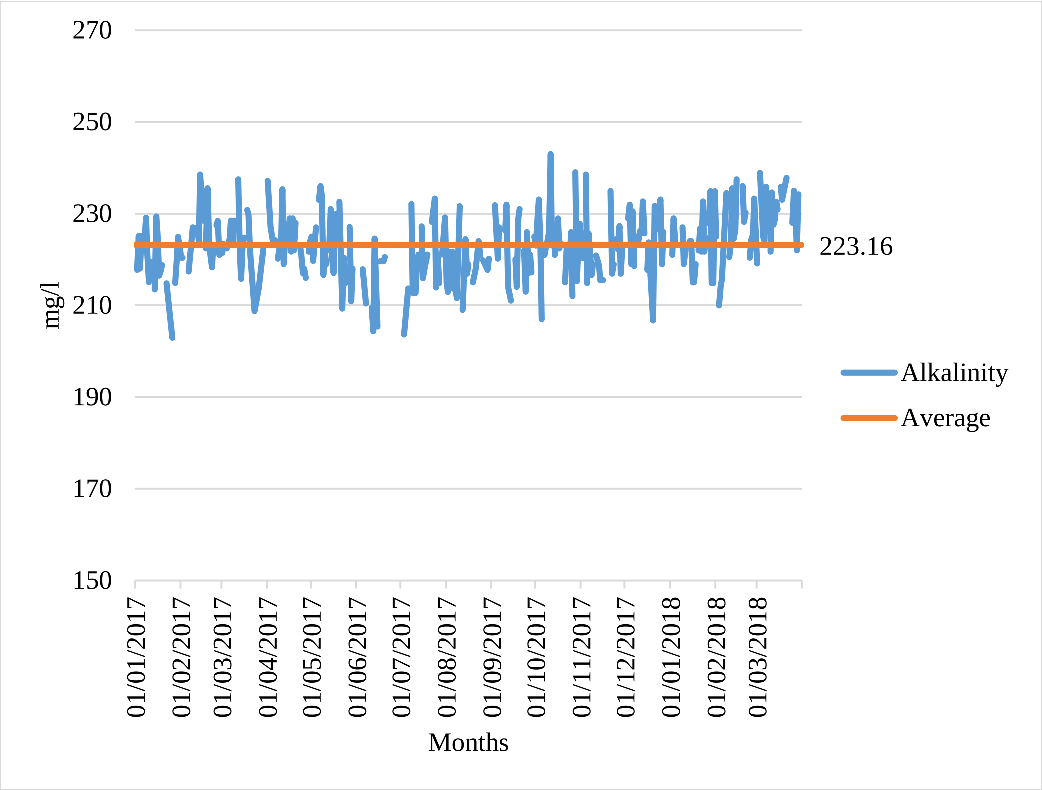

Figure B7: Influent alkalinity at Al-Saad WWTP

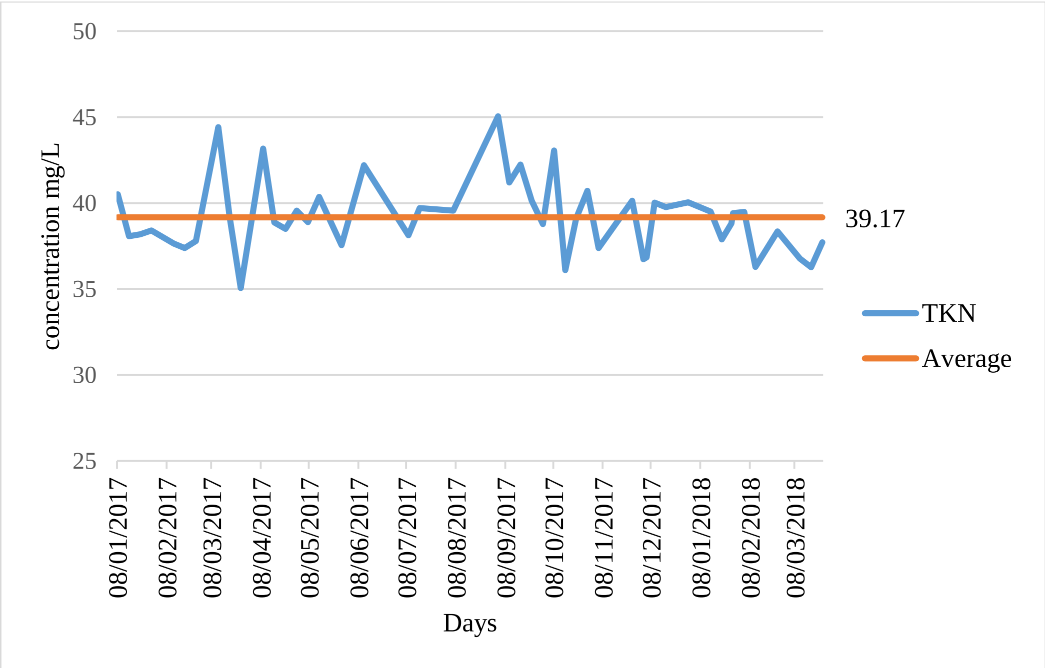

Figure B8: Influent TKN at Al-Saad WWTP

Appendix C: Sampling Campaign Result

Table C1: Activated Sludge Tank Characteristics

Parameter	23/07/20	25/07/20	27/07/20	29/07/20	31/07/20	2/8/2020	4/8/2020	Average
MLSS (mg/L)	3000	3660	3480	3570	3610	4100	3070	3555
MLVSS (mg/L)	2470	2470	2770	2800	2710	3470	2540	2895

Table C2: Return Activated Sludge Stream Characteristics

Parameter	23/07/20	25/07/20	27/07/20	29/07/20	31/07/20	2/8/2020	4/8/2020	Average
MLSS (mg/L)	6290	6410	6860	8070	8650	8060	8080	7767.5
MLVSS (mg/L)	4940	5860	5290	6130	6480	6470	6500	6097.5

Table C3: Primary Tank Overflow Characteristics

Parameter	23/07/20	25/07/20	27/07/20	29/07/20	31/07/20	2/8/2020	4/8/2020	Average
COD (mg/L)	195	245	203	198	216	220	232	213.25
BOD_5 (mg/L)	103	114	106	106	109	118	117	111.75
TKN (mg/L)	36.4	34.1	29.6	28.2	33	31	29.1	29.475
TSS (mg/L)	125	165	162	178	168	194	160	173.5
VSS (mg/L)	99	125	130	138	124	155	122	136.25
ISS (mg/L)	26	40	32	40	44	39	38	37.25

Appendix D: BioWin Influent Parameters

Table D1: Influent in BioWin™ (First Run for Calibration)

COD Influent and Operational Parameter	
Parameter	**Average Value**
Influent Flow (m^3/day)	79239
COD (mg/L)	559.00
TKN (mg/L)	54.35
NO_3 (mg/L as N)	9.94
ISS (mg/L)	40.25
TP (mg/L)	5.53
Ca (mg/L)	51.75
Mg (mg/L)	6.08
pH	7.18
Alkalinity (mmol/L)	6.19
RAS Flow (m^3/day)	70762
WAS Flow (m^3/day)	2358
Primary Underflow (m^3/day)	210

Table D2: Influent in BioWin™ (Second Run for Validation)

COD Influent and Operational Parameter	
Parameter	**Average Value**
Influent Flow (m^3/day)	75748
COD (mg/L)	835
TKN (mg/L)	65.83
ISS (mg/L)	147
TP (mg/L)	3.87
Ca (mg/L)	39.97
Mg (mg/L)	15.03
pH	7.08
Alkalinity (mmol/L)	5.54
RAS Flow (m^3/day)	76508
WAS Flow (m^3/day)	2065

Appendix E: Sensitivity Analysis Results

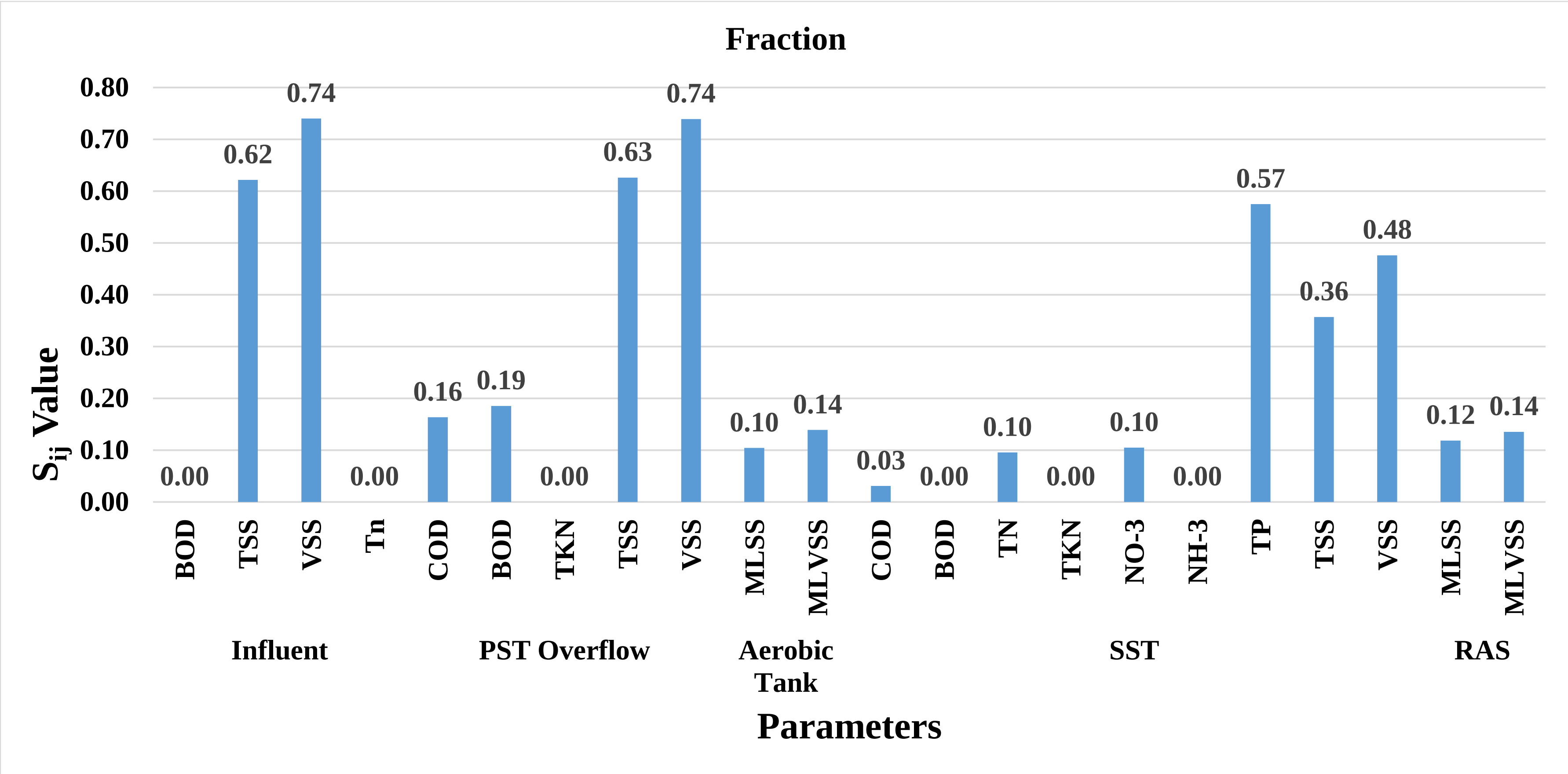

Figure E1: S_{ij} Value for F_{xsp} on Output Parameters at Different Stages

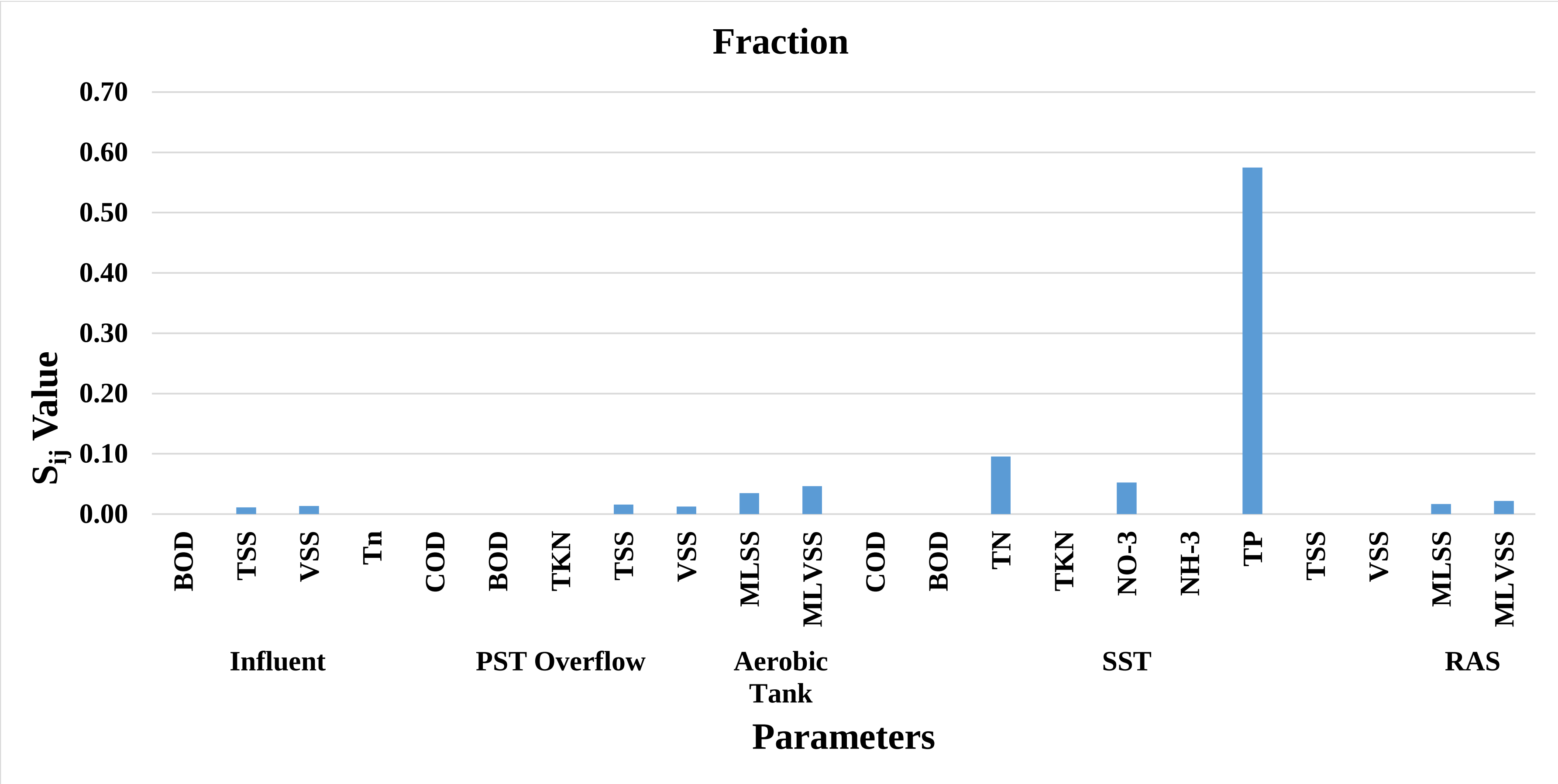

Figure E2: S_{ij} Value for F_{cel} on Output Parameters at Different Stages

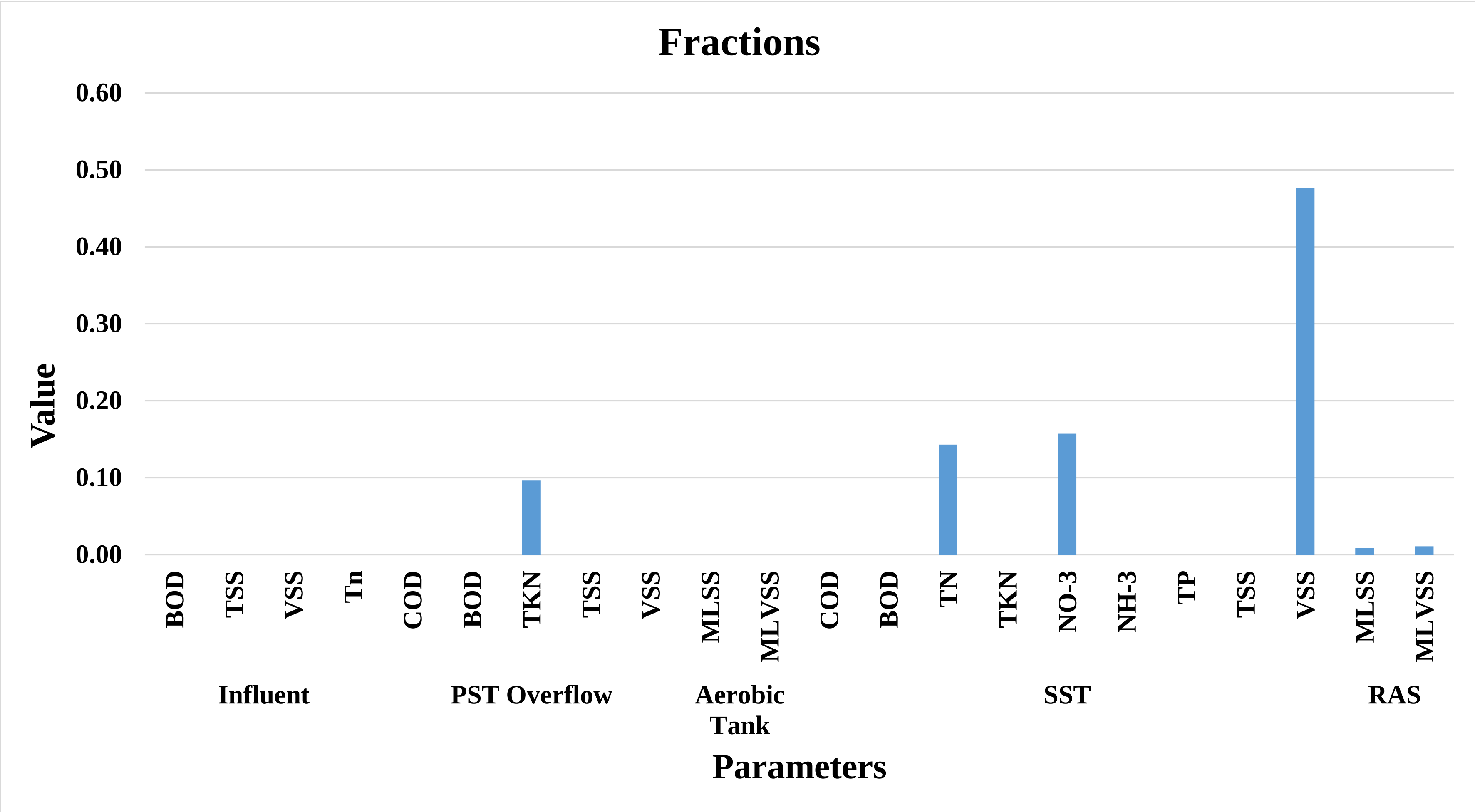

Figure E3: S_{ij} Value for F_{na} on Output Parameters at Different Stages

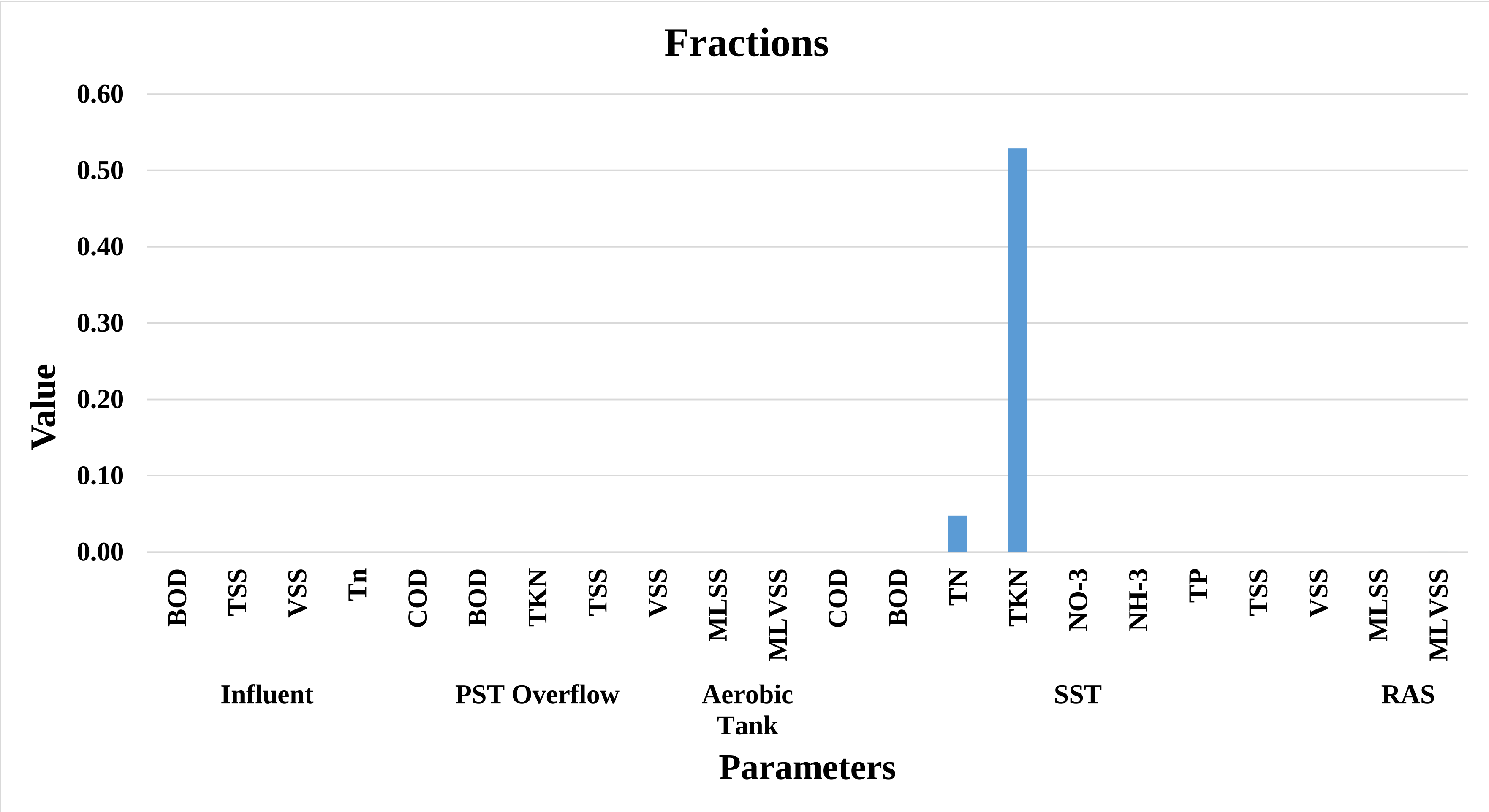

Figure E4: S_{ij} Value for F_{nus} on Output Parameters at Different Stages

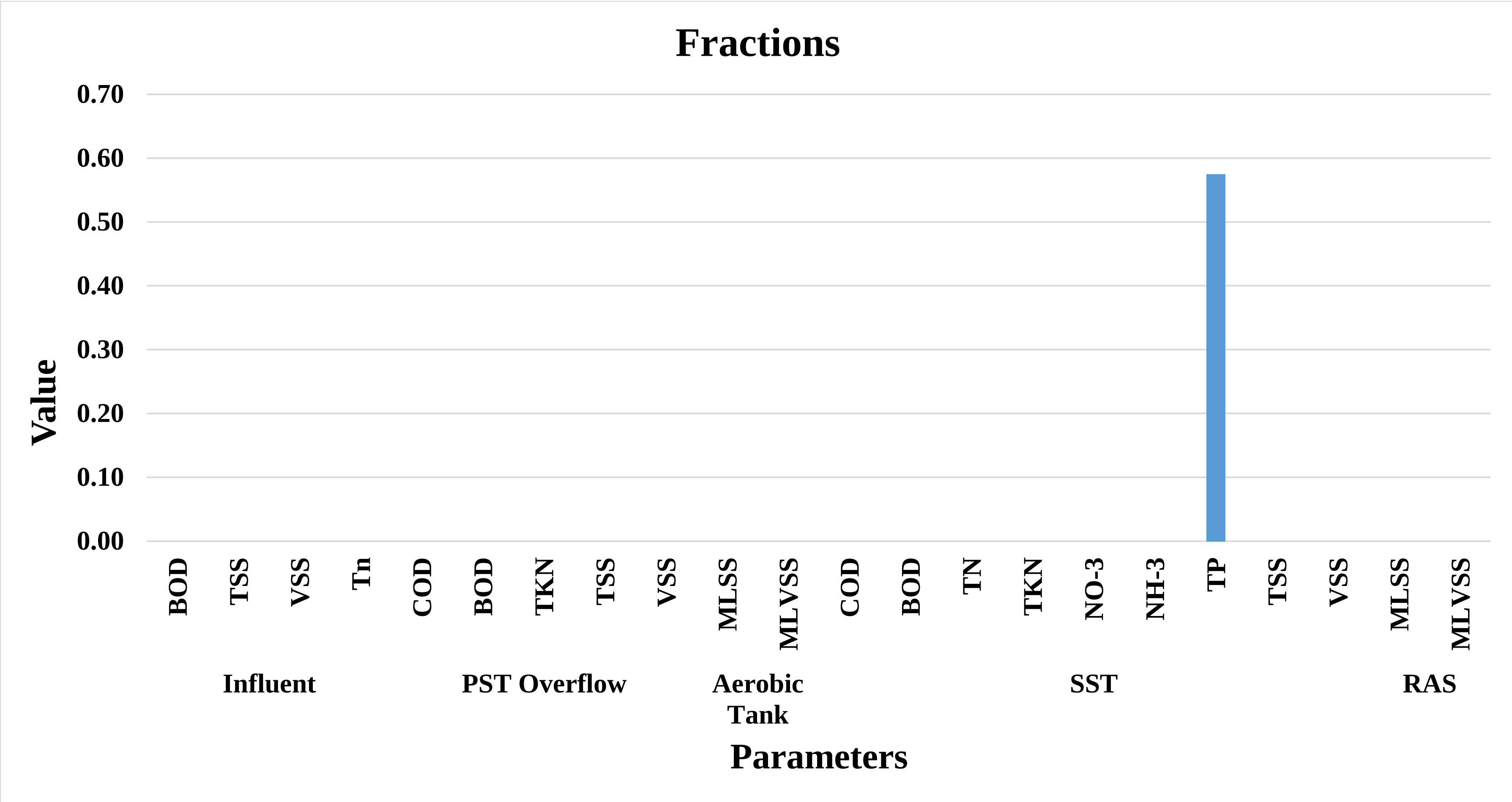

Figure E5: S_{ij} Value for F_{PO4} on Output Parameters at Different Stages

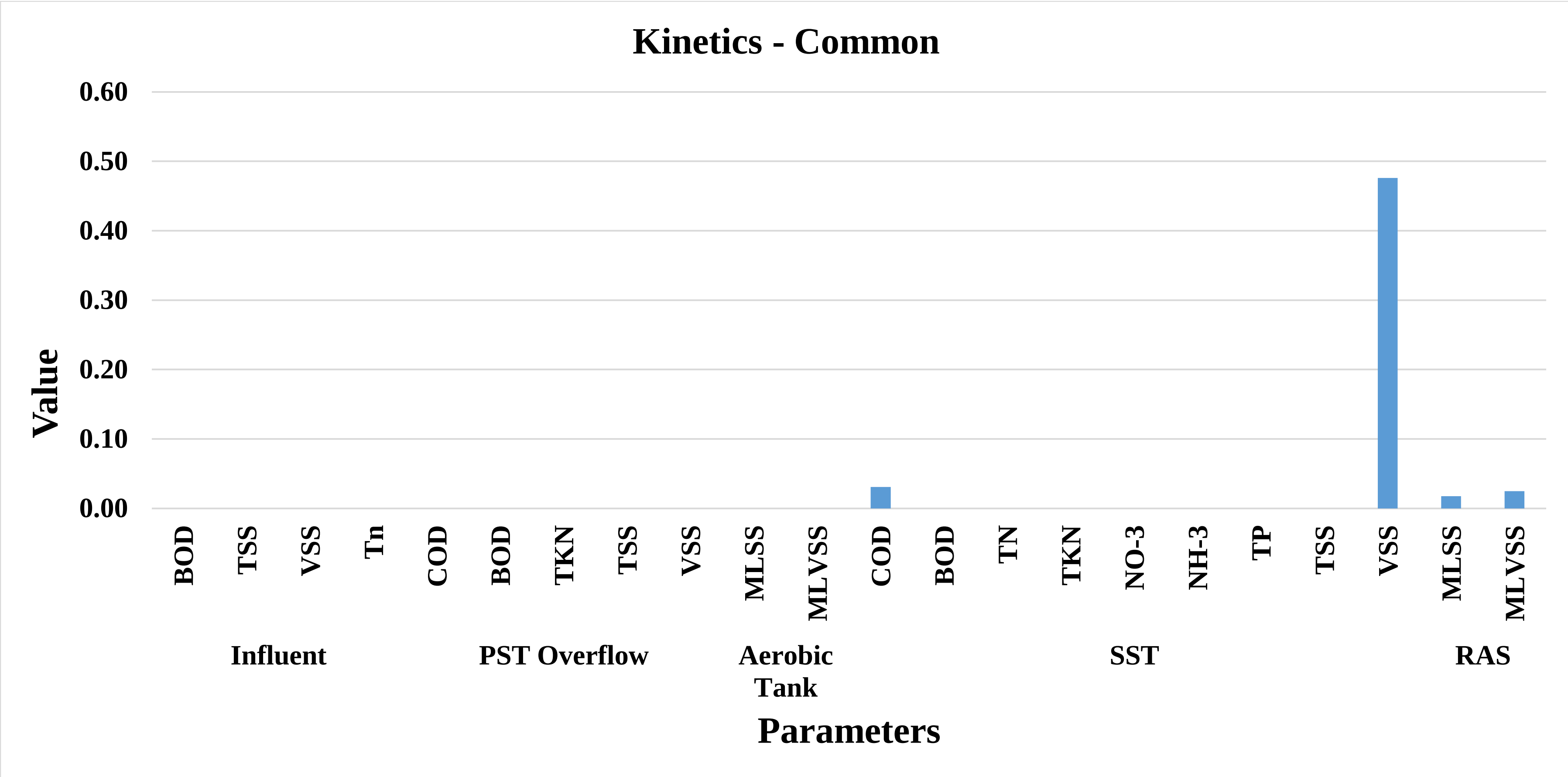

Figure E6: S_{ij} Value for Hydrolysis Rate on Output Parameters at Different Stages

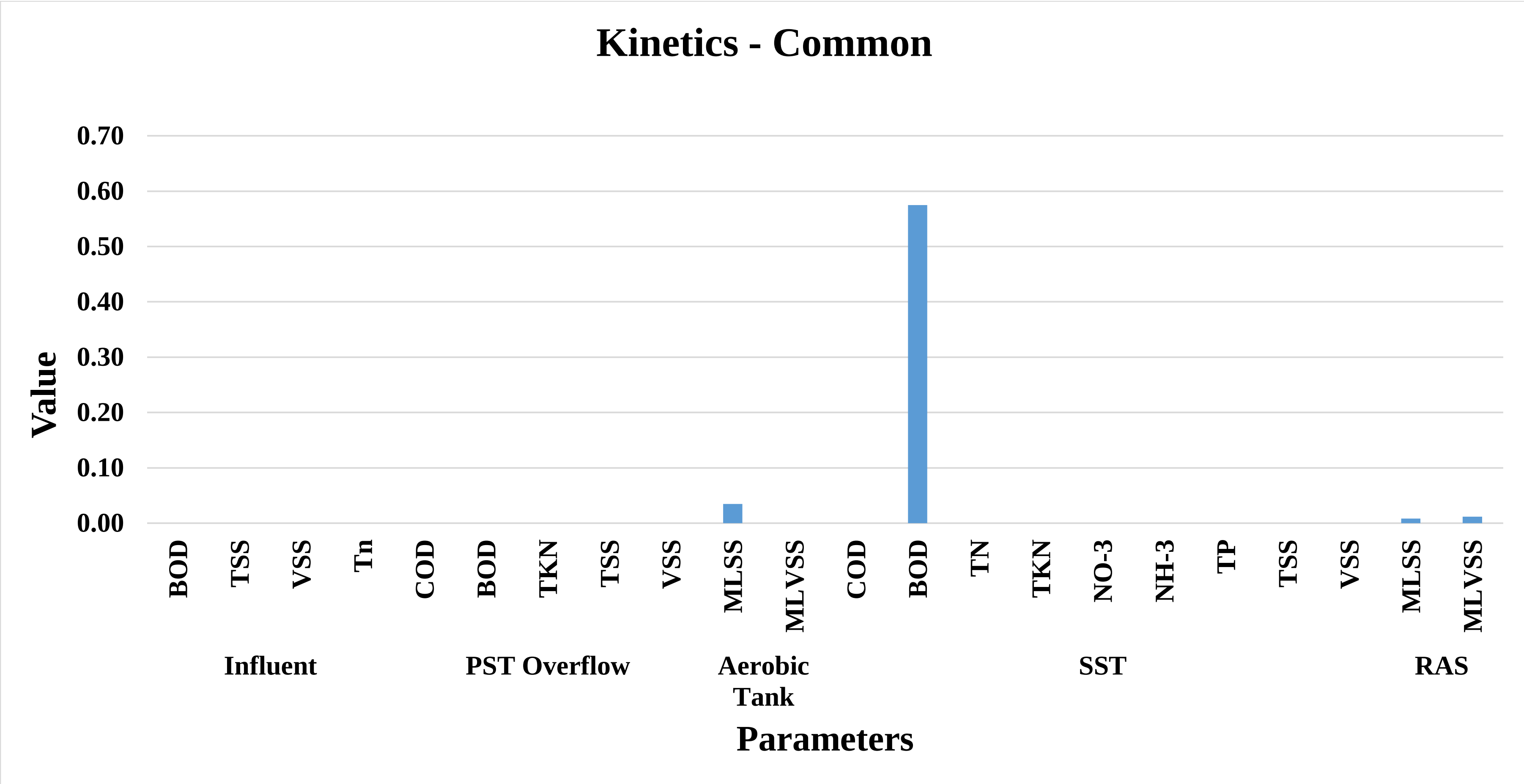

Figure E7: S_{ij} Value for Hydrolysis Half Saturation on Output Parameters at Different Stages

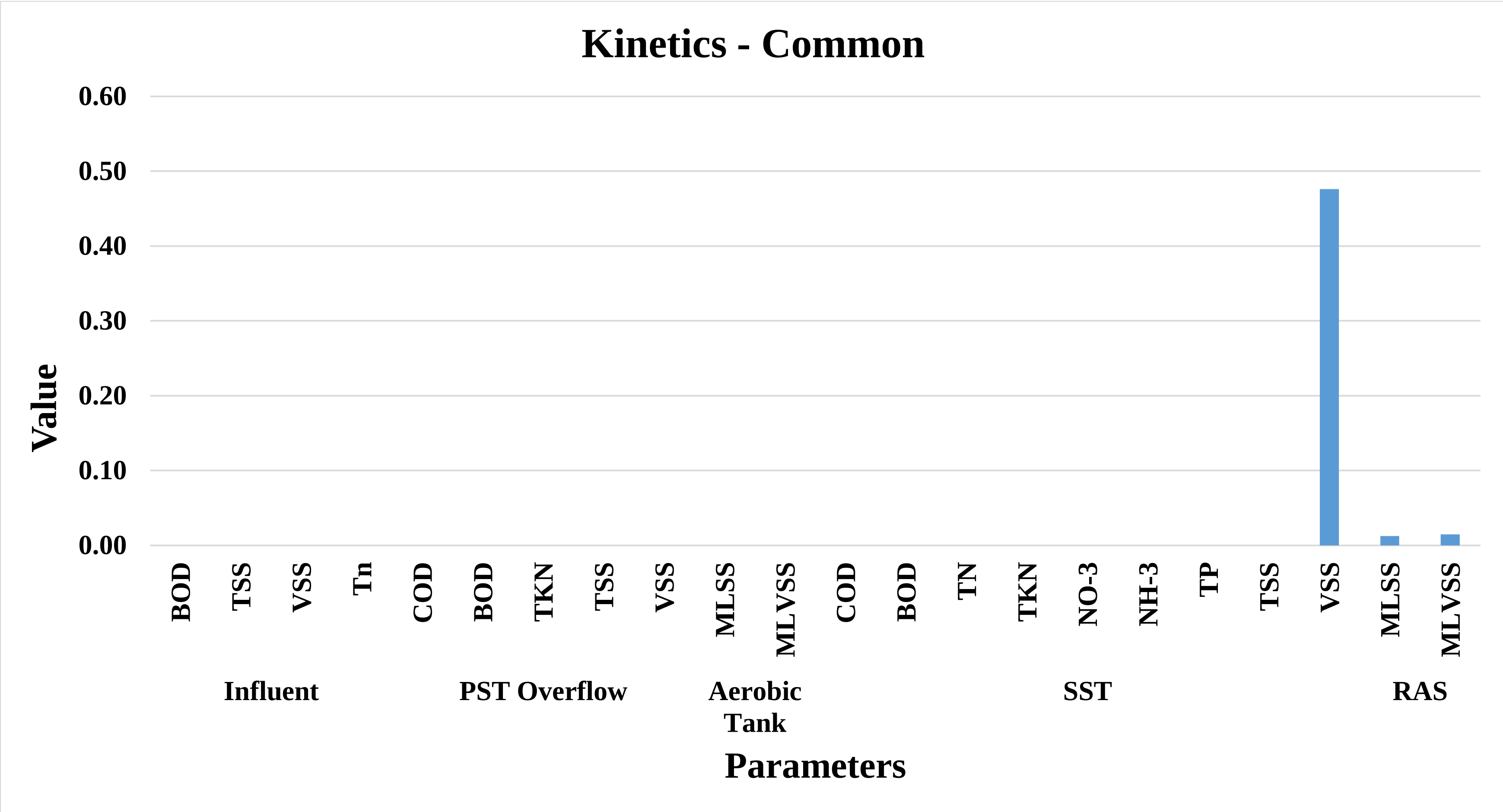

Figure E8: S_{ij} Value for Assimilative NO_3/NO_2 Reduction Rate on Output Parameters at Different Stages

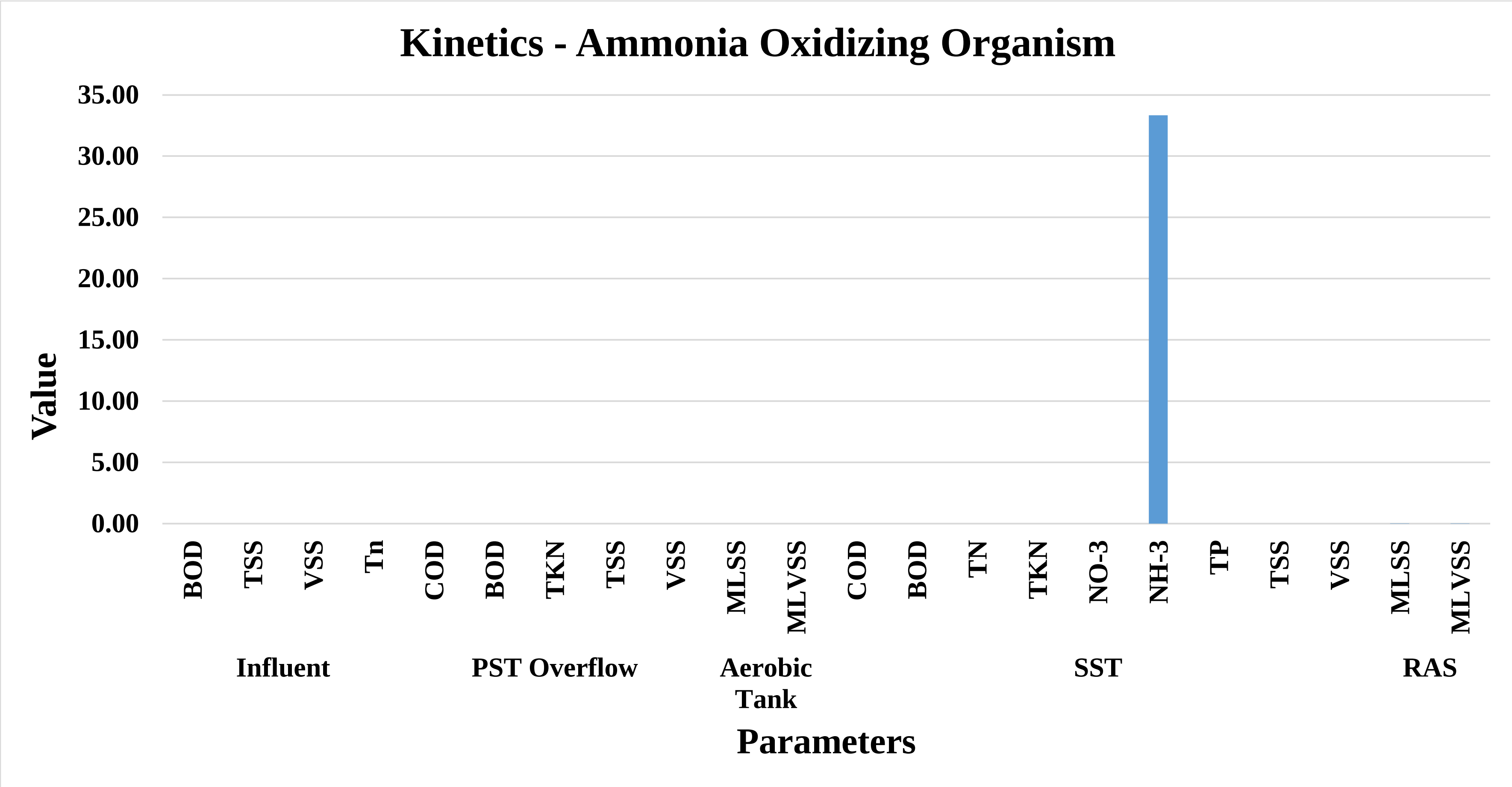

Figure E9: S_{ij} Value for Aerobic Decay Rate on Output Parameters at Different Stages

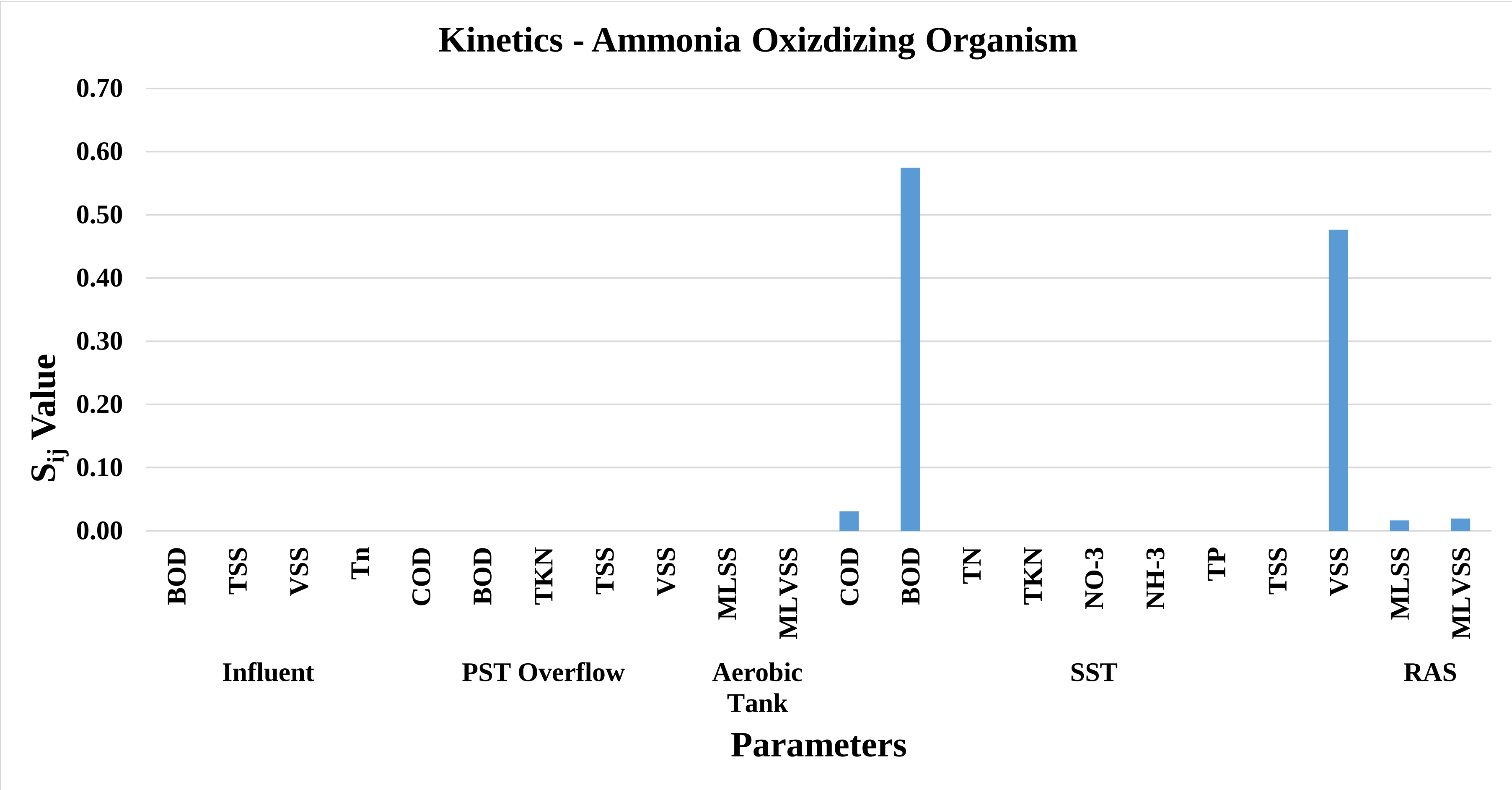

Figure E10: Sij Value for Maximum Specific Growth Rate on Output Parameters at Different Stages

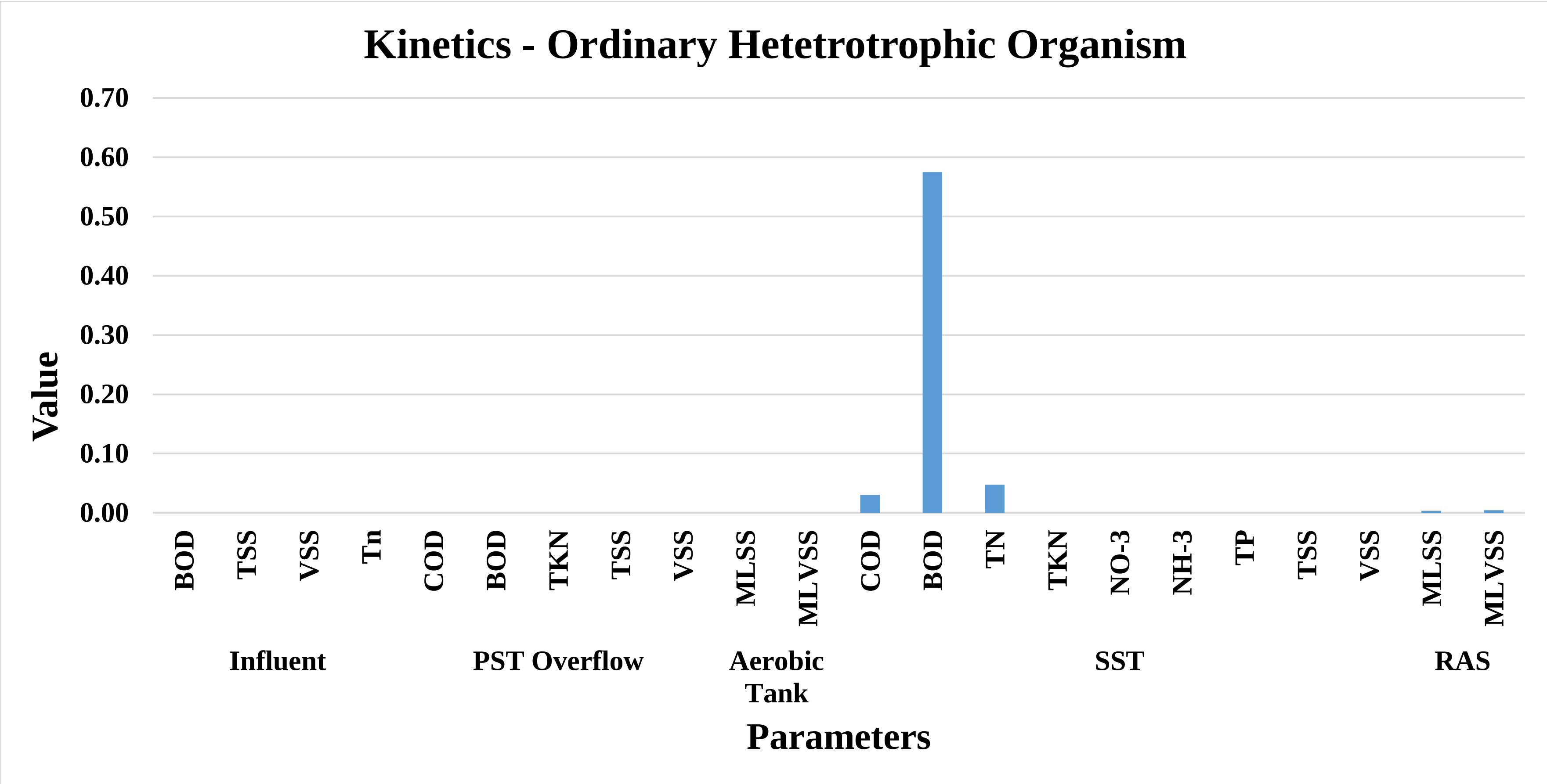

Figure E11: S_{ij} Value for Substrate Half Saturation on Output Parameters at Different Stages

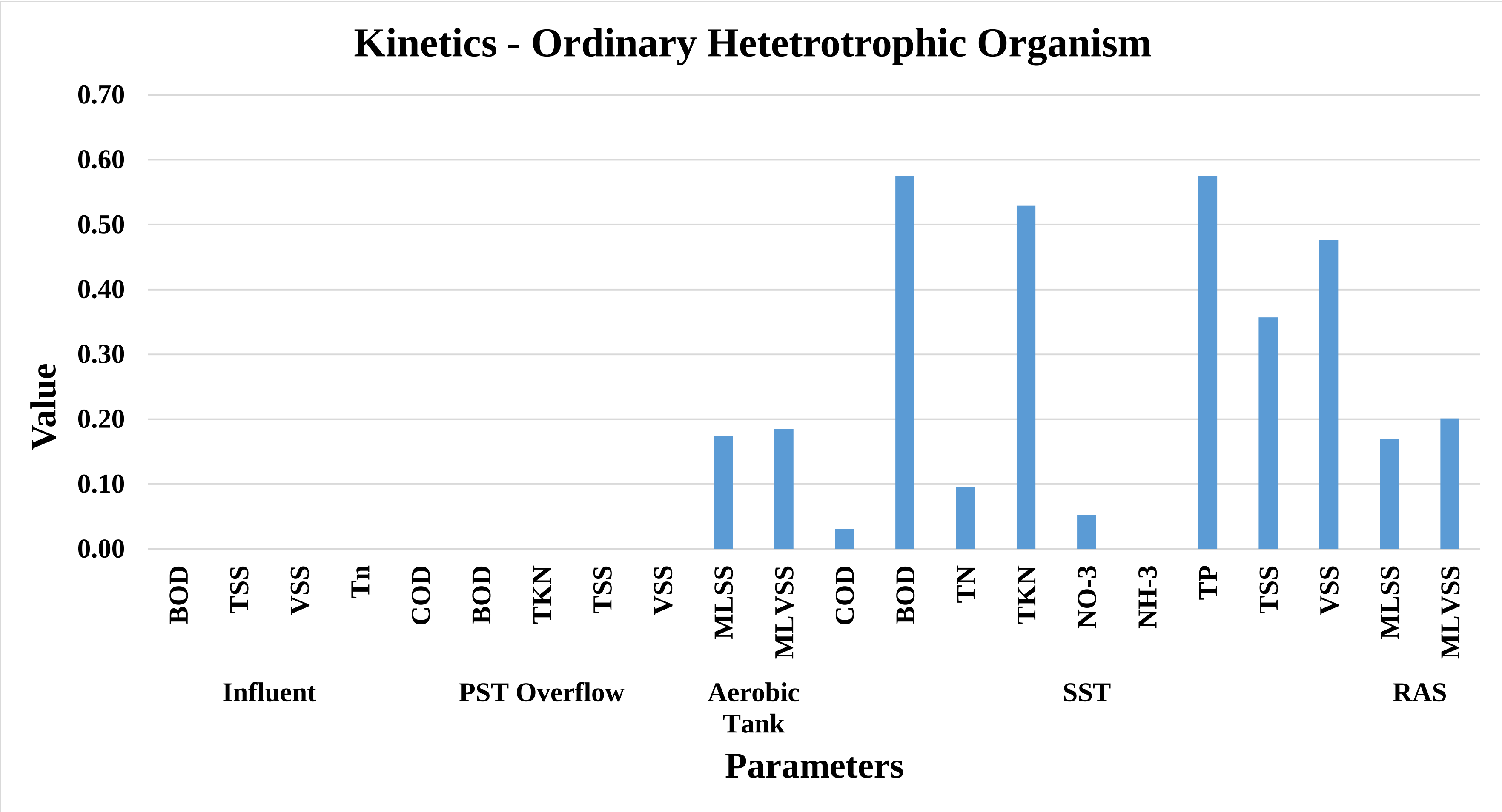

Figure E12: S_{ij} Value for Aerobic Decay Rate on Output Parameters at Different Stages

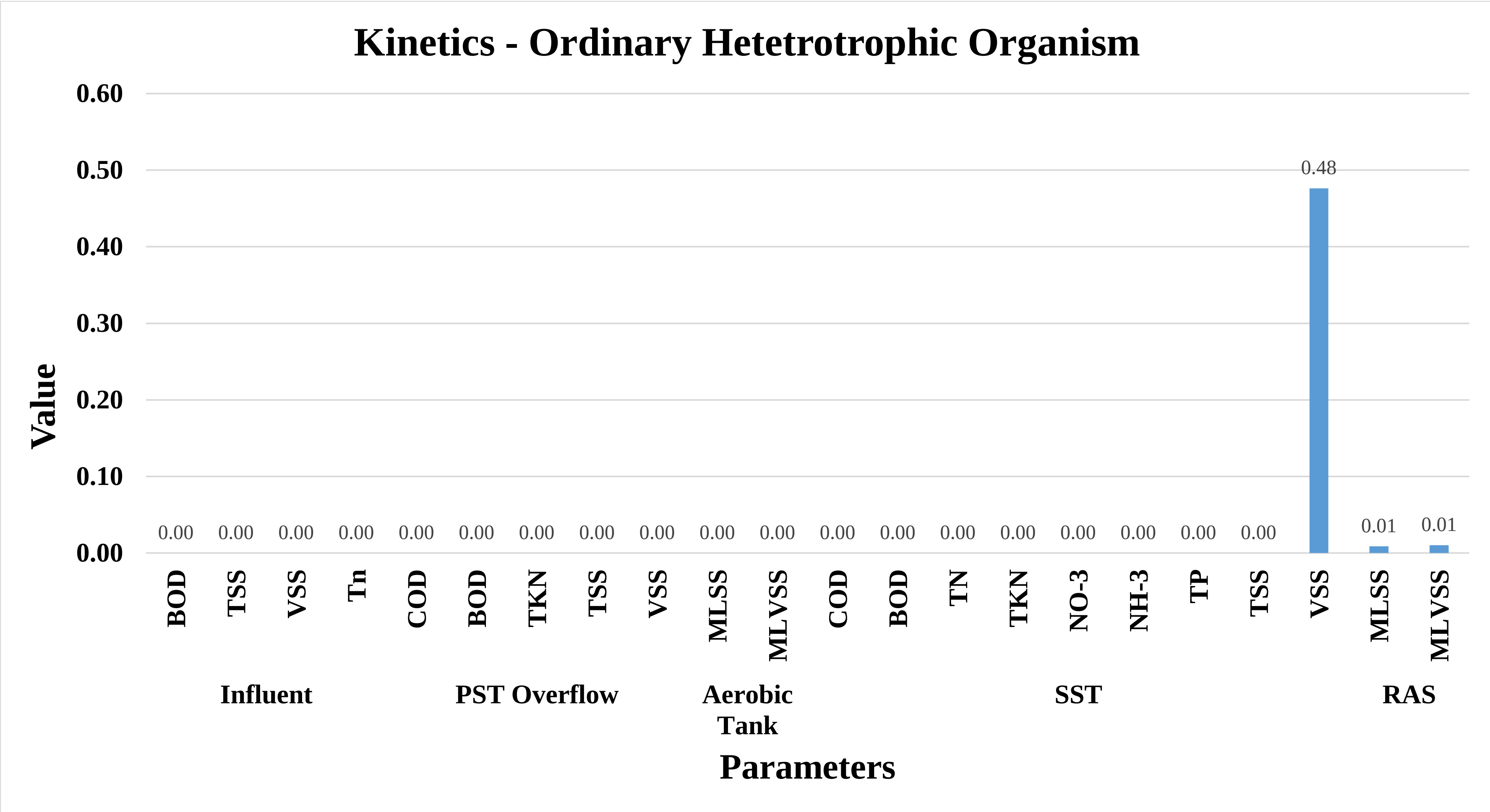

Figure E13: S_{ij} Value for Anoxic Decay Rate on Output Parameters at Different Stages

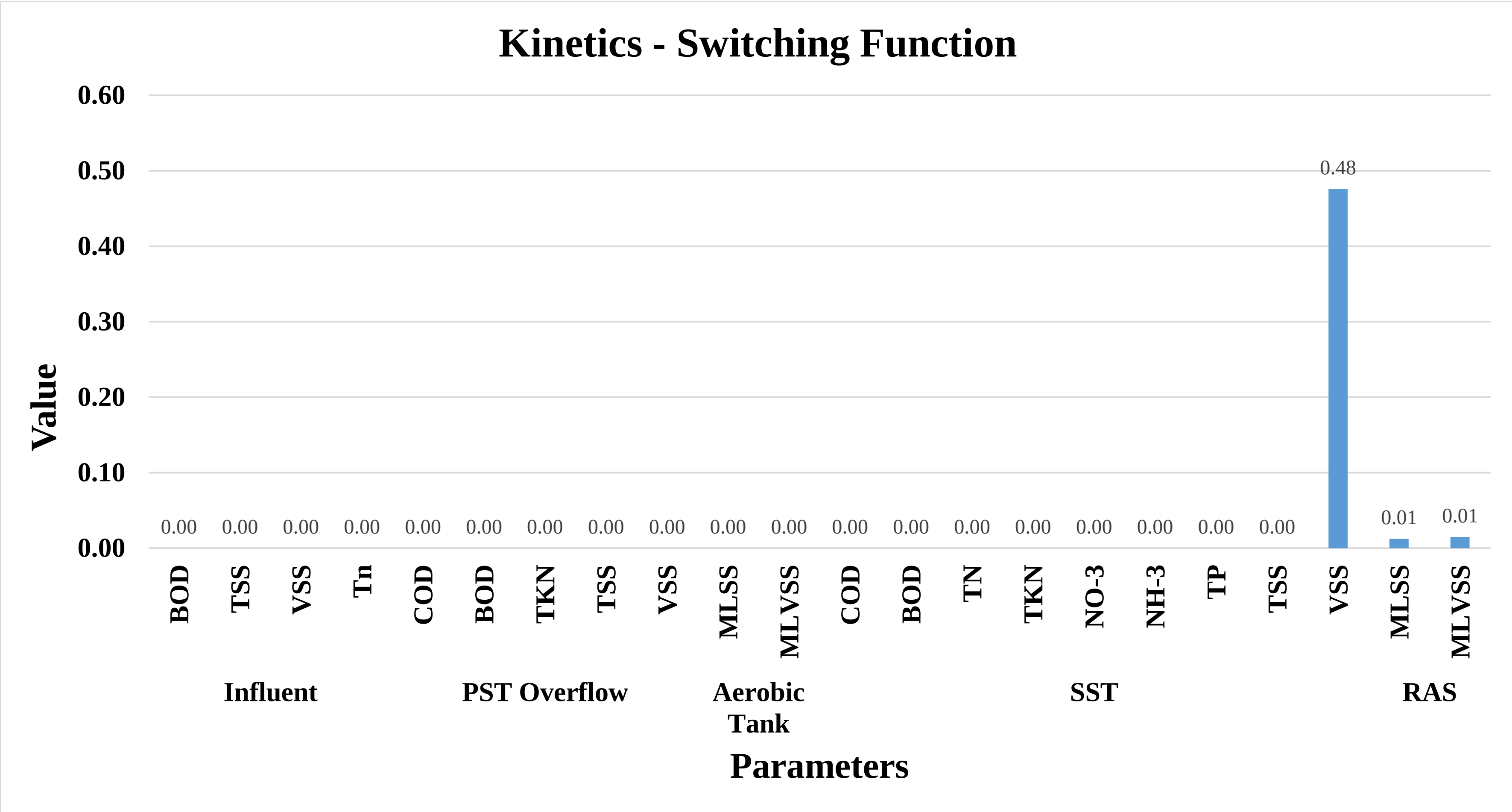

Figure E14: S_{ij} Value for NH_3 Nutrient Half Saturation on Output Parameters at Different Stages

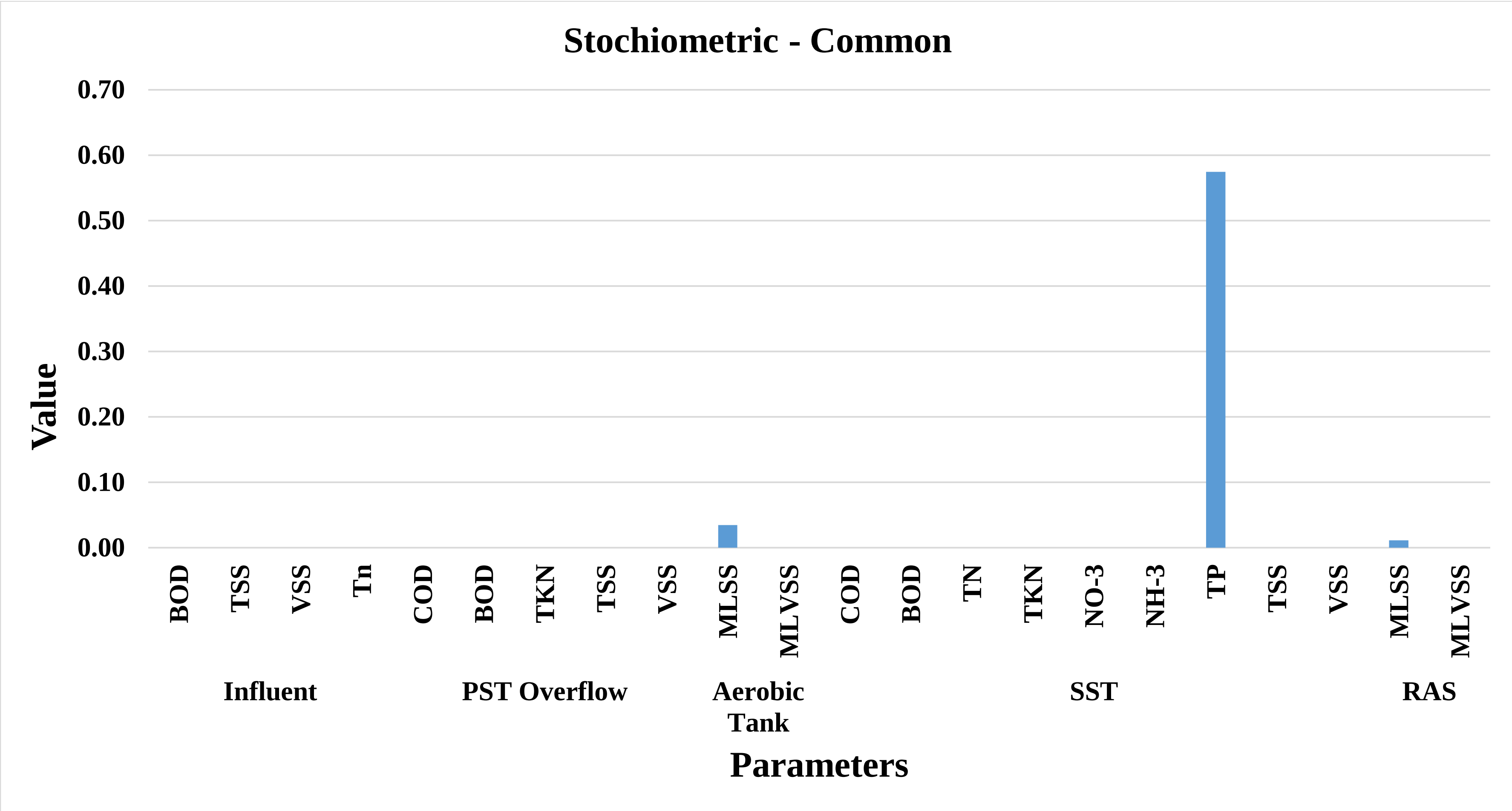

Figure E15: S_{ij} Value for P in Endogenous Residue on Output Parameters at Different Stages

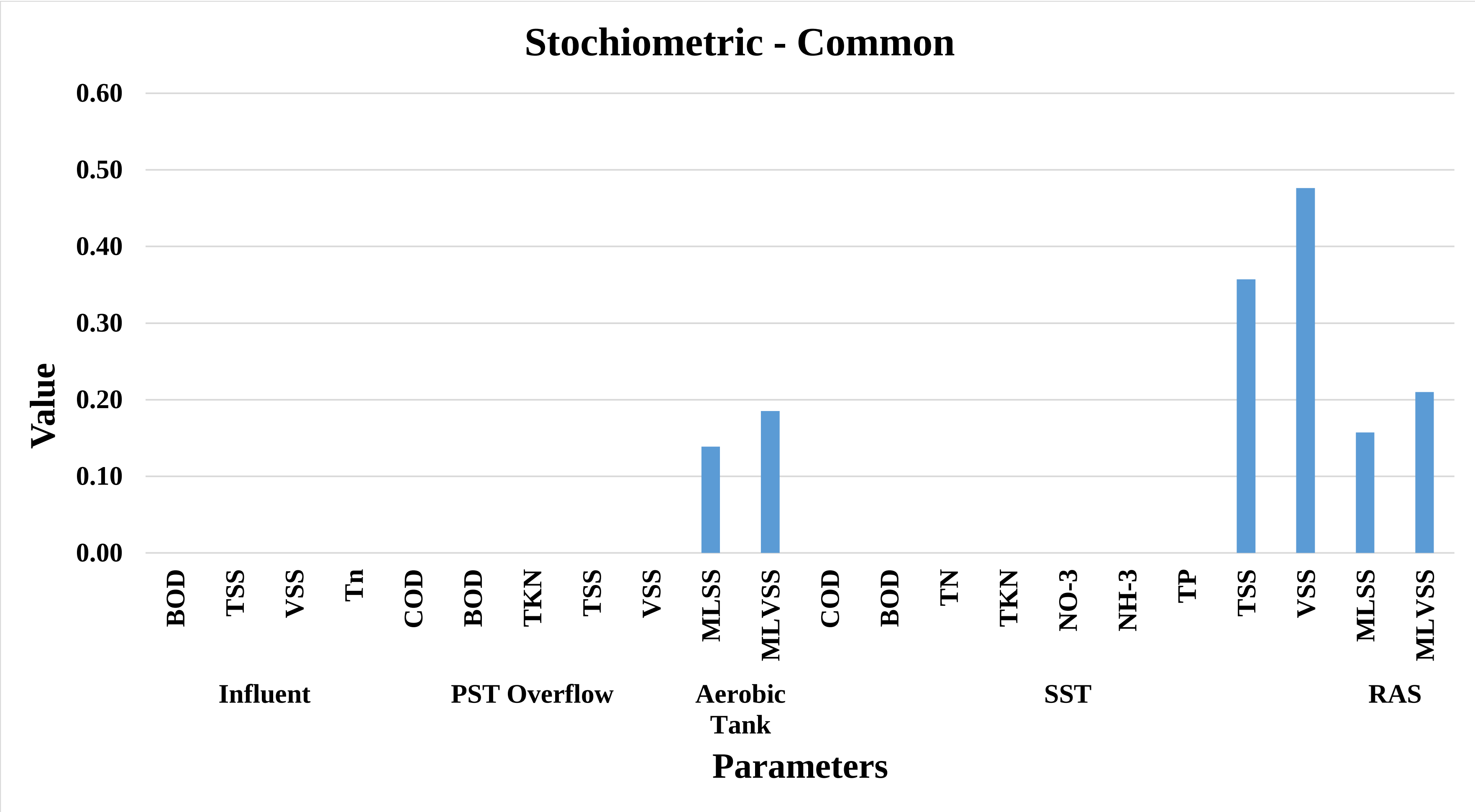

Figure E16: S_{ij} Value for Endogenous Residue COD: VSS Ratio on Output Parameters at Different Stages

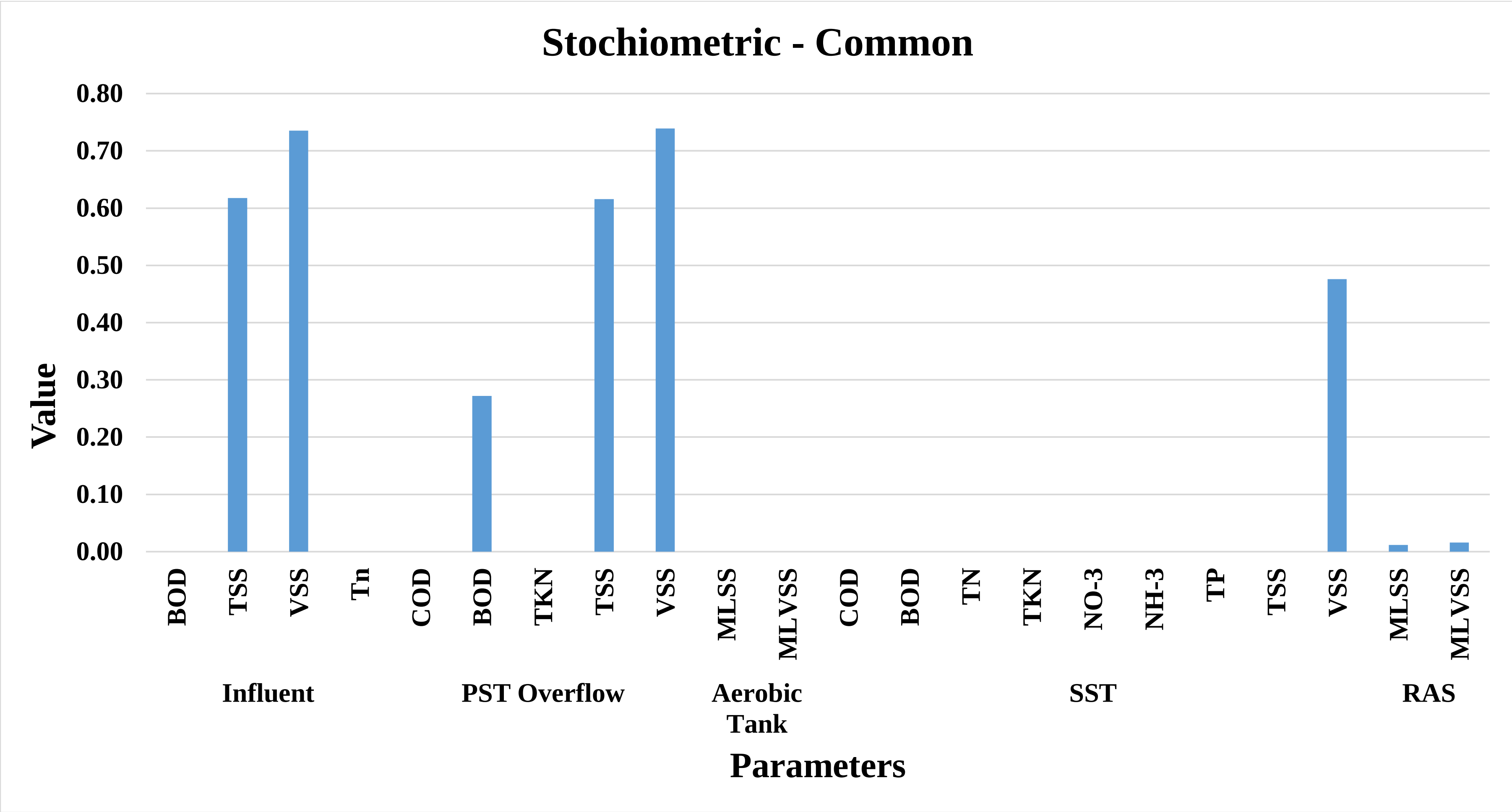

Figure E17: S_{ij} Value for Particulate Substrate COD: VSS Ratio on Output Parameters at Different Stages

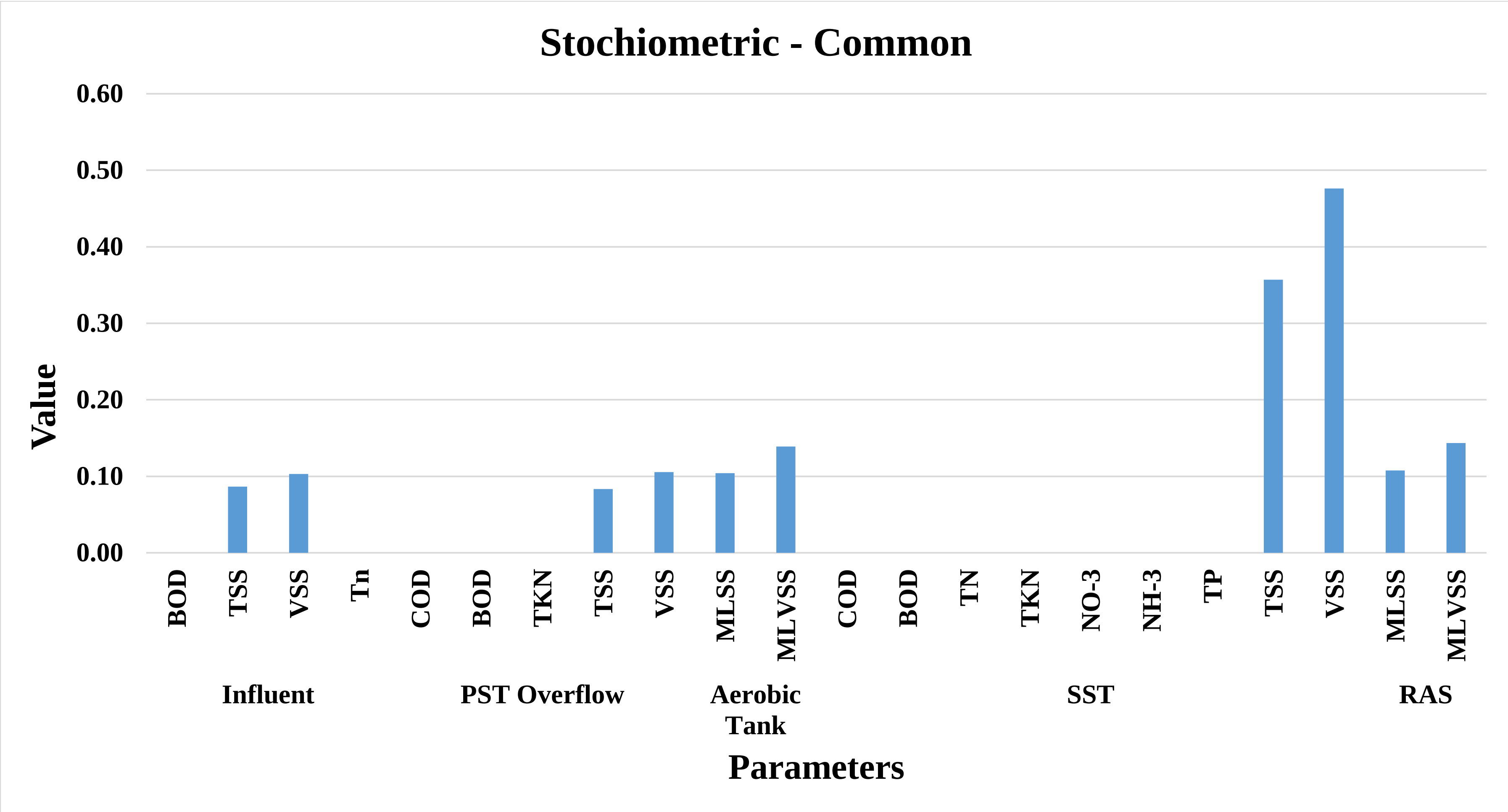

Figure E18: S_{ij} Value for Particulate Inert COD: VSS Ratio on Output Parameters at Different Stages

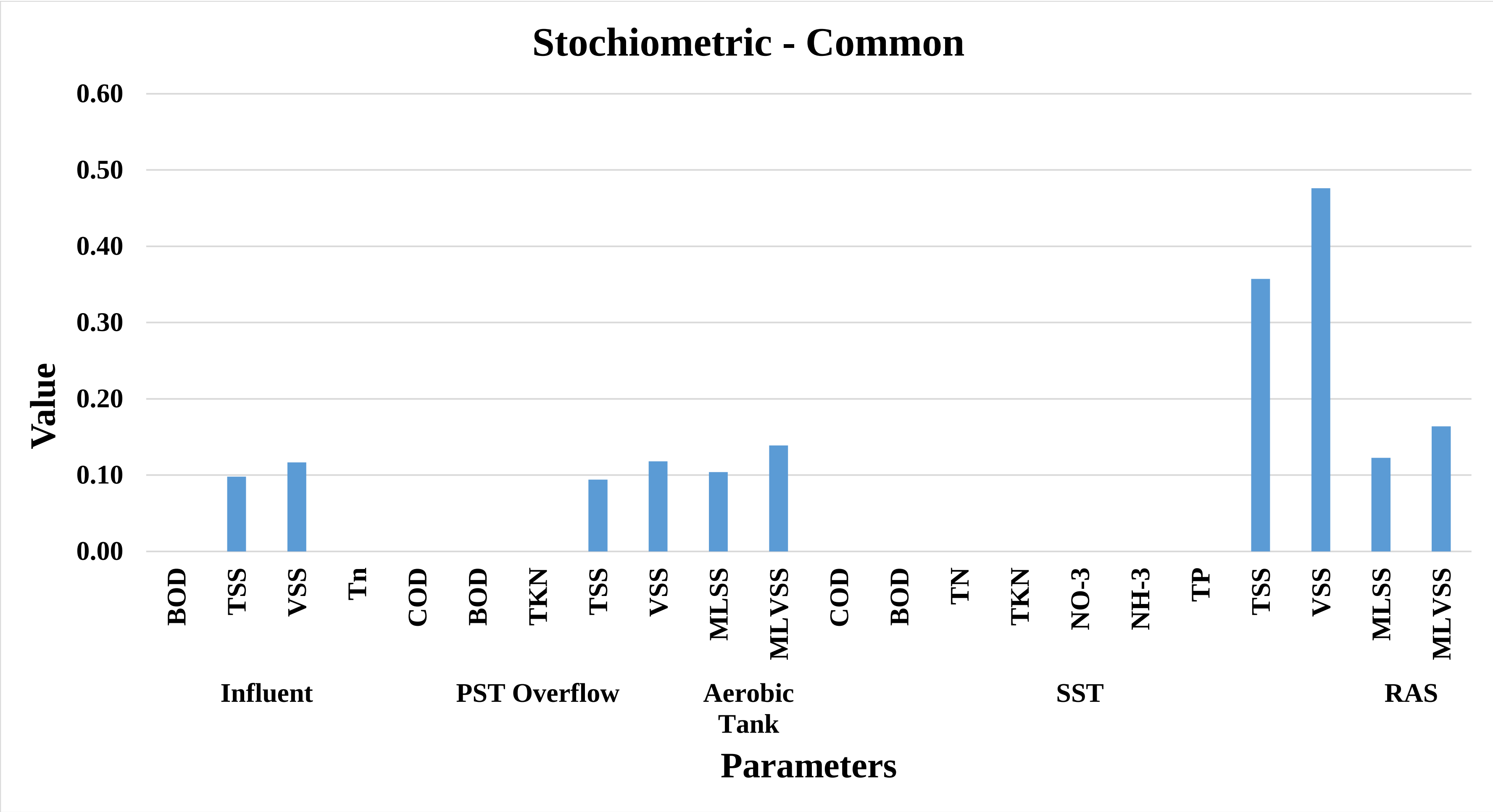

Figure E19: S_{ij} Value for Cellulose COD: VSS Ratio on Output Parameters at Different Stages

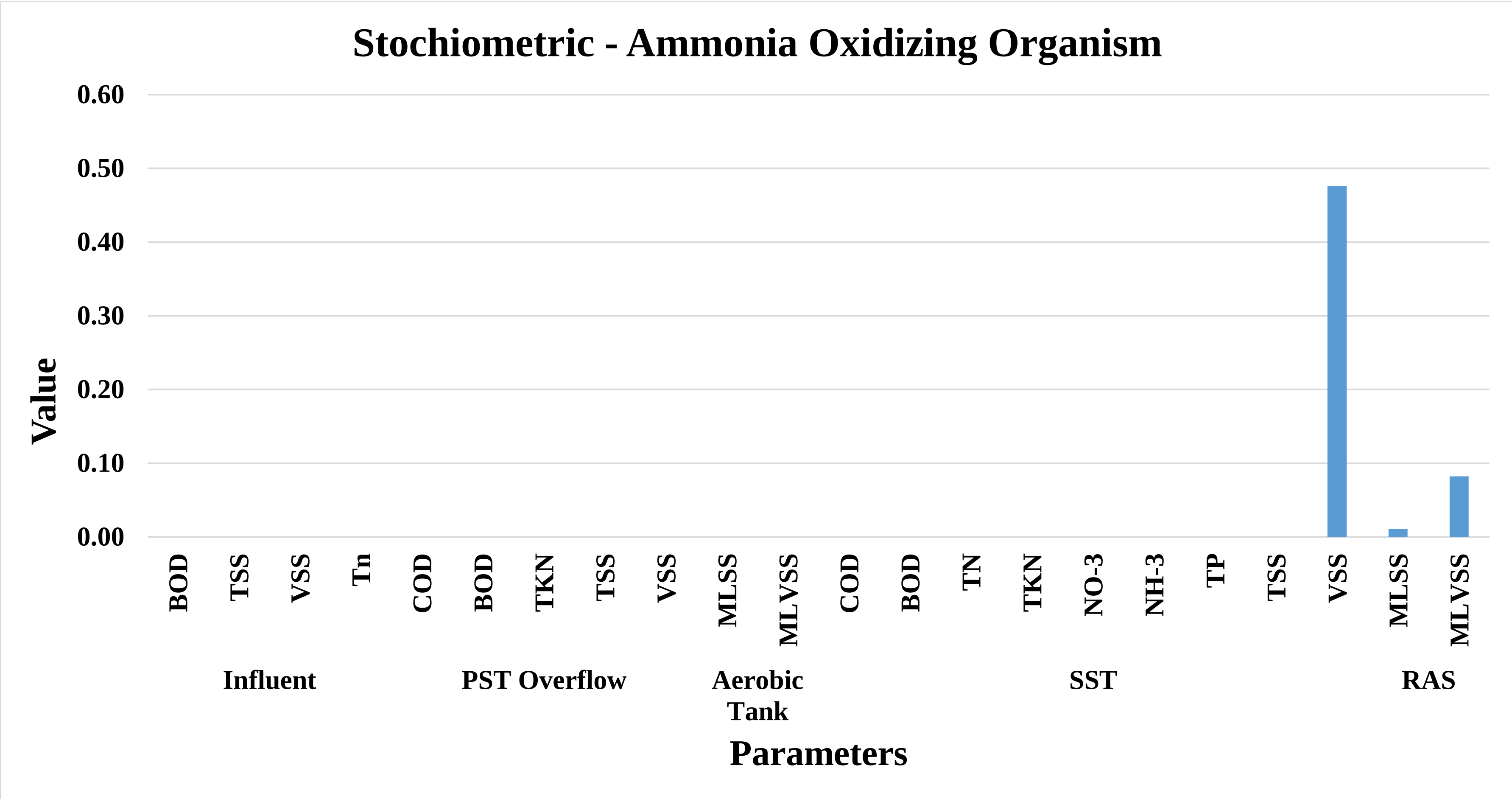

Figure E20: S_{ij} Value for COD: VSS Ratio on Output Parameters at Different Stages

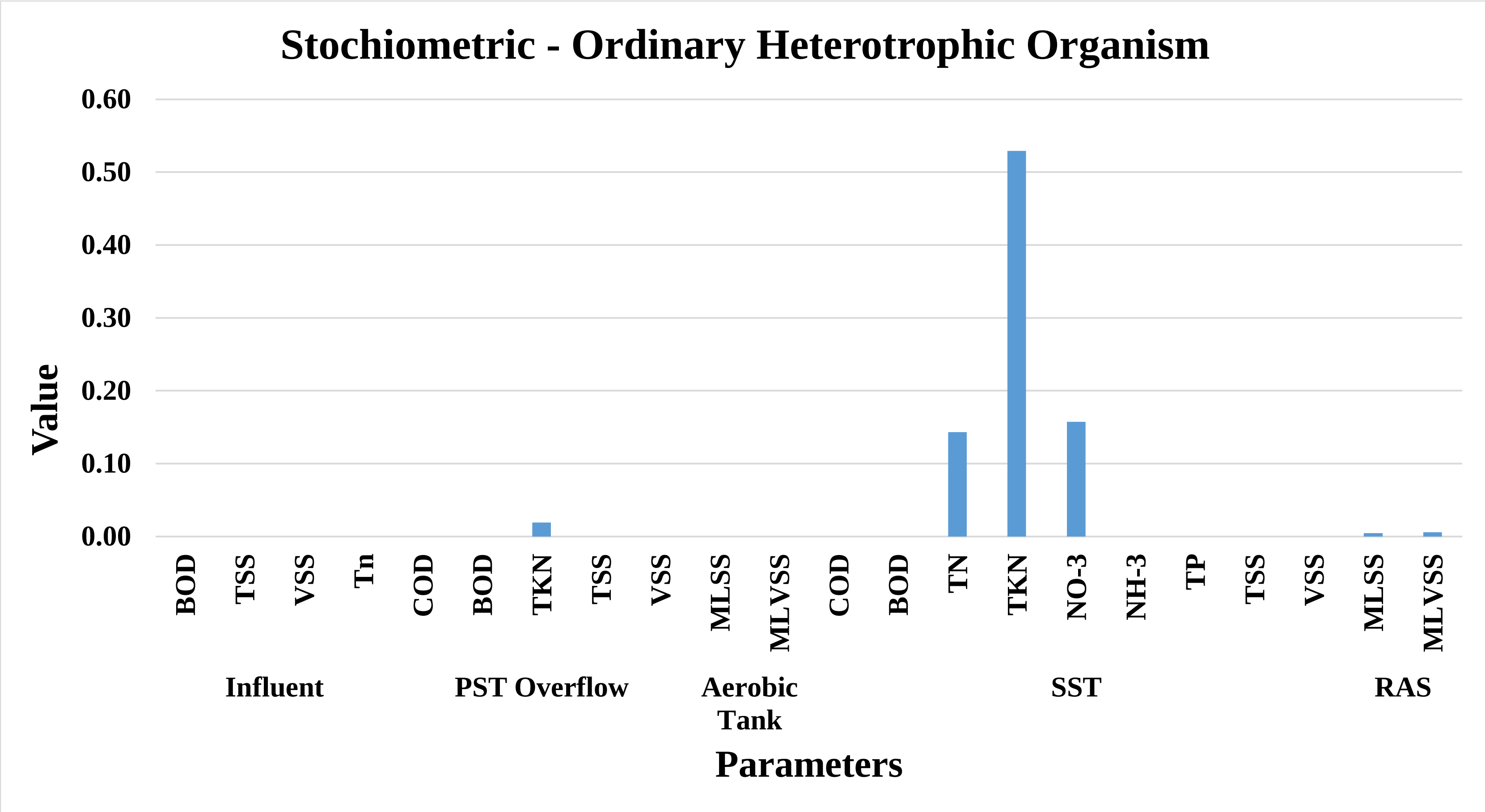

Figure E21: S_{ij} Value for N in Biomass on Output Parameters at Different Stages

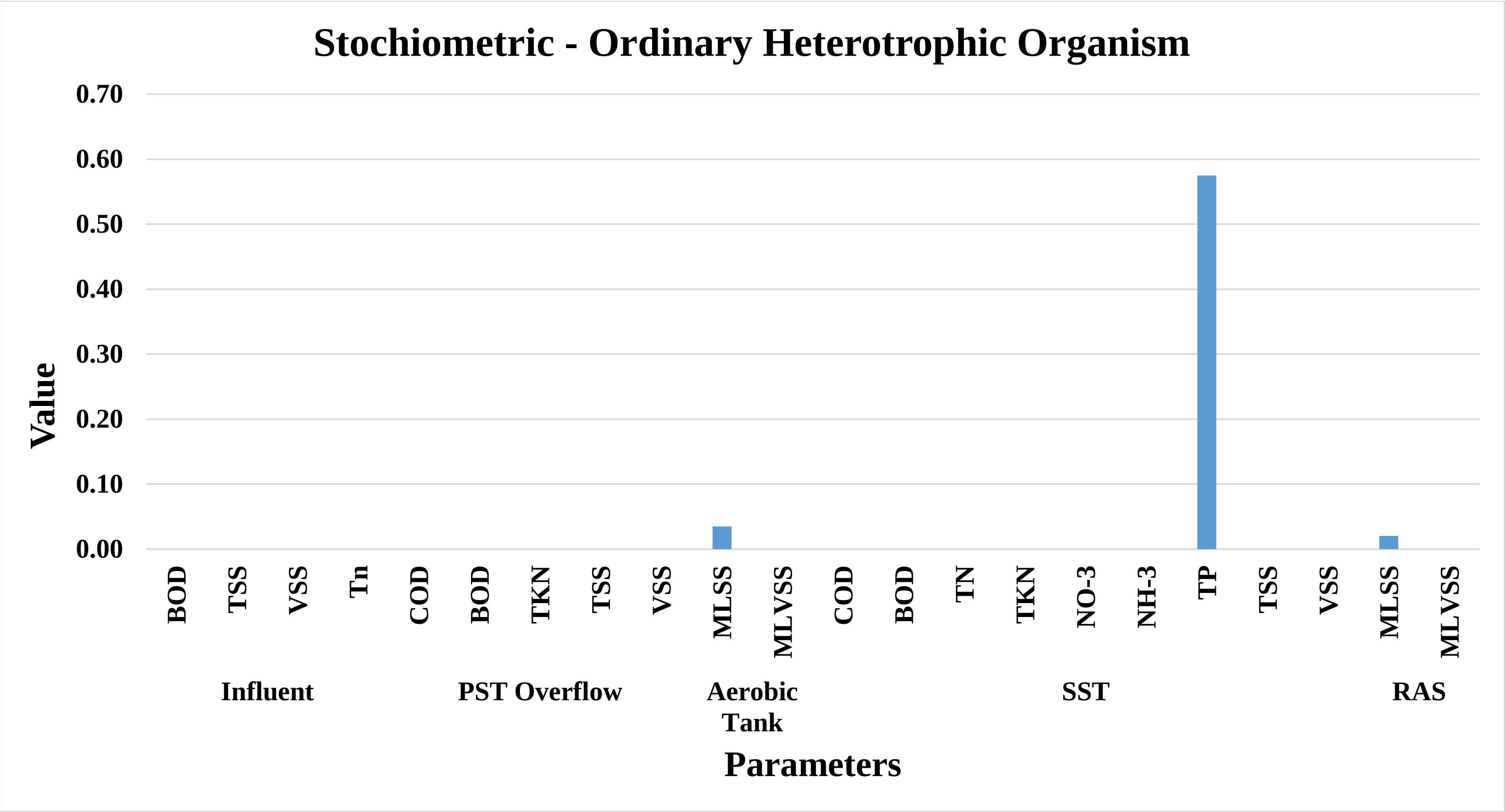

Figure E22: S_{ij} Value for P in Biomass on Output Parameters at Different Stages

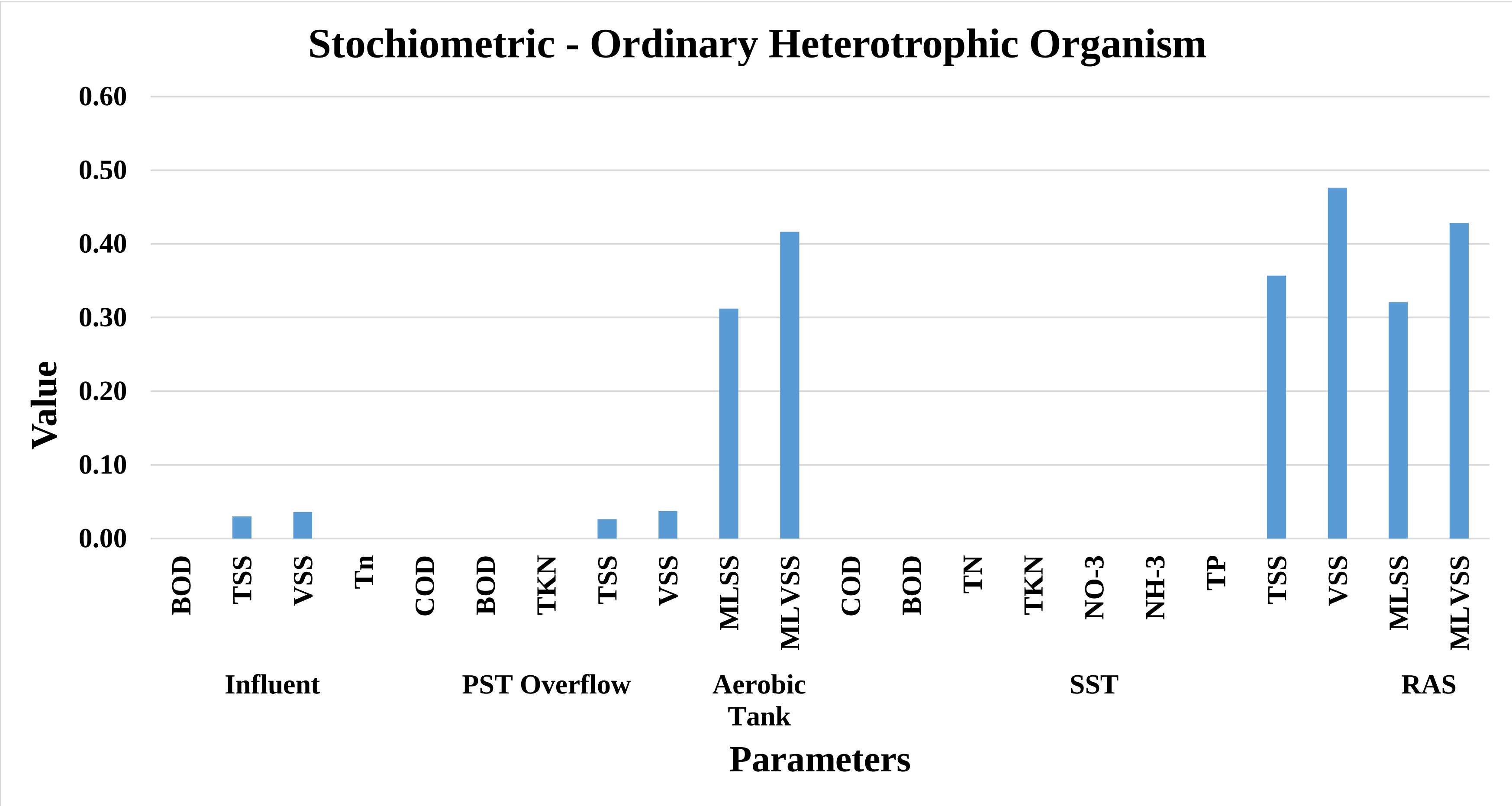

Figure E23: S_{ij} Value for COD: VSS Ratio on Output Parameters at Different Stages

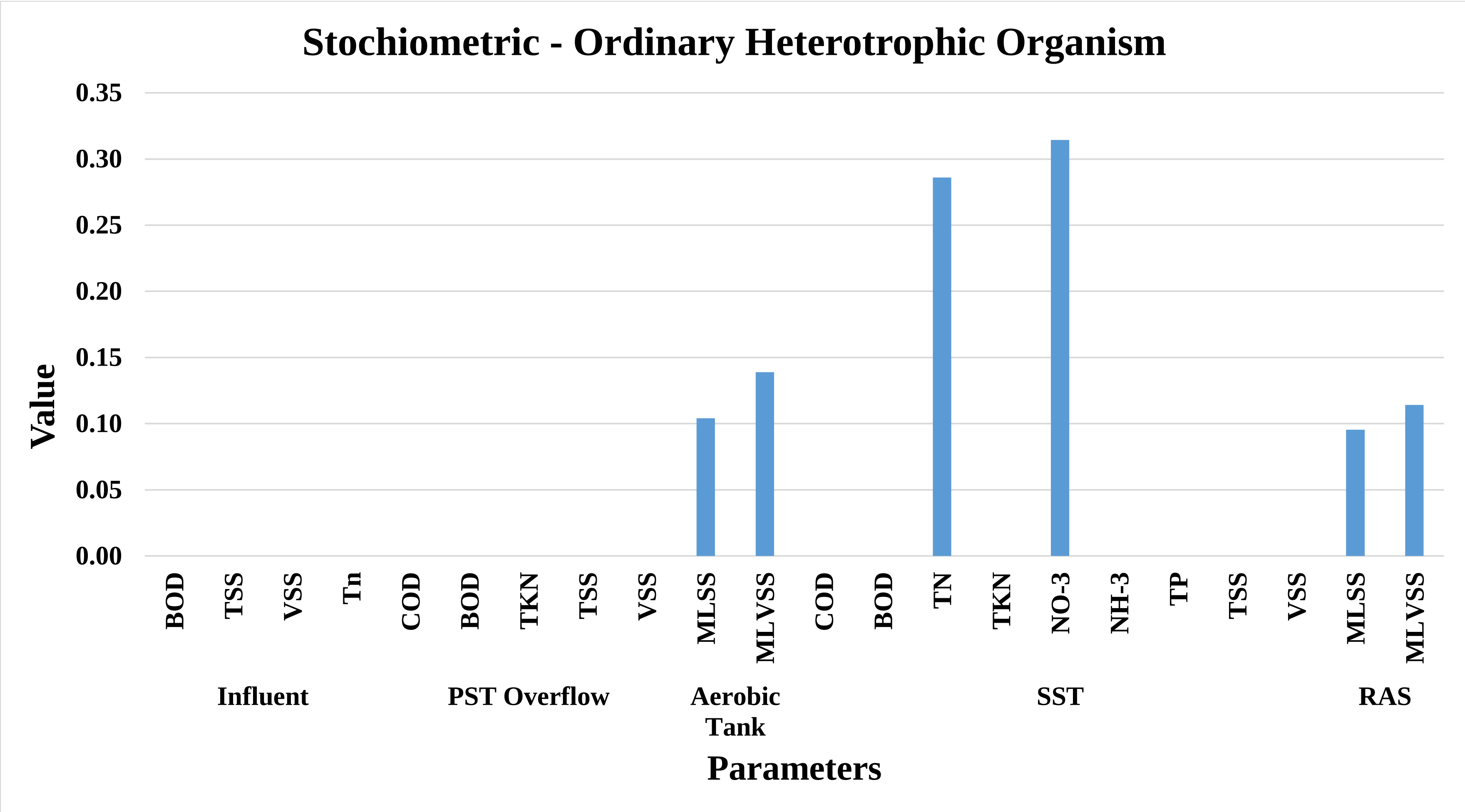

Figure E24: S_{ij} Value for Anoxic Yield on Output Parameter at Different Stages