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The Application of Six Sigma for Process Control Analysis in the Malaysian Poultry Wastewater Treatment

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ABSTRACT

In this paper, the researchers presented the process control analysis of a Poultry Wastewater (PWW) treatment plant that was designed to comply with the Environmental Quality (Industrial Effluent) Regulations, 2009. In this pilot case study, the researchers highlighted the fact that owing to the existing global environmental challenges, a Six Sigma approach needs to be used for developing a new technique that helps in optimising process capability and assesses the treatment reliability. This would allow the effective treatment of different pollutants like pH, BOD_5, TSS, COD, O&G and NH_3-N before their discharge into the environment. The researchers used several quality control process tools like the I-MR control charts, treatment process capability analysis and treatment reliability assessment in the study. After analysing the data, the researchers concluded that the plant could effectively treat NH_3-N, as well as fairly decrease the pH, BOD_5, and COD values, whereas it displayed low ability in treating TSS and O&G within the research period. The researchers noted that the process showed low reliability in the treatment of TSS and O&G, i.e., 88.6% and 29.8% respectively, led to the discharge of fine colloids in the effluent. This was attributed to problematic processes in the PWW treatment procedure, such as malfunction of the DAF unit process, ineffective physical-chemical treatment, and tertiary filtration breakdown. The researchers concluded that this PWW plant required additional control and design improvement so that it released a low concentration of toxic compounds in the effluent discharge, and complied with the standards. This research could be used as a reference for additional studies that aimed to improve the quality of the wastewater treatment processes.

Keywords: six sigma, wastewater treatment, poultry wastewater, statistical quality control, process capability, treatment reliability.

INTRODUCTION

Water quality is essential for better public health and is regarded as a vital resource for economic and human growth along with environmental balance. Increasing industrialisation has degraded the natural environment, which makes it essential to preserve the water quality. The untreated wastewater discharged into water bodies, owing to industrial, agricultural and municipal activities, significantly pollutes the environment, which indirectly affects the human and animal health. This has highlighted the need to implement wastewater management and better pollution control (UN World Water Assessment Programme 2021). The lack of proper wastewater treatment processes in the world has led to a discharge of 80% wastewater in the environment, which has affected ≈1.8 billion people, who unknowingly drink water that is contaminated with faecal waste. As a result, they become vulnerable to different water-borne diseases like cholera, polio, dysentery and typhoid. Furthermore, even the water-quality based guidelines and objectives, proposed by the Sustainable Development Goal (SDG) that aimed to improve the water and sanitation quality in the world by 2030, have not been established and implemented properly (Khalek et al., 2019). Numerous food industries like dairy, beverage, fruit and seafood, generate a lot of wastewaters. Furthermore, the poultry and meat processes in these industries consume masses of fresh water, while generating large quantities of wastewater. There has been a 6% increase in the world poultry market from 2018 to 2019, which indicates a per capita increase in consumption, i.e., 58 kg per capita in the U.S., 57 kg in Brazil, and ≈50 kg in Malaysia. According to the hygiene and food safety standards proposed by the Hazard Analysis and Critical Control Point (HACCP), poultry processing consumes plenty of fresh water in different operations like rinsing, cleaning, cutting and meat packaging. Additionally, many poultry slaughterhouse operations like de-feathering, scalding, washing and evisceration are water-intensive activities that generate a huge volume of wastewater. It was noted that a 2.3 kg bird consumes ≈26.5 litres of freshwater and discharges the wastewater that is contaminated with organic matter. This increases the Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and increases the concentration of nitrogen, phosphorous, blood, fats, suspended solids, oil, grease and proteins in the wastewater (Fatima et al., 2021). Hence, the improperly treated Poultry Wastewater leads to water pollution owing to deoxygenation and eutrophication, thus increasing groundwater contamination and the risk of water-borne diseases.

In the past few years, increased environmental awareness regarding industrial waste has encouraged people to become sensitive and apply pressure on the industries to implement better wastewater management. The PWW treatment processes are very sophisticated and need various units for eliminating specific contaminants using physical, chemical, and biological techniques with different treatment steps for decreasing environmental contamination. Moreover, effective PWW treatment activities must concentrate on a few potent and cost-effective treatment techniques that comply with the legislative guidelines. It was noted that the environmental policies, laws, standards and guidelines in the world are very strict. Even in Malaysia, the discharge standards for PWW were regulated by the Environmental Quality (Industrial Effluent) Regulation of 2009. It was stated that the values of different parameters like BOD_5, COD, Total Suspended Solid (TSS), Nitrogen Ammonia (NH_3-N), Oil and Grease (O&G) as well as pH must be ≤ 20, 80, 50, 10, 1 mg/L and ranging between 6 and 9, respectively, as per the Standard A requirements.

It was noted that any variation in wastewater treatment processes is dependent on many factors like influent load variation, condition of reactors, source of pollutants, presence/absence of toxic substances, variability in the biological treatment processes, mechanical errors and human competency (Oliveira and Von Sperling 2008). These factors could affect the treatment process and make it unstable, which can negatively affect the effluent quality. Many efficient techniques are needed for identifying the process deficiencies. In the past, numerous techniques were developed for solving the issues related to instability and improper wastewater treatment procedures. Formerly, the Lean Manufacturing and Six Sigma philosophy was combined to develop one technique that could overcome all problems noted in the production processes. This structured process could help in optimising the company performance, quality, customer satisfaction, eliminating waste, decreasing costs as well as increasing the financial, social and environmental benefits (Mohamad et al., 2019). The environmental practitioners stated that some issues related to the environmental control equipment failure like component damage, breakdown and unplanned downtime, were regarded as major issues. The six-sigma technique that refers to the manifestation of quality improvement is developed using statistically-processed data. This is an empirically effective technique that is commonly implemented by health care institutes, manufacturing industries, construction and service sectors (Gholami et al., 2021; Ishak et al., 2021). However, very few researchers have investigated the use of the Six Sigma technique in the internal functioning of non-manufacturing sectors particularly in the wastewater treatment processes (Sagnak and Kazancoglu 2016). The statistical quality control techniques used for verifying the efficiency of manufacturing processes are commonly employed in many industrial sectors, however, they can also be applied in non-industrial processes. The Six Sigma process can be employed for quality control. This technique was first implemented by Motorola in the 1980s and included a systematic framework that addressed many challenges faced by the company. It also offered better customer values after product and process development. A combination of Six Sigma and Lean manufacturing processes is used in the service and product industries, for evaluating process variations, using statistical and scientific indicators (US EPA 2009). In the past, many researchers implemented the Six Sigma technique in numerous fields like clinical care, healthcare, pollution control programs (Calia et al., 2009) and wastewater treatment (Boruah et al., 2015), for developing a complementary framework that could decrease waste, improve resource optimisation and increase customer satisfaction, after offering better, high-quality products and more reliable processes.

Some researchers used a comprehensive approach, based on the Lean and Six-Sigma principles, where they upskilled the workers so that they could identify and decrease environmental waste, thereby reducing the negative environmental effect and improving regulatory adherence (Dieste et al., 2019). A decrease in the process instability by using process control analysis can enhnace the effectiveness of the PWW treatment as it evaluates the performance, determines the errors and assesses the probable causes. In this study, the researchers have investigated the efficacy of using a Six Sigma process for determining the existing wastewater treatment ability and treatment reliability of a Malaysian poultry processing plant.

MATERIALS AND METHODS

Some of the earlier studies stated that the DMAIC application could help in the detection of defects regarding the deviation from variability noted in the sewage and petroleum wastewater treatment processes (Boruah and Nath 2015; Robescu et al., 2016). The expected target must be zero defects or very few Defects Per Million Opportunities (DPMO) based on the process variability. In general, any wastewater treatment plant undergoes routine performance monitoring and needs an expensive data collection campaign. This complex data can only be properly analysed by data scientists or experts in the field of wastewater management. However, as it adds to the cost of the whole process, these datasets remain under-utilised.

The analysis of the performance monitoring data for wastewater treatment operations could help in the detection and timely response to the inefficiencies, process failures and operational abnormalities noted in the process. However, data collection is an expensive and complicated process (Graf et al., 2018). The use of complex monitoring instruments, highly-skilled workers with adequate technical know-how and unique features related to wastewater treatment processes, is limited by different process variables. This has highlighted the need to use Six Sigma technology for overcoming the issues noted during wastewater treatment. Process capability refers to an analytical tool that determines the stability of variables related to product requirements or process specifications. Two types of variabilities have been defined, i.e., 1) Natural or inherent variability at any time; and 2) Special variability based on time (Rimantho and Nugraha 2020). Many graphical control charts like the Exponentially Weighted Moving Average graph (EWMA), Shewhart control chart and Cumulative Sum control chart (CUSUM) have been used for hypothetically testing if the process was statistically controlled after plotting all parameters within the control limits (Montgomery 2020). The Shewhart control chart was characterised by 3 lines, i.e., Central Line (CL) that presented the average in the dataset; Upper Control Line (UCL) and Lower Control Line (LCL) that were obtained using Eq. 1 to 3:

$$\mathrm{CL} = \overline{x} \tag{1}$$

$$\mathrm{UCL} = \overline{x} + 3\,\frac{\overline{AM}}{d_2} \tag{2}$$

$$\mathrm{LCL} = \overline{x} - 3\,\frac{\overline{AM}}{d_2} \tag{3}$$

where: $\overline{x}$ – midline or medium observations;
$\overline{\mathrm{AM}}$ – amplitude of the sample;
d_2 – factor for constructing a variable control chart (Montgomery 2020).

It was noted that the process stability (*Cp*) determines the potential ability of a defined process, whereas the process capacity index (*Cpk*) calculates the actual capacity of this process. These values help in assessing if the process could reach its desired value, as presented in Eq. 4–7. The process stability was expressed as the ratio of the process specification interval variations and 6 standard deviations σ. In many practical applications, this value is not known and is estimated as follows:

$$Cp = \frac{USL - LSL}{UCL - LCL} = \frac{USL - LSL}{6\sigma} \tag{4}$$

$$Cpk = \min\{Cpu,\ Cpl\} \tag{5}$$

$$Cpu = \frac{USL - \overline{x}}{3\sigma} \tag{6}$$

$$Cpl = \frac{\overline{\mathrm{x}} - \mathrm{LSL}}{3\sigma} \tag{7}$$

where: USL – upper specification limit;
LSL – lower specification limit;
Cpu – upper one-sided capability ratio;
Cpl – lower one-sided capability ratio.

The analytical technique used for improving the quality generally applies the process capability criteria for comparing the *Cp* and *Cpk* values. Here, the researchers followed the specification limits based on the standard requirements as below:

- Value of *Cp* = *Cpk*, which indicates that the treatment process is in-line with the specifications.
- If *Cp* > 1.33, the treatment process shows a high capability.
- If *Cp* < 1.00, the treatment process is unable to comply with the specifications.
- A negative *Cp* value states that the average treatment process is not within the specification limits.
- If *Cpk* = 1.0, the process variation is within the specification limits.
- If *Cpk* < 1.0, the treatment process is not within specification limits.

Hence, in the wastewater treatment process, if the index was ≥ 1.33, the PWW treatment process followed the standard requirements. However, if the value ranged between 1.0 and 1.33, the treatment process complied with the discharge standards; and the process needed to be improved. Lastly, if the index value was <1 or was negative, the PWW treatment process could not fulfil the discharge standard requirements. A majority of the wastewater treatment processes were designed for collecting and treating the effluent waste from internal processes within the facilities. This involved different qualities and quantities of effluent waste. Hence, the treatment reliability of these systems is determined from the variability in effluent properties. The treatment plant needs to be naturally designed for generating the mean concentration below the established discharge limits (Oliveira and Von Sperling 2008). Metcalf and Eddy (2003) presented some evidence that indicated the treatment reliability referred to "the percentage of times the effluent concentration fulfilled the specific standard limit requirements". This presented an additional challenge to the PWW treatment operators.

A popular paper that is cited in the literature related to treatment reliability, determined the average concentration (i.e., design value) using a specific reliability level (threshold values that must be fulfilled), based on the probabilistic analysis (Niku et al., 1979). However, it was seen that the effluent data does not always display a normal distribution, since it is an industrial process. As a result, even the treatment reliability does not show a normal distribution (Niku et al., 1982); however, it follows the asymmetrical, lognormal (Oliveira and Von Sperling 2008) and Weibull statistical distributions (Bugajski et al. 2016), which complicates the process of determining the probability of occurrence of selected pollutant values. Furthermore, the asymmetrical wastewater treatment data that follows the lognormal and Weibull distribution helps in generalising the probability distribution for reliability assessment (Bugajski et al., 2016; Jóźwiakowski 2017; Micek et al., 2021; Zawadzka et al., 2021). In this study, the researchers used the elements of Weibull reliability theory based on a probability density function, shown in Eq. 8, with parameters like b, c and θ:

$$f(x) = \frac{c}{b} \cdot \left(\frac{x-\theta}{b}\right)^{c-1} \cdot e^{-\left(\frac{x-\theta}{b}\right)^{c}} \quad (8)$$

where: x – variable that indicates the concentration of particular pollution using a specific pollution indicator in the treated PWW;
b – scale parameter;
c – shape parameter;
θ – location parameter.
They assumed: $\theta < x$, $b > 0$, $c > 0$.

All Weibull parameters were calculated using the maximum likelihood technique and the normality test for data distribution was carried out using the Minitab 18.0 process for verification. The above-mentioned techniques indicated that the treatment reliability process was an effective technique for supporting the process capability results that helped in resolving the issues noted in the performance of the PWW treatment used in Malaysia. Very few studies estimated the PWW treatment process capability and its reliability performance while pursuing a strategic merger, using the Six Sigma approach for wastewater treatment.The market competition allows the industries to make use of sustainable techniques for production and proper consumption; however, these techniques are expensive and require the implementation of Six Sigma principles for addressing the environmental issues and producing eco-friendly, inexpensive and high-quality products. This study investigated the local poultry processing plant in Melaka, Malaysia, which started operating in 1999 and is committed to providing good-quality and fresh poultry products for local consumption. This PWW treatment plant showed a processing capacity of 200 m^3/day that included preliminary treatment, primary treatment, physical-chemical processes, biological processes like an Extended Aeration Activated Sludge (EAAS), and a tertiary advance filtration process catered to the daily use of 15,000 birds. The PWW is generated after stunning, feather removal, scalding, halal slaughtering, bleeding, chilling, evisceration and equipment cleaning processes. The treated effluents are drained into the Sungai Melaka tributaries, in compliance with the strict Standard A requirements. The PWW showed a high concentration of organic compounds, which was reflected in the higher BOD_5 and COD values. Thus, it was concluded that the PWW contained a high concentration of oxidizable compounds. The PWW also contained organic nitrogen compounds, in the form of proteins, and inorganic nitrogen compounds like (NO_2^-) and nitrate (NO_3^-). These compounds increase the algal bloom, which leads to fish poisoning, oxygen depletion and release of putrid odours in the receiver water bodies. This highlights the need to treat PWW according to the standard limits. Fig. 1 presents the components involved in PWW treatment.

The preliminary treatment step involved 6.4 m^3 of Collection Sump and 8.7 m^3 of Scrapper Tank with 1.5 mm static screening units for removing residual waste like feathers, grit and grease for protecting the upper equipment from clogging, fouling and jamming. Theoretically, the preliminary treatment decreases 30% and 10% of the TSS and BOD_5, respectively. In the next step, 134.7 m^3 of Equalisation tank regulates the PWW properties like pH, temperature, pollution level and flow rate. In the primary treatment, the colloidal particles in PWW aggregate with the large particles to form flocs. The colloidal particles are negatively charged and become stabilised after adding positively charged coagulants for reducing the floc formation, thereby decreasing the sedimentation process. As per the design, the chemical treatment step included factors like coagulation, pH adjustment and flocculation, using caustic soda and polymers for removing 60% of BOD_5, 70% of COD, 70% of TSS and 90% of O&G. Then, the design included the Primary Clarifier, which used 67.8 m^3 of Dissolved Air Floatation (DAF) unit for separating fine solids from liquid, where compressed air was introduced from the tank bottom. The light-weight grease, solids and fats move to the surface and create a sludge blanket that is collected using a scrapper. This step helps in reducing BOD_5, COD, TSS, and O&G by 60 to 70%. However, the primary limitations of DAF include regular malfunctioning and improper TSS separation. The sludge collected from the scrapper and tank bottom is transferred to the sludge holding tank. The soluble organic compounds in the PWW that cannot be removed after primary treatment can be treated using a secondary aerobic biological treatment with 2 units of 164 m^3 Aeration Tank. The aerobic process needs oxygen and the extended treatment time is directly proportional to the PWW strength. The use of the aerobic process

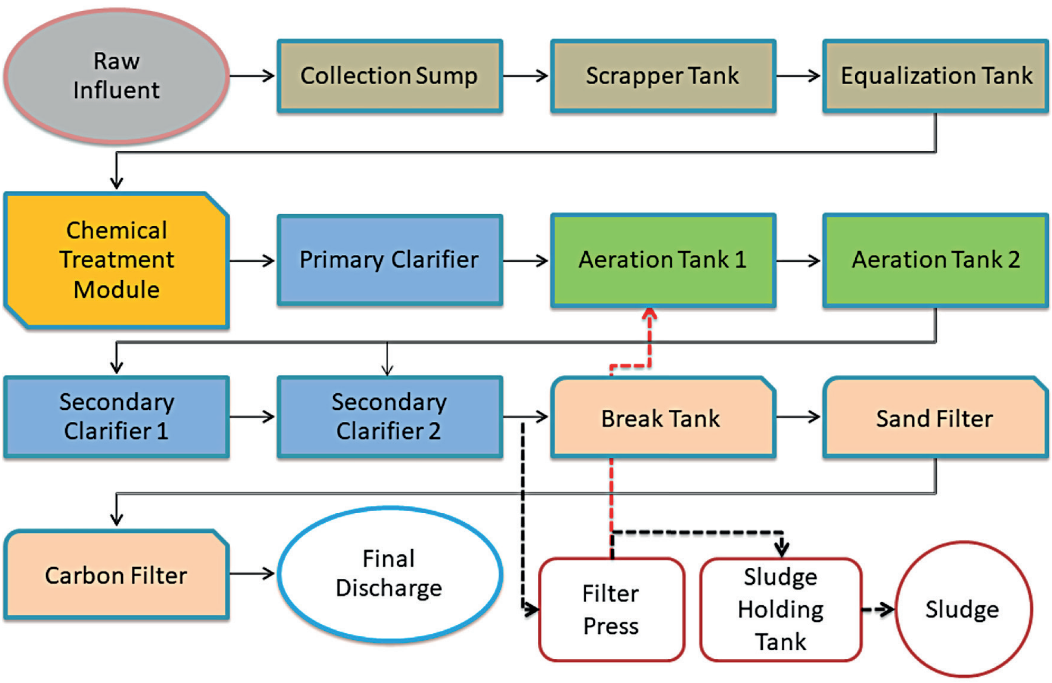


Fig. 1. PWW treatment process

has many advantages like fast biological growth rate, low odour and rapid adjustment to variations in loading rate and temperature. However, operational costs of the system were higher compared to the anaerobic systems owing to a higher energy requirement for oxygen supply and maintenance. Two units of 62 m^3 Secondary Clarifier then separate the final processed effluent from the supernatant, where the bio-sludge is collected and sludge recovery is facilitated. The advanced tertiary treatment step includes carbon and sand filters for removing residual compounds, followed by the discharge of processed effluents. For maintaining the microbial population, the system regulates the Waste Activated Sludge (WAS) and Returned Activated Sludge (RAS) pumping circulation. The treatment plant was designed for catering to the BOD_5, COD, TSS, O&G and NH_3-N load at 213, 1875, 915, 0.5, and 63.84 mg/L of PWW, respectively, from the production process.

The results of the study were examined in 3 phases. Phase 1 included the PWW quality parameters that were collected from the final discharge point using the June to Dec 2020 weekly records. The performance monitoring parameters that were evaluated included Hydrogen Ionic Potential (pH), TSS, Biological Oxygen Demand in five days (BOD_5), COD, O&G and NH_3-N. The researchers quantified the pH using a potentiometric method, while other parameters were determined using the Standard Method recommendations (APHA 2005). They used a descriptive analysis for estimating other parameters like mean, median, maximum, minimum, standard deviation and coefficient of variation. This data is used as a standard for assessing the efficiency of the PWW treatment process.

Phase 2 was carried out for determining the values of various performance monitoring parameters and estimating the capability of the PWW treatment process. The researchers conducted a normality test, wherein the normal data distribution was determined at a 5% significance level using the Kolmogorov-Smirnov technique. The data should be independent, which helps in assessing the database and identifying the common and specific causes of process variability. Then, the researchers selected the Individual – Moving Range (I-MR) control chart for graphically determining the process variability as the PWW treatment process was carried out constantly. Since the testing process in the laboratory was expensive, the individual performance monitoring results were derived. The researchers calculated the Cp and Cpk values after comparing the acquired values with the standard limits set by the regulatory bodies, i.e., LSL and USL for all parameters used in the study.

Finally, the researchers studied the treatment reliability for assessing if the PWW facility could fulfil all the requirements of every parameter. This treatment reliability was determined after estimating the Weibull distribution parameters and applying the highest reliability technique. Furthermore, the null hypothesis of performance monitoring parameters was based on the data distribution model; i.e., normal (Niku et al., 1982), lognormal (Niku et al., 1979; Oliveira and Von Sperling 2008), and Weibull (Jóźwiakowski 2017; Micek et al., 2021; Zawadzka et al., 2021); it was verified using the Goodness of Fit test in the Anderson-Darling method, at a significance level of 0.05%. The researchers determined the reliability using the cumulative distribution figures after comparing them to the standard values mentioned by the Environmental Quality (Industrial Effluent) Regulations of 2009.

RESULTS AND DISCUSSION

Evaluating the performance monitoring parameters

Table 1 presents the concentration of the various performance monitoring parameters that were discharged from the PWW treatment plant under study. The values of the organic parameters like BOD_5, COD and TSS showed a higher variability, i.e., 44.93%, 50.71%, and 20.33%, respectively, as their coefficient variation percentage was >20% (Orssatto et al., 2014). The O&G parameter showed a higher variability, with a 68.65% coefficient of variation, while the nutrient content in NH_3-N showed variability of 29.49%. After noting the maximal O&G limit of 1.0 mg/L, the researchers observed that 19 of the 28 analysed samples showed higher values than the Standard A requirements. A daily flow rate was determined for analysing the actual PWW load, which was 56.50 m^3/day. However, higher variability in the influent volume was noted within the research period. A maximal flow rate of 110 m^3/day was based on the design criteria, which was <120 m^3/day. A few factors like COD, O&G and BOD_5 showed higher C.V% values, which could be attributed to the presence of fine solid particles in the effluent, even after the wastewater was

Table 1. Descriptive analysis of the treated PWW (n=28)

Parameter	Flow rate (m^3/day)	pH	BOD_5	COD	TSS	O&G	AN
Mean	56.50	6.79	8.94	27.25	39.61	1.82	1.04
Median	56.50	6.90	8.60	24.50	40.00	1.56	1.05
Min	12.00	5.80	4.30	6.00	27.00	0.80	0.39
Max	110.00	7.80	19.90	37.00	59.00	4.90	1.56
Std. Dev[1]	28.70	0.51	4.02	13.82	8.05	0.24	0.31
C.V%[2]	50.79	7.54	44.93	50.71	20.33	68.65	29.49
p-value[3]	N.A	>0.15	>0.15	>0.15	>0.15	>0.15	>0.15

[1] Standard deviation; [2] Coefficient of variation percentage; [3] p-value of normality test.

physically treated using a secondary clarifier. The higher variability also could be due to a poor DAF operation and inaccurate application of the coagulant dosage for optimising the iso-electric point. This led to the destabilisation of the colloidal particles and the O&G flakes were formed with an insufficient weight for decantation (Fatima et al., 2021). Furthermore, after assessing the weekly maintenance record, the researchers noted that the tertiary advance filtration step was not optimised due to an exhausted breakthrough time and the absence of the backwash process.

Assessment of the PWW treatment process capability

After determining the p-values of the normality test shown in Table 1, the researchers hypothesised that the data was statistically normal at a 5% significance level when they used a random sampling process for treatment. They plotted an I-MR control chart for graphically measuring the behaviour of the performance monitoring parameters. Figure 2 presents the I-MR control chart for the randomly independent parameters studied here. The data indicated that the pH value had good statistical control. The bottom part of Moving-Range (MR) chart showed that the BOD_5, and COD parameters in Fig. 2b and 2c had a 1-point higher value than 3σ from the Centre Line (CL). However, 2 points of individual value for TSS and O&G were not in the statistical control, i.e., 59 and 56 mg/L for TSS, 4.9 and 3.8 mg/L for O&G in the Fig. 2d and 2e. These point values were also higher than the specification limit of 50 mg/L and 1.0 mg/L, respectively. Thus, the researchers attributed the improper solid separation to the ineffective DAF and chemical dosing steps. Additionally, the processes for the Jar test had to be evaluated for determining the optimal dosing base during treatment. The results showed that 1-point individual value for BOD_5, and COD, was not in statistical control, however, this value was lesser than the USL at 20, and 80 mg/L, respectively.

a)

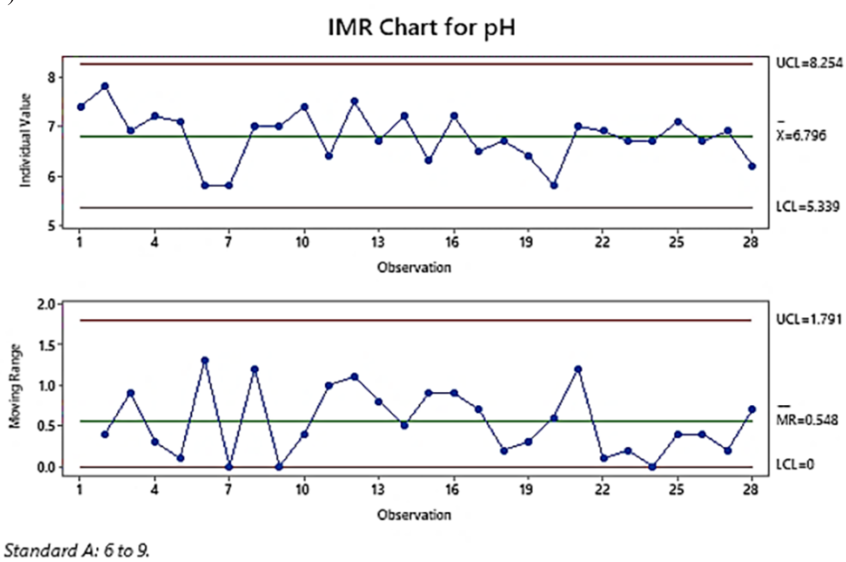
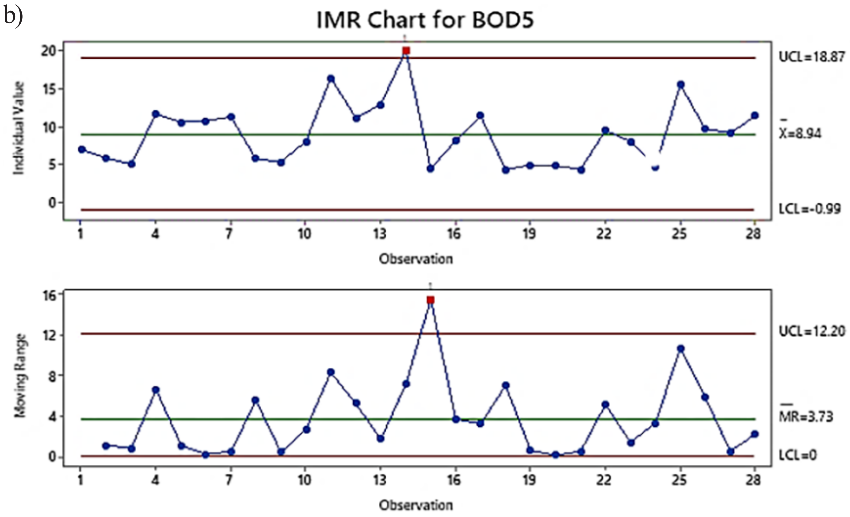


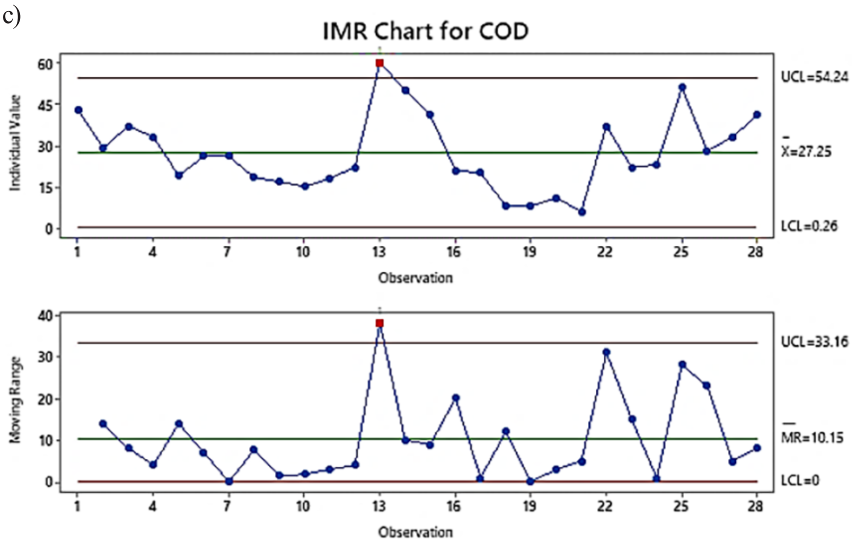
Fig. 2. I-MR control charts for the assessed parameters

b)



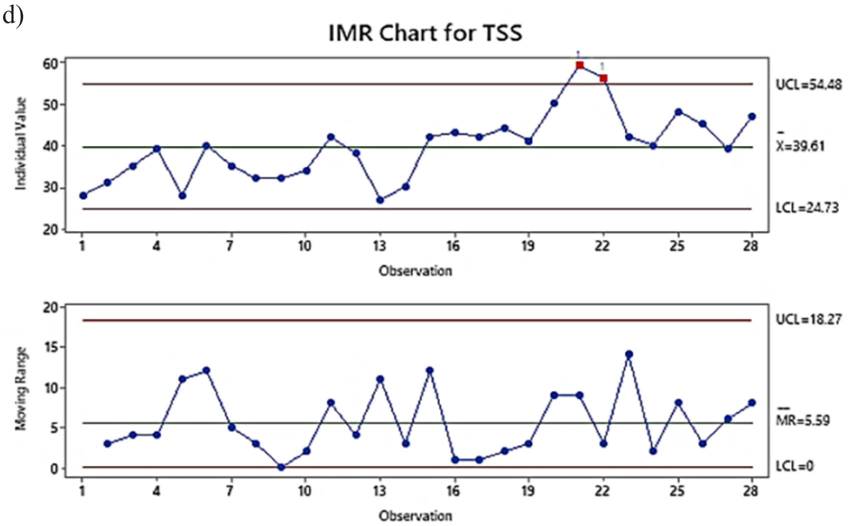
Standard A: <20mg/L.

c)



Standard A: <80mg/L.

d)



Standard A: <50mg/L.

Fig. 2. Cont. I-MR control charts for the assessed parameters

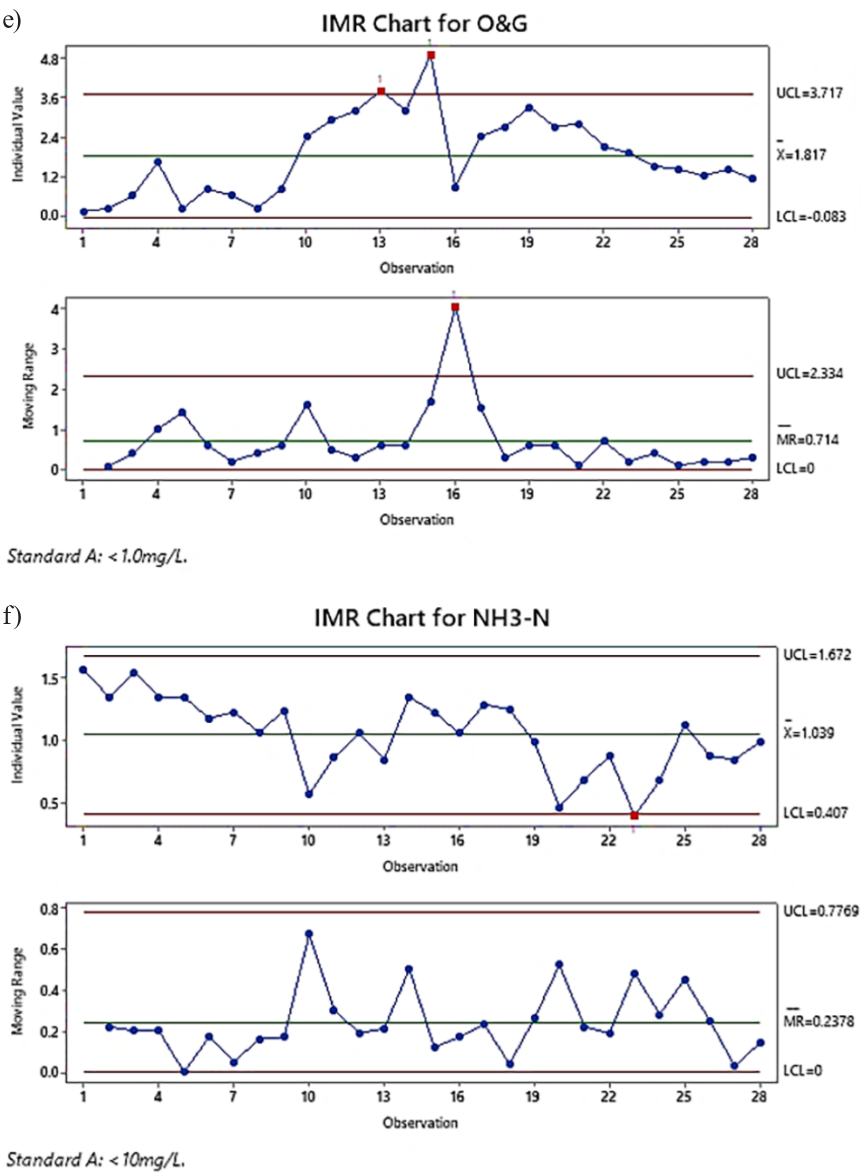


Fig. 2. Cont. I-MR control charts for the assessed parameters

On the basis of the above-mentioned results, the researchers proposed the use of I-MR control charts for understanding the PWW treatment systems, after analysing the process capability. Figure 3c, 3d and 3f presents the *Cp* value for COD, TSS and NH_3-N, i.e., 1.48, 1.68 and 7.91. These values were >1.33, which indicated that the process capability was high. In general, the researchers noted that the COD and NH_3-N treatment of the PWW was effective as the *Cpk* values for COD and NH_3-N parameters in Figure 3c and 3f were >1.0, and the data complied with USL at 80 and 10 mg/L respectively. However, the *Cpk* value for TSS in Figure 3d was 0.7, which was <1.0. This result supported the earlier assessment that the fine particles were still present in the effluent, which aggravated the issue. The initial data the Figure 2a indicated that the pH value was statistically controlled, however, Figure 3a showed that the *Cpk* value of pH was 0.55. This indicated that 3 samples showed pH values <6 (i.e., LSL value). Furthermore, though BOD_5 in Figure 3b showed a *Cp* value of 1.01, the result indicated that the treatment was effective, as the *Cpk* value of 0.9 indicated the need for improvement in the biological process. This highlighted the need to optimise the aeration tank for fulfilling the specifications. The *Cp* and *Cpk* values for the O&G factor in Figure 3e were 0.26 and -0.43, respectively, which indicated that the treatment of this parameter did not fit into the specification limits. Thus, it was concluded that the PWW plant studied in this paper did not display satisfactory performance (Rimantho and Nugraha 2020).

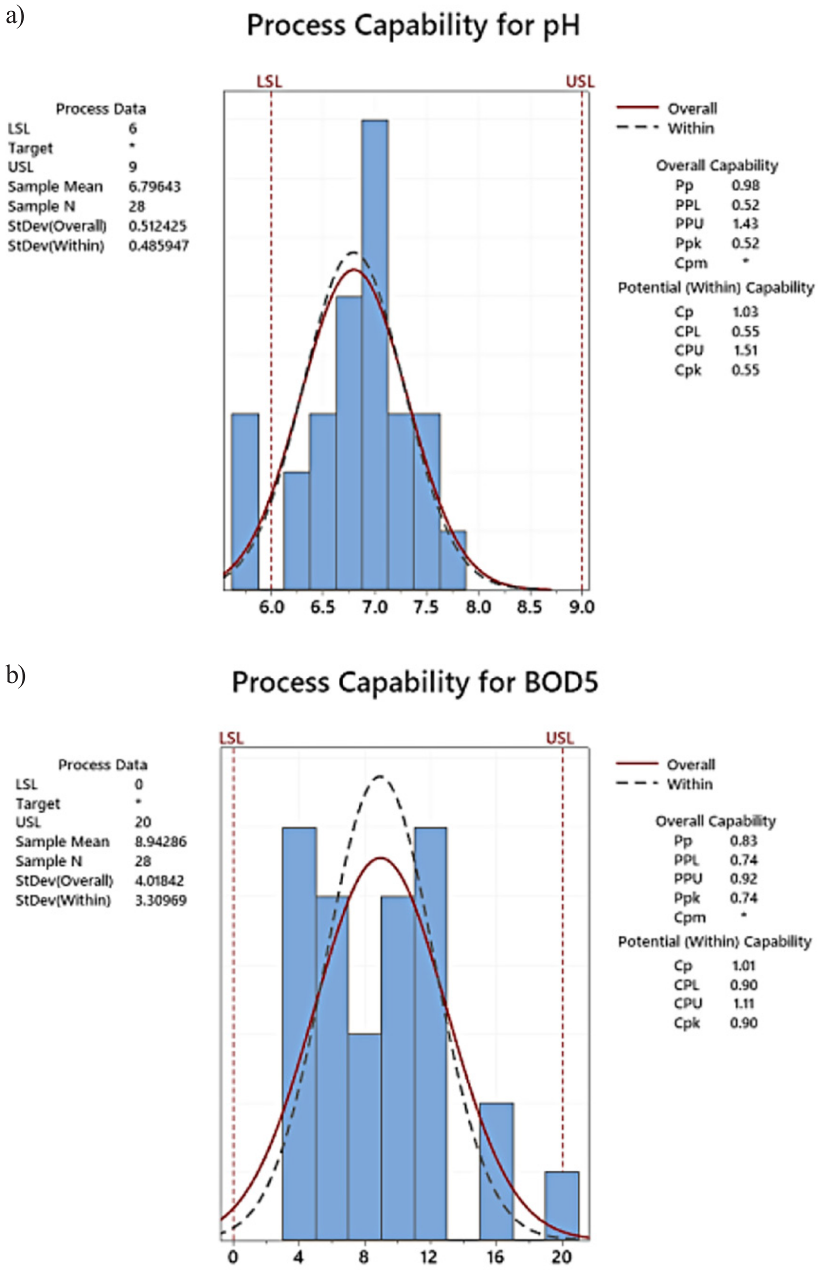
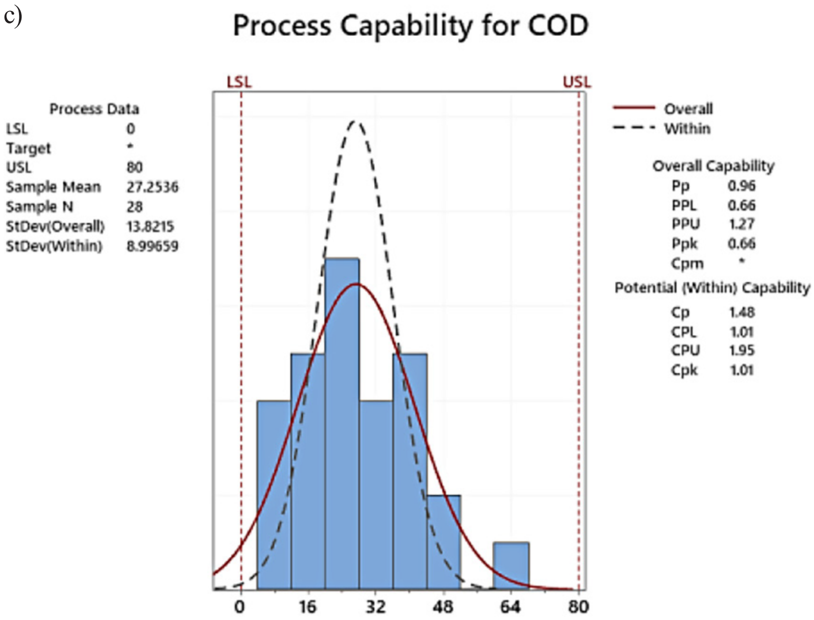


Fig. 3. Process capability for the assessed parameters

Evaluation of the PWW treatment reliability

A few efforts were made for improving the PWW treatment system after analysing the substandard levels of the critical *Cp* and *Cpk* values for various monitoring parameters. The researchers also determined the treatment reliability of the PWW treatment plant, with regards to its ability to remove all pollutants, using the Weibull reliability theory (Eq. 8). They tested the hypothesis that the Weibull data distribution presented the approximated empirical data using the Anderson-Darling goodness-of-fit tests at a significance level of 0.05. The data distribution showed higher goodness of fit and a *p*-value >0.05, which indicated that the null hypothesis cannot be rejected. Thus, little evidence was provided for concluding that this data did not follow Weibull distribution. The treatment reliability of a PWW treatment plant indicates its ability to eliminate toxic pollutants to fulfil the standard levels. Figure 4 presents the Weibull cumulative distribution functions for the evaluation parameters. As shown in Figure 4f, the treatment showed 100% reliability for NH_3-N, thereby indicating that during the study period (ranging from June to December 2020) the plant did not show an exceedance limit and the PWW outflow fulfil the Standard A requirements. Furthermore, the treatment reliability c)



d)

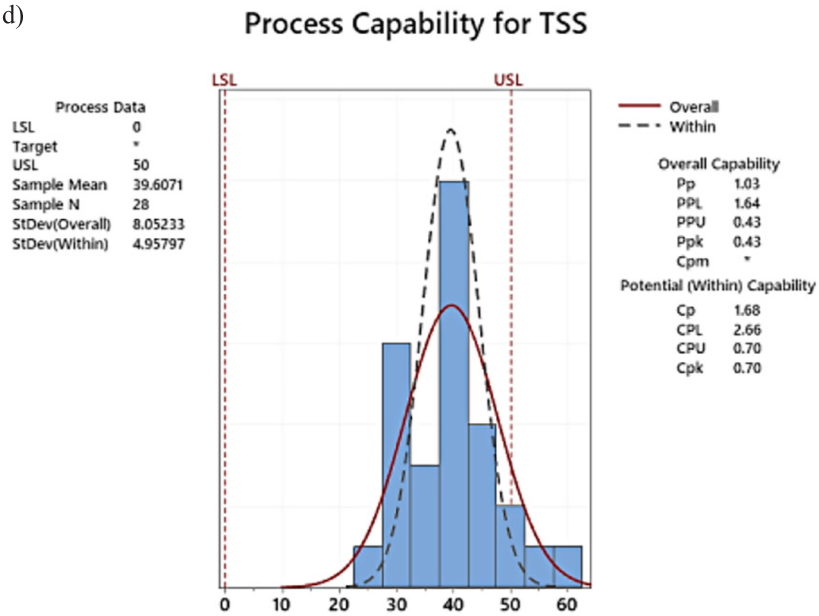
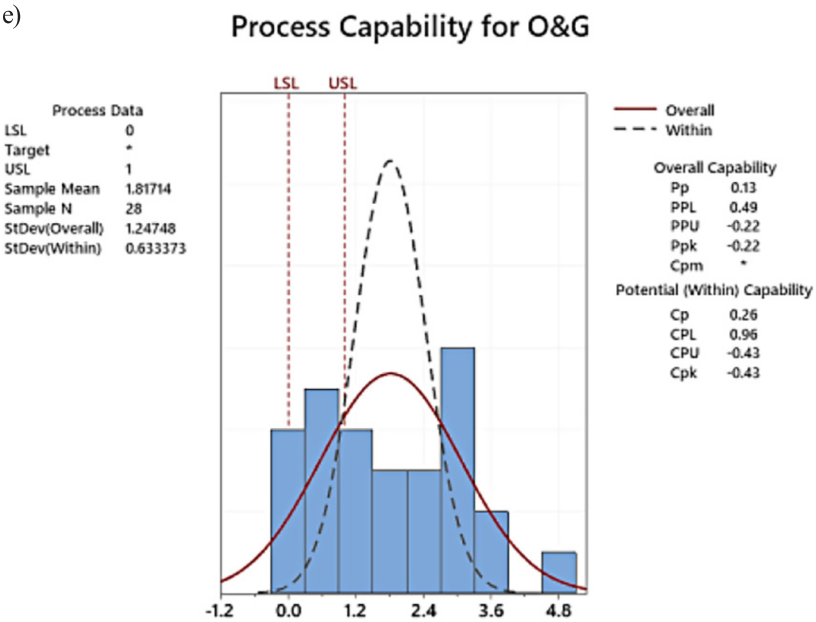


Fig. 3. Cont. Process capability for the assessed parameters

for other parameters like pH, BOD_5 and COD in Fig. 4a to 4c was >90% (Oliveira and Von Sperling 2008; Micek et al., 2021), which was typical for the activated sludge systems, indicating that it was less reliable, though the plant was still operational under the design capacity. However, Fig. 4d and 4e for TSS showed treatment reliability of 88.6%, while it was 29.8% for O&G, during the study period. Hence, a lot of improvement is needed for overcoming the low treatment reliability that resulted due to the DAF unit malfunctioning, poor physical-chemical processing and a tertiary filtration process breakdown, which led to the drainage of the colloidal particles from the treatment system into the discharged effluent (Jóźwiakowski 2017).

CONCLUSIONS

On the basis of the results noted in this study, the researchers concluded that the studied PWW treatment process was not properly and statistically controlled. The use of a traditional performance monitoring process that does not involve the Six Sigma principles for wastewater treatment, did not allow the system operators to understand the "actual state" of their treatment level. The researchers assessed 6 parameters in this study, i.e., pH, BOD_5, COD, NH_3-N, TSS and O&G. From their values, the researchers estimated the process capabilities values i.e.; Cp and Cpk and the treatment reliability percentage, for understanding the general performance e)



f)

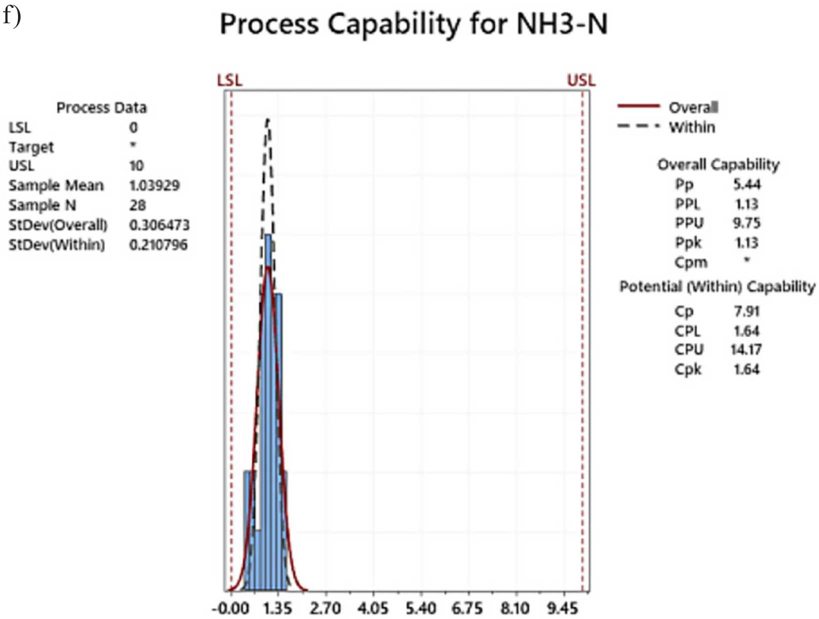


Fig. 3. Cont. Process capability for the assessed parameters

of this PWW treatment plant. As the values of the Cp and Cpk were >1.33 and good treatment reliability was noted for NH_3-N (i.e., 100%), the researchers concluded that the biological process was in line with the design capacity. Thus, the mean process capability and treatment reliability values for other parameters like pH, BOD_5 and COD at 99.7%, 94.3% and 99.9%, respectively, indicated that these values complied with the necessary standardised limits. Despite these values, it was concluded that the colloidal particles were present in the effluent, based on the low *Cp*, *Cpk* and treatment reliability values for TSS at 88.6%. This issue needs to be urgently addressed by the operators.

A low design value for O&G at 0.5 mg/L indicated that this parameter showed the worst process capability and lowest treatment reliability values. This factor exhibited a *Cp* of 0.26, Cpk of -0.43, and treatment reliability of 29.8%, which indicated that the PWW plant is unable to reach a maximum general reliability level. All these issues led to the discharge of a higher concentration of organic and inorganic pollutants into the water bodies, which can affect the environment and subsequently, human health. Here, the researchers identified many problematic steps involved in the PWW treatment process that was used in the Malaysian poultry plant during the study period, such as the

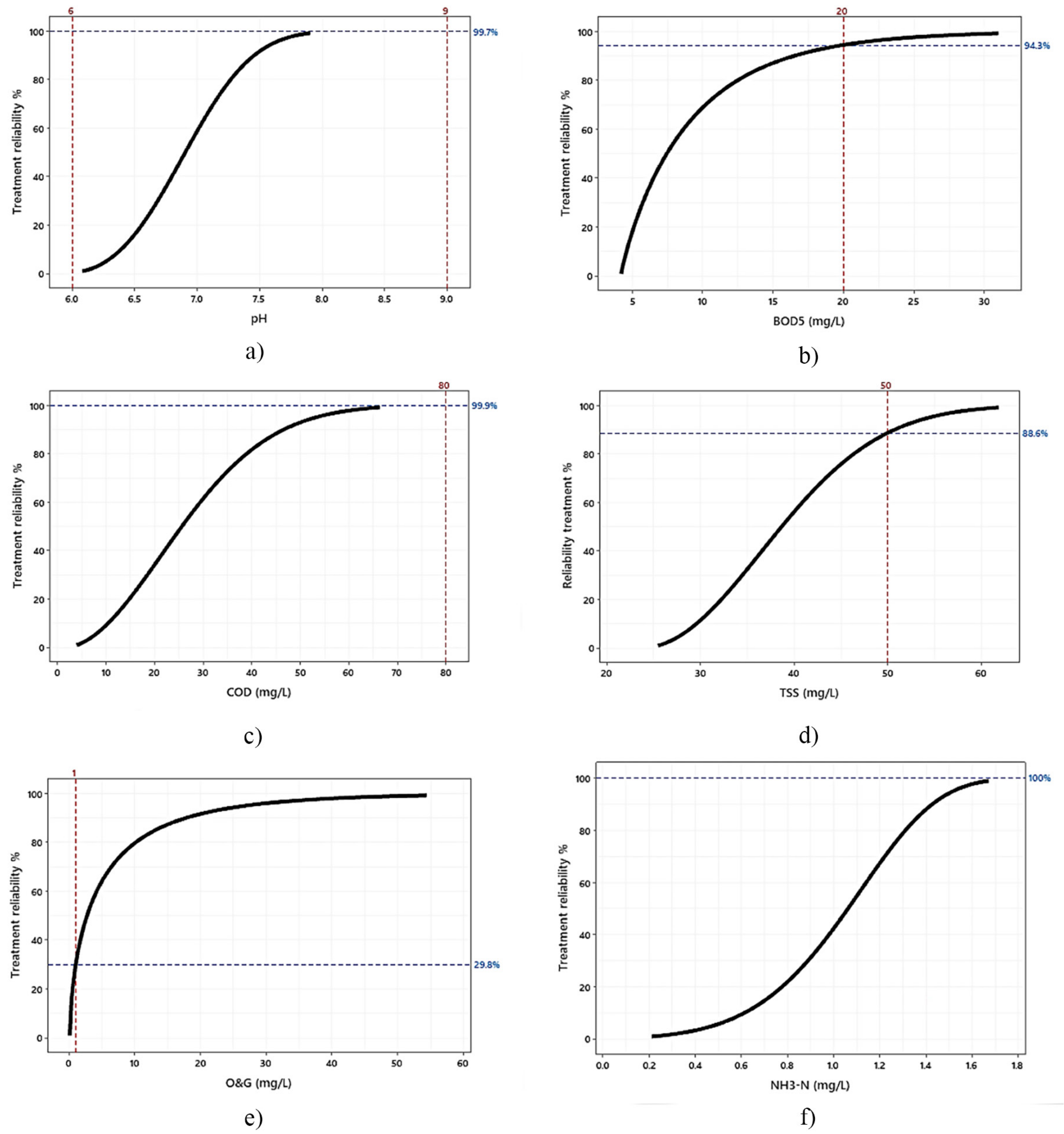


Fig. 4. Weibull cumulative distribution functions and treatment reliability for the assessed parameters

physical-chemical dosing step, physical DAF operations and maintenance of the tertiary filtration unit.

This study has highlighted the need to integrate the Six Sigma principles with the traditional technique for improving the quality of the PWW treatment process, based on the process capability and treatment reliability appraisal. The integration of the technique could improve the PWW treatment as it could facilitate a lower process variability at better costs. In this study, the researchers presented a successful pilot case study that was conducted at a poultry processing plant in Malaysia. Their study showed that the integration of the Six Sigma principles for improving the quality of the wastewater treatment process offered a viable option for reducing the concentration of colloids and oil and grease, optimising the chemical usage, improving the settlement of particles through the coagulation and flocculation unit processes, and enhancing the filtration capabilities of the PWW treatment plant.

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