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Management of Industrial Wastewater Quality Using IoT

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Abstract — *Industrial wastewater treatment should be the focus of any industry using water to decrease the dependency on the scarce fresh water and to guarantee a safe disposal of the treated water. Wastewater treatment requires tailored processes based on the desired input wastewater quality measured by parameters such as pH, TDS, and turbidity and the desired application of the treated water. Wastewater properties vary by source, such as municipal, industrial, agricultural, and household, with the industrial wastewater being the most polluted. Water quality standards are set by organizations like the World Health Organization (WHO) and the Ministry of Environment in each country. This work proposes a system that involves a smart water quality management system using Internet of Things (IoT) devices such as sensors for real-time monitoring and actuators for controlling the water quality. This system treats the output wastewater from a detergent production line through sedimentation and filtration. Key water quality parameters: pH, TDS, and turbidity are monitored and controlled to meet the Egyptian Ministry of Environment's standards for disposal into Nobaria Canal. The treated water can be reused in applications like production lines, firefighting, or irrigating of ornamental plants. The system is programmed with Arduino software, and sensor data is displayed using Realterm software.*

Keywords — *Industrial Water Recycling, Smart Water Treatment, Industry 4.0, Quality 4.0, IoT*

I. INTRODUCTION

Since freshwater is an essential component for all living species, a key issue that humanity is currently facing is the shortage of such vital source of life. The demand for freshwater has increased due to the growing population, so it is necessary to expand access to water resources by employing water treatment, particularly treating wastewater such as home, industrial, and municipal wastewater and direct it to be used for suitable applications. This will reduce the demand for freshwater.

It is necessary to monitor and regulate the quality of the treated water and wastewater by removing and lowering the pollutants and toxins in the used water. The environment and the welfare of human health will be harmed if the pollutants and toxins included in the wastewater reached the freshwater resources or being used for irrigation purposes for example. Industrial effluents from a variety of production systems, including the detergent production systems, are sources for contaminated wastewater. Water quality indicators like pH (potential of hydrogen), TDS (total dissolved solids), and turbidity can be used to track and control the treated wastewater quality. The Quality 4.0 concepts, which stem from the Industry 4.0 technology, can be used to manage the quality of the treated wastewater through the implementation of smart sensors and actuators.

The primary goal of the designed smart wastewater treatment system is to improve the treated industrial wastewater quality leading to wastewater recycling, addressing the freshwater supply shortage.

The Industry 4.0 concept was introduced in 2011, focusing on automation, digitization, data analytics, real-time data collection, smart production systems, and improved product quality [1–7].

The Quality 4.0 concept combines Industry 4.0 technologies with traditional quality approaches to enhance the process performance, process output quality, and to minimize the errors and defects. This idea is put into practice

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through the digitalization of processes, data collection and analysis employing sensors for quality control and improvement. Eleven axes, including management system, analytics, data, app development, connectivity, scalability, collaboration, competency, leadership, culture, and compliance, are forming the Quality 4.0 concept [3, 7–15].

Internet of Things (IoT) refers to connected electrical gadgets, coined in 1999 by Kevin Ashton. [16–19] Data transmission between linked devices is the main emphasis of IoT [20]. The Internet of Things (IoT) technology has various advantages for water management, including energy management, cost reduction, and system efficiency [21].

In order to monitor and regulate the water quality management system's parameters, smart water quality management uses IoT technology [22]. Real-time analysis, time savings, and cost savings are the three primary advantages of the smart water quality monitoring system [23, 24].

An automated water treatment system that incorporates Industry 4.0 technologies including the Internet of Things (IoT), big data, machine learning, and artificial intelligence is referred to as a smart water treatment system [25–27].

An example of industrial wastewater treatment process is shown in Figure 1, which is used to remove pollutants and contaminants from the wastewater and involves pre-treatment, screening, grit removal and disinfection. Primary sedimentation is followed by biological treatment and filtration to get rid of the suspended particles. In order to remove the smaller particles and dissolved solids, tertiary treatment uses chemical flocculation, filters, and chlorination is used. The disinfected water can be recycled for use in industry or agriculture, [28–31].

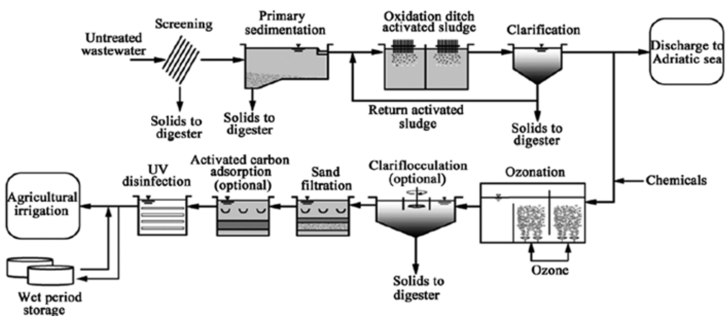

Figure 1. Wastewater treatment process [30]

A. Detergent Manufacturing Process

The production of powder detergent involves using raw materials in the form of solid ingredients, and liquid ingredients that are shown in Table 1. [31, 32]

TABLE 1. INGREDIENTS PER 1 KG OF DETERGENT

Solid ingredients	Amount (g)	Liquid ingredients	Amount (ml)
Caustic Soda	117.65	Oils	706
Soda ash	11.765	Water	353
Sodium tripolyphosphate	58.825	Sulfonic acid	14.12
Sodium perborate	1.18	Oxygenated water	29.41
Carboxymethylcellulose (CMC)	11.76	Fragrances	8.24

The detergent production process involves combining ingredients, including filtered and recycled powder detergent dust. Treatment of the industrial water that is used in washing the production line is necessary to remove the pollutants coming from the line that are listed in Table 2. Pollutants like suspended solids, dissolved solids, and excessive acidity or alkalinity. [33]

TABLE 2. POLLUTANTS IN THE DETERGENT MANUFACTURING PROCESS INDUSTRIAL WASTEWATER AND TREATMENT METHOD [33]

Pollutant	Treatment
• Suspended Solids	• Plain Sedimentation • Chemically Enhanced Sedimentation
• Dissolved Solids (Inorganic)	• Sedimentation • Filtration
• Unacceptable acidity or alkalinity	• pH Adjustment
• Organic Contaminates	• Disinfection

II. EXPERIMENTAL

The detergent production line of Abo El Hol Company for Salt and Soda together with the washing water flow line is shown in Figure 2. The production line consists of Tank 1, where the ingredients are weighed and put into the tank. Tank 2, referred to as the "primary mixing tank", where the preliminary mixing takes place. Tank 3, referred to as the "secondary mixing tank" where homogenization takes place to form a paste. Tank 4 is the contrasting tank that is used to move the paste back from the drying chamber for homogenization in case the slurry was not mixed well. A high-pressure pump sprays the paste flowing from Tank 4 to the drying chamber to be sprayed into the chamber walls using spray nozzles and drying air at temperature range between 100°C-160°C. Following drying by the hot air, exhaust fans remove the powder sticking to the drying chamber walls. The soft powder (dust) is removed by the dust filters and recycled back with the ingredients. The product flows by conveyor lines then packaged and stored.

When the process is complete, the production line is washed/rinsed with water. Washing water flows through all the tanks and the drying chamber using to a high-pressure pump and then collected in a collection tank. From the collection tank, the washing water flows to the water treatment facility where it is treated then dumped into the Nobaria Canal.

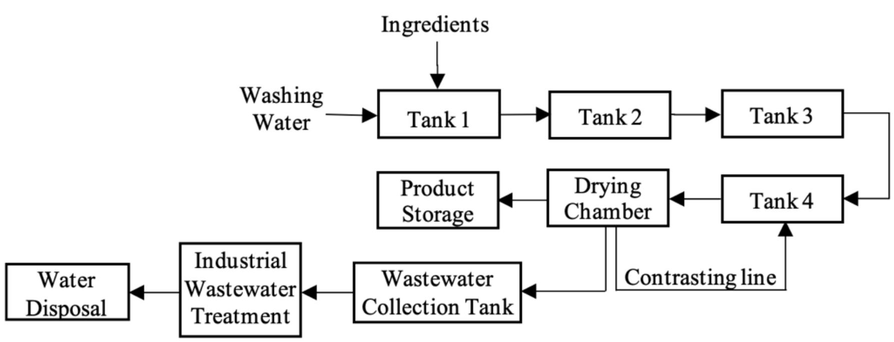

Figure 2. Detergent production line and washing water flow line

A. *Smart Wastewater Treatment System*

The designed smart wastewater treatment process is illustrated in Figure 3. The figure demonstrates how water moves through the system from Tank 0 to Tank 1 where lime solution is injected via a dosing pump for coagulation before moving to Tank 2 for precipitation. As the water in Tank 1 reaches a specific level, it is pumped via the pipeline to Tank 2. It takes almost two hours to fill Tank 2, to enable for the precipitation process. Water moves by gravity from Tank 2 to Tank 3, where alum is injected for flocculation using a dosing pump and a mixer. Water moves from Tank 3 to Tank 4 by gravity, where it also takes two hours to fills Tank 4. The barrier in Tank 4 prevents any extra alum and leftovers "flocculated particles" from settling at the tank bottom.

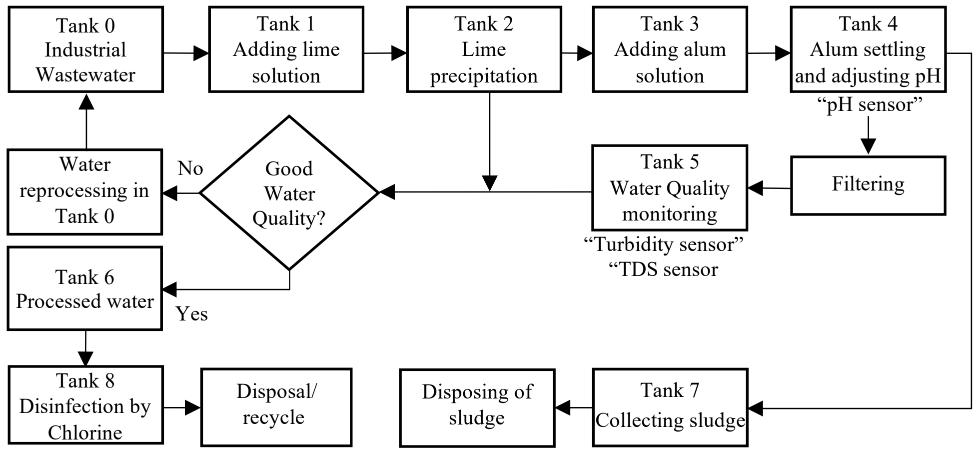

Figure 3. Smart wastewater treatment diagram

Tank 4 is used for alum settling and has a sensor for measuring pH. If the pH is outside the acceptable range, which is from 6 to 9, acid or base is injected in tank 4 using a pH neutralization dosing pump. Using a dosing pump, the water is transferred from Tank 4 to the filtering membrane for filtration. TDS and turbidity are monitored in Tank 5 using TDS and turbidity sensors after the water exits the filtering membrane. In Tank 5, the water quality is assessed, if the TDS level is more than 1500 mg/l or the turbidity level was greater than 50 NTU the water is pumped back to Tank 0 using a feedback pump for retreatment. If the TDS and Turbidity levels are within the acceptable limits, the water is pumped to Tank 6 as treated water. The water then is pumped from Tank 6 to Tank 8 where it is chlorinated to sterilize it. The chlorine limit should be between 0.5 and 1 ppm, which is measured by DPD (diethyl-p-phenylenediamine) tablets. The excess chlorine is then removed by aerating the water. Following chlorination, the treated water is either released into the Nobaria Canal or recycled for industrial use or to be used for agriculture purposes for non-food producing trees. The sediments in Tanks 2 and 4 are drained into Tank 7 using the taps located at the bottom of each tank. In Tank 7, $Fe\,Cl_3$ flocculant is added to the water sedimented particles to form a cake after 10 minutes of reaction time. Government specialists collect the sediments/cakes to be transferred to landfills.

B. System Components

The above system is composed of the following components: Hardware, Microprocessor, and Sensors.

1) Hardware

Water tanks: Water tanks play a crucial role in the water treatment system, catering to various stages of the treatment. Two 100-liter tanks are employed, Tank 0 and Tank 6. Tank 0 collects the out of specs industrial wastewater, and Tank 6 stores the final treated water. If the water quality parameters meet standards, the water is directed to Tank 6 for discharge or reuse; otherwise, it is redirected to Tank 0 for retreatment. Three 16-liter tanks are utilized, Tank 1, Tank 3 and tank 5. As mentioned, Tank 1 is used for mixing lime for coagulation, Tank 3 where alum is added for flocculation, and Tank 5 where monitoring the TDS and turbidity takes place. Two 20-liter tanks are used for sedimentation, Tank 2 and Tank 4. Tank 2 allows excess lime and coagulated particles to settle at the bottom, and Tank 4 is utilized for sedimentation of excess alum and flocculated particles. Sediments from Tanks 2 and 4 are transferred through the taps to Tank 7 (20-liter tank), where the sediments cake is formed. Different sizes of tanks and the sediments cake are shown in Figure 4. Meanwhile, Tank 8 (20-liter tank) is utilized for injecting chlorine solution into the wastewater to effectively eliminate the microorganisms before recycling.

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(a) (b) (c)

Figure 4. (a) 100-Liter tank (b) 20-Liter tank (c) Sediments cake

Pumps: Pumps play an important role in the water treatment system. The system has 8 pumps, 4 water transfer pumps and 4 chemical injection pumps. Water pumps transfer water from Tank 0 to Tank 1, from Tank 1 to the filter, from Tank 4 to Tank 5, and from Tank 5 to either Tank 6 or to the feedback line for retreatment. The flow rate of the water pimps is 174 liters per hour. Chemical injection pumps inject lime, alum, acid, and base into the system at a rate of 4 liters per hour. Figure 5 displays the water pump. Table 3 displays the specifications of the water pumps, and Table 4 displays the specifications of the chemicals' injection pumps.

Figure 5. Water flow pump

TABLE 3. WATER PUMP SPECIFICATIONS

Brand Name	Model	Max Pressure	Flow Rate	Voltage	Motor Type	Max Amp
Kunfun	KF-2203	2.0 MPa	2.9 L/min	12 V	DC	4.0 A

TABLE 4. CHEMICALS INJECTION PUMP SPECIFICATIONS

Brand Name	Model	Max Pressure	Flow Rate	Voltage	Motor Type	Max Amp
Kunfun	KF-14087	0.45 MPa	25-70 ml/min	12 V	DC	1.8 A

Membrane Filter: The membrane filter is shown in Figure 6 and is used for filtering the suspended particles in the wastewater. Membrane filters are available in a multitude of forms and configurations, but they all work on the basic principle of having a surface with pores that let water through but, depending on the size of the pore, are too small to let other materials or particles through. Membrane filtration can be categorized based on the pollutants' molecular weight retained by the membrane or on the diameter of its pores. The membrane used was of the Microfiltration type that has a pore size of 0.1–10 micron (100–10,000 nm).

Figure 6. Water filter

Tank barriers: The tank barriers shown in Figure 7, are used to prevent the accumulation of excessive lime and coagulated particles in Tank 2, and the overabundance of alum and flocs in sedimentation Tank 4 during the lime sedimentation stage, it is essential to install tank barriers. The installation of the tank barriers is essential to regulate water flow, ensuring efficient treatment during the lime sedimentation stage. The gaps at the bottom of these barriers facilitate the controlled passage of water while impeding the transfer of sediments and the excess lime or excess alum. This design ensures that the treated water moves leaving behind most of the sediments ensuring the effectiveness of the lime and sedimentation.

Figure 7. Tank barrier

Mixers: Figure 8 demonstrates the M14x2 Rubi mixing paddles. Mixers are utilized aid in the mixing lime, alum, acid, or alkali with the wastewater in tanks 1 and 3. The efficient functioning of these mixers is crucial to guaranteeing an appropriate dispersion and chemical reaction, thereby improving the overall effectiveness of the treatment process.

Taps: Taps are utilized to aid in the transfer of sediments, including settled water and particles as part of the treatment process from Tanks 2 and 4 to Tank 7. Figure 9 shows a garden tap - G1/2" Water Supply Faucet.

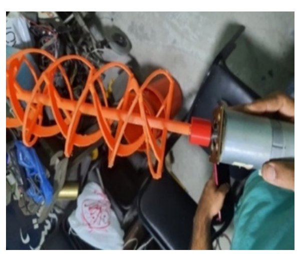

Figure 8. M14 x 2 threaded connections Rubi mixing paddles

Figure 9. G1/2" Water supply faucet

Valves: Two types of valves are used that serve essential functions within the system. Four units of Injection valves and two units of Input/Output valves as shown in Figure 10. Injection valves are utilized for the injection of chemical solutions into the injection tanks. Meanwhile, an Input/Output valve regulates the flow of wastewater pumped from the wastewater tank into Tank 1, where coagulation with lime occurs. Additionally, an Input/Output valve enables the flow of water from the treated wastewater tank to the Tank 5 designated for TDS and turbidity testing. Figure 10 shows the different types of valves used.

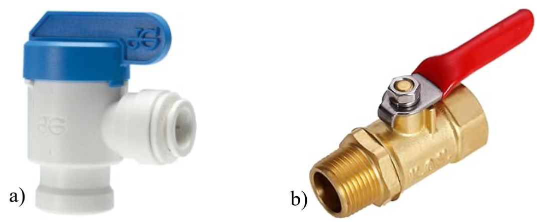

Figure 10. Types of valves injection valve. a) injection valve, b) input/output valve

2) Microprocessor: The Arduino Mega 2520 Rev3 microprocessor illustrated in Figure 11 acts as the central processing unit of the system, overseeing the management and transmission of sensor data to the user interface. Data retrieval from the system can occur either through a USB port on the processor and cable to a computer or via an integrated LED panel within the system. The selection of the Arduino Mega as the preferred microprocessor is based on its augmented computational power, expanded memory capacity, and extensive array of input/output pins, rendering it particularly well-suited for handling intricate algorithms and substantial datasets in large-scale industrial projects such as the smart wastewater treatment systems.

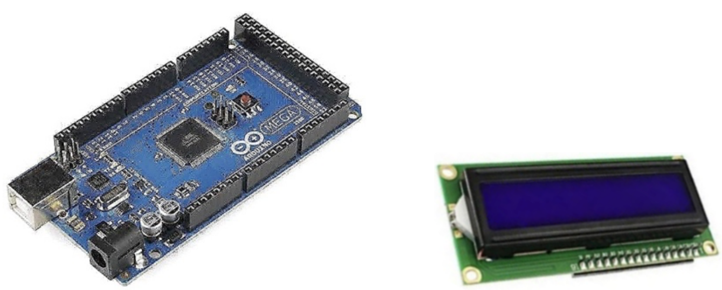

Figure 11. Arduino mega microprocessor and its display

The system information can be viewed on a computer using the USB Channel on the microprocessor and a USB cable. The processor includes an LED panel for displaying data as illustrated in Figure 11.
Although the Arduino Uno is widely appreciated for its simplicity and affordability, its suitability is better aligned with elementary projects due to constraints in computational power, input/output pins, and communication capabilities. On the other hand, the Arduino Due, equipped with an advanced 32-bit ARM Cortex-M3 processor, offers even superior computational power and performance compared to the Arduino Mega. Tailored for

applications demanding real-time processing and the management of rigorous computational tasks, its higher cost may be justified for specific systems. The specifications of the microprocessor are shown in Table 5.

TABLE 5. ARDUINO MEGA MICROPROCESSOR SPECIFICATIONS

Specification	**Value**
Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 14 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

3) Sensors: The sensors for pH, TDS, and turbidity are used for monitoring and controlling the water quality during the treatment process. They are used for evaluating the effectiveness of wastewater treatment, ensuring compliance, and producing quality treated water for recycling purposes.

pH sensor: The pH sensor is used for evaluating the treatment effectiveness and ensuring the quality of the wastewater treatment system regarding the acidity/alkalinity. It is used to maintain the pH in the desired range for efficient treatment and environmental compliance. Figure 12 illustrates a low-cost pH sensor, and Table 6 outlines its specifications.

Figure 12. The pH sensor

TABLE 6. pH SENSOR SPECIFICATIONS

Feature	Specification
Operating Voltage	5-24V
Output	RS485, MOD-BUS communication protocol
pH Measurement range	0-14 pH
pH Resolution	0.01 pH
pH Accuracy	±0.02 pH
Working Environment	Temperature: 0～60℃, Humidity: 0-100%
Protection Isolation	Up to four isolation, Power isolation, Protection grade 3000V
Standard Cable Length	5 meters
Farthest Lead Length	RS485: 1000 meters
Protection Level	IP68

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TDS sensor: A low-cost TDS sensor is shown in Figure 13 that measures the Total Dissolved Solids concentration, playing a vital role in assessing water quality and treatment effectiveness to ensure regulatory compliance before reuse or disposal. The sensor specifications are outlined in Table 7.

Figure 13. The TDS sensor

TABLE 7. TDS SENSOR SPECIFICATIONS

Feature	Specification
Operating Voltage	3.3-5V
TDS Measurement Range	0 ~ 1000 ppm
TDS Waterproof Probe Length	3 meters
Module Size	42 * 32mm
Measurement Accuracy	± 10% F.S. (25 ℃)

Turbidity sensor: The turbidity sensor measures the water haziness due to the suspended particles, which is crucial for assessing the treatment effectiveness and the water quality. Figure 14 illustrates a low-cost turbidity sensor, and its specifications are detailed in Table 8.

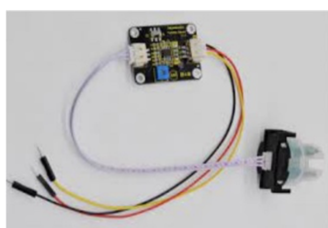

Figure 14. The turbidity sensor

TABLE 8. TURBIDITY SENSOR SPECIFICATIONS

Feature	Specification
Operating Voltage	DC 5V
Operating Current	30mA (MAX)
Operating Temperature	-30℃ ~ 80℃

III. RESULTS AND DISCUSSION

A. Jar Test Procedure for Chemicals Dosage Optimization

The Jar test involves a laboratory-scale simulation of the coagulation and flocculation processes used in water treatment. This method allows for the systematic evaluation of various coagulants and flocculants to determine the most effective chemicals' amounts needed for treatment of a specific wastewater. For instance, the Total Dissolved Solids (TDS) parameter, which represents the total amount of mobile charged ions in water, can be used as an example to assess the efficiency of the treatment process. By conducting jar tests with different dosages of

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coagulants, such as lime, and flocculants, such as alum, the optimal combination and dosage can be determined to achieve the desired reduction in TDS levels. In the context of jar testing, the addition of coagulants and flocculants, exemplified by the use of lime and alum, respectively, allows for the observation of their impact on water quality parameters such as TDS (which in part affects the turbidity as well). Through a systematic experimentation, the most effective dosage of these chemicals can be identified, leading to the optimization of the treatment process. [34]

1) Jar Test Procedure for Optimizing Lime Dosage as a TDS Coagulant: The main aim of the lime dosing jar test is to establish the optimal lime concentration required for coagulating the industrial wastewater. This involves collecting six samples of industrial wastewater requiring coagulation from the industrial wastewater tank and placing them in 1-liter containers. Lime dosages ranging from 50 mg/L to 300 mg/L are then prepared and added to the samples. Prior to the addition of the lime dosages, TDS parameter readings of the industrial wastewater samples are obtained using a TDS sensor. The industrial wastewater samples are mixed and injected with the lime doses; they are then allowed for an hour to enable the lime to settle. After the lime sedimentation happens, the TDS sensor readings are obtained for the coagulated wastewater samples.

Figure 15 (a) displays the results of the jar test samples, demonstrating the influence of the different lime concentrations on the TDS parameter. The findings indicate that, increasing the lime concentration from 50 mg/L to 150 mg/L causes the TDS to drop from 1820 mg/L to 1720 mg/L. Increasing the lime concentration behind the 150 mg/L dosage, causes the TDS to start increasing due to the excess of calcium bicarbonate in the wastewater. When excess lime is used in the coagulation process, it can lead to an increase in the total dissolved solids (TDS). This result indicates that, the optimum lime dosage for this wastewater is 150 mg/L.

2) Jar Test Procedure for Optimizing Alum Dosage as a TDS Flocculant: The jar test is also conducted to ascertain the suitable alum concentration required for flocculating the coagulated industrial wastewater after the lime treatment (coagulation). This involves treating coagulated six 1-liter jar samples from the wastewater that was previously treated with the lime and reached the minimum TDS level of 1720 mg/L as a starting point for the flocculation stage after the lime sedimentation in the jars. Alum dosages ranging from 50 mg/L to 300 mg/L are prepared and added to the samples. After the alum doses are injected and mixed with the coagulated wastewater samples, they are allowed for an hour to allow the alum to settle down. Following the process of alum sedimentation, TDS sensor readings are obtained from the flocculated wastewater samples.

Figure 15 (b) shows the results obtained from the flocculated jar test samples, illustrating the influence of alum concentration on the TDS parameter. The readings show that when the alum concentration increases from 50 to 200 mg/L, there is a reduction in TDS from 1720 mg/L to 1520 mg/L. With increasing the alum concentration, more aluminum ions (Al^{3+}) become available in the wastewater, leading to increased formation of aluminum hydroxide precipitates. These precipitates effectively flocculate impurities, resulting in a more substantial reduction in TDS. An increase in the alum concentration behind the 200 mg/L leads to an increase in TDS due to an excess of alum in the wastewater. This result indicates that, the optimum alum dosage for this wastewater is 200 mg/L.

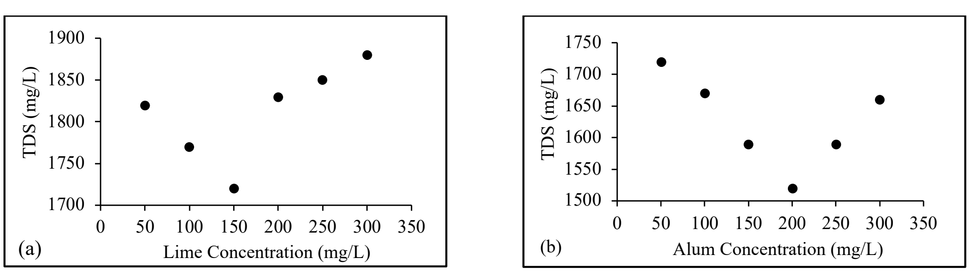

Figure 15. Lime and alum jar test results. (a) lime (b) alum

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B. System Validation

The system's pH, TDS and Turbidity sensor measurements are sent to the microprocessor. If the values are outside of the specification limits, the microprocessor sends commands to the actuators/pumps on the different tanks. If the pH is low, an alkaline is injected by the pump, and if the pH is high, acid is injected. If the TDS and/or turbidity was out of the spec limits, the water is recirculated to Tank 0 to go through the treatment system again to adjust these values.

The validation is defined as: ensuring that the system meets the needs of the intended use, which is the ability to control the quality of the treated wastewater. To validate the system, the pH, TDS, and turbidity sensors were set to collect data points for 15 hours. The data points were averaged and displayed every hour from both the industrial wastewater before treatment in Tank 0 and the treated wastewater in Tank 6. This is done to show the quality difference between the Input and Output wastewater to judge the system validity.

1) Tank 0 Measurements: Tank 0 contains the industrial wastewater before treatment and the out of specifications treated water that was recirculated back in the system as its measurements are not conforming to regulations to be disposed. Figure 16 (a) displays the pH measurements at an average value of 10.0, which is higher than the pH Upper Specification Limit (USL) of 9. Figure 16 (b) displays the TDS measurements at an average value of 1824 mg/L, which is higher than the TDS USL of 1500 mg/L. Figure 16 (c) displays the turbidity measurements at an average value of 100 NTU, which is greater than the regulatory USL of 50 NTU.

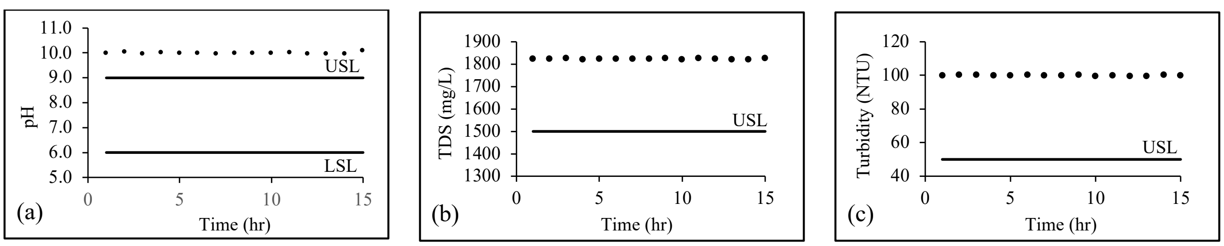

Figure 16. Tank 0 Wastewater measurements before treatment (a) pH (b) TDS (c) Turbidity

2) Tank 6 Measurements: Tank 6 contains the industrial wastewater after treatment. Figure 17 (a) displays the pH results, Figure 17 (b) displays the TDS results and Figure 17 (c) displays the turbidity results. As shown on the control charts all measurements are within the specification limits, which means the system is working according to the design needs. The pH was kept at an average value of 7.79, the TDS was at an average value of 919 mg/L and the turbidity was at an average value of 34.8 NTU.

From the above results of Tank 0 and Tank 6, the system is validated and works according to the design intended outcomes.

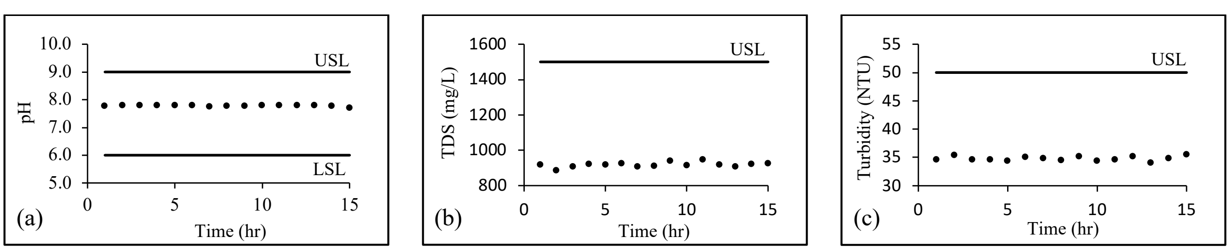

Figure 17. Tank 6 Wastewater measurements after treatment (a) pH (b) TDS (c) Turbidity

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C. *System Verification*

Verification evaluates if the system meets a regulation, requirement, or specification. The chemical analysis of the wastewater is vital in assessing its quality and identifying contaminants. In this study, samples from untreated industrial wastewater in Tank 0 and treated wastewater in Tank 6 were analyzed at the external laboratories of the Egyptian Foundation for Scientific Services and Analysis of Water, Soil, and Food. The analysis focused on determining biological, physical, physicochemical, and unwanted chemicals present in the samples, adhering to the standards set by the Egyptian Ministry of Health. This analysis is done to confirm if the treated wastewater is meeting the country regulations to be disposed of in the city water canals system or if it can be used for irrigation purposes of non-food trees. The analysis is also done to adjust the amount of chlorine injected in Tank 8 in case the biological contents were outside of the regulations' limits. The biological content is judged by the BOD_5 test, which is the 5-day biochemical oxygen demand and measures the total amount of oxygen used by microorganisms decomposing organic matter in 5 days.

The results, summarized in Table 9 provide valuable insights into the composition of both the untreated and treated wastewater, aiding in discovering the potential contaminants and pollutants. These findings are essential for the decision-making regarding treatment strategies, management practices, and regulatory compliance.

Furthermore, the data obtained from the analysis are crucial for evaluating the effectiveness of the treatment process and assessing the environmental impact of the wastewater disposal or reuse. By comparing concentrations of various chemical parameters before and after treatment, insights into the efficiency of the treatment process are gained. Additionally, the interpretation of the results aids in identifying any remaining contaminants, microorganisms, or pollutants in the treated wastewater, facilitating compliance with environmental regulations. The data shows that the quality of the treated wastewater conforms to the Egyptian regulations for the disposal of the treated industrial wastewater. These results verify that the system meets the Egyptian regulations.

TABLE 9. ANALYSIS RESULTS OF THE WASTEWATER BEFORE AND AFTER TREATMENT

Element to be analyzed	Before Treatment	After Treatment	Units	Accepted Limits
[1] Physical Parameters				
- Turbidity	1.72	<1	NTU	< 1
[2] Physicochemical Parameters				
- pH	9.16	7.7		6.5-8.5
- Total dissolved solids [TDS]	2030	316	mg/L	<1000
[3] Biological Parameters				
- BOD_5	123	18	mg/L	<60

IV. CONCLUSION

The developed detergent production line smart wastewater treatment system was successful in treating the industrial wastewater to the limits of the Egyptian regulations. The key advantages of the smart wastewater treatment process are the dependency on a smart system rather than labor, cost savings, as well as improving the treatment process through real-time data collection, monitoring, and management. The most important result is the real-time control of the quality of the treated wastewater so that it can be used in agriculture purposes.

The concept of the Quality 4.0 was used in designing the smart wastewater treatment. The main tenets of the Quality 4.0 concept that are utilized in the intelligent wastewater treatment are data collection in the form of readings collected using smart sensors. Also, the development of applications in the form to collect and store readings data, analysis in the form of parameter data analysis to determine whether or not the parameters are within limits, and connectivity between the system, computer, sensors, actuators and users.

The pilot system can treat up to 190 liter/day. For industrial use, planned upgrades to the smart industrial wastewater treatment system aim to boost its capacity to 960 m^3/day, which is a typical number for the amount of wastewater that maybe generated by the detergent manufacturing plant in the case study. This involves installing more precise sensors and probably using machine learning to optimize resource allocation and enhance wastewater treatment. Additionally, reverse osmosis technology maybe used to improve the treated wastewater quality for reuse in the detergent production line. Future plans may include automating the chlorination process and potentially integrating aerobic biological treatment stages to enhance contaminant removal and regulatory compliance. Efforts may also focus on applying the Industry 4.0 principles in automating the detergent production line itself to reduce the contaminants discharge rates, improving overall water quality and environmental sustainability. These initiatives mark significant advancements in the industrial wastewater treatment for environmental health and resource conservation.

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