Efficient organic carbon utilization for combined nutrient removal and biogas production in hybrid biofilm activated sludge process

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ABSTRACT

Moving bed biofilm technology is a successful and promising biological treatment process considered for eco-friendly management of wastewaters. In this study, a hybrid moving bed biofilm pilot plant was operated and obtained results were compared with simulation results of two biological processes: a conventional biological nutrient (CBNR) system and a hybrid moving bed biofilm reactor (HAS-MBBR). Both systems were designed and simulated with an influent flowrate of 100,000 m^3/day. Pilot-scale application and simulation outputs indicated that HAS-MBBR system requires 40% less reactor volume than the CBNR system. Pilot plant and simulation studies emphasized the efficacy of organic carbon entrapment (87%) with HAS-MBBR to improve the biogas production potential in anaerobic systems. Investigation of the economic aspects indicated that HAS-MBBR system has a lower operating cost (i.e., 9% less air requirement, 39% less mixing energy requirement, no need for internal recirculation pumps, and produces more energy by anaerobic digestion) then the CBNR. Therefore, the HAS-MBBR system was more effective and attractive option for the treatment of municipal wastewater in terms of capital expenditures (CAPEX) and operational expenditures (OPEX) within the circular economy.

Keywords: Organic carbon diversion, hybrid activated sludge configuration, moving bed bioreactor, denitrification potential.

INTRODUCTION

Biological wastewater treatment processes are still developing technologies motivated by increasing wastewater treatment needs and goals. Increasing pressure on nutrient discharge had led to the new implementation of advanced biological treatment processes in recent years. Nutrient removal targeted biological treatment processes have the ultimate economical advantage, both in terms of capital investment and operating costs for municipal wastewater treatment. Organic carbon redirection for biogas production targeting energy recovery from waste has become the ultimate goal for sustainable wastewater management [1]. However, the overall sustainability of conventional single sludge activated sludge systems (CAS) do not satisfy both nutrient removal with effective use of organic carbon. Besides that, energy and land requirements also discourage the utilization of conventional plant designs especially in crowded agglomerations.

An important drawback for conventional activated sludge (CAS) process is that around 60% of the operating cost is attributable to the energy consumption [2]. Conventional treatment systems are extremely energy demanding systems and increases in energy costs will remarkably increase the costs of these treatment systems. Additionally, conventional aerobic biological treatment processes produce large amount of waste that pose further cost requirement for disposal [3-4]. Waste sludge from different biological systems reveals that the biomass structure and concentration plays a major role in sludge digestion and biogas production. The present approach in wastewater treatment plants prefers the nutrient removal system coupled with old-fashioned primary sedimentation nearly 25-30% of inlet organic matter load could be directed to anaerobic digestion process. Although, bio-flocculation capability of activated sludge favours the organic carbon capture for biogas production at low sludge age conditions, high rate system namely the “A-Process” still suffers from biomass separation in the final clarification phase [1,5-6]. Accordingly, there is still a demand for those systems’ improvement to be complied with strict discharge limits. In this respect, hybrid systems integrated with biofilm processes could serve as a viable alternative for cost-effective and reliable process upgrades.

Hybrid systems (i.e., moving bed bioreactor, MBBR, integrated fixed film activated sludge, IFAS), gained attention since they improved nutrient removal efficiency over conventional suspended activated sludge systems [7]. MBBR, IFAS systems can be used for a variety of reasons, including enhanced COD removal, enhanced nitrification, enhanced N removal, enhanced biological P removal, improved settling, reduced footprint, improved operational stability [8]. MBBR was introduced for biological treatment of different types of wastewater, and it has been successfully used in treating domestic and industrial wastewater with recalcitrant character [9-10]. MBBR

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is a suitable system for treated wastewater reuse [11]. Hybrid systems are simple to operate, compact, easily retrofitted with a small footprint, low capital cost, and stable under load variations. MBBR technology may easily facilitate the operation of the system with no additional construction and can be integrated in a combined system of wastewater treatment, enabling the development of a specific attached biomass on the carriers [12]. Different commercial carrier technologies (i.e., Bio-2, Linpor®, Captor®, HybasTM) have been integrated with activated sludge processes namely called as Integrated Fixed Activated Sludge IFAS systems [13].

Hybrid systems are advantageous through entrapping and diverting organic matter before oxidizing it in subsequent aerobic phases [14-15]. The process efficacy in the hybrid systems allow working at low sludge retention times holding the biomass on the carrier for longer times which could also let to efficient biogas recovery. The comparison of the three sludge sources originating from suspended biomass (i.e., activated sludge process) and attached biomass (i.e., moving bed bioreactor (MBBR), and packed bed biofilm (PBBR) reactors indicated that the attached growth processes were more manageable in aerobic digestion process as they would create a small footprint due to the lower hydraulic retention time (HRT) [16]. Efficient nutrient as well as specific pollutants removal performances were obtained experimentally in the literature with hybrid activated sludge systems [10,17-18].

In the present study, a plant-wide simulation approach has been tested to investigate the nutrient removal efficiency and biogas production potential by applying organic carbon redirection in a Hybrid Activated Sludge-Moving Bed Bio-Reactor (HAS-MBBR) system in comparison to Conventional Biological Nutrient Removal (CBNR) system, by means of the follow-up of our previous study [14] and patented technology [19]. The capital expenditures (CAPEX) and 15 years of operational expenditures (OPEX) for the proposed treatment configuration was also evaluated. Within the scope of this study it is proposed an innovative, cost-effective, sustainable and integrated solution to resolve the design and operational problems related with wastewater treatment surrounded by the zero discharge and circular economy approach.

MATERIAL AND METHODS

Pilot Studies

The objective of the pilot study was to illustrate organic carbon diversion from raw sewage that is used for nitrogen removal and enhanced biological phosphorus removal processes without requiring internal recirculation for nitrate. The hybrid biofilm pilot plant was located at the headwork of a full-scale municipal wastewater treatment plant in Istanbul. Raw wastewater (7 m^3/day) is introduced to anaerobic mixing tank followed by a reactive primary sedimentation tank [14]. The return sludge (RAS) and influent wastewater are mixed in the anaerobic tank (1.1 m^3) in which the soluble organic matter is pre- stored and particulate organic matter is adsorbed by active biomass. The mixture is sent to the primary clarifier for separation of organic carbon. Nitrogen rich supernatant is directed to biofilm nitrification tank (MBBR) (1.4 m^3). Ammonia (NH_4-N) is completely oxidized to nitrate in biofilm tank. Organic carbon rich sludge stream and nitrified stream are further mixed in denitrification tank (1.0 m^3). Post-aerobic tank is placed to eliminate remaining COD and nitrogen gas (N_2) prior to final clarification. The return activated sludge is sent back to anaerobic tank for mixing with raw influent. MBBR biofilm media was used in biofilm reactor. Dissolved oxygen concentration in MBBR tank is kept around 2-3 mg/L by means of 9″Aquaflex, EPDM diffusers bubbled with 200 Nm^3/h centrifuge blower. The mixing in anaerobic and anoxic tanks were provided by vertical mixers.

Process Configurations and Simulation

The patented hybrid process [19] used in this study consists of 2-sludge system (Figure 1a). This hybrid process configuration enables to integrate nutrient removal (nitrification-denitrification and phosphorus removal) through carbon diversion by bio-flocculation and primary sludge fermentation. The separation of organic carbon and nutrients at the head of the system adds promising advantages over single sludge systems. A distinguishing feature of the first segment is that the bio-flocculation property of high rate activated sludge is used to divert 85-90% of organic matter from the main stream without aeration. Different from high rate “A” system [1], the raw influent is mixed with a fraction of return activated sludge followed by intermediate reactive clarifier [14-15,20]. In this manner, no soluble biodegradable COD required for EBPR is consumed, but internally stored by phosphorus accumulating organisms (PAOs). The following process segment includes the biofilm reactor equipped with MBBR system providing that (low) nitrification capacity is no more a limiting factor for sizing the overall bioreactor. Ammonia rich supernatant after reactive (intermediate) clarifier is introduced to MBBR reactor for converting NH_4-N to NO_X form. However, the phosphorus passes through the biofilm (MBBR) reactor and is introduced to subsequent anoxic reactor where the effluent of biofilm (MBBR) is mixed with settled organics rich sludge from reactive clarification phase. The final aeration phase must oxidize remaining soluble COD with flushing the N_2 gas for efficient clarification before discharge. Compared to single sludge systems, nitrate recirculation is not required for denitrification, since the proposed configuration (HAS-MBBR) is operated as post denitrification. The excess sludge can be withdrawn from the sludge streams of reactive primary and/or final clarifier to be processed in anaerobic digestion. Figure 1 presents the model configuration of the two systems; the HAS-MBBR (a) and Conventional BNR (5-Stage Bardenpho) system (b) integrated with anaerobic sludge digestion. The conventional system designed with a RAS denitrification reactor to deplete nitrate before Bio-P reactor. Therefore, the RAS denitrification unit has to be placed in both configurations for the accurate comparison of the EBPR capacity of the two systems [21].

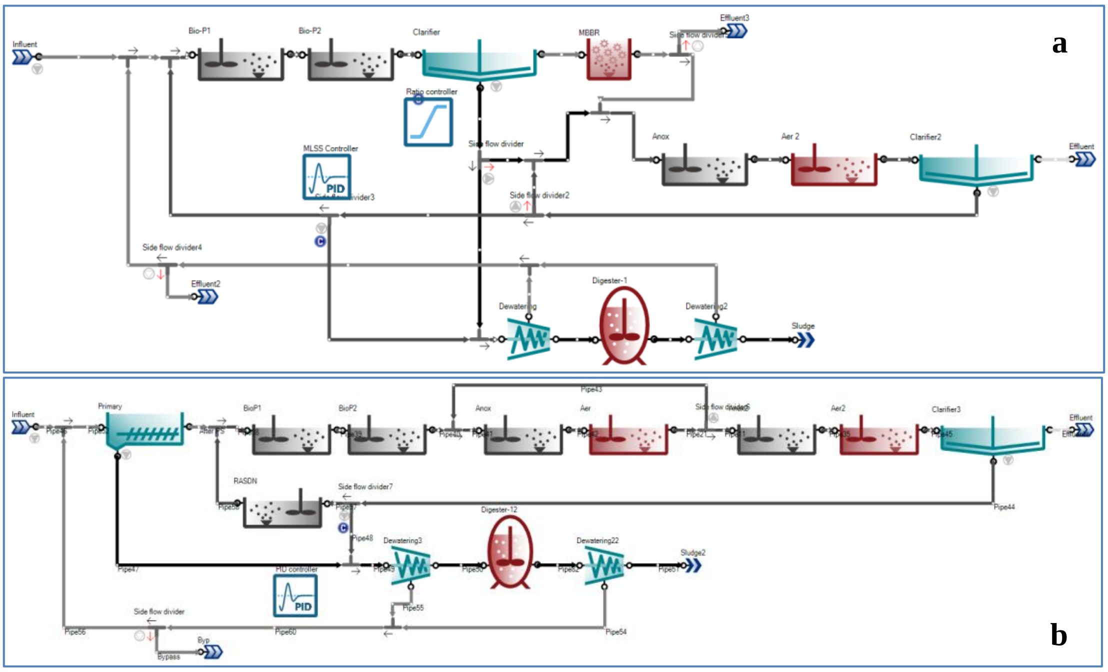

Figure 1. Sumo layouts for (a) HAS-MBBR (b) CBNR

Model simulation and design of both systems were carried out using SUMO® software [22] considering the influent flowrate of 100,000 m^3/day (26.4 MGD). The encrypted biofilm model in SUMO® software was used to simulate processes in a plant-wide approach including biofilm system. The fixed biofilm model encrypted in SUMO consists of (*i*) diffusion of soluble/colloidal compounds (*ii*) displacement of particulate states through the biofilm layers, (*iii*) attachment of particulate states from the bulk to the biofilm surface layer and (*iv*) internal transfer of particulates between the granule layers, (*v*) detachment of particulate components from the outer layer of the biofilm. The kinetic model used in this study was SUMO1 taking into account single step nitrification-denitrification processes including EBPR processes.

Shortly, the nitrate nitrogen (NO_3-N) can be used as electron acceptor by ordinary heterotrophic organisms (OHO), glycogen accumulating organisms (GAO), PAOs. The OHO and PAOs can ferment readily biodegradable COD, S_B into VFA. The separation of biomass is modelled according to 3-exponential function settling model available in SUMO. The wastewater characteristics for Istanbul is adopted for comparison of configurations. The average total COD and TKN concentration was measured to be 610 and 55 mg/L respectively. In simulation study the COD fractions considered for municipal wastewater are summarized in Table 1.

Table 1. COD fractions for referred municipal wastewater

Parameter	Concentration, mg/L	Fraction, % of C_T
Total COD, C_T	610	
Soluble COD, S_T	180	30
Soluble inert COD, S_I	35	5
Readily biodegradable COD*, S_B	125	20
Slowly biodegradable COD, X_B	370	60
Particulate inert COD, X_I	60	15

*Total VFA: 70 mgCOD/L

The kinetic and stoichiometric parameters obtained for İstanbul municipal wastewaters were used in this study [14,23]. The maximum growth rate of nitrifiers were estimated to be 0.55 day^{-1} at 20°C previously reported by Güneş et al. [14]. In addition, the maximum hydrolysis rate (k_h) was experimentally determined as 1.2 day^{-1} comparably lower than its default suggested by Henze et al. [24]. The design parameters including reactor volumes, main equipment capacities were compared with effluent qualities of both systems.

Cost Analysis

The cost of proposed HAS-MBBR system was analyzed in terms of capital (CAPEX) and operating expenditures (OPEX) in comparison to the CBNR systems. The comparison of CAPEX depends merely on civil and electromechanical works at construction phase. Land expropriation, excavation-foundation costs, taxes, and other levies are excluded from the estimated investment costs. OPEX considers the energy consumption due to aeration, mixing, internal recirculation and other processing units and energy production from biogas that was produced in anaerobic digesters. It should be noted that personnel and equipment maintenance costs were not considered in OPEX calculations. Treatment plant configurations were compared based on investment (CAPEX) and 15 years of operation covering a reasonable economical life of mechanical equipment. Total energy produced (Heat and Electricity) with biogas from mesophilic anaerobic digestion (MAD) was also considered as a revenue in the operation. Construction and installation unit prices promulgated by Ministry of Environment and Urban Planning of Turkey [25] were used in cost calculations.

RESULTS AND DISCUSSION

Pilot Plant Operation and Mass Balances

The performance of the pilot plant together with the calculated mass balances were given in Figure 2. The results presented for the pilot plant operation belong to the summer season (20°C). The pilot plant receives wastewater with influent COD and TKN concentrations of 534 mg/L and 72 mgN/L, respectively. The effluent COD concentration after the primary reactive clarifier was measured as 71 mg/L, indicating that about 87% of influent COD could be diverted via bio-flocculation and gravity sedimentation before biofilm nitrification. The soluble COD concentration was reduced from 226 to 56 mg/L during mixing and sedimentation step. The complete nitrification was achieved in the biofilm system (MBBR) leading to an effluent NH_4-N concentration of 0.5 mg/L. According to the effluent quality evaluation results, TN and TP removal efficiencies were obtained as 86% and 89%, respectively. The pilot plant operation shows that the HAS-MBBR system is able to divert carbon from the main stream to be used as carbon source for post denitrification. The advantage of the tested novel HAS-MBBR system is that soluble COD is not consumed as in the high-rate activated sludge systems (HRAS; A-System) that is used for enhanced biological phosphorus removal (EBPR).

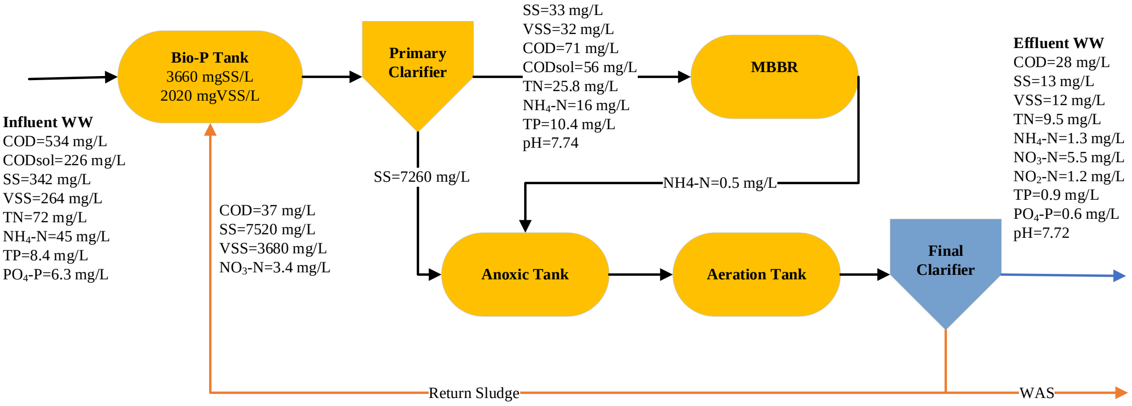

Figure 2. Pilot plant layout and the mass balance obtained in the HAS-MBBR configuration

Simulation Studies

The process design of HAS-MBBR and CBNR configurations were performed considering the EU discharge regulations (EEC, 1991). Accordingly, the effluent TN and TP limits were accepted as 10 mgN/L and 1 mgP/L, respectively. Based on the simulation calculations, the required volumes of the units for proposed HAS-MBBR system (Figure 1a) and CBNR (5-stage Bardenpho system) (Figure 1b) were presented in Table 2. CBNR system required minimum 70,000 m^3 aeration volume to achieve nitrification process (@15 °C). On the other hand, the HAS-MBBR system nitrified at 60% filling ratio and 500 m^2/m^3 of specific media surface area. This corresponds to specific nitrogen loading of 0.84 gN/m^2/day, selected for the attainment of nitrification. The nitrification rate remains at the safe limit according to an experimental study conducted by Forrest et al. [26] where the nitrification rate of biofilm was reported around 1.5 gN/m^2/day at low organic loading rate. Rusten et al. [27] reported well nitrified effluents where organic carbon load into the biofilm reactor is kept at the minimum. The post aerobic system in the hybrid system is selected as 18% of the total bioreactor volume which is, in agreement with Hu et al. [15] for external post denitrification system integrated with an aerobic trickling filter. The nitrate utilization rate in anoxic reactor of the hybrid system was simulated to be 40% higher than that of a conventional BNR system. Therefore, the volume requirement of anoxic reactor in the proposed hybrid configuration is about 44% smaller compared to the conventional system (Table 2). This gives a competitive advantage to the proposed HAS-MBBR system. Total reactor volumes for hybrid and conventional system were calculated as 62,000 m^3 and 102,000 m^3, respectively, providing nearly 40% reduction in the total volume. Land occupation is one of the bottlenecks for the construction and design of treatment plants [28]. Therefore, improvements in wastewater treatment systems with efficient nutrient removal (TN, TP) and less land occupation are promising achievements for the further implementations. On the other hand, the overall clarifier surface area requirement is relatively higher for the hybrid system since the RAS recirculation back to the Bio-P tank requires larger surface area of primary reactive clarifier.

Table 2. Dimensions and required installations for treatment plant units (@15 °C)

Process Unit	**Unit**	**Plant Configuration**	
		HAS-MBBR	**CBNR**
Bio-P volume	m^3	7,000	7,000
Aerobic reactor volume	m^3	11,000	70,000
Biofilm Reactor, MBBR	m^3	30,000	-
Anoxic reactor volume	m^3	14,000	25,000
Total reactor volume	m^3	62,000	102,000
Total biofilm area	m^2	8,250,000	-
Internal Recirculation	m^3/hour	-	12,500
Anaerobic Digester volume	m^3	12,000	12,000
Total clarifier surface area	m^2	20,000	17,000

The comparison of the effluent quality for HAS-MBBR and CBNR is summarized in Table 3. Both of the systems provided closer effluent quality regarding nutrient removal efficacies (i.e., TN and TP concentrations). The hybrid system provided relatively low effluent TN concentration. However, effluent ammonia (NH_4-N) concentration in the HAS-MBBR system (5.64 mgN/L) was slightly higher than the CBNR system (1.84 mgN/L). This was due to the ammonia carry over from the primary sludge directly fed to the anoxic reactor, by-passing the aerobic MBBR unit designed for nitrification. The CBNR has higher NO_3-N concentration since all influent is introduced to nitrification reactor (Figure 1b).

Table 3. Process comparison regarding steady state effluent quality

Parameter	**Unit**	**Influent**	**Effluent Quality**	
			HAS-MBBR	**CBNR**
Total chemical oxygen demand	mgO_2/L	610	40	40
Total nitrogen	mgN/L	55	7.94	9.44
Total ammonia (NH_4)	mgN/L	41	5.64	1.84
Nitrate (NO_3)	mgN/L	-	1.08	6.44
Total phosphorus	mgP/L	8	0.72	0.58
Orthophosphate (PO_4)	mgP/L	5	0.52	0.35

The dissolved oxygen concentration in HAS-MBBR was set to 3 mgO_2/L in the bulk for nitrification in MBBR system. Compared to conventional activated sludge systems, higher DO level in bulk is required for biofilm systems to penetrate oxygen through the biofilm [7]. Under average loading, air flowrate of 33,000 $Nm^3/hour$ was calculated for HAS-MBBR, whilst 80% airflow was diverted to MBBR module. The remaining portion of the air (20%) was provided to the final aeration (Figure 1a). The operational parameters of the systems are presented in Table 4. In total, the HAS-MBBR system yielded 9% lower air requirement compared to the CBNR system (Table 4). The simulation results showed that biogas production of hybrid system is 22% higher providing more energy obtained from sludge digestion. The expected increase in the carbon capture and biogas production in HAS-MBBR can be correlated with the operational sludge character [29]. The solid retention time of mixed liquor (excluding MBBR) at HAS-MBBR was around 3.5 days. On the other hand, solid retention time of CBNR was 18 days. Furthermore, HAS-MBBR system consumes 35% less overall electricity than the CBNR system. Finally, 55% reduction in mixing energy requirement was also another advantage due to smaller volume of the reactors (unit mixing energy: 5 W/m^3).

Table 4. Operational Parameters for hybrid AS-MBBR and CBNR systems

Parameter	Unit	Configuration	
		HAS-MBBR	CBNR
Average air requirement, Q_{Air}	$Nm^3/hour$	33000	36000
Mixing energy requirement*	kWh/day	2500	3850
Daily biogas production	m^3/day	8900	7000
Solids retention time	days	3.5	18

*based on unit mixing intensity of 5 W/m^3

Cost Analysis for System Configurations

The economic assessment of capital expenditures (CAPEX) and operational expenditures (OPEX) for two process configurations are determined comparatively. The calculation of CAPEX depends merely on civil and electromechanical works at construction phase. Land expropriation, excavation-foundation costs, taxes, and other levies are excluded from the estimated investment costs. The comparative picture of CAPEX for the two systems is illustrated in Figure 3. HAS-MBBR has lower ($27.9M) CAPEX compared to the CBNR ($30.0M) system, which corresponds to a CAPEX advantage of about 7%. The cost of carrier media ($4.5M, based on the information taken from the supplier) for MBBR is a significant cost component which resembles to about 16% of the CAPEX. Although the CAPEX advantage of HAS-MBBR over CBNR is quite low ($2.1M), this amount can be significant for the developing countries.

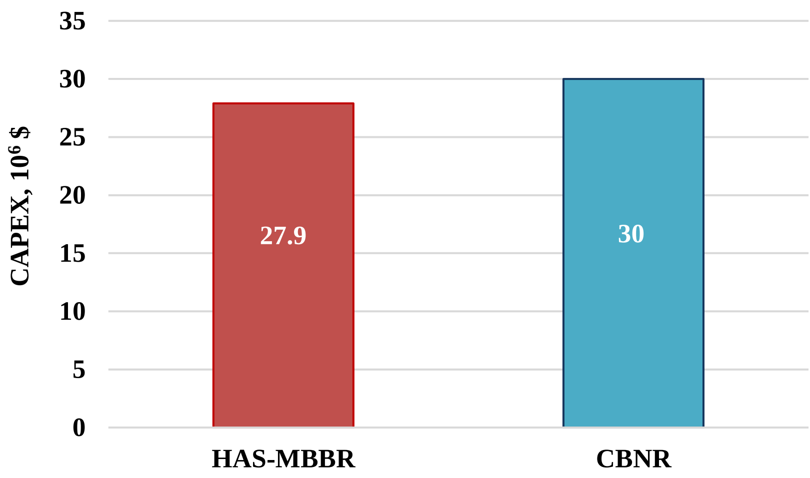

Figure 3. Capital expenditures (CAPEX) for configurations

OPEX estimation considers the energy consumption due to aeration, mixing, internal recirculation and other processing units and energy production from biogas that was produced in anaerobic digesters for proposed HAS-MBBR and CBNR systems (Table 5 and 6). Comparative energy budget for the proposed HAS-MBBR and CBNR is visualized in Figure 4.

Table 5. HAS-MBBR system operational cost for wastewater treatment

Component	**Unit**	**Amount**	**Unit**	**Unit price**	$/ m^3	**Total Price** $/*day*
(a) Consumption						
Aeration	kW/m^3	0.238	$/kw	0.1	0.024	2376
Mixing*	kW/m^3	0.030	$/kw	0.1	0.003	298
Internal Recirculation	kW/m^3	NA	$/kw	NA	NA	NA
Other Units	kW/m^3	0.208	$/kw	0.1	0.021	2080
(b) Production						
Electricity from biogas	kW/m^3	0.230	$/kw	0.1	0.023	2301
Average Electricity Usage	***kW***/m^3	***0.245***	***$/kw***	***0.1***	***0.025***	***2453***
(c) Environmental tax					$/**kg**	
Sludge Disposal	ton/d	38.89	$/ton	3	0.077	117
TOTAL						***2570***

Table 6. CBNR system operational cost for wastewater treatment

Component	**Unit**	**Amount**	**Unit**	**Unit price**	**$/$m^3$**	**Total Price** $/*day*
(a) Consumption						
Aeration	kW/m^3	0.259	$/kw	0.1	0.026	2592
Mixing	kW/m^3	0.049	$/kw	0.1	0.005	490
Internal Recirculation	kW/m^3	0.041	$/kw	0.1	0.004	409
Other Units	kW/m^3	0.208	$/kw	0.1	0.021	2080
(b) Production						
Electricity from biogas	kW/m^3	0.181	$/kw	0.1	0.018	1810
Average Electricity Usage	***kW/m^3***	***0.376***	***$/kw***	***0.1***	***0.038***	***3761***
(c) Environmental tax					$/**kg**	
Sludge Disposal	ton/d	38.89	$/ton	3	0.077	117
TOTAL						***3878***

*based on unit mixing intensity of 5 W/m^3

**CHP conversion efficiency 55%

***Dry solids content of sludge 90%

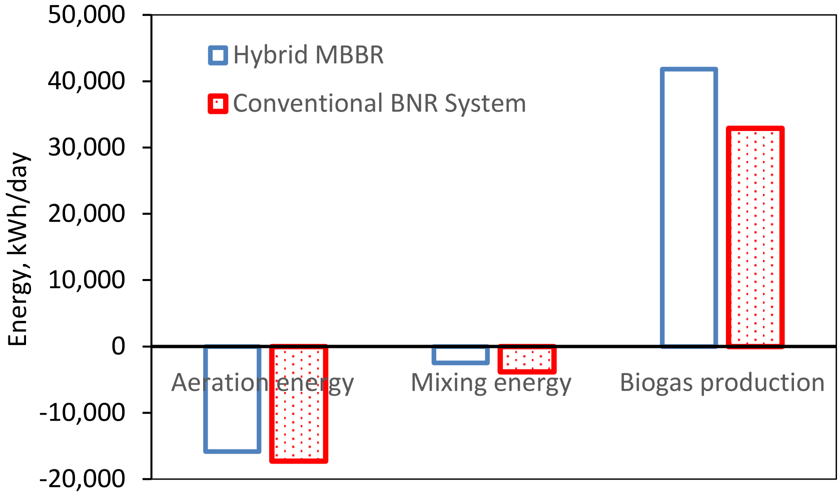

Figure 4. Energy budget for HAS-MBBR and CBNR

In terms of energy usage, the CBNR system had the highest expense (0.038 $/m^3) since the process needs more electricity to run and sustain. Due to more energy input from biogas, lower air and mixing requirements, and no internal recirculation, the HAS-MBBR system has the lowest overall consumption cost (0.025 $/m^3). Apparently, the energy requirement for CBNR system based on the 15 years of OPEX calculation ($7,1M) is higher than HAS-MBBR system. Increased biogas generation (22%) in HAS-MBBR corresponds to about $1.87M revenue with the assumption that 1 m^3 of biogas produces 4.7 kWh electricity and the unit cost of electricity is 0.1 $/kWh. In view of the analysis elaborated on a range of financial parameters it can be concluded that HAS-MBBR treatment plant is financially the most viable option for the treatment of wastewater especially have low nitrification rate.

CONCLUSIONS

This study presents the simulation-based evaluation of a pilot-scale HAS-MBBR system for the combined improvement of nutrient removal and biogas production with an efficient organic carbon recovery approach in comparison to a conventional BNR system. The proposed configuration was built on the basis of organic carbon capture to improve carbon dependent denitrification, phosphorus removal and anaerobic digestion processes while enhancing nitrification efficiency by low organic loading due to flow separation and by MBBR application.

The prominent feature of this hybrid system is that the nitrification process will not be the decisive factor for sizing the bioreactor compared to conventional BNR system. Moreover, the adsorption capability of return activated sludge provides ultimate organic carbon capture without loosing carbon aerobically. The diversion at the head of the configuration allows management of organic carbon (i.e., using in denitrification or/and anaerobic digestion) during real time operation. Model simulations and techno-economic analysis proved that the proposed treatment configuration has great advantages over conventional activated sludge systems. Our findings will be pioneering demonstration for the implementation of such configuration, either for newly designed or for upgrading of existing treatment plants.

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