Plant Redesign for pH Neutralization Process of Textile Wastewater Treatment

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Abstract. This study reports the redesign of a laboratory-scale pilot plant for textile wastewater treatment, especially in the pH neutralization process. The goal was to improve the plant structure, to facilitate more efficient process control. The result was a modular wastewater treatment plant that easy to operate and more efficient. A microcontroller controlled the plant. The plant was equipped with sensors and actuators to enable process monitoring and control in real-time. The control system was able to maintain the waste pH close to the setpoint (pH 8.5) despite the process disturbances.

Keyword: textile, wastewater treatment, pilot plant, pH neutralization, restructuration plant

1. Introduction

Textile wastewater is the byproduct of textile dyeing and finishing [1]. The wastewater contains many pollutants, such as dyes, high acidity, detergents, and degradable organics [1],[2]. Before discharge safely into the environment, the waste must be treated to meet quality standards [1],[2],[3].

Various methods have been developed for the textile waste treatment process. These methods may combine chemical reactions (such as pH neutralization), physics processes (equalization, adsorption), even biological processes. This study focused on textile wastewater treatment that combined the equalization, pH neutralization, electro-coagulation, and filtration processes.

Efficient wastewater treatment requires thorough consideration in plant design. This requirement highlights the importance of integrated process design and control to increase system performance. The plant structure must be improved, such that the dynamic performance is easily optimized. The plant design should facilitate the application of control strategies within the operational constraints.[4].

Therefore, this study focused on redesigning our first-generation, laboratory-scale pilot plant of wastewater treatment [5]. The first-generation plant was built mainly to study the possibility of combining and controlling both the pH neutralization and the electro-coagulation processes. The operation ease and efficiency were not the primary consideration during the study. Therefore, the plant did have several problems. Firstly, the tanks needed better positioning. Secondly, the sensors and actuators were also needed proper positioning and reliable circuitry. Finally, the plant required a control panel. The lack of these requirements made the first-generation plant tricky to operate. It was challenging to work around the plant. It also occupied a larger space.
The focus of this study was to redesign the plant to enable ease and efficient operation of the pH neutralization unit. The pH neutralization was a critical process in this plant. The plant design consists of several activities, namely flowsheet configuration, equipment selection and sizing, material selection, and conditioning of the operation [4].

This paper begins with the descriptions of the first generation of laboratory-scale, wastewater treatment pilot-plant in this study. The design of the second-generation plant follows. Then, it discusses the design of the pH neutralization process. Finally, the performance of the pH neutralization process is measured and analyzed.

2. First Generation Plant
This first-generation plant is shown in Figure 1. It consisted of equalization, neutralization, electro-coagulation, transition, and filtration units [5]. The maximum capacity of the pilot plant was 54.94 liters, and it operated continuously.

The plant has several weaknesses. This plant occupied the area of 1.5 x 1.35 m², and the tanks were positioned at various levels. There was no control panel nor a strengthening framework. The fluid circulation was impractical due to the lack of a drainage path. Therefore, the plant needs improvement to enable better operation.

![Figure 1](image1)

The first-generation of pilot plant consisted of (a) equalization (b) neutralization (c) electro-coagulation (d) transition (e) filtration units [5]

3. Design of Second-Generation Pilot Plant
The spirit of the second-generation design is an integrated system. The system was designed to run continuously and automatically. It was supported by monitoring and control systems that were easy and reliable to operate.

While designing the overall plant, this study focused on the pH neutralization process. The textile waste is a strong alkali of pH 8-10. It was the byproduct of textile industry processes, such as scouring, bleaching, mercerizing, and dyeing [6]. The goal was to achieve the standard quality of waste at pH 6 - 9 by adding a weak acid solution.

The design of the second-generation of the pilot plant is shown in Figure 2. This plant was located within a two-level framework. The equalization, neutralizer I, and the product tanks occupied the bottom level. In the equalization tank, the waste was homogenized by agitation. The neutralizer I tank was the reservoir of acid solutions. It supplied the second tank, which operated the neutralization process. The product was collected in the product tank, ready to release into the environment.
The second level was allocated for the pH neutralization tank, electro-coagulation tank, the transition tank, and the filtration tank. The electro-coagulation tank facilitated the coagulation, floatation, and electrochemical process to purify the waste. The results went to the filtration tank, in which suspended solids and colloids were filtered using active sand.

All tanks were connected through pipes. Most pipes in this plant were 1/2 inches polyvinyl chloride. The exception was the connection between the pumps and the flowmeter that used 1/4 inches transparent water hose.

According to the guideline for small textile industry waste management, the capacity of the first-generation plant was appropriate. For example, the jeans industries produce as much as 20 m$^3$ per day of wastewater. It was equivalent to 20,000 liters per day. It was equivalent to 0.23 l/second.

The size of the equalization tank in the typical textile industry is 1.5 x 4 x 1.5 m$^3$. The volume of the equalization tank in this study was 1:300 to the industrial tank. It is the basis for upscaling the tank for full-scale industrial applications.

Piping and Instrumentation Diagram (P&ID) of pilot plant wastewater treatment is shown in Figure 3. There were several sensors and actuators to monitor and control the system. First, the equalization unit consisted of a pH meter to measure the pH of waste in the pH unit, a turbidity sensor to measure the turbidity, and a flowmeter to measure the flowrate. The actuators were pumps for the waste and an agitator.

Then, the neutralizer tank consisted of neutralizer I and neutralizer II. The neutralizer I tank was a reservoir to maintain the stock of acid neutralizer. It had a motor pump, called pump 2. This pump supplied the acid to the neutralizer II tank, whereas the neutralization process occurred.

The pHneutralization tank collected inputs from the equalization and the neutralizer II tanks. In this unit, the pH meter measured the pH of the neutralization product, and the flowmeter measured the waste flowrate. The microcontroller determined the speed of the pumps (pump 1 from the equalization and pump 3 from the neutralizer II tank) based on the pH reading. Compared to the first-generation system, the solenoid valve components were replaced by the pump.

After the neutralization process, the waste went to the electro-coagulation tank, then to the transition and filtration processes. It was finally collected in the product tank. The desired output was a waste pH between 6 to 9.
4. Design of pH Neutralization Unit

The pH neutralization process was designed based on the chemical reaction between alkali waste and neutralizing acid. The resulting pH was the function of the acid dissociations ($x_1$) and alkali dissociations ($x_2$) values. The dynamic models of the pH neutralization process were first introduced in [7] using a Controlled Stirred Tank Reactor (CSTR) between strong alkaline and weak acid [7]. This dynamic model was used in several studies. These include the design of the neutralization process for the first-generation plant [5], the Internal Mode Control in the process of waste neutralization [8], and the design of PID Neural Network control for the pH neutralization process [9].

$$\frac{dx_1}{dt} = \frac{F_a}{V_t}C_a - \frac{F_a + F_b}{V_t}x_1$$  \hspace{1cm} (1)

$$\frac{dx_2}{dt} = \frac{F_b}{V_t}C_b - \frac{F_a + F_b}{V_t}x_2$$  \hspace{1cm} (2)

Based on equation (1)-(2), the neutralization process was affected by the waste flowrate $F_b$, the concentration of waste $C_b$, the neutralizer flow rate $F_a$ and the concentration of neutralizer $C_a$. Therefore, the design of the pH neutralization process consisted of three main tanks. These were the neutralizer tank, alkaline tank, and reactor tank, as shown in Figure 4. This design was also based on the research of [10], [11], and [8] about the pH neutralization process.

The P&ID diagram shows that the pH neutralization unit was equipped with sensors and actuators and a control panel to support the monitoring and control process in real-time. The sensors consisted of the pH meter sensor, temperature sensor, and flowmeter sensors—the actuators such as pump and agitator (to speed up the reaction of solutions). Sensors and actuators were integrated into panel control and controlled using microcontrollers.

The data acquisition utilized two microcontrollers. The first microcontroller acquired pH, flowrate, and temperature measurements, calculated control actions, and sent the control signals to the pump. The second microcontroller operated the level sensor and the agitator.

The flowchart of the monitoring and control pH neutralization process is shown in Figure 5. The flowchart began with initialization parameters of waste such as pH, temperature, flowmeter, turbidity, and level parameters. The system operated two controls, namely pH control and level control.

![Figure 3: Piping and Instrumentation Diagram (P&ID) of second-generation plant](image-url)
The pH was controlled in two stages. Stage 0 was activated when the waste pH is higher than 8.5. The microcontroller activated the acid pump and deactivated the waste pump. Next, Stage I was activated to operate the acid pump using the digital Proportional Integral control until the setpoint was achieved. Else, the acid pump was off, and the waste pump was on. The control cycle continued until the waste pH met the setpoint.

A level control system maintained the volume of fluid in neutralizer tank II. The setpoint was the acid level of 20 cm. If the acid level was higher than 20 cm, the pump of neutralizer I (reservoir of acid) was off. Else, if the acid level was less than 20 cm, the pump of neutralizer I was on.

5. Results

5.1. Realized Plant

The realized second-generation plant is shown in Figure 6. The functional space was 1.25 x 0.7 x 1 m³. This pilot plant is equipped with a panel control with grounding and a framework from iron. It was easier to operate and to move. The monitoring was more effective and efficient. Fluid replacement in the tank is more easier because the drainage was available, along with a relief pump. The comparison to the first-generation plants is listed in Table 1.
Table 1 The improvement between the first and second-generation plants

| Aspects                  | First Generation | Second-generation |
|--------------------------|------------------|-------------------|
| 1 Space requirement      | 1.5 x 1.35 m²    | 1.25 x 70 m²      |
| 2 Framework              | No strengthening framework | The framework from the iron material |
| 3 Control panel          | None             | Control panel with proper grounding. |
| 4 Actuator for pH neutralization process | Solenoid valve with on-off controller | Acid pump using PI Controller |
| 5 Flowmeter Stand        | None             | Yes               |
| 6 Level                  | Three levels     | Two levels        |
| 7 Fluid replacement in the tank | No drainage system | Drainage system available |

All sensors and actuators were integrated into the control panel, especially for the pH neutralization process. The electrical schematic in the control panel is shown in Fig 7. The sensors were of two pH meters, two turbidity sensors, one temperature sensors, and two flowmeters. All sensors were connected to the microcontroller. The L298 module was connected to neutralizer pump II and waste pump, relay, and level sensor. The microcontroller controls the flowrate of acid into the neutralization II tank. The acid pump performance was reported in [12].

5.2. Measuring the Performance
An experiment was done to measure plant performance. It utilized artificial textile waste. The artificial textile waste was made to mimic the real waste, of which pH is greater than 9. It consisted of NaOH, 375 mg/ l dyes, and 1000 - 2000 mg/l starch. The neutralizer was CH₃COOH. A subsubsection. The paragraph text follows on from the subsubsection heading but should not be in italic.

The first experiment of the pH neutralization process was performed to observe the open-loop responses. The responses are shown in Fig 8. The waste pH was 9.7, the acid pH was 5.0, and the setpoint is 8.5. The responses showed that the acid pumps were operated for 248.2 seconds to reach a waste pH of 8.5 at the open-loop system.
The closed-loop responses were shown in Fig 9. The initial pH of waste being 9.5, the pH of acid solutions is 5, the flowrate of the acid-neutralizing pump was 0.6 - 1 l/minute, and the flow rate of waste is 0.8 l/minute. A digital Proportional Integral controller was programmed into the microcontroller, with controller parameters \( K_p = -0.07 \) and \( T_i = 30.54 \).

In the first cycle, the pH of waste 9.5 reached the setpoints (pH 8.5) within 350 seconds. The pH meter continued reading the pH of waste until it reached a minimum pH of 8 within 400 seconds. The acid pump was on for 233.2 seconds. This duration was 15 seconds faster than the open-loop response. The experiment also showed some delays in pH sensor readings. After reaching the setpoint, the waste pH continued to decreases to 7.6. Nevertheless, this pH was within the required pH between 6-9.
In the second cycle, the addition of waste caused an increase in the pH of 8.8. The neutralizing pump was on for 92 seconds so that the waste pH reached 8.5. In the subsequent cycle, the control performed better. The waste pH was maintained in a steady-state with a smaller error. Within 1400 seconds, the waste treatment was achieved.

This experiment demonstrated that the controller maintained the waste pH close to the setpoint (pH 8.5) despite the disturbances.

6. Conclusion

The redesign of the pilot plant of textile wastewater treatment has been completed. The pilot plant is easy to use for further research and more efficient. The control panel of the pH neutralization process was available to monitor and control the plants in real-time. The pH neutralization process has the controller to maintain the pH of the waste close to the setpoint of 8.5.

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