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# Performance enhancement of up-flow anaerobic sludge blanket reactor for psychrophilic temperature during the dry season: Kality wastewater treatment plant

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ABSTRACT

The main purpose of wastewater treatment plant (WWTP) is to reduce organic and inorganic pollutants to meet standards. But WWTPs employing up flow anaerobic sludge blanket (UASB) reactors under psychrophilic temperature are currently removing about 55% chemical oxygen demand (COD) and 70% total dissolved solids (TSS). The research was done to increase the treatment efficiencies of UASB reactor working under psychrophilic conditions through optimization of operational parameters like temperature, organic loading rate (OLR), pH and hydraulic retention time (HRT). Experimentation was carried out in a 0.0486 $m^3$ square-shaped pilot-scale UASB reactor. Experimental design response surface method (RSM) for performance enhancement and optimization of UASB reactor operational parameters through five levels of central composite design (CCD) was used. The optimized operational parameters obtained from CCD-RSM were as follows: temperature of 21.58 °C, OLR of 2.99 kg $COD/m^3.d$, HRT of 4.37hrs and pH of 6.3. Using optimized parameters, tests yielded efficiencies of 92.70%, 99.06%, and 94.50% for COD, TSS, and volatile suspended solid (VSS) respectively. The outlet concentrations of alkalinity, and volatile fatty acids (VFA), were found to be lower than the inlet concentrations. The alkalinity in the system accepts the hydrogen ion released by acids and the system is taken over by methanogensis to maintain the pH. The outlet concentration of sulfate ion was found to be increasing due to inhabitation of sulfur-reducing bacteria by an anaerobic condition of VFA and alkalinity at a pH less than 7.8.This process favors the production of $CH_4$ than $H_2S$ gas. In general, there was a high likelihood of improving the performance of UASB reactor operating at psychrophilic temperature by optimizing operational parameters.

## 1. Introduction

One of several anaerobic wastewater treatment processes is the up-flow anaerobic sludge blanket (UASB) reactor. The UASB reactor is a popular method for removing organic matter from wastewater [1]. It is an anaerobic process in which microorganisms remove organic matter. It does not require any media to grow microorganisms and has lower operation and maintenance costs than aerobic treatment. The UASB reactor can treat both domestic and industrial wastewater because it performs better in mesophilic conditions [2–4]]. It may be the best method for treating these two types of wastewater in developing countries [5,6]. The main objectives of

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wastewater treatment plants are to reduce the organic and inorganic pollutants in the wastewater while enhancing the treatment efficiency. The treatment efficiency of the UASB reactor is evaluated using the removal efficiencies of the biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solid (TSS), and total dissolved solid (TDS) [7–9]. An increase in treatment efficiency of the WWTP is in line with the sustainable development goals (SDGs) that states, in the year 2030 the quality of the water either supplied or discharged to the environment should be improved by reducing pollution, minimizing toxic metals and halving the proportion of untreated wastewater and increasing water reuse and recycling. To foster SDGs, many researchers considered various operational parameters in order to remove these pollutants and improve the treatment efficiency of the UASB reactor. To increase the performance of UASB reactor, there were researchers that considered HRT to be the only parameter. These researchers treated wastewater under various HRT (15.7 to 8d) and discovered optimal COD removal ranges ranging from 86.3% to 90.6% [10].Again in the other research done by Klesyk D. [11], they considered HRT as a sole parameter to increase the performance efficiency of the UASB reactor through the control of temperature, flow and up flow velocity. But, they concluded changes in HRT would not result in an expected result. Other researchers demonstrated that, HRT was not the only parameter that improves the performance of the UASB reactor. They combined temperature (10–20 °C) with fixed HRT (6hrs.) and found COD removal of 60 ± 4.5% and 51.5 ± 5.5% at 12.5–20 °C [12]. Other researchers also combined temperature and HRT to look the performance efficiency of UASB reactor. They used a fixed HRT of 4.7 days at temperatures ranging from 13 °C to 25 °C and achieved a COD removal efficiency of 70%.They eventually concluded that the UASB reactor's removal efficiency was not only affected by the combined effect of HRT and temperature, but also by influent strength, particularly on COD concentration [13,14].But other researcher tried to associate the effect of up flow velocity on the combined effects of temperature and HRT. They concluded that, as long as you keep the up flow velocity lower than 0.35 m/h, the removal efficiency of the UASB reactor remains constant for that specific temperature (82% for 28 °C, 68% for 14 °C and 44% for 10 °C) [15]. Furthermore, researchers also tried to increase the removal efficiency of the UASB reactor by considering a fixed HRT (3hrs.) and OLR (4kgCOD/m$^3$.d) at an ambient temperature. They concluded that 90–92% COD and 94–96% BOD reductions were achieved [16]. Again in the research done by Ref. [17],they determined the removal efficiency of the UASB reactor for a fixed OLR(1kgCOD/m$^3$.d) and HRT(8.74d) and obtained 78% COD and 53% TSS. This experimental study was done for one thing several researcher combined only two different operational parameters to enhance the performance efficiency of the UASB reactor. For another thing, the study was conducted since the WWTP's UASB reactor's manual set a removal efficiency of 55% for COD and 70% for TSS at psychrophilic temperature. Hence, the combined effect of two parameters for psychrophilic temperature will not permanently result in an increase in removal efficiency for UASB reactor. Therefore, this study focuses on the optimization of operational parameters such as temperature, OLR, HRT, and pH that enhances the removal efficiency at psychrophilic temperature. For optimization of these operational parameters CCD-RSM tool was used. The tool was also used to develop models that show the percentage removal of COD, TSS and VSS. It also graphically gives the combined effect of operational parameters on the COD, TSS and VSS removal.

**Table 1**
HRT values for 30 experimental runs.

| Experimental number | Temperature(°C) | pH | OLR (kgCOD/m$^3$.d) | Inlet COD (mg/l) | HRT (hrs.) |
|---|---|---|---|---|---|
| 1 | 30 | 6.30 | 1 | 80 | 1.92 |
| 2 | 30 | 6.30 | 3 | 580 | 4.64 |
| 3 | 30 | 7.80 | 3 | 730 | 5.84 |
| 4 | 30 | 7.80 | 3 | 840 | 6.43 |
| 5 | 30 | 6.30 | 3 | 580 | 4.64 |
| 6 | 30 | 7.80 | 3 | 550 | 4.25 |
| 7 | 15 | 5.55 | 2 | 590 | 7.05 |
| 8 | 30 | 7.05 | 2 | 690 | 8.17 |
| 9 | 15 | 7.05 | 2 | 490 | 5.53 |
| 10 | 15 | 7.05 | 4 | 790 | 4.45 |
| 11 | 15 | 7.05 | 2 | 480 | 5.46 |
| 12 | 15 | 7.05 | 2 | 830 | 9.57 |
| 13 | 15 | 7.05 | 2 | 530 | 6.22 |
| 14 | 15 | 7.05 | 2 | 540 | 6.29 |
| 15 | 15 | 7.05 | 2 | 740 | 8.53 |
| 16 | 15 | 7.05 | 2 | 700 | 8.24 |
| 17 | 15 | 8.55 | 2 | 640 | 7.41 |
| 18 | 0 | 6.30 | 3 | 800 | 6.24 |
| 19 | 0 | 6.30 | 3 | 990 | 7.55 |
| 20 | 0 | 6.30 | 1 | 730 | 17.32 |
| 21 | 0 | 6.30 | 1 | 540 | 12.58 |
| 22 | 0 | 7.80 | 3 | 700 | 5.36 |
| 23 | 0 | 7.80 | 3 | 610 | 4.53 |
| 24 | 0 | 7.80 | 1 | 980 | 23.32 |
| 25 | 0 | 7.80 | 1 | 830 | 19.53 |
| 26 | −5 | 7.05 | 2 | 830 | 9.58 |
| 27 | 45 | 7.05 | 2 | 810 | 9.44 |
| 28 | 15 | 7.05 | 0 | 850 | 0.00 |
| 29 | 15 | 7.05 | 0 | 980 | 0.00 |
| 30 | 15 | 7.05 | 0 | 720 | 0.00 |

## 2. Materials and methods

### 2.1. Chemicals and materials

Tables 1 and 2 illustrate the instruments/apparatuses and chemicals utilized throughout the experimental research (Supplemental-Tables 1 and 2).

### 2.2. Experimental reactor set up

The experimental reactor setup consisted of a barrel filled with 100L of water and refrigerator's evaporator mounted on opposite sides of the barrel. Evaporators were linked to the compressors, radiator, and supply fan mounted on the setup's exterior which was used for cooling the wastewater. Inside the water-filled barrel, a 2500W heater was installed. It was used to heat the wastewater when the temperature of the wastewater was needed to be raised. A timer, thermostat, and temperature sensors were all part of the control board panel. The cooling system, heating system, the sensor and the power sources were finally connected to the process integrated derivatives (PID) control board. The PID control board was the master mind to control temperature, HRT, heating and cooling systems in the pilot scale UASB reactor. Measuring the initial concentration of COD of the sample wastewater helps to determine HRT which later on was filled in the timer. The HRT determined the length of time the wastewater stayed in the pilot scale reactor. The thermostat on the PID was used to set the experimentally required temperature which was obtained from CCD-RSM tool, and the reactor sensor was used to sense the wastewater temperature. A 0.0486 $m^3$ square reactor was immersed inside the barrel and filled with wastewater. This volume of reactor was used for experimentation, for one thing since a compressor(hp) of higher capacity for cooling can't be found locally and for another thing to make manageable inlet and outlet wastewater. Finally the barrel and pilot scale UASB reactor were wrapped with aluminum insulator to preserve the wastewater temperature. The strength of this research was that the inversion of the PID control board for data collection through the control of temperature by heating and cooling systems,and HRT.The reactor set up with the PID control board can stand by itself like WWTP employing UASB reactor for data collection.Further, the achievement of higher %COD, %TSS and %VSS than the removal deficiency set by the manual makes the research outstanding. Moreover, higher removal efficiency through the optimization of operational parameters for psychrophilic temperature with out incurring energy was the great achievement for this research.Fig. 1 depicts the reactor setup used with the pilot scale reactor for the experiment (see Fig. 2).

### 2.3. Inoculation of the pilot UASB reactor

It is well known that UASB rector takes a couple of months(around 120 days) for startup [18,19]. 10L of sludge was taken from the sludge blanket zone of the existing WWTP's UASB reactor and inoculated to the experimental pilot scale UASB reactor to shorten the startup period.

### 2.4. Sampling techniques

For every 30 experimental runs obtained from CCD-RSM the initial sample was taken from the existing WWTP employing UASB reactor. But outlet concentrations for each run were taken from the pilot scale UASB reactor after the wastewater had stayed for the determined HRT and temperature. Grab sampling technique was employed for inlet and outlet samples concentration determination.

### 2.5. HRT determination

For every experimental test set by CCD-RSM, initial sample was taken from the existing WWTP. After achieving the initial COD concentration (mg/l), the following formula can be used to calculate HRT.

$$OLR = \frac{Q * So}{V} = \frac{So}{HRT}, HRT = \frac{So}{OLR} \tag{1}$$

Where Q-is discharge ($m^3$/d), $S_o$ –is initial COD concentrations in kg COD/$m^3$, V-is volume of the reactor ($m^3$), OLR is organic loading rate (kgCOD/$m^3$.d). Table 3 shows the HRT determined for each experimental test using equation (1). The determined HRT denotes the amount of time the wastewater remained in the reactor set up for the test[20].

**Table 2**
coded operational parameters and five levels used by CCD-RSM.

| Operational Parameters | Code with unit | Five levels used in CCD-RSM | | | | |
|---|---|---|---|---|---|---|
| | | -α | −1 | 0 | +1 | +α |
| Temperature | A(°C) | −15 | 0 | 15 | 30 | 45 |
| OLR | B(kgCOD/$m^3$.d) | 0 | 1 | 2 | 3 | 4 |
| pH | C | 5.55 | 6.3 | 7.05 | 7.8 | 8.55 |
| HRT | D(hrs.) | 0 | 4 | 8 | 12 | 16 |

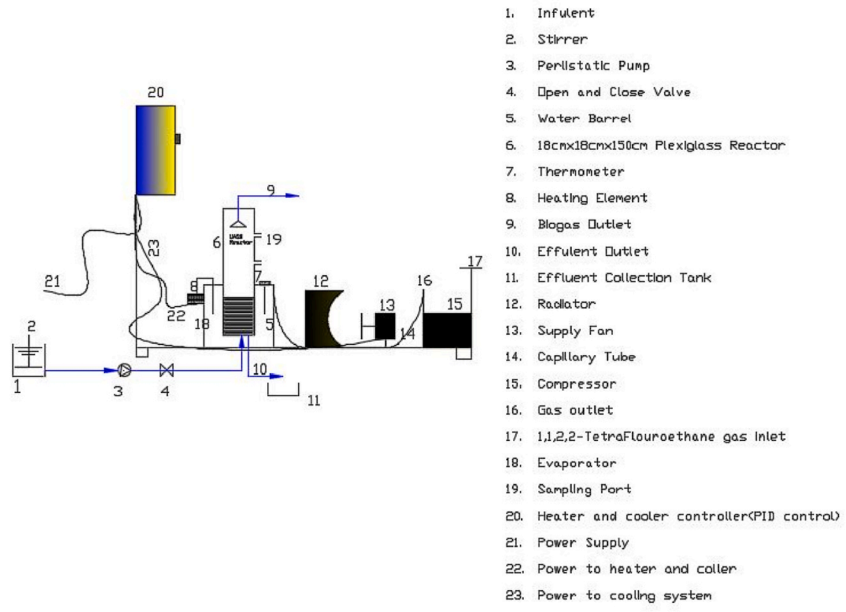

**Fig. 1.** Schematic diagram of PID control board with pilot scale UASB reactor.

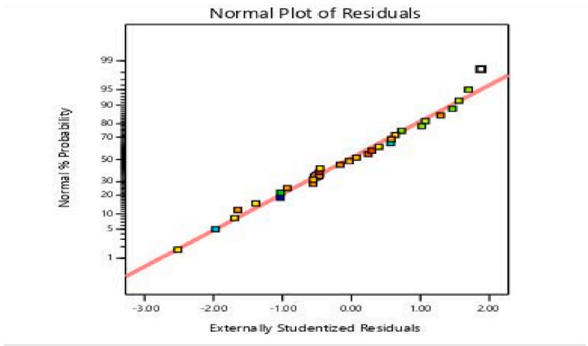

**Fig. 2.** Plot of Studentized residuals versus experimental data collected.

### 2.6. Operational parameters

Temperature, OLR, pH, and HRT were used as operational parameters to improve the performance of the UASB reactor at psychrophilic temperatures. Since psychrophilic temperature was used in the study, a temperature range of 0 °C–30 °C was taken into account. An OLR of 1kgCOD/m$^3$.d to 3kgCOD/m$^3$.d was chosen since domestic wastewater was used throughout the experiment. The pH range of 6.3–7.8 was chosen because methanogenis thrives in this range. Furthermore, HRT of 4–12 h was chosen because this time span includes the average and peak flow (dry and wet weather flow).

### 2.7. Methods for determination of physicochemical characteristics of the wastewater

The wastewater samples were analyzed for the physicochemical parameters during the dry season. This season was selected since it was part of the design criteria as the wastewater got concentrated. UASB reactor operational Parameters such as temperature (0 °C–30 °C), OLR (1kgCOD/m$^3$.d - 3kgCOD/m$^3$.d), pH (6.3–7.8) and HRT (4-12) were combined using Design Expert (Stat-Ease, Inc., version 13.0.1.0, Minneapolis, USA). In this experimental research, CCD-RSM was used to reduce the total number of experiments in order to achieve the best overall optimization conditions of the process. The tool provided 30 experimental runs for data collection. In each and every run of the experiments, the inlet and outlet samples were analyzed for physicochemical parameters like pH, COD, TSS, VSS, alkalinity, VFA and Sulfate ions concentration. The performance efficiency of the reactor set up was measured using equation-2.

$$\%Performance\ efficiency\ of\ UASB\ Reactor = \left[\frac{C_{influent} - C_{effluent}}{C_{influent}}\right] * 100 \tag{2}$$

**Table 3**
Inlet and outlet sulfate ion concentrations.

| Expt. run | Temperature(°C) | pH | OLR (kgCOD/m$^3$.d) | HRT (hrs.) | In let $SO_4^{-2}$ (mg/l) | Out let $SO_4^{-2}$ (mg/l) |
|---|---|---|---|---|---|---|
| 1 | 30 | 6.30 | 1 | 1.92 | 16 | 40 |
| 2 | 30 | 6.30 | 3 | 4.64 | 63 | 82 |
| 3 | 30 | 7.80 | 3 | 5.84 | 52 | 75 |
| 4 | 30 | 7.80 | 3 | 6.72 | 47 | 65 |
| 5 | 30 | 6.30 | 3 | 4.64 | 51 | 80 |
| 6 | 30 | 7.80 | 3 | 4.25 | 52 | 82 |
| 7 | 15 | 5.55 | 2 | 7.08 | 49 | 56 |
| 8 | 30 | 7.05 | 2 | 8.17 | 53 | 80 |
| 9 | 15 | 7.05 | 2 | 5.53 | 55 | 80 |
| 10 | 15 | 7.05 | 4 | 4.45 | 43 | 80 |
| 11 | 15 | 7.05 | 2 | 5.46 | 30 | 80 |
| 12 | 15 | 7.05 | 2 | 9.57 | 52 | 80 |
| 13 | 15 | 7.05 | 2 | 6.22 | 38 | 80 |
| 14 | 15 | 7.05 | 2 | 6.29 | 46 | 80 |
| 15 | 15 | 7.05 | 2 | 8.53 | 31 | 80 |
| 16 | 15 | 7.05 | 2 | 8.24 | 34 | 80 |
| 17 | 15 | 8.55 | 2 | 7.41 | 39 | 80 |
| 18 | 0 | 6.30 | 3 | 6.4 | 34 | 80 |
| 19 | 0 | 6.30 | 3 | 7.55 | 27 | 80 |
| 20 | 0 | 6.30 | 1 | 17.32 | 25 | 80 |
| 21 | 0 | 6.30 | 1 | 12.58 | 30 | 80 |
| 22 | 0 | 7.80 | 3 | 5.36 | 25 | 87.5 |
| 23 | 0 | 7.80 | 3 | 4.53 | 17 | 67 |
| 24 | 0 | 7.80 | 1 | 23.32 | 26 | 32 |
| 25 | 0 | 7.80 | 1 | 19.53 | 22 | 37 |
| 26 | −5 | 7.05 | 2 | 9.58 | 31 | 4 |
| 27 | 45 | 7.05 | 2 | 9.44 | 24 | 50 |

At −5 °C, pH 7.05, OLR 2kgCOD/m$^3$.d and HRT 9.58hrs. the out let $SO_4^{-2}$ concentration were seen extremely decreasing.This is because as temperature decreases extremely to negative values the activities of anaerobic microorganisms decreases [49].

**Table 4**
VFA to alkalinity ratio.

| Expt. no | Temperature (°C) | pH | OLR (kgCOD/m$^3$.d) | HRT (hrs.) | in let $\frac{VFA}{Alkalinity}$ Ratio | out let $\frac{VFA}{Alkalinity}$ Ratio |
|---|---|---|---|---|---|---|
| 1 | 30 | 6.3 | 1 | 1.92 | 0.100 | 0.075 |
| 2 | 30 | 6.3 | 3 | 4.64 | 0.070 | 0.150 |
| 3 | 30 | 7.8 | 3 | 5.84 | 0.060 | 0.069 |
| 4 | 30 | 7.8 | 3 | 6.72 | 0.090 | 0.100 |
| 5 | 30 | 6.3 | 3 | 4.64 | 0.120 | 0.120 |
| 6 | 30 | 7.8 | 3 | 4.25 | 0.130 | 0.110 |
| 7 | 15 | 8.55 | 2 | 7.08 | 0.080 | 0.090 |
| 8 | 30 | 7.05 | 2 | 8.17 | 0.070 | 0.140 |
| 9 | 15 | 7.05 | 2 | 5.53 | 0.090 | 0.120 |
| 10 | 15 | 7.05 | 4 | 4.45 | 0.100 | 0.120 |
| 11 | 15 | 7.05 | 2 | 5.46 | 0.130 | 0.150 |
| 12 | 15 | 7.05 | 2 | 9.57 | 0.120 | 0.090 |
| 13 | 15 | 7.05 | 2 | 6.22 | 0.140 | 0.100 |
| 14 | 15 | 7.05 | 2 | 6.29 | 0.090 | 0.140 |
| 15 | 15 | 7.05 | 2 | 8.53 | 0.110 | 0.130 |
| 16 | 15 | 7.05 | 2 | 8.24 | 0.090 | 0.120 |
| 17 | 15 | 8.55 | 2 | 7.41 | 0.080 | 0.140 |
| 18 | 0 | 6.30 | 3 | 6.40 | 0.077 | 0.087 |
| 19 | 0 | 6.30 | 3 | 7.55 | 0.085 | 0.110 |
| 20 | 0 | 6.30 | 1 | 17.3 | 0.100 | 0.150 |
| 21 | 0 | 6.30 | 1 | 12.6 | 0.097 | 0.120 |
| 22 | 0 | 7.80 | 3 | 5.36 | 0.120 | 0.090 |
| 23 | 0 | 7.80 | 3 | 4.53 | 0.130 | 0.089 |
| 24 | 0 | 7.80 | 1 | 23.3 | 0.096 | 0.110 |
| 25 | 0 | 7.80 | 1 | 19.5 | 0.100 | 0.058 |
| 26 | −5 | 7.05 | 2 | 9.58 | 0.120 | 0.02 |
| 27 | 45 | 7.05 | 2 | 9.44 | 0.100 | 0.100 |

At −5 °C, pH 7.05, OLR 2kgCOD/m$^3$.d, and HRT 9.58hrs. the outlet VFA to alkalinity ratio was seen out of the range since acidogenesis and methanogenesis were hindered with decrease in temperature [54].

*Where:* $C_{influent}$ *is the concentration of raw sewage in mg/l* [21]
$C_{effluent}$ *is the concentration of sewage leaving the reactor set up in mg/l*

### *2.8. Statistical analysis*

CCD-RSM was used for data analysis. It was also used for performance enhancement and optimization of operational parameters of the UASB reactor [22,23]. CCD-RSM used five different levels for each experiment. These five different levels for each experiment in coded form is from -α,-1, 0, +1, to +α. In order to investigate the effect of various independent operational parameters such as temperature (A), OLR (B), pH(C) and HRT (D) a CCD-RSM with 30 experimental runs were used for the optimization of process parameters. The total number of runs was determined by equation (3).

$$N = \mathrm{K}^2 + 2\mathrm{k} + \mathrm{c}_0 = 4^2 + 2 * 4 + 6 = 30 \tag{3}$$

Where N is the total number of experimental run, K is the number of operational parameters; '$\mathrm{c}_0$' is center point.

### *2.9. Modeling performance efficiency of COD, TSS and VSS*

Modeling of the performance of COD, TSS and VSS were carried out by using CCD-RSM. The adequacy of the model equations were evaluated using analysis of variance (ANOVA). Quality of fit of the model equations and their statistical significance were expressed using F-test, coefficient of determination ($R^2$), prediction coefficients of determination (Pred. $R^2$), adjusted coefficients of determination (adj-$R^2$), and coefficients of variation (CV). In CCD-RSM the effect of main factors as well as the effect of their interactions on the response was determined. For the four experimental factors the general mathematical model developed by using central composite design is as follows.

$$Y = \beta_0 + \sum_{i=1}^{k} (\beta_i x_i) + \sum_{i=1}^{k} (\beta_{ii} x_i{}^2) + \sum_{i=1}^{k} \sum_{i=1}^{k} \beta_{ij} x_i x_j + \varepsilon \tag{4}$$

*Where; Y is the experimental response variable,* $\beta_0$ *is the intercept,* $\beta_i$, *and* $\beta_{ij}$ *are the regression coefficients for intercept, linear effect, double interaction and quadratic effects respectively.* $x_i$, $x_j$ *are the independent variables (experimental variables) and* $\mathcal{E}$ *is random error*[24,25]

### *2.10.* ***Limitation of the research***

The experimental reactor set up has cooling system which encompasses compressor. The cooling system's compressor had a lower capacity and could cool 48.6L of wastewater. This was due to the inability to get a larger capacity compressor locally. Because parameters such as granulation and mixing were uncontrollable in this study, only four controllable operational parameters were considered.

## 3. Result and discussion

### *3.1. Experimental validation*

To validate the optimization results, an experiment was done for the conditions developed by the model. The model estimated COD, TSS and VSS removal efficiency of 91.06%, 98.35%, and 93.26% respectively at temperature of 21.58 °C, OLR of 2.99kgCOD/$m^3$.d, pH of 6.3, and HRT of 4.37hrs. Using the estimated operational parameters by the model, an experiment was performed and removal efficiencies of 92.70%, 97.38%, 96.50%, COD, TSS and VSS were obtained which was in agreement with the result predicted by the model and hence the model was validated.

### *3.2. Characterization of wastewater parameters*

Wastewater is characterized based on origin, composition and flow variation. In practice inlet and outlet samples were collected for 30 different runs for dry season. Parameters such as COD, $SO_4^{-2}$, VFA, Alkalinity, TSS and VSS were measured. The parameters load showed variation of (pH:5.55–8.55), ($SO_4^{-2}$16-87.5 mg/l), VFA to alkalinity ratio (0.06-0.058), alkalinity (260-170 mg/l as $CaCO_3$), TSS (3–235.44 mg/l) and VSS (10–260 mg/l).The collected data showed that the wastewater strength comply with the standard set for the WWTP supplementary-1 Table 3, 4 and 5. The inlet and outlet Wastewater data collected during the dry season is tabulated in supplementary-1 Table 5.

### *3.3. Performance enhancement modeling and model analysis*

Performance enhancement experiments were carried out using the reactor set up according to CCD-RSM. The results %COD, %TSS and %VSS removal from the wastewater on the interaction of four operational parameters were used for the model generation. Since the adjusted R-Squared (0.9269), predicted R-Squared (0.6350), and R squared values (0.9622) of quadratic model were greater than linear adjusted R-Squared (0.4068), predicted R-Squared (0.6350), and R squared (0.4886), the CCD-RSM suggested quadratic model. Quadratic regression was done for the prediction of the responses as a second order. For the response percentage COD, TSS and VSS removal the model fit summery showed that second order polynomial model was statically significant. The quadratic model developed by CCD-RSM showed a response with coded operational parameters like temperature (A),OLR(B),pH(C) and HRT(D).To the best of the researchers' knowledge no work has been done to develop similar model using CCD-RSM and combining four UASB operational parameters. But other researchers had done models with different software tools like MATLAB2011a, Monod models, and Contois model [26–28] for two UASB operational parameter and got successful performance prediction and optimizations of parameters. The analysis of variance supported the quadratic model's adequacy and significance (ANOVA). The ANOVA analysis is the best fit for CCD models and it is used to analyze experimental data.

### 3.3.1. COD model

The %COD removal model shown in equation (5) was obtained from the CCD-RSM.

$$\%\text{COD Removal} = 76.8045 + 12.3033A + 7.0157B - 10.6719AB - 15.7041AD - 4.1237BC - 6.0331BD - 8.9942A^2 + 2.8596C^2 \tag{5}$$

The model parameters A, B, AB, AD, BC, BD, $A^2$, $C^2$ were statistically significant ($P < 0.05$) at 95% confidence level. The percentage removal of COD was affected by single parameter or the interaction of parameters. They can affect the model negatively or positively. Fisher's 'F'-test was used for ANOVA analysis. The model was significant since the model's F-value was obtained to be 27 [29].There was only 0.01% chance that an F-value this large could occur due to noise. For this study the probability of P statics obtained were <0.0001.The P-value <0.05 indicated the model terms were significant. The lack of fit F-value 1.11 implied the lack of fit was not significant relative to the pure error. There was 64.14% chance that a lack of fit F- value this large could occur due to noise. Non-significant lack of fit was good because we need the model to fit. The adjusted $R^2$ determination coefficient value (0.927) was used to explain the fit between experimental data and the model data. The adjusted $R^2 = 0.927$ means that about 92.7% of the total percentage removal of COD data could described with the model developed. The adequate precision in the fit statics was used to measure the signal to noise ratio. A ratio greater than four was desirable. In this model, adequate precision ratio of 22.22 indicated an adequate signal. That means this model could be used to navigate the design space. Furthermore, a plot was done between predicted percentage removal and studentized residual in which the values were scattered between ±4.00.The plots indicated that the model best fitted with experimental data collected.

### 3.3.2. TSS model

Equation (6) shows the TSS removal model

$$\begin{aligned}\%\text{TSS Removal} = {} & 75.5637 + 6.2977A - 8.9878B - 4.5348C - 14.9922D - 9.0683AB + 9.5147AD + 7.8825BC + -28.7737BD \\ & + 13.1374CD - 6.4923A^2 - 6.1265B^2\end{aligned} \tag{6}$$

The percentage removal of TSS was affected by linear or combined interactions of operational parameters. They affect the model negatively or positively. The ANOVA analysis, %TSS removal coded parameters, adjusted coefficient of determination, and plot of studentized residuals for percentage removal of TSS are shown in supplementary-2.

### 3.3.3. VSS model

Equation (7) shows the VSS removal model

$$\begin{aligned}\%\text{VSS Removal} = {} & 56.0954 + 9.1897A - 16.3308B - 18.1609D - 11.4775AB + 10.6264AC + 17.9508AD + 11.9614BC - 34.054BD \\ & + 21.9357CD - 6.8842A^2 + 7.3882C^2 + 7.3529D^2\end{aligned} \tag{7}$$

Single or double interactions of operational parameters were affecting the percentage removal of VSS negatively or positively. The ANOVA analysis, %VSS removal parameters, adjusted coefficient of determination, and plot of studentized residuals for percentage removal of VSS are shown in Supplementary-3.

### 3.4. Model generated results

The model generated a percentage removal range from 0 up to 94.83% for COD, 0 up to 98.35% for TSS and −15 to 93.26% for VSS. From all out puts generated by the model an optimal value of temperature 21.58 °C, COD of 2.99kgCOD/$m^3$.d, pH of 6.3 and HRT of 4.37hrs.were selected. This optimal condition was selected since the aim of the research was a way to enhance the performance efficiency of UASB reactor for psychrophilic temperature without encoring cost like heat. But if there is a mechanism by which the temperature of the wastewater is increased there is a probability to increase the percentage removal of COD, TSS and VSS respectively to 94.83%, 98.35%, and 93.26%.

## 3.5. *Interactional effects of operational parameters on %COD removal*

### 3.5.1. *Interactional effect of temperature and OLR*

Fig. 3 depicts the combined effect of temperature and OLR on removal efficiency of COD. The percentage removal of COD increased with an increase in temperature and OLR, it was seen from figure that the removal efficiency increased with an increase in OLR from 1kgCOD/m$^3$.d to 3kgCOD/m$^3$.d. In addition, temperature has a significant impact on the performance of a UASB reactor because it affects the hydrolysis process, substrate utilization rate, solids settling, and gas transfer rates [29,30].

### 3.5.2. *Interactional effect of temperature and HRT*

The interaction effect of temperature and HRT on the percent removal of COD was shown in Fig. 4. As temperature increases with lower HRT the removal efficiency of COD get increased. This is because as temperature increases the activities of microorganism's increases and the chance in contact between the microorganisms and substrate in wastewater get increases [31,32]. From the 3D figure it can be seen that at lower temperature and lower HRT the removal efficiency of COD reached minimum. This is because as temperature and HRT get reduced the contact time between microorganisms and substrate get reduced and insufficient methanogens occurs. In the research done by Kapumbe DJ et al. [33] the COD removal decreases by 50% for every temperature decrease by 10 °C.

### 3.5.3. *The combined effect of temperature and pH*

The combined effect of temperature and pH on the percentage removal of COD was shown in Fig. 5. From the plot it was seen that, temperature and pH were increased at about 7 resulted in to increase in percent removal of COD. For higher temperature at pH = 7 the COD removal was higher [34]. This was because an increase in pH in the range of 6.3–7.8 increase methanogenesis [35,36]. The plot also showed that at pH 7, the % removal of COD was seen to be maximum at a temperature of 24.5 °C beyond this pH the % removal of COD was decreased this is because methanogenesis process is hindered [37,38].

### 3.5.4. *The combined effect of OLR and HRT*

The interactional effect of OLR and HRT on the percentage removal of COD is shown in Fig. 6. As OLR increased from 1 to 3kgCOD/m$^3$.d and HRT decreased from 12 to 4hrs. the percentage removal of COD was seen increased. The reason might be as substrate concentration get increased with optimum HRT, the probability of the microorganisms to get in contact with the substrate will be enhanced and hence the removal efficiency of the COD get increases [39].

### 3.5.5. *The combined effect of OLR and pH*

Fig. 7 presented the interactional effect between OLR and pH on COD. It was observed that a sharp increase in the COD removal occurred when the pH value of the solutions changed from 7.8 to 6.3 this was occurred up to 3kgCOD/m$^3$.d. But as OLR decreases with an increase in pH the % removal of COD was seen decreasing. The decrease in COD removal efficiency at higher pH might be due to the methanogenesis process hindrance [40–42].

### 3.5.6. *The combined effect of HRT and pH*

Fig. 8 below presented the interaction effect of HRT and pH on the percent removal of COD. From the plot it was seen that, increasing in both HRT and pH up to certain limit but beyond the concentrations the % removal was decreased, due to weak

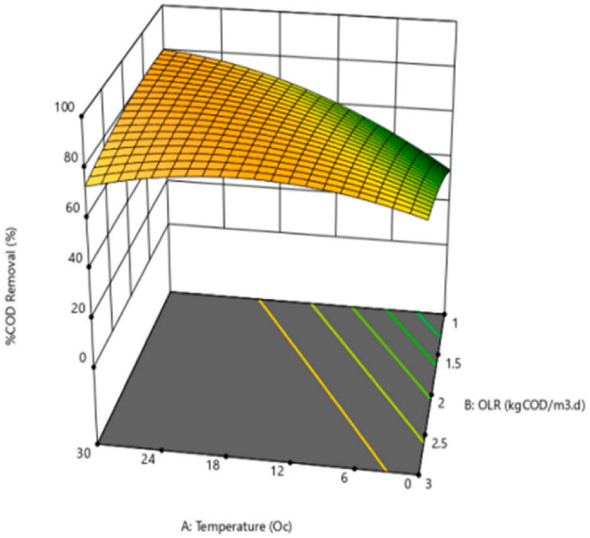

**Fig. 3.** interactional effects of temperature and OLR on % COD removal.

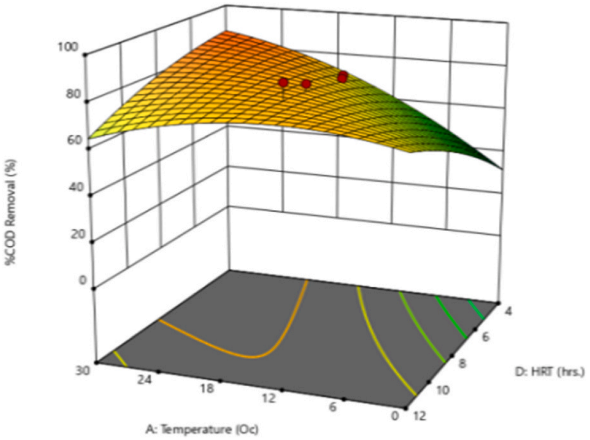

**Fig. 4.** interactional effects of temperature and HRT on % COD removal.

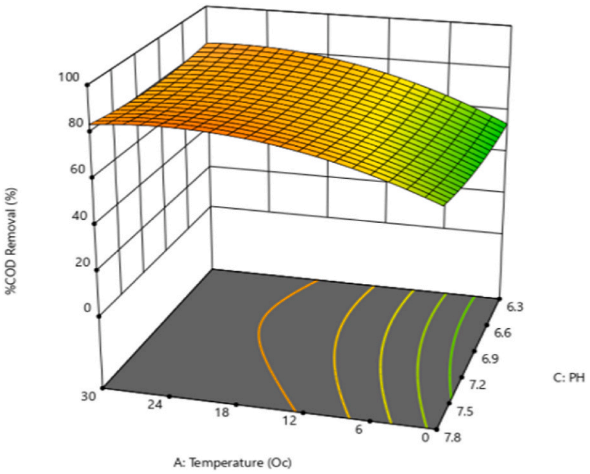

**Fig. 5.** interactional effects of temperature and pH on %COD removal.

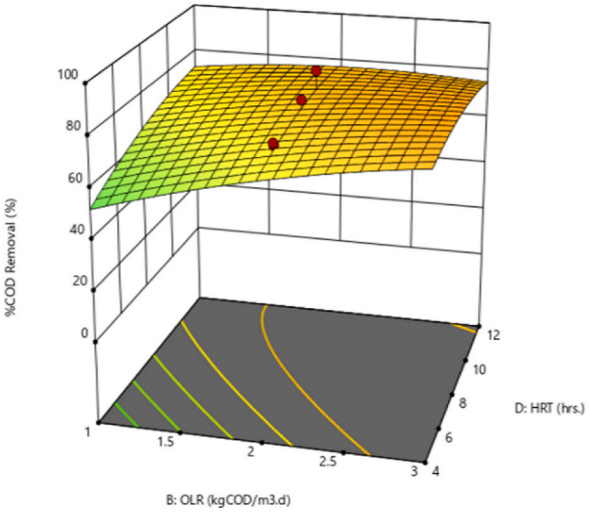

**Fig. 6.** interactional effects of OLR and HRT on %COD removal.

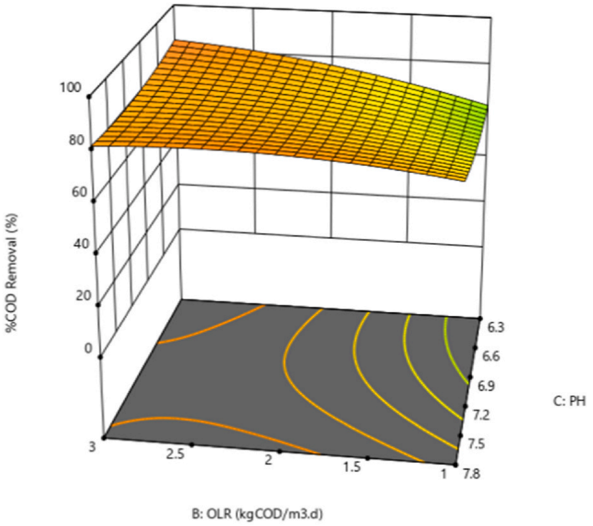

**Fig. 7.** interactional effects of OLR and pH on %COD removal.

degradation of organic compounds and hence this was due to the hindrance in methanonogenesis process [43–45]. *In the same way the combined effects of temperature against OLR, temperature against HRT and OLR against HRT, temperature against* pH, *OLR against* pH *and HRT against* pH *for % removal of TSS and VSS were given in supplementary-4 and 5 respectively.*

### 3.5.7. *Sulfate ion concentration*

In this experimental research the outlet sulfate ion concentration was found to be greater than the inlet. This is due to high methanogesis process which hinders sulfur reducing bacteria [46–48].

### 3.5.8. *VFA to alkalinity ratio*

In this research, VFA to alkalinity ratio was seen in the rage of 0.05–0.15.This showed that the UASB reactor was operating at normal condition. As saprophytes break down complex molecules acids are produced in the system (acetic acid, propionic acid and butyric acids) [50–52]. The alkalinity in the system accepts the hydrogen ion released by acids and the system is taken over by methanogensis to maintain the pH [53].

## 4. Conclusion

The aim of this research was to presented to improve the performance efficiency of an unregulated WWTP using the UASB reactor at psychrophilic temperatures. The effect of selected operational parameters such as temperature (0°C–30 °C), OLR (1kgCOD/$m^3$.d-3kgCOD/$m^3$.d), pH (6.3–7.8), and HRT (4–12hrs.) were investigated and optimized for higher removal efficiencies of COD, TSS and VSS using CCD-RSM. The optimal parameters were found to be: temperature = 21.58 °C, OLR = 2.99kgCOD/$m^3$.d, pH = 6.3 and HRT = 4.37hrs. This optimal condition was selected since the aim of the research was to enhance the performance efficiency of UASB reactor for psychrophilic temperature without incurring additional cost like heat cost for heating. With these optimal conditions, the

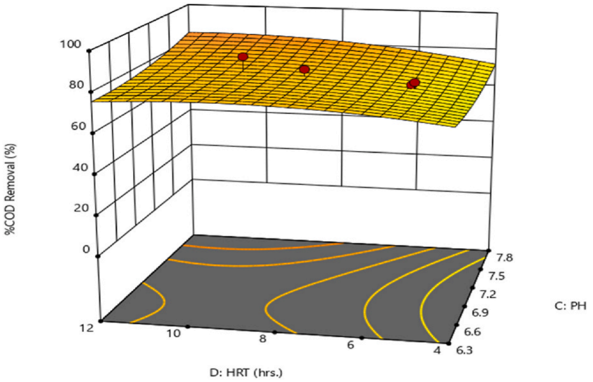

**Fig. 8.** interactional effects of pH and HRT on %COD removal.

CCD-RSM's maximum removal efficiencies were 91.06% COD, 98.35% TSS, and 93.26% VSS. At these optimum conditions, removal efficiencies of 92.70% COD, 99.06% TSS, and 94.50% VSS were achieved experimentally. However, if there is a means of increasing temperature of the wastewater there is a potential to increase the percentage removal of COD, TSS, and VSS to 94.83%, 98.35%, and 93.26%, respectively. Moreover, the inlet and outlet concentrations of VFA, alkalinity, sulfate ion, VFA to alkalinity ratio and pH were measured. Outlet concentration of VFA and alkalinity were found to be decreasing. This is because as saprophytes break down complex molecules acids are produced in the system (acetic acid, propionic acid and butyric acids). The alkalinity in the system accepts the hydrogen ion released by acids and the system is taken over by methanogensis to maintain the pH. The out let concentration of sulfate ion was found to be decreasing. with respect to inlet concentration. The reason is that the existence of sulfur-reducing bacteria is hampered by an anaerobic condition of VFA and alkalinity at a pH less than 7.8.This inturn increases the production of $CH_4$ than $H_2S$ gas. Generally, from the experimental investigation, one can conclude that there is a room to enhance the performance of the UASB reactor working at psychrophilic temperature by optimizing the operational parameters such as temperature, OLR, pH and HRT. Furthermore, these optimizations give hope that energy-scarce countries will benefit from optimizing UASB reactor operational parameters.

5. The authors declare that they have no conflict of interests.
7. There is no funding to support this research.

## Author contribution statement

1 - Conceived and designed the experiments.
2 - Performed the experiments.
3 - Analyzed and interpreted the data.
4 - Contributed reagents, materials, analysis tools or data.
5 - Wrote the paper.

## 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.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e19781.

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