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Development and modeling of an integrated fixed-film activated sludge (IFAS) system for simultaneous nitrogen and carbon removal from an industrial estate wastewater

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ABSTRACT

The potential of an integrated fixed film activated sludge (IFAS) bioreactor for developing simultaneous aerobic and anoxic micro-zones under continuous aeration regime to promote carbon and nitrogen removal from Faraman industrial estate wastewater was evaluated in the present research. The effects of three independent variables on carbon and nitrogen removal were assessed. Overall, the optimum condition with 94 %, 77 %, and 2 NTU of COD (chemical oxygen demand) removal, Total nitrogen (TN) removal, and effluent turbidity has been specified with hydraulic retention time (HRT) of 11 h, air flow rate (AFR) of 3.5 L/min, and filling ratio (FR) of 50 %. To assess the stability of treating processes in the system, the IFAS system was operated in this optimal condition. Moreover, the simulation of the bioreactor was accomplished via calibration and verification of GPS-X model. GPSX simulation results and experimental data were compared using an independent sample T-test, which the T-test result confirmed that there was no significant difference between them.

1. Introduction

Water pollution is one of the serious environmental issues in the contemporary world, which has been arising from an accelerated urbanization, population growth, and industrialization. The role of wastewater treatment plants has been crucial in preventing contaminated environments and minimizing negative impacts on human lives and economic development [1,2]. Organic carbon content and nutrients (nitrogen and phosphorus) are known to be significant contaminants of industrial and municipal wastewaters, which to meet the effluent discharge standards, it is necessary to eliminate them effectively before releasing into the water body [3,4]. Due to strict regulations on wastewater discharge standards, industrial wastewater treatment has been carried out in various approaches over the years i.e. membrane filtration [5,6], adsorption [7,8], advanced oxidation [9–11], and biological processes [12,13]. The easy operation and economical cost of biological processes, along with their satisfactory treatment efficiency, have led to their development into industries. Most of wastewater treatment plants in all over the worlds are equipped with biological process; nevertheless, they often need to be upgraded to meet the discharge requirements, especially for carbon/nitrogen (CN) removal. To achieve proficient biological CN removal, aerobic and anoxic zones are required [14]. Consequently, to provide different oxidation zones, diverse categories of bioreactors have been investigated in recent years such as combined high-rate bioreactors and integrated systems [15–17].

Integrated fixed-film activated sludge (IFAS) process via integrating the suspended and the attached growth approaches provides considerable aerobic and anoxic zones in a single column bioreactor [18]. IFAS systems with co-existence of both autotrophic and heterotrophic bacteria in suspended and attached biomass have caught the attention of researchers owing to promoting organic carbon and nitrogen removal, mitigating footprint, maximizing working volume of bioreactor, and improving hydraulic shock resistance [19]. In a study, Veuillet and his colleagues [20] treated reject water from a mesophilic anaerobic sludge digester using IFAS bioreactor. Two IFAS systems were fed by ammonium rich industrial wastewater (907±200 mg/l) which ammonium and nitrogen removal from IFAS systems were found to be 95 % and 90 %, respectively. In another recent work, Zhang et al. [21] reported the operation of both the full and pilot-scale domestic IFAS for sludge dewatering liquors treatment. The pilot and full-scale IFAS maintained

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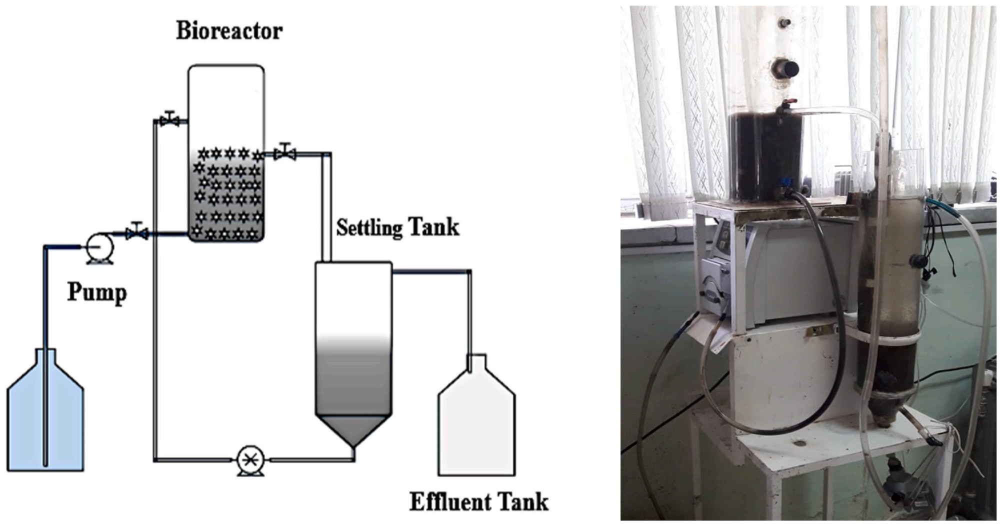
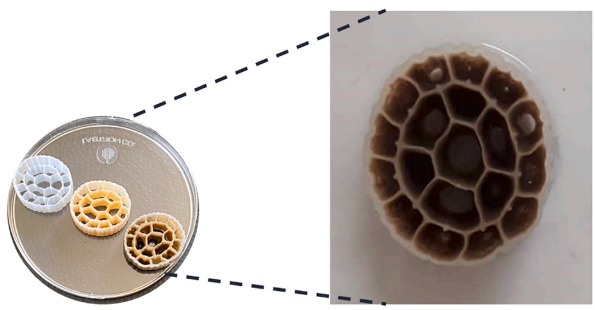


(a)



(b)

Fig. 1. Schematic of the IFAS bioreactor (a) and biofilm development on the Kaldness-3 carrier surface (b).

80 and 85 % nitrogen removal at 0.48 kg N/m^3.d and 0.7–1.3 kg N/m^3.d of ammonium loading rates, respectively.

Also, the effect of chemical oxygen demand/nitrogen (COD/N) ratio and hydraulic retention time (HRT) on the microbial community composition and performance of IFAS bioreactor for the treatment of raw and ozonated oil sands process-affected water were explored by Huang's research team [22]. In this research study, 54.56 % and 56.83 % of COD removal were reported for raw and ozonated wastewaters, respectively. Furthermore, it was concluded that HRT had no noticeable effect on CN removal; however, COD/N ratio showed a negative effect on CN removal. In another research reported by the aforesaid research team [23], the elimination of recalcitrant organics has been compared in IFAS, moving bed bioreactor (MBBR) and membrane bioreactor (MBR) systems for treating oil sands process-affected water. Based on the reported data, COD removal efficiency was 64.42 %, 58.2 %, and 53.6 % for IFAS, MBBR, and MBR, respectively, indicating higher ability of hybrid system compared to merely suspended and attached systems.

IFAS system as a biological system is a complex process, which its efficiency is influenced by various operating and structure variables, including mixed liquor suspended solids (MLSS), hydraulic retention time (HRT), type and filling ratio of biofilm carrier, food to microorganism (F/M) ratio, air flow rate (AFR), temperature, pH, nutrient (nitrogen and phosphorus) levels and organic loading rate (OLR) [24]. Optimization of IFAS requires much time and effort to achieve higher pollutant removal while also reducing energy consumption, therefore, simulation could be a good strategy to predict its efficiency and fine-tuning of the effective variables [25]. Simulating biological treatment systems is a significant demand due to their widespread use in industrial and municipal wastewater plants. GPS-X is one of the simulator software for biological process, which is a modular and user-friendly software benefiting from all-inclusive database of various biological units facilitates quick design of dynamic modelling [26,27].

In the present study, the capability of IFAS in removing carbon and nutrients from real industrial estate wastewater was evaluated as a function of three independent variables, including filling ratio (FR), hydraulic retention time (HRT), and air flow rate (AFR) for the first time. As a fact, the purpose of this study is to develop an IFAS system that is effective and economical in treating real industrial wastewater, which in this regard seven responses, including the removal of COD, BOD_5, and TN, SVI, total effluent turbidity, and effluent NO_2^- and NO_3^-concentrations were measured under different operating conditions. Moreover, the result of modeling and optimization confirms with the calibration and simulation via GPS-X software for the evaluation of the IFAS bioreactor under 15 non-repetitive experimental conditions designed by Design Expert software. The versatility of the GPSX-simulation results and experimental data of IFAS bioreactor performance was evaluated via T-test.

2. Materials and methods

2.1. Analytical methods

Specimens from influent (feed) and effluent (treated wastewater) of the bioreactor daily were taken and centrifuged to measure COD, BOD, turbidity, TKN (NH_4^++*N*-organic), NO_2^-, NO_3^-, and SVI according to Standard Methods (APHA, 2005). COD measurement was carried out by using a closed reflux method and subsequently colorimetric method using a spectrophotometer DR 5000 model (Hach, Jenway, USA) at 600 nm. N—NH_4^+ and N-organic were determined by the macro-Kjeldahl method, via total Kjeldahl nitrogen (TKN) meter (Gerhardt model, vapodest 10, Germany). Turbidity was determined by a turbidity meter (2100 P, Hach Co., USA).

To measure the dried attached biofilm, at the end of each run, a carrier has been selected randomly and before weighing, it was dried at 80 °C for 24 h. The carrier was thoroughly cleaned to avoid any microorganisms on its surface, and then dried and weighed again under the aforementioned conditions. Finally, the attached biomass concentration in the bioreactor was calculated accroding to the following equation:

$$\text{Attachedbiomassconcentration}(\text{mg}/\text{l}) = \frac{(\text{A} - \text{B})*\text{C}*1000}{\text{V}}$$

Where A is the weight of biofilm-attached carrier, B is the weight of cleansed carrier, C is the total number of the carriers, and V is the bioreactor's working volume.

2.2. Configuration of the IFAS bioreactor

The schematic and real picture of the operated IFAS system was displayed in Fig. 1a. As observed in the Fig., the bioreactor consists of a plexi-glass column with a height of 70 cm and an internal diameter of 13 cm. The working volume was maintained at 2.2 L with height of 16.9 cm. The bioreactor was fed continuously by a peristaltic pump. The bioreactor was packed with carriers made of high density polyethylene (Kaldnes-3) with a specific surface area of 500 m^2/m^3. Aeration, mixing and free circulation of the Kaldnes-3 carriers in the bioreactor were provided by an aerator set at the bottom of the bioreactor column. In order to adjust the air flow rate, a gas flow meter was utilized.

2.3. Biofilm development of the carriers

To attain biofilm on the moving carriers, at first the carriers were dipped into agar solution with concentration of 2 g/l and then they were dried at ambient temperature for a full day. After that, the carriers were transferred in an aerated column containing 7000 mg/l of mixed liquor suspended solids (MLSS) for 24 h and then MLSS content was drained out and the column was filled up with milk solution. The column was operated based on batch mode with 24 h of cycle time. After approximately 2 weeks, biofilm was developed onto the carriers' surfaces glaringly and after that to adapt biofilm with Faraman industrial estate wastewater, it was fed by a mixture of industrial wastewater and milk solution for 2 weeks. Over time, the portion of real wastewater was increased step by step to 100 % of feed after 2 weeks. The picture of matured biofilm on a carrier has been displayed in Fig. 1b.

2.4. Bioreactor operation

The IFAS bioreactor firstly operated by the inoculation of activated sludge collected from an aerobic tank of Faraman industrial estate wastewater treatment plant in Kermanshah, Iran. The bioreactor was started up with MLSS of 2000 mg/l and 50 % of FR. The bioreactor was fed by Faraman wastewater using a peristaltic pump under continuous aeration regime for two weeks. During start-up, AFR and HRT were set at 2 L/min and 10 h, respectively. After receiving a steady state condition, the bioreactor was operated according to the experimental circumstances designed by three independent operational factors, including HRT (5, 10, 15 h), AFR (1, 2.5, 4 L/min), and FR (30, 50, 70 %). The adapted microorganism population and steady response values were established by conducting each experimental run for roughly 10 days. In each run, MLSS concentration was measured every day to adjust the specified recycle flow rate to obtain a constant MLSS of 2000 mg/l. Also, MLSS concentration of the bioreactor was set around 2000 ± 200 mg/l by discharging excess sludge from time to time.

Table 1
Faraman industrial wastewater composition.

Parameters	Concentration (mg/l)
COD	939–1090
BOD_5	185–845
N-NH_4	161–216
N—NO_3	3–11
TN	173–221
TP	2–4

Table 2
Range levels of the studied independent variables.

Variables	Range and levels		
	-1	0	+1
HRT, h	5	10	15
Air Flow Rate, L/min	1	2.5	4
Filling Fraction,%	30	50	70

2.5. Wastewater characteristics

Wastewater was collected from Faraman industrial estate wastewater treatment plant, Kermanshah, Iran. To avoid any changes in wastewater composition, samples were stored in the refrigerator at 4 °C. The details of the wastewater composition are shown in Table 1.

2.6. Experimental design and statistical analysis

Design Expert Software (DOE, version 11.0) was employed to design experimental conditions and analyze data statistically. Three independent variables including HRT, AFR, and FR at three levels based on central composite design (2k + (2k+1) +5) were selected. The effective variables range and levels in real and coded units are provided in Table 2. The process performance of the bioreactor was determined by measuring seven different responses during 20 runs composed of COD removal, BOD removal, TN removal, effluent NO_3^- and NO_2^- concentrations, sludge volume index (SVI) and effluent turbidity. The correlation of the responses with the operational variables was presented through polynomial models as follows:

$$Y = a_0 + \sum_{i=1}^{k} a_i x_i + \sum_{i=1}^{k} a_{ii} x_i^2 + \sum_{i \neq 1}^{n} a_{ij} x_i x_j + \varepsilon$$

Where Y denotes the predicted response, and x_i, x_j stands for the independent variables in coded levels. The regression coefficient for linear, quadratic and interactive effects denote by a_i, a_{ii}, a_{ij}, respectively. The b_0 is the constant coefficient, n is assigned to the number of operational variables, and ε represents the model error.

2.7. GPS-X modeling and validation

The evaluation of the IFAS system for Faraman industrial wastewater treatment was done by developing a simulated model. GPS-X software is used in this study to simulate integrated biological wastewater treatment plants as it is a multipurpose and modular modeling environment. GPS-X was utilized to predict MLSS concentration, influent and effluent COD concentrations, and also COD removal under different designed operating conditions by altering three independent aforesaid variables.

The simulation of IFAS system through GPS-X under the different designed operating conditions (by DOE) was started by using the default values of kinetic and stoichiometric parameters. After that, the operating variables (FR, HRT, AFR) were adjusted in accordance with their implemented values in actual. Subsequently, a statistical package for the social sciences (SPSS) was used to assess whether there was a significant difference between the experimental and GPSX-simulation data or not. The SPSS software is utilized to determine the mean, standard deviation,

Table 3
The obtained results of the experiments.

Variables Run	A:HRT (h)	B:FR (%)	C:AFR (L/min)	Responses COD removal (%)	BOD removal (%)	SVI (ml/g)	Turbidity (NTU)	TN removal (%)
1	5	30	1	92.6	94.4	81.02	1.8	28.7
2	5	30	4	94.5	97.8	88.9	1.68	29.2
3	10	30	2.5	91.5	96.6	78.6	1.15	55.16
4	15	30	1	95.6	93.7	79.3	3	47.7
5	15	30	4	94.3	98.7	79.75	1.3	54.5
6	5	50	2.5	93.9	94.4	82.7	4.7	30.7
7	10	50	1	92.1	92.1	81.2	1.07	33.4
8	10	50	2.5	94.1	95.1	85.3	1.05	47.4
9	10	50	4	95.7	96	80.7	2.05	36.6
10	15	50	2.5	95.4	95.5	81.7	2.02	57.6
11	5	70	1	94.8	95.5	101.5	3.07	43.1
12	5	70	4	96.3	96.8	213	7	43.1
13	10	70	2.5	95.7	96.5	181	3.3	77.3
14	15	70	1	95.6	96.5	86.6	3	55.5
15	15	70	4	96.9	97	106.3	4	38.1
16	10	50	2.5	94.2	95.2	86.3	1.6	56
17	10	50	2.5	93.9	95	54.3	1.75	52
18	10	50	2.5	93.8	95.3	87.3	1.4	50
19	10	50	2.5	94.3	94.9	83.3	1.14	48.5
20	10	50	2.5	92.5	95.8	89.3	2.2	45

Table 4
. ANOVA results for the studied process responses.

Response	Modified equations with significant terms	Probability	R^2	Adj. R^2	Adeq. precision	S.D	CV	Probability for lack of fit
SVI	$83.6116 - 13.347A + 28.083B + 13.903C - 13.8413AB - 12.4038AC + 15.3588 BCE - 12.0081A^2 + 35.5919B^2$	0.0034	0.8193	0.6879	10.6642	20.39	21.39	0.0938
Turbidity	$1.668 - 0.493A + 1.147B + 0.409C - 0.48625AB - 0.56375AC + 0.84375BC + 1.489A^2$	<0.0001	0.9104	0.8581	18.5173	0.5617	23.28	0.1898
COD removal	$93.78 + 0.57A + 1.08B + 0.7C - 0.425AC + 0.275BC + 1.21A^2$	0.0023	0.7513	0.6365	9.2151	0.8621	0.9134	0.2118
BOD removal	$95.065 + 0.25A + 0.11B + 1.41C + 0.125AB + 0.1AC - 0.825BC + 1.825B^2 - 0.675C^2$	<0.0001	0.9281	0.8758	16.1289	0.5162	0.5397	0.759
TN removal	$50.2907 + 7.86A + 4.184B - 0.69C - 4.6125AB - 3.0875BC - 6.85182A^2 + 15.2282B^2 - 16.0018C^2$	0.0010	0.8596	0.7575	11.7863	5.83	12.54	0.1009

and significant difference through the independent T-tests and descriptive tests.

3. Results and discussion

The obtained data of operating the IFAS system under 20 different designed experimental conditions was tabulated in Table 3.

3.1. Statistical analysis

The high degree regression equations (quadratic and two-factor interactions) were used to fit the experimental data and predicted data for

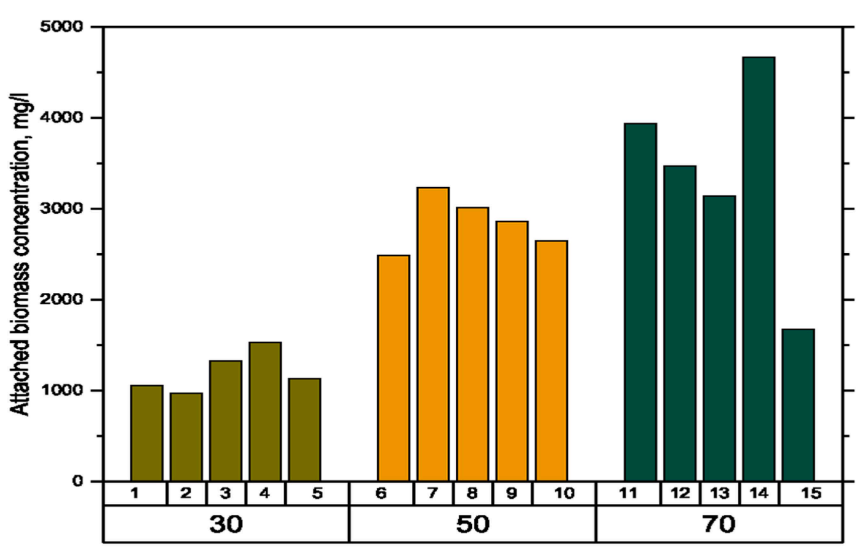


Fig. 2. Biomass concentrations attached on the carriers under different operational conditions.

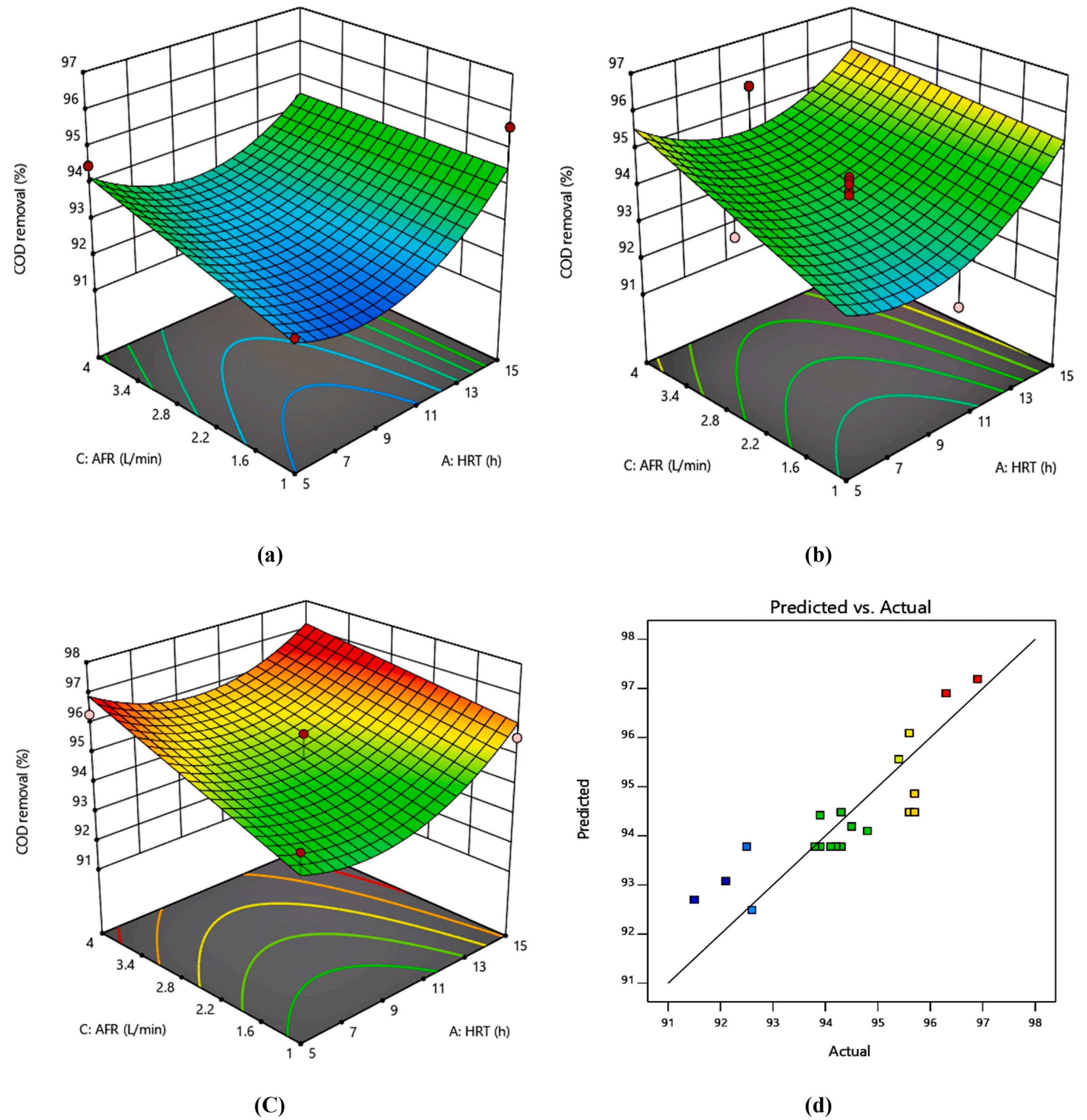


Fig. 3. 3D surface plots for COD removal efficiency at (a) 30 %, (b) 50 %, (c) 70 % of FR, and (d) predicted vs. actual values for COD removal response.

five main responses as shown in Table 4. After removing insignificant model terms, the reduced equations and analysis of variance (ANOVA) for the responses are represented in Table 4. From ANOVA, the model terms with p-value and probability values less than 0.05 and 0.0001, respectively, are considered to be significant at more than 95% of confidence level. The difference between the measured and predicted values could be calculated by the determination coefficient (R-squared). In this research, R^2 was obtained in the range of 0.75–0.92 for different responses, verifying the appropriateness of the models. Adequate precision (Adeq. pre.) reveals a ratio of signal to noise which Adeq. pre, more than 4 is favorite and indicates the powerful signal of the suggested model to be applied. The CV value determines how accurate a process can be, so that the lower it is, the higher the accuracy will be. Coefficient of variation (CV Lack-of-fit represents the adequacy of suggested models. The lack-of-fit should not be significant, verifying that the suggested model is sufficient for prediction.

3.2. *Attached biomass concentration*

The IFAS performance in terms of carbon and nitrogen removal is influenced by attached biomass concentration. Fig. 2 shows the biomass concentration attached to the carrier versus run number in accordance with the operating conditions presented in Table 3. As expected, an obvious ascending trend for attached biomass concentration could be

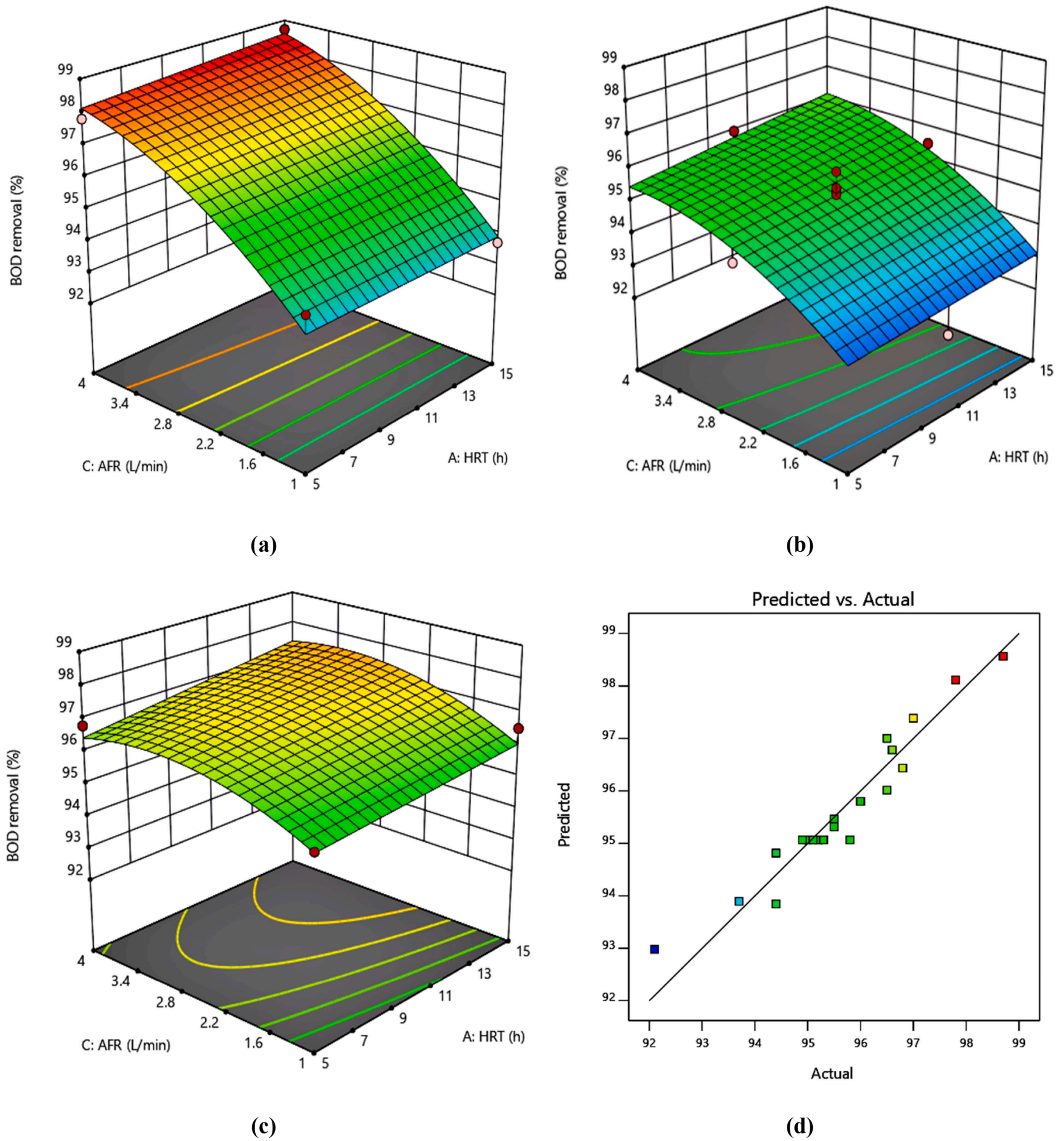


Fig. 4. 3D surface plots for BOD removal efficiency at (a)30 %, (b) 50 %, (c) 70 % of FR, and (d) predicted vs. actual values for BOD removal response. .

observed by increasing FR from 30 to 70 %. This result corroborates that organic loading rates within the applied range of HRT were sufficient (1.6–4.8 kg COD/m^3.d over HRT of 5–15 h) to develop biofilm on more carriers, therefore the attached biomass concentration was boosted totally in the bioreactor as the number of carries increases. As can be seen, at a constant FR, HRT showed a positive effect on the biomass concentration ascribed to the proportionate food to microorganism ratio (F/M) and providing enough time to consume organic matter by microorganisms. In spite of HRT, AFR is inversely proportional to the response, so that the attached biomass concentration increased with mitigation in AFR. This result could be attributed to lower shear stress at lower values of AFR, which lessened the sloughing phenomenon and enhanced the attached biomass concentration. The results displayed that the highest biomass concentration was obtained at HRT of 15 h, AFR of 1 L/min, and FR of 70 %.

3.3. Bioprocess analysis and modeling

3.3.1. COD and BOD_5 removal

The combination effects of HRT, AFR, and FR have been investigated

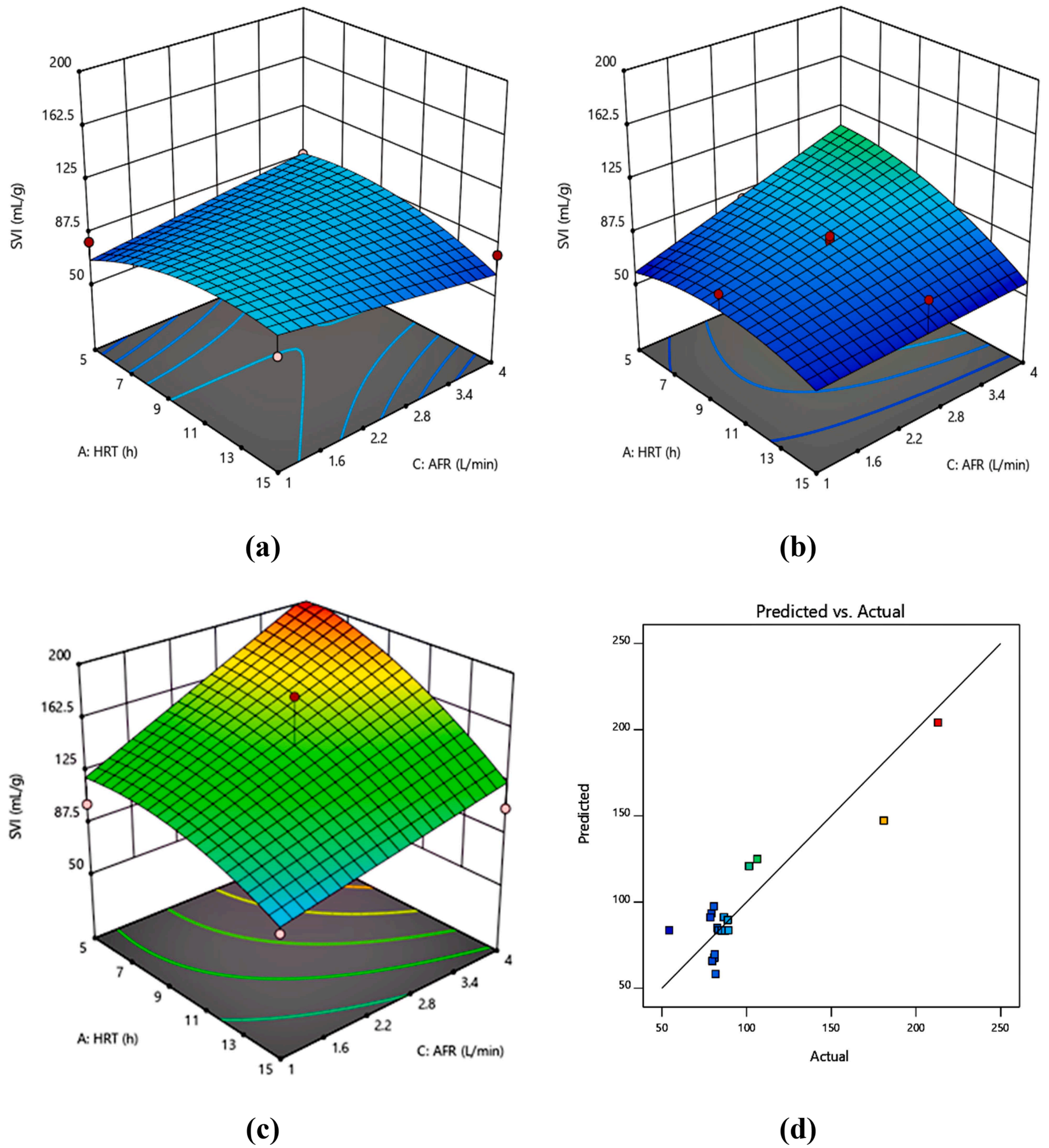


Fig. 5. 3D surface plots for SVI at (a) 30 %, (b) 50 %, (c) 70 % of FR, and (d) predicted vs. actual values for SVI response.

in the present study by measuring COD and BOD_5 in the influent and effluent of the IFAS system under the designed experimental conditions to calculate COD and BOD_5 removal efficiencies. From Table 4, modified quadratic models were utilized to model the attained data under various operational conditions. The models formulate the effect of the variables and their interactions on COD and BOD_5 removal. Figs. 3a-c and Figs. 4a-c illustrate COD and BOD_5 removal as a function of HRT and AFR at three levels of FR, respectively. COD and BOD_5 removal efficiencies were higher than 90 % at all operational conditions, substantiating the upper performance of IFAS in treating Farman industrial estate wastewater. In general, from Figs. 3 and 4a-c, it can be concluded that HRT, AFR, and FR variables have an increasing effect on the efficiency of removing organic compounds. As represented, by increasing FR from 30 to 70 %, the range of COD removal increased to reach 98 % in FR of 70 %. At the lowest HRT value (5 h), a meaningful positive effect of AFR on COD removal could be observed, while its influence has been decreased at higher levels of HRT. The role of oxygen in carbon content digestion by aerobic heterotrophic bacteria is demonstrated by this result. Higher

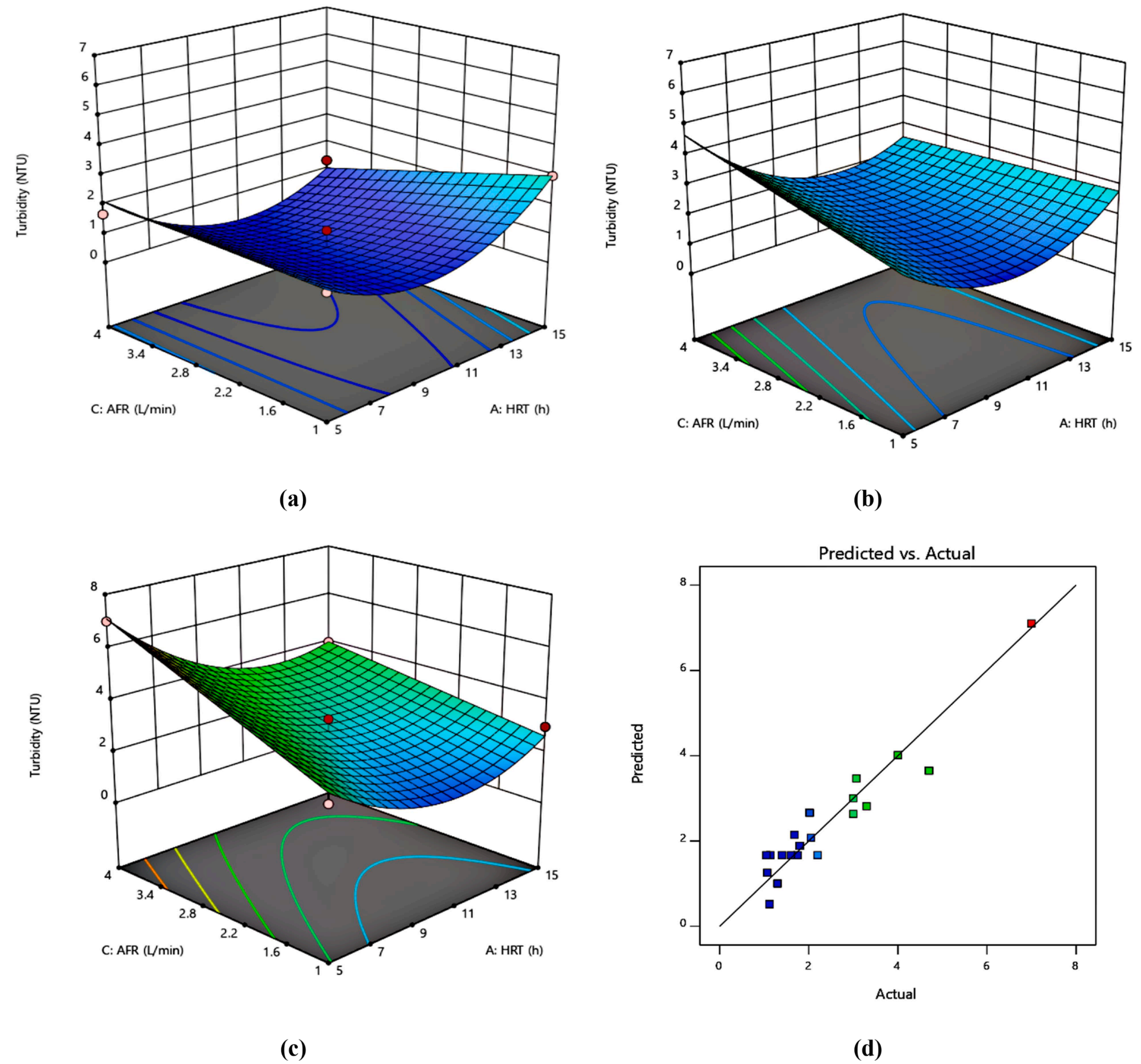


Fig. 6. 3D surface plots for effluent turbidity at (a) 30 %, (b) 50 %, (c) 70 % of FR, and (d) predicted vs. actual values for Turbidity response.

AFR accelerates digestion process by providing upper dissolved oxygen concentration, on the other hand, higher HRT resulted in higher contact time between bacteria and organic content of wastewater to use dissolved oxygen molecules. Therefore, both HRT and AFR play a major role in providing the required oxidation conditions for carbon removal.

It should be noted that by increasing HRT, COD removal decreased by 1–2 % at all three levels of FR, which could be attributable to the secretion of soluble microorganism products (SMP) compounds from bacteria over the upper oxidation potential in the bioreactor leading to normal bacteria growth and metabolism [28]. It seems at OLR values lower than 4 $kgCOD/m^3.d$, SMP secretion was enforced as a result of a reduction in carbon content availability. BOD_5 is a readily biodegradable indicator which based on the results, BOD_5 showed high and stable rejection in all HRTs (5–15 h), indicating its high digestion rate by microorganisms. However, slowly biodegradable COD refers to organic compounds that require more time to decompose by microorganisms and it is calculated by subtracting BOD_5 from COD [29]. As changes in HRT have a more noticeable impact on the removal of COD compared with BOD_5, it can be concluded that the nature of excreted SMP was mainly slowly biodegradable COD. [30].

Moreover, pursuant to Figs. 4a-c, the most effective parameter on BOD_5 removal was AFR at FR of 30 %; however, its effectiveness alleviated as FR increased. This result could be rationalized based on F/M ratio, so that higher values of FR increase the attached biomass as discussed earlier (Fig.2) despite nearly constant suspended biomass (2000 $\pm$200 mg/l) causing a decrease in F/M ratio. The lower F/M ratio leads to higher digestion rate and BOD_5 removal.

Likewise, as shown in Figs. 3d and 4d, the regression equations used were able properly to model the actual data properly as the predicted values showed a good correlation with actual data under different operational conditions.

3.3.2. Sludge volume index

The settling ability of sludge is one of the important parameters in a

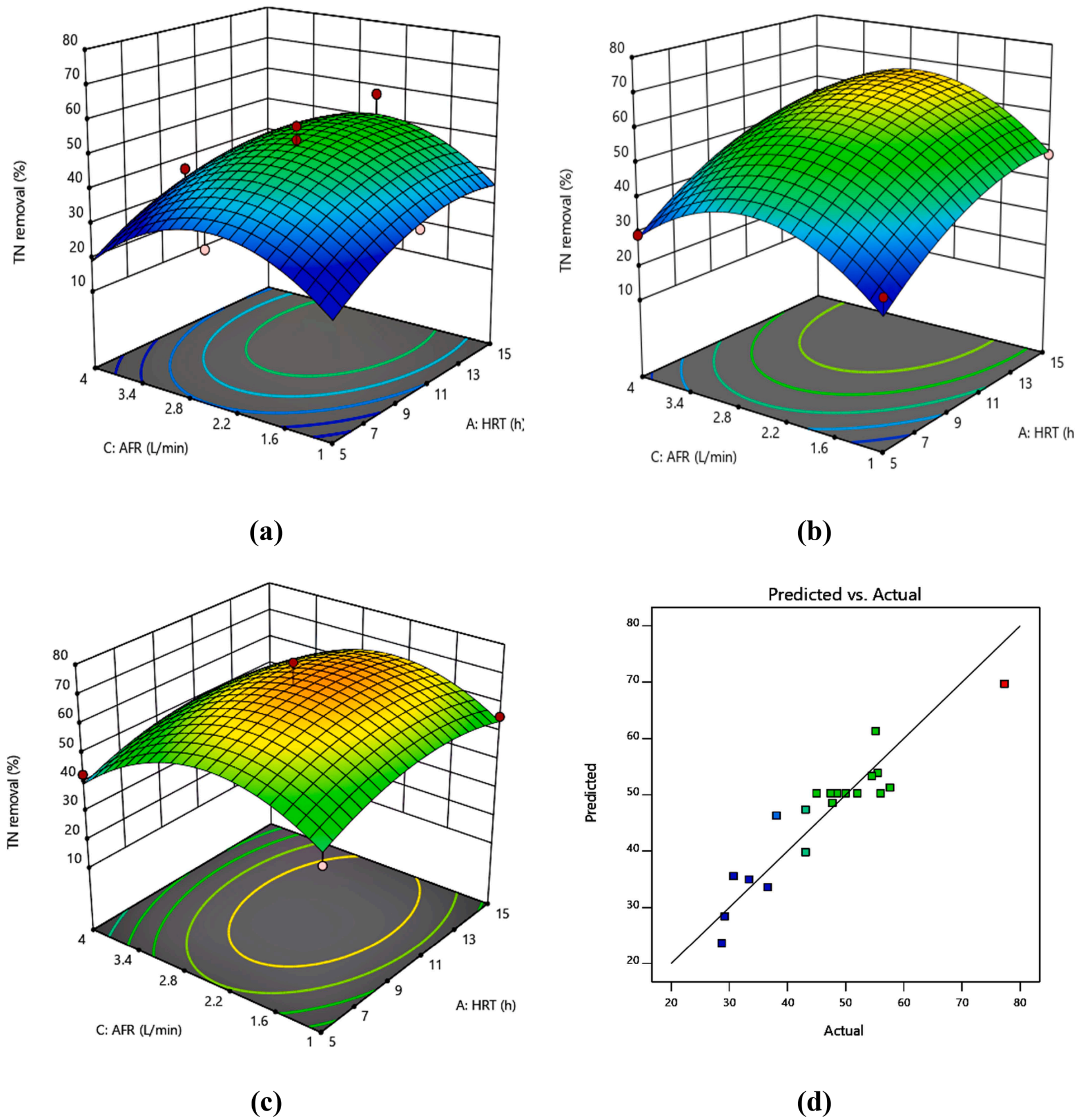
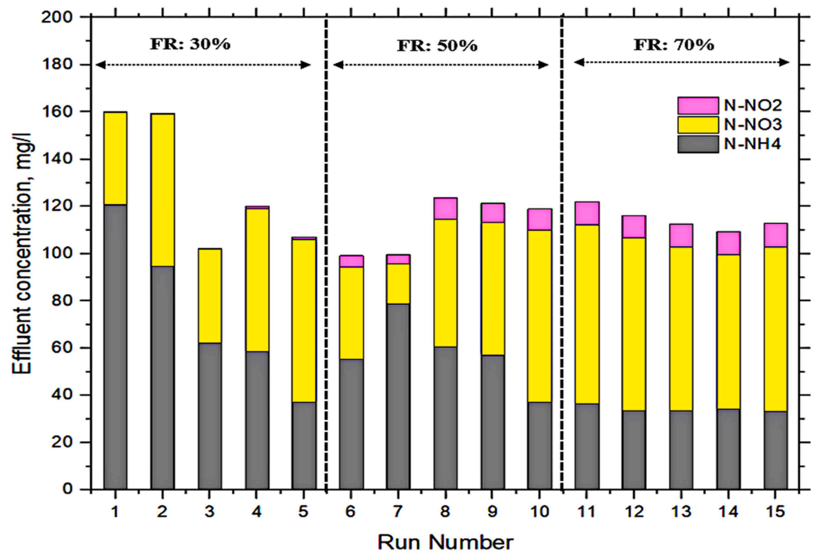


Fig. 7. 3D surface plots for TN removal at (a) 30 %, (b) 50 %, (c) 70 % of FR, and (d) predicted vs. actual values for TN removal response, (e) Nitrogen fractionation of IFAS bioreactor effluent at different operating conditions.

biological process, expressing by the sludge volume index (SVI). As IFAS process integrates attached and suspended biomass, SVI was measured under different operational conditions. The model and ANOVA parameters for SVI were represented in Table 3. Also, Fig. 5a-c indicate the impacts of HRT and AFR on the response at 30 %, 50 %, and 70 % of FR, respectively. As a clear point in the Figs., the reported range of SVI increased when FR reached 70 %, which resulted from lower F/M ratio that worsened the flocculation process. Moreover, from the Figs., it could be found that at HRT of 5 h, AFR showed an increasing impact on SVI, so that the maximum SVI was predicted to be 200 ml/g at FR, HRT, and AFR of 70 %, 5 h, and 4 l/min, respectively. This finding is related to the proliferation of filamentous bacteria under higher shear stress conditions (AFR of 4 l/min) along with higher OLR (4.8 kg COD/m^3.d) and enforced COD removal speed (higher oxidation potential) [31]. Conversely, with increasing HRT at AFR of 4, SVI considerably decreased to 125 ml/g at FR of 70 % owing to lower OLR, leading to preventing filamentous bacteria from multiplying. It is worth noting that at AFR of 1 l/min, SVI was not influenced by HRT as shear stress and oxidation potential were diminished. Furthermore, Fig.5d illustrates a good correlation between predicted and actual values.



(e)

Fig. 7. (*continued*).

3.3.3. Effluent turbidity

Effluent turbidity is an indicator for monitoring effluent quality and system stability. The regression equation obtained to describe the variations of effluent turbidity is shown in Table 4. According to the model, A, B, C, AB, AC, BC, and A^2 were effective model terms for the response. The changing trend of the response as a function of HRT and AFR at various FR could be observed in a 3D surface plot (Fig. 6a-c). Overall, the effluent turbidity of the bioreactor was found to be less than 6 NTU under various operating conditions, corroborating a prosperous biological treatment process. When the FR is increased to 70 %, a larger portion of the reactor's volume will be occupied by carriers' surfaces for attaching biofilm, resulting in a lower amount organic matter available for the high microbial population in the system (low F/M ratio). Under these circumstances, insufficient organic matter resulted in the detachment of some attached biomass into the effluent, thereby increasing the effluent turbidity.

On the other hand, the maximum effluent turbidity was reported at higher shear stress (AFR) and OLR (lower HRT) that stimulated the growth of filamentous bacteria in suspended biomass, which could be a possible reason for the obtained result. This outcome is consistent with SVI results which discussed earlier. The minimum value of the effluent turbidity was 1.14 NTU obtained at HRT of 10 h and AFR of 2.5 L/min at 50 % FR, respectively. Similar to other responses, Fig.6d corroborated an appropriate correlation between modeled and actual data.

3.3.4. TN removal

Simultaneous nitrification and denitrification (SND) processes occurred via the simultaneous activity of two bacterial species, including heterotrophic denitrifiers and autotrophic nitrifiers. In the IFAS system, anoxic micro-zones may appear in the inner layer of the developed biofilm on carriers under continuous aeration conditions. Therefore, the co-occurrence of aerobic and anoxic zones could be befallen in IFAS system due to the outer and inner layers of the formed biofilm. Consequently, TN removal efficiency was assessed as a response at different operating conditions. TN was determined by measuring all of the nitrogen constituents in the effluent (N-organic, ammonia, nitrite, and nitrate). According to the regression equation of TN removal efficiency (Table 4), A, B, C, AB, BC, A^2, B^2, and C^2 are effective model terms. The effects of HRT and AFR at 30 %, 50 %, and 70 % of FR on TN removal efficiency are illustrated in Figs. 7a-c, respectively. According to Figs. 7a-c, TN removal displayed an ascending trend as FR increased owing to increasing the number of carriers and biomass concentration (Section 3.1). Simultaneously increasing HRT from 5 to 10 h and AFR from 1 to 2.5 L/min at each FR revealed an incremental impact on TN removal response. The positive effect of HRT on the response was related to the mitigation of OLR (4.8 to 2.4 kg/m^3.d), thereby providing a preferred situation for autotrophic nitrifier proliferation in competition with heterotrophic bacteria.

On the other hand, by increasing AFR, the availability of dissolved oxygen has been increased for the attached and suspended biomass, resulting in aerobic nitrifying bacteria growing. It can be deduced from the discussed results, at lower HRT and AFR, TN removal efficiency was controlled by NO_3^- diffusion into inner layers of biofilm, whereas denitrification process potentially proceeded. In recapitulate, with increasing NO_3^- in the bulk, driving force for NO_3 diffusion has been augmented.

Conversely, a deleterious impact on TN removal was reported with further increase in HRT and AFR to 15 h and 4 l/min, which resulted from the development of aerobic zones in the bioreactor, led to inadequate anoxic micro-zones in the inner layers of the biofilm. As a fact, at the highest AFR, an augmented turbulent flow along with higher injection of oxygen molecules in the bioreactor, providing an upper homogenous dissolved oxygen concentration in the bulk and narrowing diffusion layer close to biofilm surface caused a noteworthy diffusion of oxygen into inner layers of the attached biofilm. Increased HRT corresponded to lower values of OLR, which played a similar role as AFR, reducing oxygen uptake rate, triggering a rise in dissolved oxygen levels in the bioreactor. The maximum TN removal efficiency was achieved to be 77.3 % at AFR of 2.5 l/min, HRT of 10 h, and FR of 70 %.

Moreover, nitrogen removal was investigated in depth by depicting the various ratio of nitrogen fractions ($N—NO_2$, $N—NO_3$, $N—NH_4^+$) in the bioreactor effluent under different operating conditions, as shown in Fig. 7e (the order of presenting runs was arranged based on Table 3). As a bold point in Fig. 7e, the conversion of ammonia was highlighted by increasing FR from 30 to 70 %. The higher the biomass concentration, the higher the ammonia removal as a result of the developed nitrifiers community. Another point found in Fig. 7e. is that an increase in HRT and AFR illustrated a positive effect on nitrification process as $N—NO_3$ and $N—NO_2$ were glaringly produced when HRT and AFR were set at their highest levels (see runs 5, 10, and 15). This is attributable to provide upper oxidation potential along with lower organic loading rate, preferring to nitrifiers proliferation as reported in the literature [29]. At

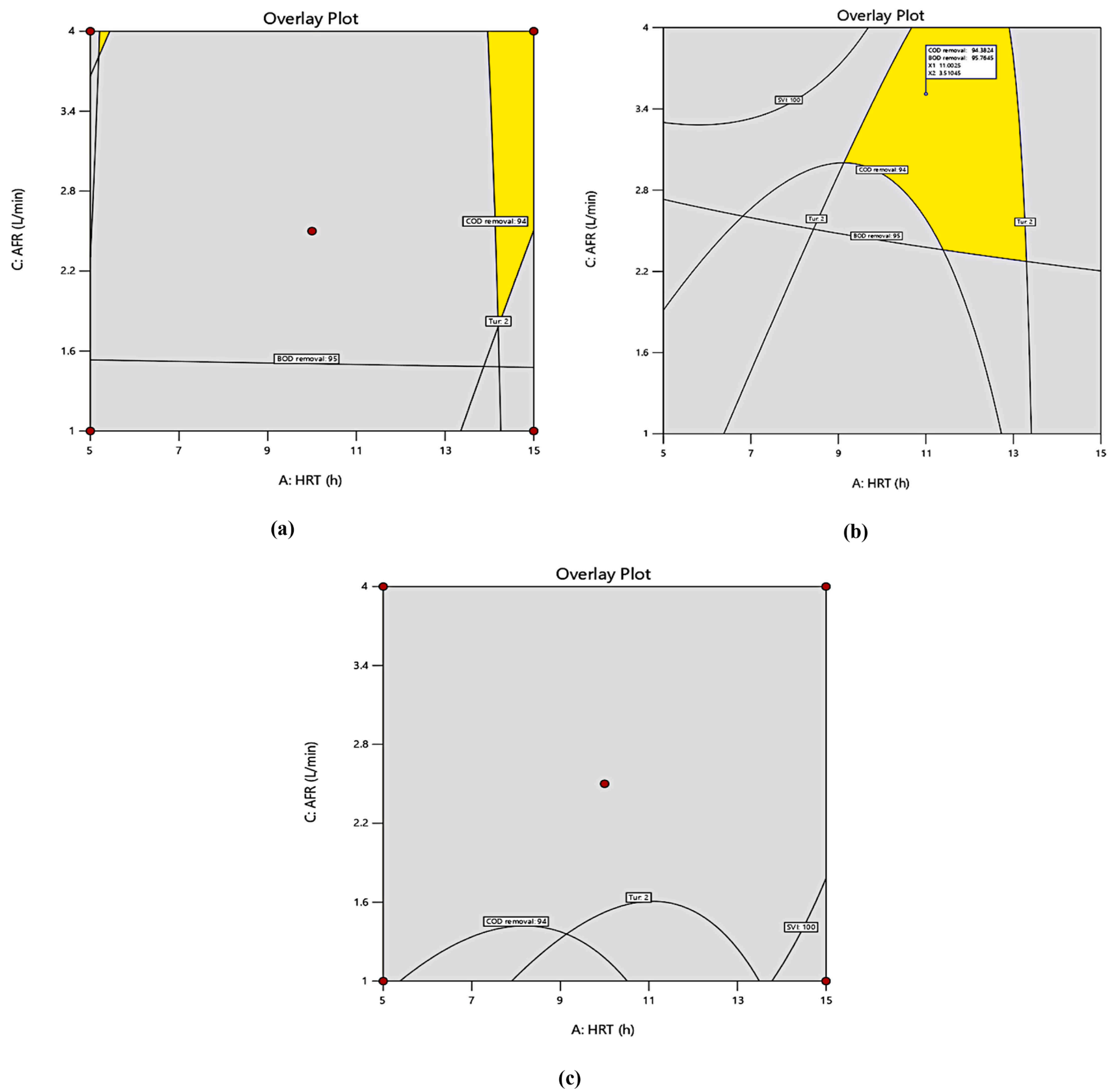


Fig. 8. Overly plot for the optimum region.

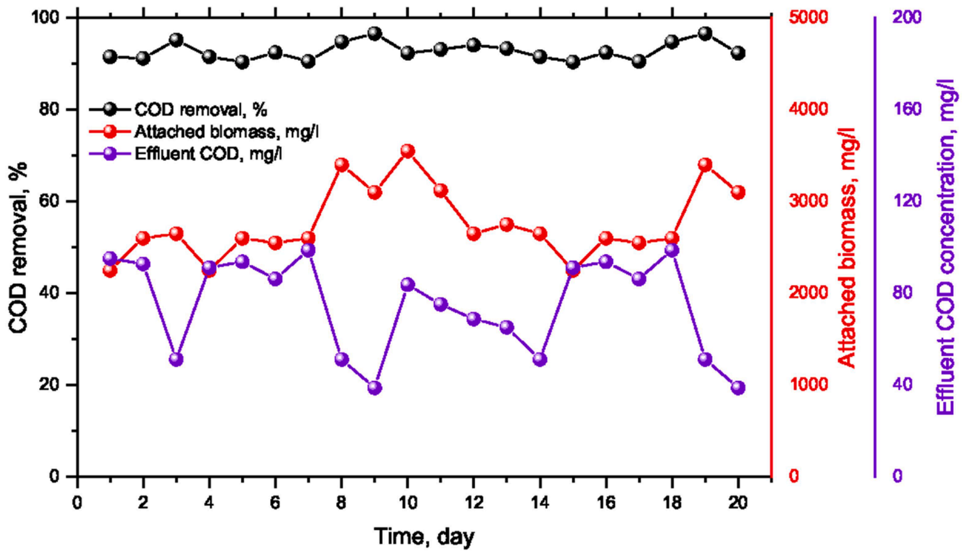
FRs of 50 and 70 %, NO_2^- appeared in the bioreactor effluent and also ammonia conversion process was augmented, implying that ammonia-oxidizing bacteria (AOB) multiply more than nitrite-oxidizing bacteria (NOB).

3.4. Optimization of bioprocess

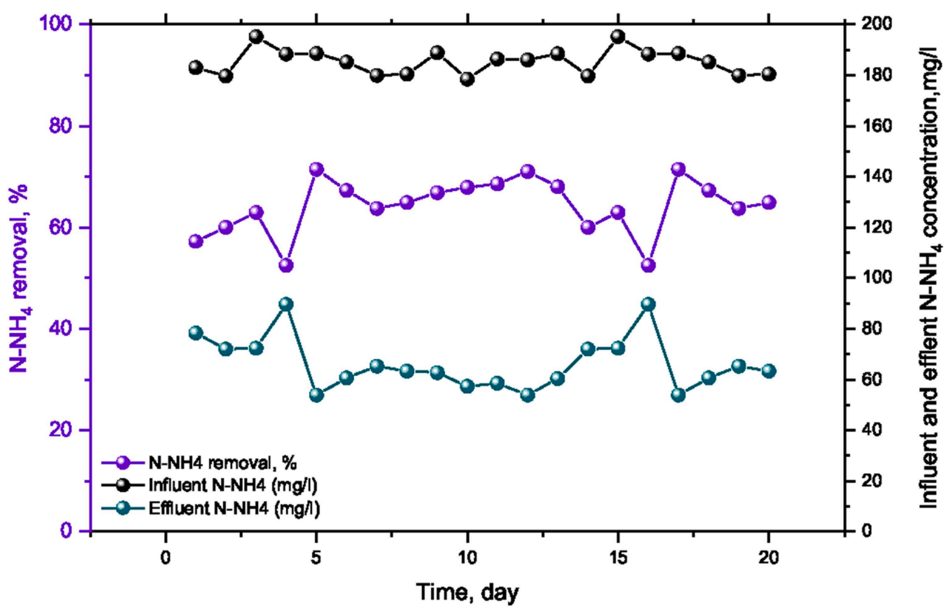
Graphical optimization depicts an overlay plot of the contour graphs to represent the areas where the criteria are considered. To obtain the optimum region of the IFAS performance, favorable values of five main criteria, including COD removal (≥ 94 %), BOD removal (≥ 95 %), effluent turbidity (≤ 2 NTU), SVI (≤ 100 ml/g), and TN removal (28–77 %) have been designated. The graphical optimization plots for three levels of FR were demonstrated in Fig.8. The yellow regions indicate the conditions covering the favorable criteria. From the Fig., a substantial yellow region for 50 % of FR has been attained; however, an optimum region was not recognized for 70 % of FR and also a narrow yellow region for 30 % of FR was revealed. With regard to the vast optimum region in 50 % of FR, a condition falling into the yellow region of 50 % of

Table 5
The predicted and actual values of the optimum condition.

	Responses COD removal,%	TN removal,%	Effluent turbidity, NTU	SVI, ml/g
Experimental values	94.4	45.5	2	84
Model value	95.18	43.36	1.86	87.32
Standard deviation	0.55	1.41	0.14	2.12



(a)



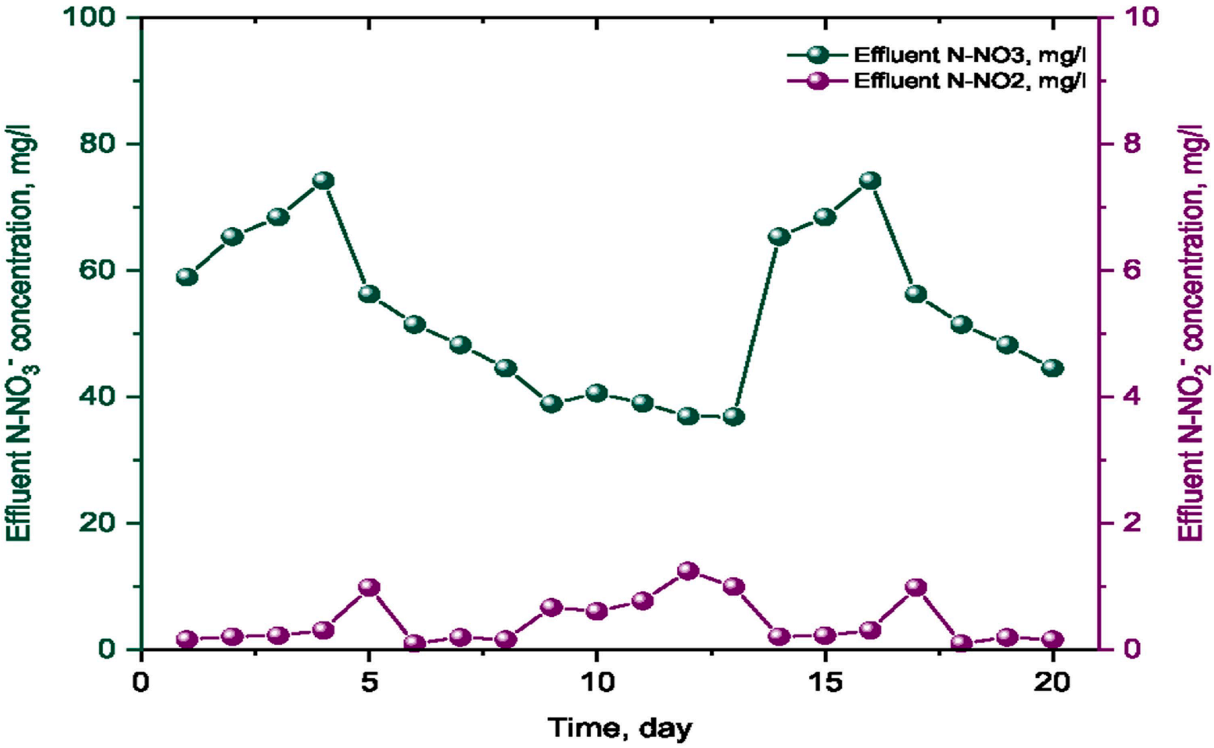
(b)

Fig.9. Long-term performance of the IFAS system in terms of a) COD removal and attached biomass concentration, b) N—NH_4 removal, c) the effluent N—NO_3 and N—NO_2 concentrations.

FR was selected to validate the modeled optimum region. The bioreactor was operated according to an experimental condition with HRT of 11 h, AFR of 3.5 l/min, and FR of 50 %, as indicated by the flag in Fig. 8b. The actual and predicted data along with the standard deviation for each response have been listed in Table 5. From the presented standard deviation for each response, it can be concluded that there is good consistency between the predicted and actual data, indicating the outstanding accuracy of the proposed model. To complement the research, the bioreactor was operated under the obtained optimum condition for 30 days.

3.5. Long-term performance evaluation

The IFAS system was operated pursuant to the achieved optimal condition for 20 days to evaluate the sustainability of the system. The changing profiles of COD removal and attached biomass over 20 days have been reported in Fig.9a. Despite the fluctuation of the attached biomass on the carriers from 2250 to 3400 mg/l, COD removal was achieved in the range of 91 %-96 %. This outcome implies that the IFAS system is prone to supply nearly steady COD removal under constant operation conditions. In fact, the deficiency of attached biomass resulted from occasional sloughing can be compensated by the suspended biomass (set on 2000±200 mg/l). Therefore, the IFAS system could be



(c)

Fig.9. (*continued*).

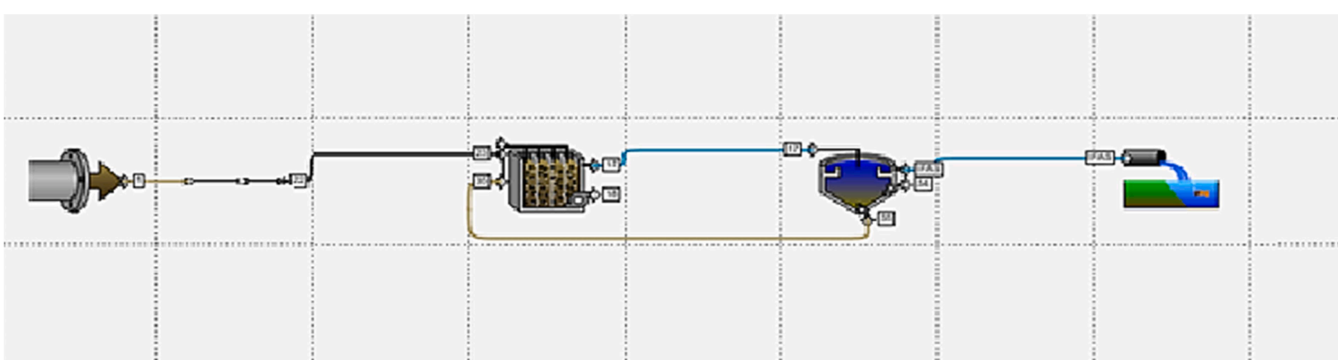


Fig. 10. General layout of IFAS bioreactor model in the GPS-X.

operated as a reliable treatment system.

Likewise, the profiles of N—NH_4 removal alongside influent and effluent N—NH_4 are illustrated in Fig.9b. An interesting result can be found from Fig.9c, in which N—NH_4 removal was meaningfully influenced by the fluctuated attached biomass concentration compared with COD removal as its altering range was 57–71 %. This finding confirms the highlighted role of attached biomass in the conversion of ammonia to oxidized species.

Similarly, the effluent N—NO_3 and N—NO_2 concentrations were reported over 20 days. Effluent N—NO_3 showed more fluctuations than N—NO_2; N—NO_3 and N—NO_2 changed in the range of 36–74 mg/l and 0.15–0.98 mg/l, respectively. The effluent N—NO_3 concentration depends on the tread-off between the nitrification and denitrification processes, which restricts anoxic micro-zones or an unbalanced developed nitrification process leads to an enhancement in N—NO_3 concentration.

3.6. *Data evaluation for verification of GPS-X model*

The bioreactor performance has been successfully simulated using the GPS-X software package. Fig. 10 displays the general layout of the simulated IFAS model in the GPS-X. The GPSX-simulation results and experimental data in terms of total biomass concentration, influent COD, effluent COD, and COD removal under 15 non-repetitive runs designed by DOE (IFAS system was operated based on them) were tabulated in Table 6. Moreover, in order to evaluate the calibration quality of GPS-X model, their standard deviation (SD) was also assessed. The SD values corroborate that GPS-X-simulation data were in concordance with the experimental data.

SPSS software was used to dig deeper into the versatility of the experimental and GPS-X-simulation data. An independent sample T-test was performed for the two simulated and actual data sets to designate significant or insignificant differences between them. The results are

Table 6
Simulated results versus actual data for IFAS system.

Designed operating variables			Total biomass concentration, mg/l			Influent COD, mg/l			Effluent COD, mg/l			COD removal, %		
FR, %	AFR, l/min	HRT, HRT	Actual	GPSX-simulation	SD	Actual	GPSX-simulation	SD	Actual	GPSX-simulation	SD	Actual	GPSX-simulation	SD
0.3	4	5	4110	4292	128.69	1182.5	1180	1.76	91.25	97.3	4.27	92.28	91.75	0.37
0.3	1	5	4660	4710	35.355	937.5	937	0.35	68.75	58	7.60	92.66	93.81	0.80
0.3	2.5	10	3126	3155	20.51	1077.5	1077.5	0	116.25	98.6	12.48	89.21	90.84	1.15
0.3	1	15	3389	3320	48.79	927.5	927.3	0.14	59.75	71	7.95	93.56	92.34	0.85
0.3	4	15	3423	3425	1.41	1007.5	1007	0.35	43.75	46	1.59	95.65	95.43	0.15
0.5	2.5	15	5199	5120	55.86	1007.5	1007	0.35	46.25	34	8.66	95.41	96.62	0.86
0.5	2.5	10	5286	5120	117.37	1102.5	1102	0.35	66	74.2	5.79	94.01	93.26	0.52
0.5	4	10	5336	5235	71.417	1027.5	1027	0.35	81.25	98.4	12.13	92.09	90.41	1.18
0.5	2.5	10	4708	4820	79.19	1037.5	1037	0.35	43.75	46	1.59	95.78	95.56	0.15
0.5	1	5	4388	4350	26.87	1082.5	1080	1.76	66.25	81.3	10.64	93.87	92.47	0.99
0.7	4	15	3874	3855	13.43	1093.75	1093	0.53	34	21.4	8.91	96.89	98.04	0.81
0.7	1	5	6289	5955	236.17	852.5	852	0.35	43.75	36.7	4.98	94.86	95.69	0.58
0.7	2.5	15	6668	6655	9.19	1032.5	1032	0.35	48.75	42.9	4.13	95.27	95.84	0.39
0.7	1	10	5939	6006	47.37	1027.5	1027	0.35	46.25	71.2	17.64	95.49	93.06	1.72
0.7	4	5	5588.5	5602	9.54	1067.5	1067	0.35	41.25	73.6	22.87	96.13	93.10	2.14

Table 7
Independent sample T-test of total biomass concentration and COD removal.

		Levene's Test for Equality of Variances		*t*-test for Equality of Means						
		F	Sig.	t	Df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95 % Confidence Interval of the Difference	
									Lower	Upper
Total biomass concentration	Equal variances assumed	.064	.803	.062	28	**.951**	24.23333	389.96465	-774.57305	823.03971
	Equal variances not assumed			.062	27.965	**.951**	24.23333	389.96465	-774.61753	823.08420
COD removal	Equal variances assumed	.442	.511	.427	28	**.673**	.32977	.77211	-1.25182	1.91135
	Equal variances not assumed			.427	27.718	**.673**	.32977	.77211	-1.25255	1.91208

Table 8
The performance and parameters comparison of some published IFAS bioreactors.

Wastewater	FR (%)	DO (mg/l)	HRT (h)	MLSS (g/L)	Influent (mg/l)	N removal (%)	COD removal (%)	Ref.
Reject water from a mesophilic anaerobic sludge digester	43	0.1–1	24	2	COD = 414±150 BOD = 29±5 NH_4^+-*N* = 907±200	NH_4^+-N removal=95 % TN removal=90 %	–	[20]
Oil sands process-affected water	60	6–7	96	Suspended 1.44 attached 0.84	COD=297.86±5.67 NH_4^+-*N* = 59.08±2.1	NH_4^+-N removal=100 %	54.6	[23]
Synthetic ammonium-rich	15	0.3–0.5	21.8–24	3	COD=108–331 NH_4^+-*N* = 173–1490	TN removal=80 %	69	[21]
Domestic	40	1	180 d	1	tCOD=49–106 sCOD=44–88 NH_4^+=35–50	TN removal=70±4 %	–	[32]
Domestic	19	2–4	8	5.9	COD=411.9 ± 33.1 TN=49.5 ± 7.9	NH_4^+-N removal=95 % TN removal=42 %	93.4	[33]
Domestic	80	0.15–0.36	7–10	Suspended 3.06 Attached 5.12	COD=56.1 ± 18.6 TN=44.2 ± 4.9	TN removal=82 %,	rate=0.026 kg COD/(m3 d)	[34]
Faraman industrial estate wastewater	50	AFR=3.5	11	Suspended=2	COD=939–1090 BOD_5=185–845 TN=173–221	TN removal=77.3 %,	94	This study

summarized in Table 7. As the total biomass concentration and COD removal were calculated to be 0.95 and 0.673, respectively ($p > 0.05$), it can be inferred that no significant discrepancy exists between the two data sets. The noteworthy matching of the experimental and GPS-X-simulation data proves that GPS-X can be properly calibrated for modelling the IFAS system to treat Faraman industrial estate wastewater. Therefore. GPS-X can be considered as a reliable software to predict the effluent quality of IFAS systems by changing the operating parameters.

3.7. Comparative study of literature data for IFAS system

In order to provide deeper insight into the capability of the operated IFAS system in the present study, the performances of some relevant studies have been recapitulated in Table 8. Pursuant to the table, IFAS system displayed a remarkable potential to remove COD and TN compared to other published works. The reported IFAS for treating domestic wastewater exhibited a good performance for COD removal (93.4 %); however, it should be noted that the influent COD was nearly the half of the influent COD of Faraman industrial wastewater. Considering the influent characteristics (COD and TN content) and also operating parameters, it could be found that the IFAS operated in the present study revealed an outstanding performance in removing COD and TN under the continuous aeration strategy. As a result, the operating condition of IFAS plays a main role to reach an upper removal performance and the selected range of the operating parameters in terms of FR (50 %), HRT (11 h) and AFR (3.5 l/min) can be considered as a guideline for the efficacious operation of IFAS systems.

Conclusion

The treatment of industrial estate wastewater in terms of carbon and nitrogen removal in an IFAS system operating under continuous aeration regime was optimized by using DOE software in the present research. The effects of three independent variables, namely, filling ratio (FR), hydraulic retention time (HRT), and air flow rate (AFR) were considered for designing experimental conditions by RSM. According to the actual data obtained from operating the IFAS system, the optimum condition was obtained with HRT, AFR, and FR of 11 h, 3.5 L/min, and 50 %, respectively, providing more than 94 % COD removal, 95 % BOD removal, and 77 % TN removal. Likewise, the IFAS system showed good stability in treating the industrial wastewater over 20 operational days under the optimum conditions, implying that IFAS system could be a promising process to upgrade industrial wastewater treatment plants. On the other hand, the performance of IFAS under the designed operating conditions was satisfactorily simulated using GPS-X. To assess the conformity of the actual data and GPS-X model, the GPS-X calibrated model was verified via SPSS. T-test has verified that there are no significant discrepancies between the actual data and GPS-X results.

CRediT authorship contribution statement

Mina Dolatshah: Writing – original draft, Software. **Azar Asadi:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Foad Gholami:** Writing – original draft, Supervision, Investigation. **Safoora Nazari:** Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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