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Domestic Wastewater Treatment: A Comparison between an Integrated Hybrid UASB-IFAS System and a Conventional UASB-AS System

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Abstract: The current study presents a detailed evaluation and comparison between two integrated anaerobic–aerobic systems for biological wastewater treatment under equal conditions in all aspects (wastewater characteristics, climatic conditions, reactor sizing, and even the measurement methods). The two examined systems are (i) a hybrid upflow anaerobic sludge blanket (hybrid UASB) coupled with integrated fixed-film activated sludge (IFAS) and (ii) a conventional UASB coupled with activated sludge (AS). The present comparative study aims to evaluate and assess the effect of adding carrier-filling media on the performance of the classical integrated UASB-AS. The two parallel pilot-scale systems, hybrid UASB-IFAS and UASB-AS, were installed and operated at a wastewater treatment plant. Three sets of experiments were conducted to examine the influence of the hydraulic retention time (HRT) on the consequent organic and hydraulic loads, temperature, and recirculation rate of the proposed systems. The main results showed that the two investigated systems had a comparably high efficiency for the removal of organic matters and ammonia. Moreover, a paired sample *t*-test indicated there was a statistically significant effect of the filling media, and the performance of the hybrid UASB-IFAS increased significantly compared with that of the UASB-AS system. An additional benefit of the filling media on the hybrid system was its high stability when changing the organic and hydraulic loads. The optimum HRT was 6 h, with a total chemical oxygen demand (TCOD) percentage removal of approximately 95% in both examined systems. Treatment of sewage under high and low temperatures indicated that increasing the temperature improved the efficiency of the overall process for both systems significantly.

Keywords: upflow anaerobic sludge blanket; hybrid UASB; activated sludge; IFAS; integrated anaerobic–aerobic; domestic wastewater

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1. Introduction

Water deficiency is a major challenge to sustainable development. This challenge is compounded by rapid population growth, urbanization, environmental pollution, and climate change [1]. It is said that a "Blue Revolution" is required to end the scarcity of water and to save water for agriculture. Presently, water shortage is a worldwide issue; almost half the world's population suffers from water shortages [2]. Thus, there is a need to develop and improve technologies that mitigate water shortages and increase water supply, one of which is municipal wastewater treatment.

Biological wastewater treatment appears to be a promising technology. Both aerobic and anaerobic processes can be applied. The former involves the use of dissolved oxygen by microorganisms in the conversion of organic matter to biomass and CO_2. The latter involves the conversion of complex organic wastes into methane, CO_2, and H_2O in the absence of oxygen [3].

Anaerobic treatment is a very optimal option for wastewater treatment. It has many benefits, including low energy requirements, low sludge production, and low cost of sludge treatment [4,5]. Other advantages can include the generation of renewable energy from methane, emission mitigation, and possibly hydrogen energy [6]. In this way, anaerobic wastewater treatment is an effective approach by which both energy recovery and pollution control can be achieved [7,8].

There are many configurations of anaerobic treatment systems, among which are upflow anaerobic sludge blanket (UASB) reactors. They are promising anaerobic systems, especially in the developing countries located in warm-water regions. Anaerobic technologies are widely used in warm climates for treating low-strength streams at ambient temperature. UASB reactors are systems with a highly robust rate of treatment due to their easy operation and low construction and operating costs, in addition to their efficiency, flexibility, smaller footprint, and relatively high-quality effluent [9]. However, UASB systems still have significant restrictions when used as a single treatment process. One of these constraints is the insufficient ability to remove organic matters and nitrogen, so the effluent stream cannot meet the effluent discharge standards [10].

The aforementioned limitations of UASB reactors can be reduced by improving the effluent quality using several methods, which can be classified into two main trends. The first trend is to modify the UASB reactor configuration. For instance, Musa et al. [9] enhanced a UASB's efficiency by applying a solid separator in the upper portion slightly above the sludge blanket, which prevented washout of the sludge from the reactor.

Guiot and van den Berg [11] proposed an anaerobic hybrid UASB reactor with the following configuration: the UASB reactor was in the lower zone, while filling media was added in the upper zone to provide a surface area for additional biomass growth. Hybrid UASB has many advantages compared to classical UASB, including rapid granulation of biomass, a shorter startup period, and higher loading rates [12]. The integrated upflow anaerobic sludge blanket and anaerobic filter (UASB-AF) was recommended by many researchers who stated that adding plastic media in the top-third of the UASB reactor could enhance the efficiency of the reactor [13,14]. The hybrid UASB-AF system provides the advantages of both a UASB reactor and an anaerobic filter, so high cell concentration, good mixing, and tolerance to high loading rates are all available [15]. On the other hand, Lew et al. [16] compared hybrid UASB and the classical UASB, and concluded that both reactor designs had a similar performance at summer conditions (20–28 °C). The hybrid UASB reactor containing filter rings showed no advantage, and it performed slightly worse than the conventional UASB reactor at lower temperatures.

The second trend to achieve the desired UASB effluent standards is to select an appropriate post-treatment scheme [12]. The anaerobic effluent often contains solubilized organic matters, ammonium ions, and hydrogen sulfide. This is suitable for aerobic treatment, indicating the potential of using anaerobic–aerobic systems. Benefits of the anaerobic–aerobic process include resource recovery (biogas production), high overall treatment efficiency, less disposal of sludge, and low energy consumption [3].

A variety of aerobic post-treatment processes can be used. Results obtained from the laboratory and full-scale units in the literature demonstrated that an activated sludge (AS) reactor and a moving-bed biofilm reactor (MBBR) are very effective for post-treatment [16–18]. Show et al. [6] examined the feasibility of integrating a series of biological processes (anaerobic granular sludge blanket, aerobic carrier biofilm, and aerobic activated sludge processes) for the treatment of high-strength wastewater. The integrated anaerobic–aerobic system enhanced the effective overall treatment efficiency. A similar integrated system was also recommended by Allegue et al. [10].

On the contrary, the integrated fixed-film activated sludge (IFAS) reactor has been rarely studied as a post-treatment option. The difference between the MBBR and the IFAS relies on the presence of the return activated sludge (RAS). Many studies have strongly recommended the IFAS system over the AS and MBBR reactors. When a full-scale IFAS reactor equipped with plastic media was compared to AS, the applied loading to the

IFAS process was approximately twice that of AS, and the TCOD removal percentage and ammonia were almost the same for both processes [19]. Through a deammonification process for treating wastewater, a higher nitrogen-removal rate was achieved by the IFAS reactor in comparison with the MBBR. This was due to the higher relative abundance of ammonium-oxidizing bacteria in suspended biomass and the increase of the total aerobic capacity of the system [20]. The IFAS system gains the advantages of the biofilm reactor and the activated sludge process. IFAS increases the sludge-retention time, enhances nitrification, improves process stability, and reduces excess sludge production with better settling characteristics. IFAS achieves a high treatment efficiency even at higher organic loads compared with the AS system. The biofilm in IFAS offers several advantages: reduced footprint, enhanced nutrients removals, and longer solid-retention time [21,22].

Previous studies indicated that applying carrier-filling media in both UASB and AS reactors can enhance their performance. Moreover, the use of the filling media is costly and requires special infrastructural facilities. The current work aims to assess the effect of adding plastic filling media on the performance of the classical integrated UASB-AS system. This is to determine whether it is a beneficial option to use this filling media for the UASB-AS system. The developed system is composed of a UASB coupled with an anaerobic filter (hybrid UASB) followed by IFAS. The two investigated systems (hybrid UASB-IFAS and classical UASB-AS), will be thoroughly compared in all conditions, and the main operating parameters of HRT, temperature, and sludge recirculation will be investigated. The experimental work was performed using pilot scale reactors installed and operated in the field (a wastewater treatment plant).

2. Materials and Methods

2.1. Wastewater Characteristics

The experimental reactors were installed and operated in the field, at the Al-Qenayat Wastewater Treatment Plant (WWTP) in Zagazig, Sharkia, Egypt. The wastewater utilized was real municipal wastewater with variable characteristics. The reactors were fed with gritted wastewater using centrifugal pumps. In order to mitigate the flow-rate variation, a constant head tank was installed ahead of the reactors. A summary of the characteristics of the influent wastewater is given in Table 1.

Table 1. Influent wastewater characteristics.

Parameter	pH	TCOD (mg/L)	BOD_5 (mg/L)	NH_3 (mg/L)	TSS (mg/L)	VFA (mg/L)	Alkalinity (mg/L)
Mean values	7	635	305	16	310	84	251
Standard deviations	(0.5)	(195)	(101)	(9)	(67)	(128)	(107)

2.2. Reactor Setup and Operation

The experiments were carried out using two pilot-scale systems (hybrid UASB-IFAS and UASB-AS) operated in parallel. Figure 1 shows a process-flow diagram of the pilot plant. Each of the two anaerobic reactors (hybrid UASB and conventional UASB) was configured as a cylindrical tank with a 465-L volume. Samples were collected from four sampling ports placed at different heights. An inflow distributor system was installed at the bottom of the reactor to ensure influent distributions. The hybrid UASB had plastic media (500 m^2/m^3) filling the top part of the reactor. The media-filling ratio for the hybrid UASB was 23% of its volume.

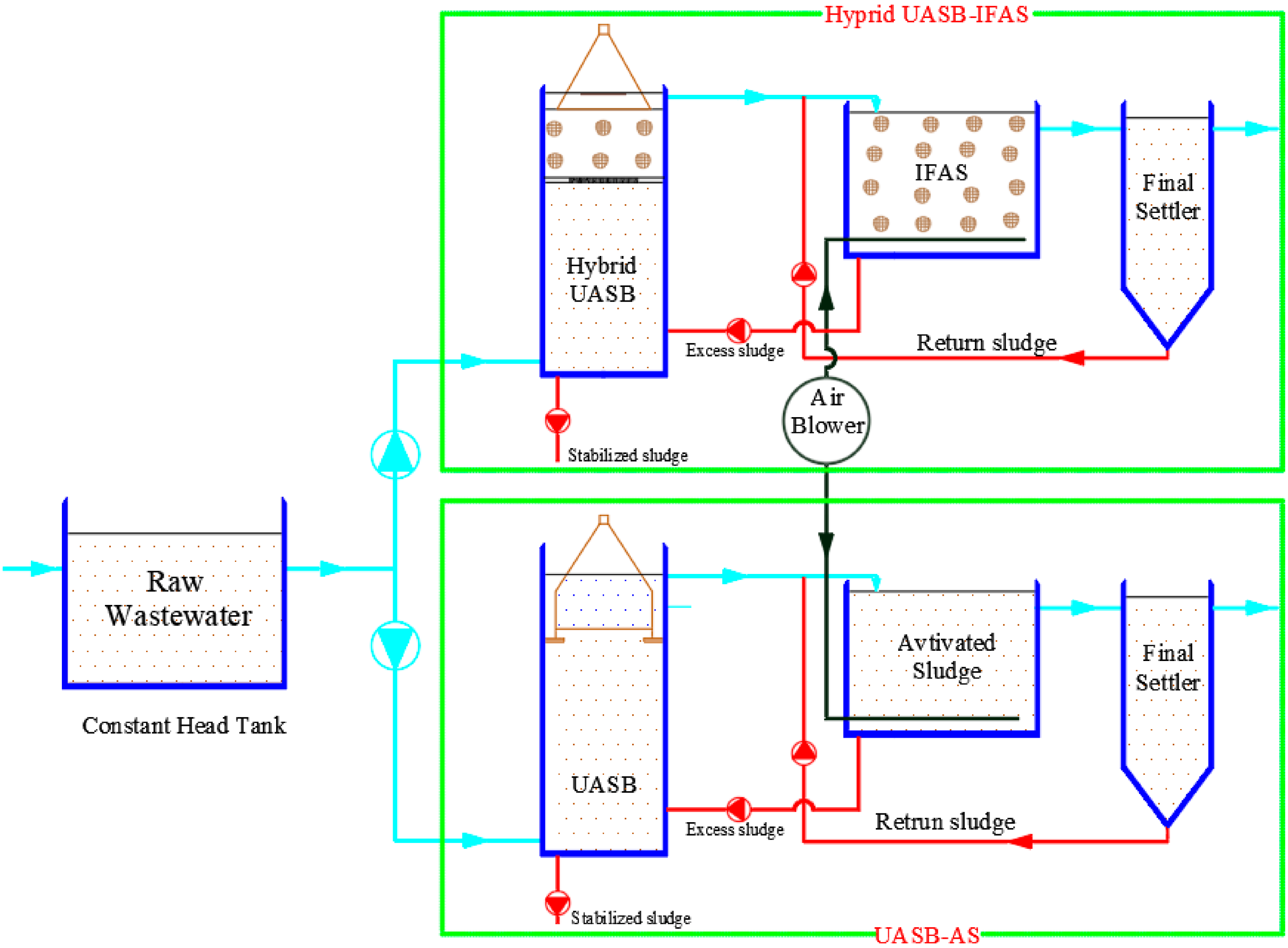

Figure 1. Schematic drawing of the pilot plant.

The effluent post-treatment of the hybrid UASB reactor was done by using IFAS. The IFAS system consisted of an aerobic bioreactor with a working volume of 525 L that had a media-filling ratio of 30% and a settling tank with a volume of 150 L. Abdo et al. [23] compared the classical activated-sludge process with the IFAS system, with different filling plastic carrier media ranging from 10–70%. They recommended 30% as the optimum media-filling ratio, and concluded that the organic-removal ratio was enhanced slightly at the 10–50% filling ratio. Similarly, Waqas et al. [22] confirmed that the media-filling ratio ranges from 30% to 70%, and the average filling ratio is about 35%. For the UASB-AS reactor, post-treatment was done with the AS system. The volume of the aerobic bioreactor and settling tanks were 525 L and 150 L, respectively. The excess sludge from aeration tanks was recirculated to the bottom of anaerobic reactors.

Three sets of experiments were conducted to examine the influence of the HRT, temperature, and recirculation rate on the performance of the hybrid UASB-IFAS and UASB-AS combinations. In the first set of experiments, the two systems were operated for 186 days, divided into five time intervals: 0–42, 42–77, 77–114, 114–146, and 146–186 days at an HRT of 15, 12, 9, 6, and 3 h, respectively. The effect of temperature was studied in the second set of experiments. The reactors were operated for cold-climate conditions at a temperature range of 9–15.5 °C for 40 days, and for hot-climate conditions at 25–33 °C for 24 days. The third experimental set was conducted to examine the effect of the sludge recirculation rate from aeration reactors to anaerobic reactors. The two systems were operated with no recirculation in the first run. In the second and third runs, the recirculation from the aeration reactors was 52.5 L/day and 210 L/day, respectively. The main operational conditions are shown in Table 2. The total HRT is defined as the residence time of wastewater in the whole system, which equals the sum of retention time of the anaerobic unit and that of the aerobic unit.

Table 2. Operational conditions of the tested systems.

Total HRT (h)	Anaerobic HRT (h)	Aerobic HRT (h)	Flow Rate (m^3/Day)
15	7	8	1.61
12	5.5	6.5	2
9	4	5	2.9
6	2.7	3.3	4
3	1.4	1.6	8

2.3. Sampling and Analytical Methods

Samples of the influent and the effluents of the anaerobic and aerobic reactors were collected and analyzed. The TCOD, biological oxygen demand (BOD_5), TSS, and ammonia were determined according to the standard methods [24]. The biomass concentration in the AS and IFAS expressed as solid concentration was measured and presented as a mixed liquor suspended solid (MLSS). The samples were taken twice weekly. Dissolved oxygen (DO) was measured and monitored with a digital meter. The DO, temperature, and pH were measured on site daily. Volatile fatty acids (VFA) were determined by the Kappa titration method [25].

3. Results and Discussion

A classical UASB reactor can be modified by using filling media in order to increase its efficiency and ability to withstand excessive organic and hydraulic loads. The efficiency of the AS process can also be upgraded in the same manner by adding the media. In the two systems that were chosen for the study, one of them—the hybrid UASB-IFAS—has the benefit of using media in both of its stages. On the other hand, the UASB-AS system consists of two parts, both of which follows traditional methods. The two pilot plants of the two systems were continuously operated over a period of 186 days, with different HRTs of 15, 12, 9, 6, and 3 h, and a wide range of organic loading rate (OLR) (from 1.5 to 15.4 Kg TCOD/m^3.day). Many measurements and parameters were observed to clarify the differences between the two systems.

3.1. TCOD Removal

Figures 2 and 3 and Table 3 illustrate the variation in the influent and the effluent TCOD and the performance of the reactors at each HRT. Due to the variance of wastewater characteristics, the organic load for each run was not constant. The results presented in Figure 3 show the effect of changing the HRTs and subsequently OLR on the TCOD removal ratio provided by the hybrid UASB-IFAS and UASB-AS systems. The COD dataset at different HRTs was statistically analyzed with a paired-sample *t*-test. IBM SPSS Statistics software package was used for the analysis. The paired-sample *t*-test can explore whether there is a statistically significant difference between the performance of the two examined systems. The results from the paired *t*-test showed that the arithmetic mean of the COD effluent (at all HRTs) for the hybrid UASB-IFAS equaled 42 mg/L, compared with 61.5 mg/L for the UASB-AS system. The paired *t*-test indicated that the *t* value was 7.48 (compared with the critical value (T_C) of 2), at a 95% level of significance and 32 degrees of freedom. The higher *t* value with positive sign denoted that outlet values of the hybrid UASB-IFAS system decreased significantly if compared with the values the UASB-AS system. The comparison also indicated that the hybrid UASB-IFAS system significantly outperformed the UASB-AS system. The higher performance of the hybrid reactors could be attributed to better granulation and biofilm establishment.

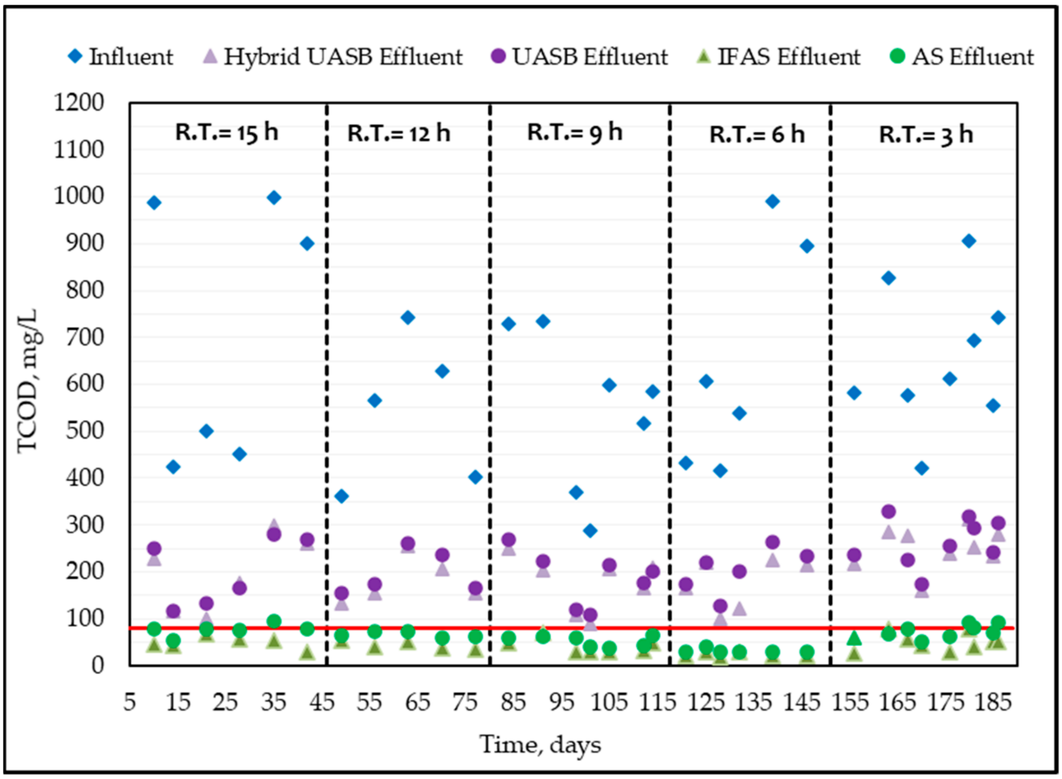

Figure 2. Variations in the influent and effluent TCOD during the HRT study.

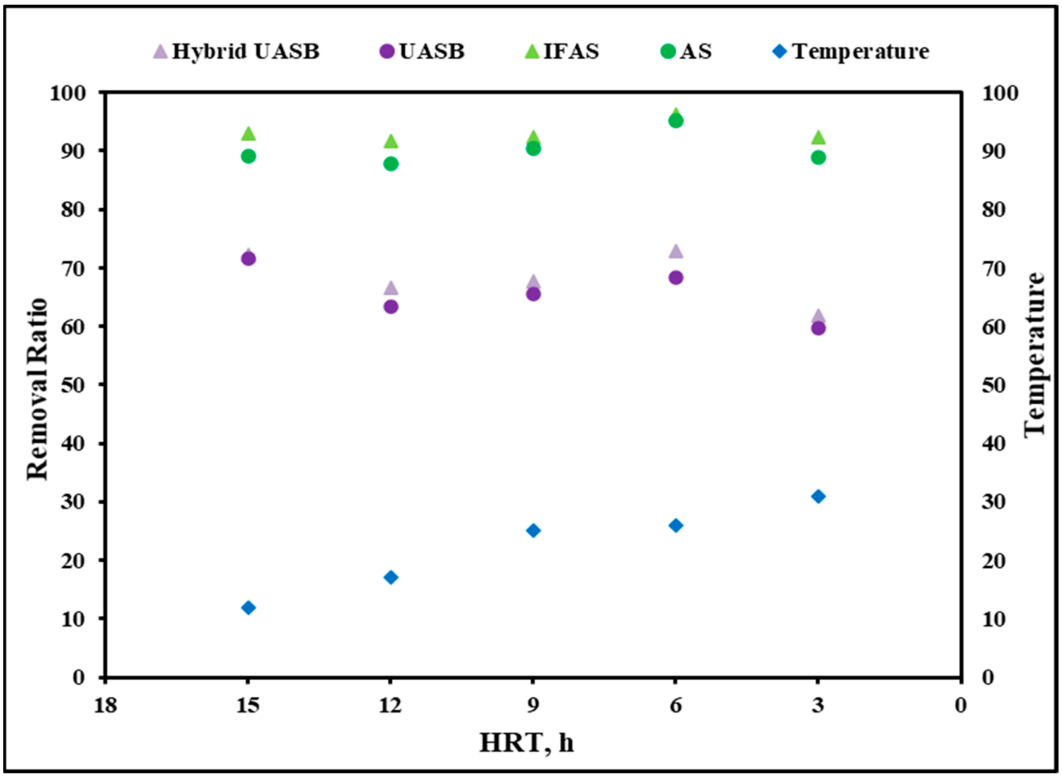

Figure 3. Effects of HRT on the TCOD removal ratio.

Table 3. TCOD results for the two investigated systems.

Parameter	Influent	Temperature	Anaerobic Effluent		Aerobic Effluent	
		(°C)	Hybrid UASB	UASB	IFAS	AS
HRT = 15 h						
Mean	711	12	197	203	49	78
Median	700		202	207	50	80
Standard error	279		80	73	13	14
Removal ratio			72.3	71.5	93.1	89.1
HRT = 12 h						
Mean	540	17	181	198	44	66
Median	567		155	175	41	65
Standard error	158		49	47	8	6
Removal ratio			66.5	63.3	91.8	87.8
HRT = 9 h						
Mean	546	25	176	188	42	53
Median	586		184	195	31	52
Standard error	170		62	63	17	11
Removal ratio			67.8	65.6	92.3	90.3
HRT = 6 h						
Mean	646	26	175	204	24	32
Median	572		190	211	21	30
Standard error	242		54	48	5	4
Removal ratio			72.9	68.4	96.3	95.1
HRT = 3 h						
Mean	658	31	251	264	51	73
Median	612		254	255	51	71
Standard error	150		45	51	18	15
Removal ratio			61.8	59.8	92.3	88.9

TCOD values for effluent were less than 78 mg/L. These values fall under the Egyptian environmental requirements (the value of TCOD should not be more than 80 mg/L). The results revealed that the removal of TCOD in the combined hybrid UASB-IFAS system was not significantly affected by decreasing the total HRT from 15 to 12 and then to 9 h. But when the HRT was reduced to 6 h, the efficiency increased; when it reached 3 h, the TCOD removal value returned to its previous rate. The TCOD removal percent was above 92% for all the HRTs. Similar results were observed by Allegue et al. [10]. They used a pilot plant composed of a UASB followed by an IFAS system. They aimed to evaluate the feasibility of using an integrated fixed-film activated sludge (IFAS) system as a post-treatment technology, and the system achieved TCOD removal efficiencies of $92 \pm 3\%$.

For the UASB-AS system, the same trend was observed. The removal percentage was above 88%, and the optimum removal achieved was 95% at 6 h. In general, TCOD values for the UASB-AS system effluent were less than the requirements of Egyptian environmental standards. However, some results (at HRT = 15 h for the UASB-AS system) did not match the standards because the effluent TCOD was more than 80 mg/L. However, removal ratios were still achieved at a high rate. It was noticed in this case that the anaerobic part of the system did its job well, and the shortening was associated with the aerobic part. This may be due to the low temperature. At HRT = 3 h, some TCOD results for the UASB-AS system effluent were more than 80 mg/L due to a high OLR, which was $\geq$11.79 kg TCOD/m^3.day. These results indicated that the IFAS system was more stable and had better results than the AS system.

The experiments were done at ambient temperature and, as shown in Figure 3, began in the winter, so as the HRT changed from 15 h to 3 h, the temperature increased. This can account for the high removal efficiency at an HRT of 6 h. Because of the uncertain relation between the increase in temperature and the increase in the removal efficiency, the effect of temperature was studied later.

The obtained trend for the effect of HRT on the overall system performance was in accordance with other studies. For the treatment of wastewater containing toxic phenolics at influent TCOD of 2240 mg/L in both the hybrid UASB and the classical UASB, the TCOD removal ratios at HRTs of 18, 15.8, 9.4, and 8 h were 84.5, 84.5, 91, and 84%, respectively in the hybrid UASB, in comparison with 83.5, 84.4, 90, and 83%, respectively, in the UASB reactor [26]. The hybrid UASB achieved a 4.5% removal ratio, higher than for the UASB at an HRT of 6 h. These results are in line with those obtained by Elmitwalli et al. [27], who compared the performances of a hybrid UASB and a UASB reactor for pre-settled sewage treatment at 13 °C and an HRT of 8 h. The hybrid UASB filter reactor reached 64% of total TCOD removal, a 4% higher removal than the classical UASB.

3.2. BOD_5 Removal

The performance data of the hybrid UASB-IFAS system shown in Figures 4 and 5 and Table 4 revealed that the high total BOD_5 removal ranged from 96% at HRT = 15 h to 92% at HRT = 3 h, with a peak value of 98% at HRT = 6 h. On the other hand, the BOD_5 removal from the outlet of the hybrid UASB unit ranged from 62% to 83%. For the UASB-AS system, the BOD_5 removal ranged from 94% at HRT = 15 h to 91% at HRT = 3 h, with a peak value of 97% at HRT = 6 h. These results indicated that the decrease in the total HRT did not have a significant effect on the total removal efficiency of BOD_5 in both systems. The reduction of the HRT led to a decrease in the BOD_5 removal efficiency of the anaerobic reactors. However, the aerobic process was able to overcome the load increase, and the final effluent quality was not significantly affected. BOD_5 values for effluent were less than the Egyptian environmental requirements, which require a value of BOD_5 no more than 60 mg/L. The BOD dataset at different HRTs was statistically analyzed. The results from the paired *t*-test showed that the BOD removal for the two examined systems had the same trend as the COD, and the hybrid UASB-IFAS system significantly outperformed the UASB-AS system.

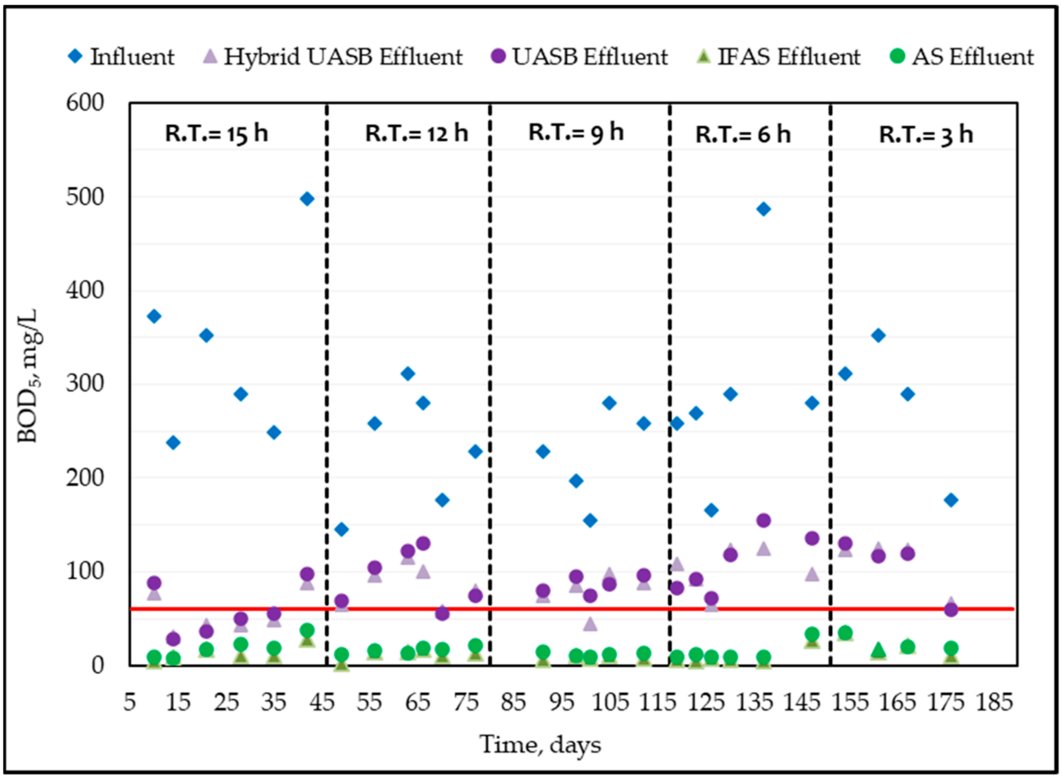

Figure 4. Variations in the influent and effluent BOD_5 during the HRT study.

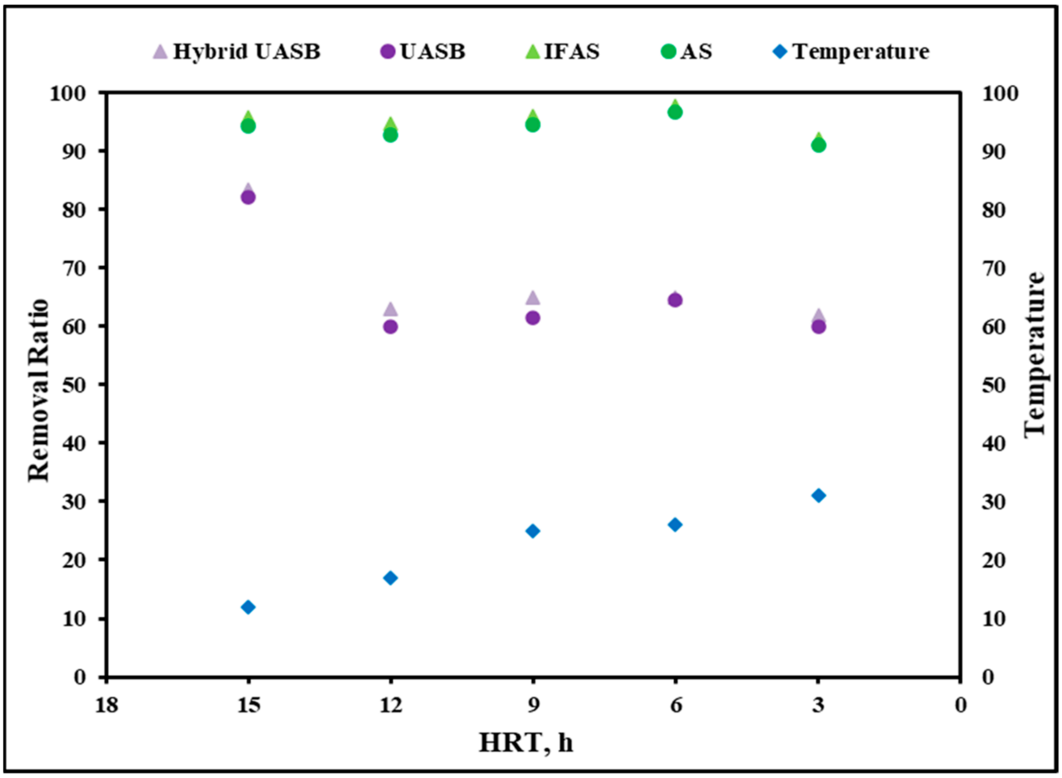

Figure 5. Effects of HRT on the BOD_5 removal ratio.

Table 4. BOD_5 results for the two investigated systems.

Parameter	Influent	Temperature (°C)	Anaerobic Effluent		Aerobic Effluent	
			Hybrid UASB	UASB	IFAS	AS
HRT = 15 h						
Mean	333	12	55	59	14	19
Median	321		47	53	11	18
Standard error	97		22	28	8	11
Removal ratio			83.4	82.2	95.9	94.3
HRT = 12 h						
Mean	233	17	86	93	12	17
Median	244		89	90	14	17
Standard error	63		22	30	5	3
Removal ratio			63.1	60.1	94.7	92.8
HRT = 9 h						
Mean	224	25	79	86	9	12
Median	228		85	87	8	12
Standard error	50		21	9	2	2
Removal ratio			64.9	61.4	96.2	94.6
HRT = 6 h						
Mean	294	26	103	104	6	10
Median	270		109	93	6	9
Standard error	118		25	33	1	1
Removal ratio			65.1	64.6	97.9	96.7
HRT = 3 h						
Mean	282	31	107	113	22	25
Median	290		124	120	21	20
Standard error	65		26	30	10	9
Removal ratio			61.9	60	92.2	91.1

3.3. Ammonia Removal

Figure 6 and Table 5 show the variations in the influent and effluent concentration of ammonia in the two systems at different HRTs. The results show that decreasing the HRT from 15 to 12 h and from 12 to 9 h, then to 6 h, did not significantly affect the efficiency of the overall system, as reflected in the residual ammonia values. Ammonia values for the effluent were less than the Egyptian environmental requirements, which require a value of ammonia no more than 3 mg/L. When the HRT was reduced to 3 h, the remaining ammonia increased and the efficiency decreased significantly. The values of the ammonia effluent were less than 1.3 for the hybrid UASB-IFAS system and 0.7 mg/L for the UASB-AS system in all phases, except the value of 8 mg/L obtained at a 3 h HRT. The good behavior of the two systems was also shown in terms of the removal efficiency. The removal efficiencies of ammonia for the hybrid UASB-IFAS and the UASB-AS systems had values higher than 90% and 94%, respectively, except the value obtained at an HRT of 3 h. It was noticed that both systems failed to maintain their stabilities for the higher hydraulic loading rate (HLR). Recorded values for removal efficiency were 51% for the hybrid UASB-IFAS and 47% for the UASB-AS system, obtained at an HRT of 3 h. The ammonia dataset at different HRTs was statistically analyzed. The paired *t*-test indicated that the *t* value was −1.5 (compared with the critical value (T_C) of −2.06), at a 95% level of significance and 25 degrees of freedom. The higher *t* value with a negative sign denoted that the increase of outlet values for the hybrid UASB-IFAS system was not significant if compared with the values the UASB-AS system.

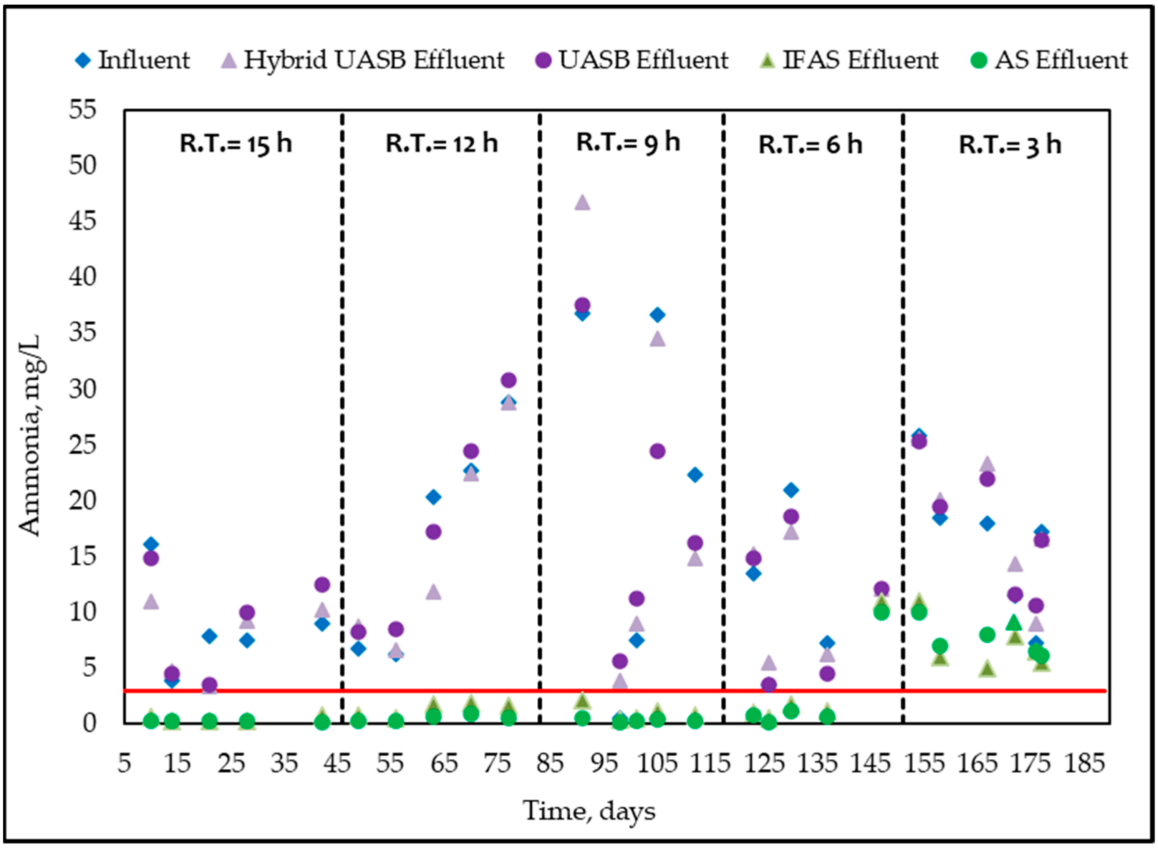

Figure 6. Variations in the influent and effluent ammonia during the HRT study.

Table 5. Ammonia results for the two investigated systems.

Parameter	Influent	Temperature	Anaerobic Effluent		Aerobic Effluent	
		(°C)	Hybrid UASB	UASB	IFAS	AS
HRT = 15 h						
Mean	9	12	8	9	0.4	0.2
Median	8		9	10	0.2	0.2
Standard error	4.5		3.4	5.0	0.3	0.1
Removal ratio			12.9	-	95.1	97.5
HRT = 12 h						
Mean	17	17	15.7	17.9	1.3	0.5
Median	20		11.9	17.2	1.6	0.6
Standard error	10.0		9.5	9.9	0.6	0.2
Removal ratio			7.4	-	92.4	97
HRT = 9 h						
Mean	20.8	25	21.8	19	1	0.3
Median	29.5		24.7	20.3	1.0	0.3
Standard error	14.0		17.5	11.5	0.7	0.2
Removal ratio			-	8.5	95.3	98.5
HRT = 6 h						
Mean	11.3	26	11	10.4	1.1	0.7
Median	10.4		10.7	9.7	1.1	0.7
Standard error	7.7		6.0	7.5	0.5	0.4
Removal ratio			2.5	8.3	90.2	94.2
HRT = 3 h						
Mean	16	31	17	17	8	8
Median	17.2		16.6	16.5	6.5	8.0
Standard error	6.2		6.1	5.7	2.5	1.6
Removal ratio			-	-	51.4	47.9

For higher HLR and OLR, the results of the present study indicated that the two systems failed to maintain a higher removal ratio for ammonia. It can be concluded that the decrease in the ammonia removal rate was because the HRT was too short to complete the nitrification process. An increase in the carbon loading, due to a short HRT, can lead to an increase in the heterotrophic bacteria numbers in both the attached and suspended biomass, and therefore to a decrease in nitrifier numbers, as there is more competition for space, oxygen, and substrate for the heterotrophic bacteria [28]. In this context, Moawad et al. [29] concluded that complete nitrification of ammonia was achieved after 5 h of aeration. Similar results were observed by Allegue et al. [10], who observed ammonium removal efficiencies of around 57 ± 16% throughout the entire operation.

3.4. Total Suspended Solid (TSS) Removal

The results shown in Table 6 and Figures 7 and 8 revealed that the percentage of TSS removal was almost the same in the anaerobic and post-treatment steps despite changing the HRT. For the hybrid UASB-IFAS, the effluent TSS was 160, 162, 143, 154, and 142 mg/L for the hybrid UASB, and 25, 25, 24, 25, and 21 mg/L for the IFAS reactor, at HRTs of 15, 12, 9, 6, and 3 h, respectively. For the UASB-AS, the effluent TSS was 164, 171, 147, 162, and 146 mg/L for the anaerobic reactor and 30, 29, 27, 28, and 27 mg/L for the aerobic reactor at HRTs of 15, 12, 9, 6, and 3 h, respectively. The overall removal rate was between 91.3–93.0% and 90.1–91.2% for the hybrid UASB-IFAS and the UASB-AS, respectively. For both systems, an almost constant removal rate above 90% and an average effluent concentration of less than 30 mg/L were observed despite changing the HRT. The TSS concentration in the influent and final effluent of the pilot-scale reactors varied from 273 to 319 mg/L and from 21 to 30 mg/L, respectively. This corresponds to a 90–93% reduction in the TSS. The obtained results indicated that the removal of TSS in the two combined systems was independent on the total HRT.

Table 6. TSS results for the two investigated systems.

Parameter	Influent	Temperature	Anaerobic Effluent		Aerobic Effluent	
		(°C)	Hybrid UASB	UASB	IFAS	AS
HRT = 15 h						
Mean	319	12	160	164	25	30
Median	311		157	166	25	30
Standard error	41.5		18.6	14.6	2.2	1.6
Removal ratio			49.9	48.7	92	90.6
HRT = 12 h						
Mean	306	17	162	171	25	29
Median	289		162	167	25	28
Standard error	73.2		24.2	24.7	2.4	4.7
Removal ratio			46.9	44.1	91.8	90.4
HRT = 9 h						
Mean	273	25	143	147	24	27
Median	258		142	143	23	26
Standard error	69.9		34.2	29.1	3.0	3.4
Removal ratio			47.5	46.3	91.3	90.1
HRT = 6 h						
Mean	310	26	154	162	25	28
Median	280		150	147	25	28
Standard error	85.4		42.3	42.4	2.5	4.6
Removal ratio			50.5	47.7	92.1	91
HRT = 3 h						
Mean	307	31	142	146	21	27
Median	296		146	151	22	26
Standard error	36.8		13.5	10.1	4.4	8.3
Removal ratio			53.8	52.2	93	91.2

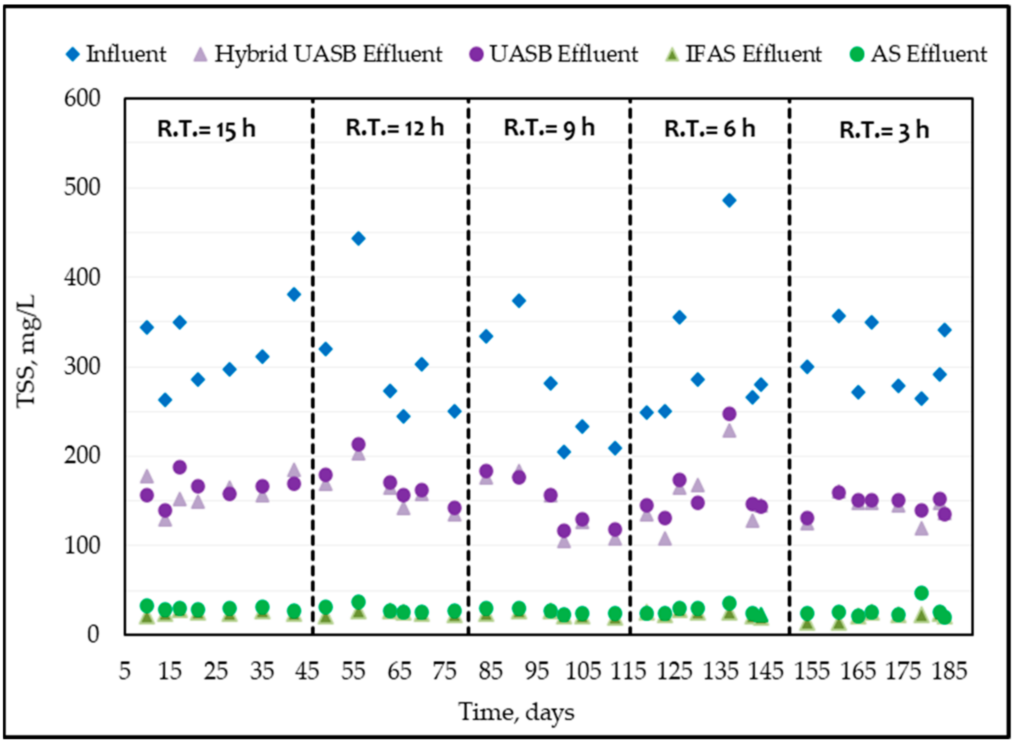

Figure 7. Variations in the influent and effluent TSS during the HRT study.

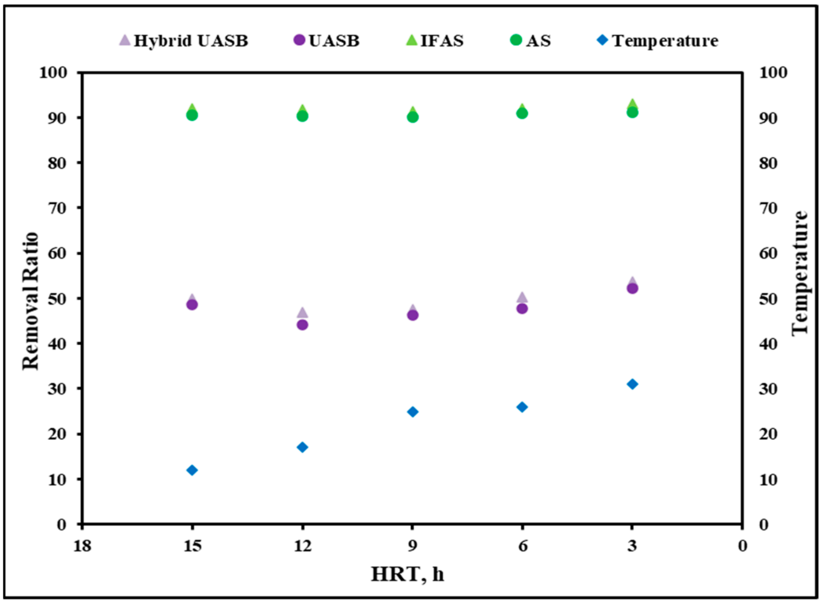

Figure 8. Effects of HRT on the TSS removal ratio.

3.5. Other Performance Parameters of the Examined Systems

Table 7 shows other performance parameters for the experimental investigated systems, including pH, DO, MLSS, VFAs, and alkalinity.

Table 7. Other performance parameters for the investigated systems.

Parameter	Raw	Anaerobic Unit		Aerobic Unit	
		Hybrid UASB	UASB	IFAS	AS
HRT = 15 h					
pH	7.2	7.4	7.5	7.7	7.5
DO (mg/L)		0.2	0.3	4.4	5.2
MLSS (mg/L)		4200	7000	5180	3445
VFA (mg/L)	20	10	10	5	5
Alkalinity (mg/L)	265	272	280	185	190
HRT = 12 h					
pH	6.8	7.1	7.2	7.5	7.6
DO (mg/L)		0.3	0.3	3.1	3.5
MLSS (mg/L)		3400	3620	4225	2650
VFA (mg/L)	11	20	7.5	1.2	3.3
Alkalinity (mg/L)	275	340	330	215	180
HRT = 9 h					
pH	7	7.2	7.4	7.8	7.7
DO (mg/L)		0.3	0.2	2	3
MLSS (mg/L)		2670	4015	3600	3560
VFA (mg/L)	67	38	32	5	5
Alkalinity (mg/L)	313	365	335	265	245
HRT = 6 h					
pH	6.8	7.2	7.3	7.6	7.7
DO (mg/L)		0.3	0.3	2	2.7
MLSS (mg/L)		3050	2325	3550	4800
VFA (mg/L)	33	39	33	14	16
Alkalinity (mg/L)	335	350	345	220	180
HRT = 3 h					
pH	7	8	8	8	8
DO (mg/L)		0.2	0.2	1.8	2.5
MLSS (mg/L)		2820	2780	2000	2500
VFA (mg/L)	43	25	20	10	5
Alkalinity (mg/L)	315	290	290	230	260

As indicated in Table 7; the pH measurements were neutral for the wastewater at all stages, and ranged from 6.8 to 8. The two investigated systems achieved high VFA removal.

The DO level inside the aeration tank for the AS and IFAS systems was maintained above 2 mg/L. This was higher than the value of 1.3 mg/L recommended by Khayi [30], who evaluated the UASB reactor by integrating it with the IFAS to find the optimal aeration DO level that could achieve the maximum nitrogen efficacy. The MLSS inside the aeration tank was variable according to the different operational conditions, and ranged from 2000 to 5180 mg/L.

3.6. Effect of Climate Temperature Fluctuations

The effect of climate temperature fluctuations on the performance of the hybrid UASB-IFAS and UASB-AS was monitored for the treatment of domestic wastewater at two different operational temperatures (9–15.5 °C and 25–30 °C) and a total HRT of 15 h. The performance of the reactors is shown in Figure 9. It is clear that the increase of temperature improved the efficiency of the overall system for both TCOD and BOD_5 by about 3–8%. The effect of temperature on the anaerobic stages accounted for about 6–17% removal enhancement. The dataset for cold and hot climate conditions was statistically analyzed. The paired *t*-test indicated that the temperature enhanced the overall performance of both examined systems significantly. These findings are in agreement with the results of other studies. Liu and Tay [31] argued that high temperatures enhance methanogenesis. Rizvi et al. [32] reported that there was an increase in the efficiency of the UASB reactors with an increase in the temperature; in their study, the TCOD removal efficiency of the UASB reached 62, 68, and 77% at 17, 20, and 25 °C, respectively. The removal ratio for ammonia in anaerobic reactors for both systems in a cold climate was very low, while the overall removal efficiency for the two investigated systems was affected slightly. The average percentage removal of TSS was also enhanced as the temperature increased.

3.7. Effect of Activated Sludge Recirculation Rate

One of the biggest advantages of the UASB reactor is the production of stabilized sludge. The excess sludge from the aeration tank was returned to the UASB reactor. The effect of the activated sludge recirculation rate, from the aerobic reactor to the anaerobic reactor, was investigated. Three experimental runs of the two systems were studied and a mixed liquor from the IFAS and AS was recirculated to the hybrid UASB and UASB at a rate of 0, 52.5, and 210 L/day and an overall HRT of 3 h. Sludge wastage in the first run was accomplished by wasting mixed liquor suspended solid (MLSS) from the aerobic reactor. In the second and third runs, the sludge was wasted from the anaerobic unit. This resulted in a sludge retention time (SRT) in the aeration tank of 10 day in the first and second runs and 2.5 day in the third run. Figure 10 depicts the TCOD, BOD_5, ammonia, and TSS removal efficiencies for both systems.

For the hybrid UASB-IFAS system, the overall TCOD removal efficiency was 93% for the first run and 92% for the second and third runs, and was not significantly affected by recirculation rate. As for the UASB-AS system, the overall TCOD removal efficiency was 91% and 89% in the first and second runs, respectively (SRT = 10 day), and decreased to 85% in the third run (SRT = 2.5 day). Similar behavior was observed for the two anaerobic reactors, with a removal ratio of 68% for the first run, 60% for the second run, and 62% for the third run.

The dataset at low and high circulation rates was statistically analyzed and compared with that of no circulation, at a 95% level of significance and 4 degrees of freedom. The statistical comparison indicated that the effect of the sludge circulation rate was not significant for the hybrid UASB-IFAS. The paired *t*-test also indicated that the low-rate circulation effect was not significant for the UASB-AS system, while the high rate reduced the performance significantly.

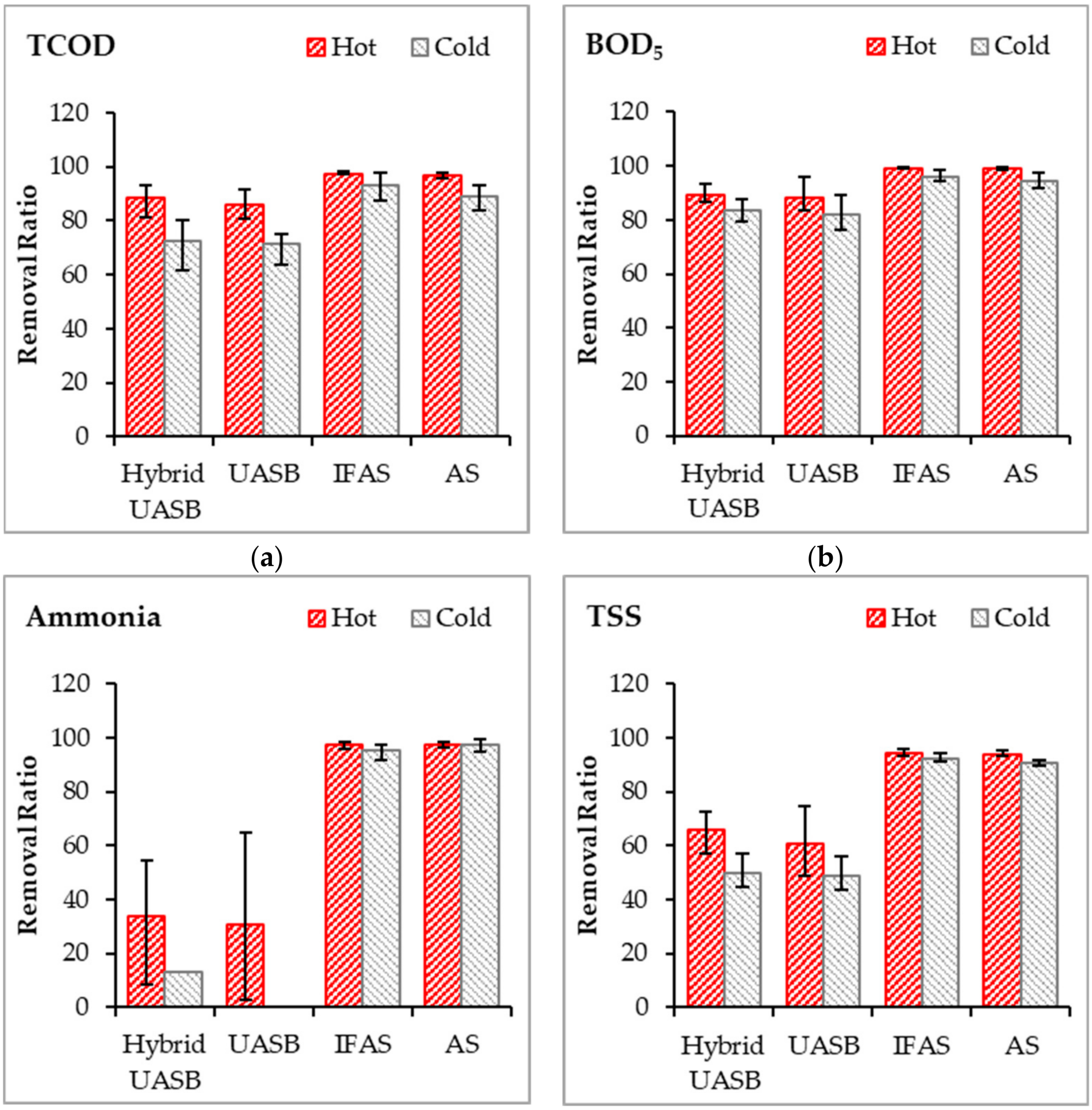

Figure 9. Average removal in hot and cold climates for (**a**) TCOD; (**b**) BOD_5; (**c**) ammonia; (**d**) TSS.

The results shown in Figure 10 revealed that the removal of BOD_5 in the combined systems was not significantly affected by the recirculation rate. The major part of BOD_5 was removed in the anaerobic reactor, and little additional removal occurred in the aerobic reactor. At recirculation rates of 0, 52.5, and 210 L/day, the overall percentage removal values for the hybrid UASB-IFAS were 93, 92, and 90%, respectively. At a recirculation rate of 0, 52.5, and 210 L/day, the overall percentage removal values for the UASB-AS were 92, 91, and 90%, respectively. This indicated that the removal of organic matter and suspended solids was independent from the recirculation ratio.

These results are in agreement with those of Pontes et al. [33], who investigated the performance of an integrated UASB and trickling filter (TF) system using domestic sewage, and studied the effect of recirculation of excess sludge produced from TF on the performance. No detrimental effect was observed due to feeding of aerobic excess sludge to the UASB reactor.

The results show that the ammonia removal improved slightly when the recirculation ratio was high, at 210 L/day. The improvement of nitrogen removal in an integrated system (consisting of anaerobic and aerobic reactors) may occur by using the anaerobic reactor for the denitrification process, as described by several researchers. Huang et al. [34]

studied a combined system consisting of an UASB reactor and an AS reactor with a recycle ratio to influent of 1, 2, and 3 for the treatment of low-strength synthetic wastewater, and concluded that a higher recycle ratio resulted in an increase in the total nitrogen removal efficiency.

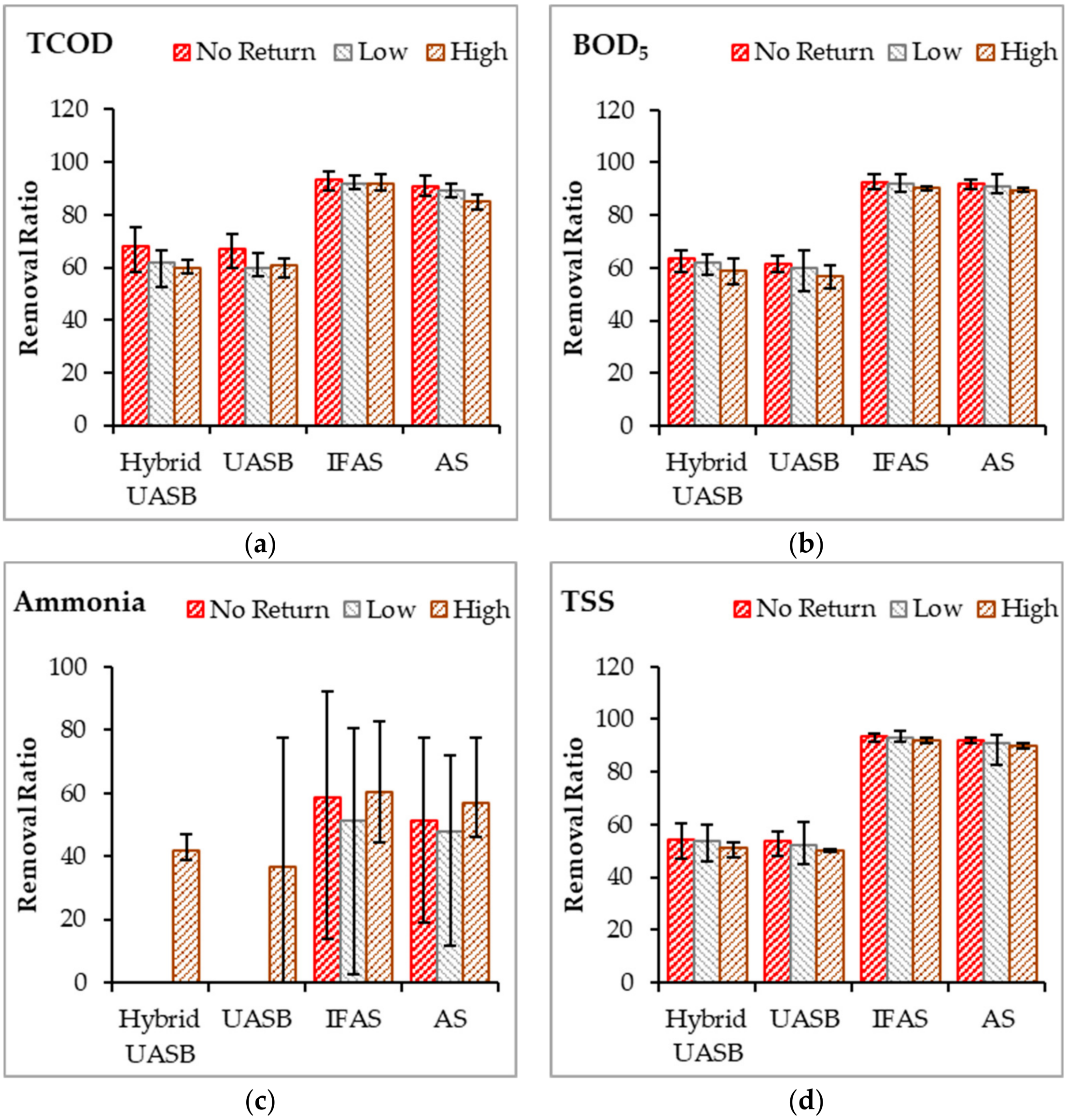

Figure 10. Effect of the recirculation rate on (**a**) TCOD; (**b**) BOD_5; (**c**) ammonia; (**d**) TSS.

4. Conclusions

The aim of our study was to evaluate the effect of carrier-filling media on the performance of a classical integrated UASB-AS system, to determine whether it is a beneficial option to apply this filling media in UASB/AS systems, because the use of the filling media is cost-intensive and requires special infrastructure. The comparison between the conventional UASB-AS integrated system and the hybrid UASB-IFAS modified reactors demonstrated that both systems have comparably high efficiencies in organic matter removal (attained > 95%). Statistical analysis indicated that the carrier-filling media enhanced the efficiency significantly. An additional observed benefit of the carrier-filling media on the hybrid system was its high stability when changing the organic and hydraulic loads. For both examined systems, the results indicated that a large part of the organic matter was removed in the anaerobic reactors, and little additional removal occurred in the aerobic units. As for the ammonia, residuals values were in the accepted range for both systems at all HRTs except 3 h. Also, the results showed that nitrogen removal was very low or absent in the anaerobic units. Treatment of sewage by hybrid UASB-IFAS or UASB-AS reactors, under high and low temperatures, indicated that an increase in temperature improves the efficiency of the overall system significantly, especially the anaerobic reactors. There was a not significant change in the removal ratios of TCOD and BOD_5, as the recirculation ratio of the activated sludge, from the aeration tank to the anaerobic unit, increased. On the contrary, the removal ratio of ammonia improved slightly when the recirculation ratio increased.

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