



Performance Assessment of an Activated Sludge Wastewater Treatment Plant Treating Chocolate Processing Wastewater

Rizal Aulia Ahadi Putra Karim*, Rida Oktorida Khastini, Najmi Firdaus

Department of Environmental Studies, Universitas Sultan Ageng Tirtayasa, Indonesia

*Correspondence: rizalkarim.id@gmail.com

SUBMITTED: 20 May 2026; REVISED: 1 June 2026; ACCEPTED: 4 June 2026

ABSTRACT: The chocolate processing industry generated wastewater containing high concentrations of organic pollutants that could pose significant environmental risks if not properly treated. This study aimed to analyze the characteristics of wastewater generated from the chocolate-based food industry and to evaluate the effectiveness of a Wastewater Treatment Plant (WWTP) employing an activated sludge system. The research was conducted through field observations and laboratory analyses of 33 physical, chemical, and biological parameters at the WWTP inlet and outlet points. Sampling was performed using the grab sampling method in accordance with SNI 6989.59:2008, with a total of 33 samples collected during the period from October 2025 to April 2026. The results indicated that the main pollutant parameters at the WWTP inlet were Biochemical Oxygen Demand (BOD) at 1524 mg/l, Chemical Oxygen Demand (COD) at 6470 mg/l, and Total Coliform at 19,000 MPN/100 ml, all of which exceeded the environmental quality standards. Following the treatment process, the concentrations decreased to 12.94 mg/l for BOD, 54.70 mg/l for COD, and 560 MPN/100 ml for Total Coliform. The removal efficiencies achieved were 99.15% for BOD, 99.15% for COD, and 97.05% for Total Coliform. These findings demonstrated that the combination of chemical treatment and activated sludge processes was effective in reducing organic and microbiological pollutant loads to comply with the environmental quality standards stipulated in the Indonesian Ministry of Environment and Forestry Regulation No. 5 of 2014. Optimal wastewater treatment not only contributed to environmental protection but also supported social responsibility and industrial sustainability.

KEYWORDS: Chocolate industry wastewater; activated sludge; BOD; COD; Total Coliform; WWTP.

1. Introduction

The chocolate processing industry is one of the fastest-growing sectors within the global food and beverage industry, driven by increasing consumer demand for chocolate-based products. The production process involves various stages, including cocoa bean cleaning, roasting,

grinding, mixing, conching, and packaging [1]. These operations require substantial amounts of water for processing activities, equipment washing, and facility sanitation. Consequently, chocolate manufacturing facilities generate considerable volumes of wastewater containing dissolved and suspended organic matter derived from cocoa solids, sugar residues, fats, proteins, and other food-processing by-products. Wastewater generated from the chocolate industry generally originates from raw material mixing, refining, conching, molding, and equipment cleaning processes, resulting in effluents with relatively high concentrations of BOD and COD [2, 3]. If not properly treated, such wastewater may cause deterioration of water quality, including depletion of dissolved oxygen, eutrophication, and disruption of aquatic ecosystems [4, 5]. Therefore, wastewater treatment through a WWTP is an essential measure for pollution control. In Indonesia, industrial wastewater quality standards are regulated under the Ministry of Environment and Forestry Regulation No. 5 of 2014, which establishes the maximum allowable pollutant concentrations before discharge into the environment.

The characteristics and volume of wastewater generated by the food processing industry varied depending on the type of product and production methods employed [6]. Wastewater generated from the chocolate processing industry generally contained very high concentrations of organic matter, as reflected by significant levels of BOD and COD. BOD concentrations in chocolate industry wastewater were reported to range from 5,000–12,000 mg/L, while COD concentrations ranged between 10,000–20,000 mg/L. These elevated BOD and COD values indicated high concentrations of dissolved and suspended organic substances, such as sugars, cocoa fats, proteins, and polyphenolic compounds originating from chocolate production processes. This condition was consistent with findings indicating that chocolate industry wastewater possessed high biodegradability characteristics, as demonstrated by a relatively high BOD/COD ratio [7]. Recent studies also demonstrated that pH control was a key factor in improving BOD and COD removal efficiencies in food industry wastewater treatment systems [8].

Wastewater containing high pollutant concentrations requires proper treatment before being discharged into the environment. To determine appropriate wastewater treatment technologies and predict potential environmental impacts, it is necessary to identify wastewater characteristics according to their specific sources [9]. Although numerous studies have investigated wastewater treatment in the food-processing sector, research specifically addressing chocolate-processing wastewater remains limited. Existing studies have primarily focused on anaerobic treatment technologies, operational temperature effects, and bioenergy recovery using pilot-scale UASB reactors, whereas evaluations of full-scale WWTP performance through inlet–outlet assessments under actual industrial operating conditions are still scarce, particularly in developing countries such as Indonesia [10]. In this study, the identified wastewater characteristics were obtained from a chocolate-based food processing industry. The objective of this research was to analyze the characteristics of wastewater generated by the industry and evaluate potential technologies for reducing wastewater pollutant parameters. This study analyzed the results of 33 wastewater quality parameters measured during a seven month monitoring period in order to identify the dominant wastewater parameters generated by the chocolate industry.

Unlike previous studies that mainly focused on general food industry wastewater characteristics, this study provided a comprehensive long-term evaluation of wastewater treatment performance in a chocolate-processing industry using a combined physicochemical and activated sludge system under actual industrial operating conditions in Indonesia. The study not only evaluated pollutant removal efficiency but also analyzed biodegradability characteristics, environmental compliance, and the sustainability implications of wastewater treatment performance. This integrated approach provided a more comprehensive understanding of the effectiveness and operational stability of industrial wastewater treatment systems in the food-processing sector.

2. Materials and Methods

2.1. Research location.

This study was conducted at a chocolate processing industry located in Tangerang Regency, Indonesia, which is equipped with a WWTP facility for treating industrial wastewater prior to its discharge into the receiving water body. The chocolate processing industry is categorized as one of the food industries that generates wastewater with relatively high organic pollutant content, primarily originating from equipment washing processes, raw material mixing, cooking, cooling, and production area sanitation activities. The organic load is generally characterized by elevated concentrations of BOD, COD, total coliform, which may adversely affect environmental quality if not treated properly and optimally. The selection of the research location was based on the consideration that the industry has implemented an integrated wastewater treatment system, thereby enabling the evaluation of wastewater characteristics under both pre-treatment and post-treatment conditions. According to [11], food industry wastewater generally contains high concentrations of organic matter that require integrated treatment systems to prevent environmental pollution and to maintain the quality of receiving water bodies. The study was conducted over the period from October 2025 to April 2026. The relatively long research period was intended to obtain wastewater quality data that are more representative of variations in industrial production operations.

2.2. Research method.

The research method employed in this study was a quantitative descriptive approach through the collection of primary data obtained from field observations and laboratory testing results. The descriptive method was applied to describe the actual conditions of wastewater characteristics generated by the chocolate processing industry based on physical, chemical, and biological parameters. Meanwhile, the quantitative approach was used to analyze the concentrations of pollutant parameters contained in the wastewater. Field observations were conducted directly at the WWTP area to understand the wastewater treatment process flow, the operational conditions of the treatment units, as well as potential pollution sources that may affect wastewater quality. The observations included preliminary treatment units (pre-treatment), biological treatment processes, sedimentation units, and the final treatment stage prior to wastewater discharge into the environment.

This study also aimed to evaluate the effectiveness of the wastewater treatment system in reducing pollutant concentrations through a comparison of wastewater quality at the inlet and outlet of the WWTP. The evaluation was conducted by analyzing changes in the values of key parameters such as BOD, COD, TSS, oil and grease, as well as other pollutant parameters commonly found in chocolate-based food industry wastewater. This research approach was considered appropriate because it was able to provide a scientific description of the characteristics of wastewater generated by the chocolate processing industry while simultaneously evaluating the performance level of the WWTP based on actual laboratory testing results. According to [1], explained that a quantitative descriptive approach is effective for evaluating the performance of food industry wastewater treatment systems through the identification of major pollutant parameters and treatment efficiency analysis. In addition, [12] stated that WWTP operational observations combined with laboratory analyses are capable of providing a comprehensive evaluation of the stability of biological processes in the treatment of food industry wastewater containing high organic carbon concentrations.

2.3. Sampling technique.

Wastewater sampling was conducted using the grab sampling method, which refers to the collection of samples at a specific point and time considered representative of the wastewater condition during the observation period. The grab sampling method is widely applied in industrial wastewater quality studies because it is capable of representing the actual condition of wastewater at a specific time. According to, [13] reported that wastewater sampling at the inlet and outlet points of a WWTP is effective for evaluating the stability of industrial wastewater treatment processes as well as the removal efficiency of organic pollutant loads. Sampling at these two locations was intended to determine the reduction level of pollutant parameter concentrations as an indicator of the effectiveness of the wastewater treatment process.

The sampling procedure referred to SNI 6989.59:2008 concerning wastewater sampling methods. This standard was applied to ensure that the processes of sampling, preservation, and sample transportation were carried out in accordance with standardized procedures, thereby ensuring high accuracy and validity of laboratory test results. The collected samples were placed in sterile containers, labeled for identification, and stored under specific conditions to prevent changes in their characteristics prior to laboratory analysis. A total of 33 samples were analyzed, consisting of inlet and outlet samples collected over the study period. Sampling was conducted every six months from October 2025 to April 2026. Periodic sampling was carried out to obtain data capable of representing variations in wastewater quality due to changes in industrial operations and WWTP treatment conditions.

2.4. Wastewater testing parameters.

Wastewater quality testing was carried out in an accredited laboratory to ensure that the analytical results met the required standards of precision, accuracy, and reliability for environmental testing. The analyzed parameters included physical, chemical, and biological indicators selected based on the general characteristics of food industry wastewater, particularly from the chocolate processing industry.

2.4.1. *Physical parameters.*

The physical parameters analyzed included temperature, TDS, and TSS. Temperature measurements were conducted to determine the thermal condition of the wastewater, as temperature can influence microbial activity in biological treatment processes as well as dissolved oxygen levels in water. TDS was used to quantify the amount of dissolved solids in the wastewater, while TSS was used to determine the concentration of suspended particulate matter that may contribute to turbidity and sedimentation in the receiving water body. High TSS levels in food industry wastewater are generally derived from raw material residues, chocolate particles, and production process waste. According to [14], high suspended solids in WWTP influent can affect the efficiency of biological processes and increase the load on sedimentation units. The study also explained that temperature has a significant influence on microbial activity in biological treatment systems.

2.4.2. *Chemical parameters.*

Chemical parameters include pH, dissolved iron (Fe), dissolved manganese (Mn), barium (Ba), copper (Cu), zinc (Zn), hexavalent chromium (Cr^{6+}), total chromium (Cr), cadmium (Cd), mercury (Hg), lead (Pb), stannous (Sn), arsenic (As), selenium (Se), nickel (Ni), cobalt (Co), cyanide (CN), sulfide (H_2S), fluoride (F), free chlorine (Cl_2), ammonia-nitrogen ($\text{NH}_3\text{-N}$), nitrate ($\text{NO}_3\text{-N}$), nitrite ($\text{NO}_2\text{-N}$), total nitrogen, BOD, COD, active methylene blue compounds, phenol, oil & fat. BOD and COD were the primary parameters in this study, as they represent the organic pollutant load in wastewater. BOD indicates the amount of oxygen required by microorganisms to biologically decompose organic matter, whereas COD represents the oxygen demand needed to chemically oxidize organic compounds [15]. High BOD and COD values in chocolate industry wastewater are generally attributed to the presence of sugars, fats, proteins, and other organic residues from production processes [2, 3]. According to [3], reported that food industry wastewater contains high levels of COD and oil and grease due to the accumulation of complex organic compounds from production processes. Meanwhile, [5] stated that BOD and COD are key indicators for evaluating biological treatment performance because they are directly related to the organic load in food industry wastewater.

2.4.3. *Biological parameters.*

The biological parameter analyzed in this study was total coliform. Total coliform testing was conducted to determine the potential microbial contamination in wastewater originating from sanitation activities and domestic waste within the industrial area. The presence of coliform bacteria serves as an indicator of biological pollution and reflects the level of hygiene in the wastewater treatment system [16]. The analysis of biological parameters is important because food industry wastewater not only contains organic and chemical pollutants but may also harbor microorganisms that can affect environmental quality if not properly treated. According to [17], the control of biological parameters in food industry wastewater is essential to maintain the quality of final effluent and to enhance the efficiency of biological processes in WWTP systems.

2.5. Data analysis methods.

Data analysis was conducted using a quantitative descriptive method to describe the characteristics of wastewater at the WWTP inlet and outlet based on laboratory testing results. The collected data were processed to determine the mean, maximum, and minimum values of each tested parameter. Descriptive statistical analysis was used to provide an overview of pollutant concentration fluctuations during the study period. The mean value was used to represent the general characteristics of the wastewater, while the maximum and minimum values were used to identify variations in parameter concentrations due to changes in production activities and WWTP operational conditions. Wastewater quality evaluation was carried out by comparing the analytical results with the wastewater quality standards stipulated in the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia No. 5 of 2014, Appendix XLVII Class II. This comparison aimed to determine the level of compliance of wastewater quality with applicable environmental standards. Treatment efficiency indicates the capability of the WWTP system to reduce pollutant concentrations, thereby producing wastewater that is safer for discharge into the environment. The higher the removal efficiency value, the better the performance of the wastewater treatment units in reducing pollutant loads. According to [18], the analysis of pollutant removal efficiency in WWTP systems is a key approach for evaluating the performance of industrial wastewater treatment processes. In addition, [19] pos stated that the evaluation of influent and effluent quality is essential to determine treatment effectiveness and compliance with environmental quality standards. In addition to descriptive statistical analysis, standard deviation analysis was applied to evaluate fluctuations in wastewater quality parameters during the observation period. Correlation analysis between BOD and COD concentrations was also conducted to evaluate the relationship between biodegradable organic matter and total organic pollutant load in the wastewater treatment process.

3. Results and Discussion

3.1. Influent WWTP test results (before processing).

The variability in influent characteristics is generally influenced by fluctuations in production activities, wastewater flow rates, and raw material composition within the industrial process. Industrial wastewater is typically characterized by unstable organic loads and significant temporal variations, which can directly affect the operational stability of biological treatment systems. Industrial wastewater may significantly increase the hydraulic and organic loading rate, thereby influencing microbial activity and overall treatment performance in activated sludge systems [20]. Based on Table 1, the laboratory test results of WWTP influent, representing the average values from 33 samples, indicate that the wastewater characteristics of the chocolate industry can be comprehensively evaluated from physical, chemical, and biological aspects. The physical parameters show that temperature (29.8 °C), TDS (974 mg/l), and TSS (64 mg/l) are still below the applicable regulatory standards. This indicates that, in terms of dissolved and suspended solids, the wastewater does not yet exhibit an extreme pollutant load at the influent stage, further treatment is still required. The physical parameters show that temperature (29.8 °C), TDS (974 mg/l), and TSS (64 mg/l) are still below the

applicable standards. This suggests that the wastewater does not yet present an extreme pollutant load in terms of dissolved and suspended solids at the influent stage, although further treatment remains necessary.

Table 1. Laboratory test results of WWTP influent chocolate industry.

No.	Parameter	Unit	Quality Standard	Analysis Result
1	Temperature	°C	40	29.8
2	TDS	mg/l	4000	974
3	TSS	mg/l	400	64
4	pH	-	6–9	6.86
5	Dissolved Iron (Fe)	mg/l	10	0.500
6	Dissolved Manganese (Mn)	mg/l	5	0.300
7	Barium (Ba)	mg/l	3	0.500
8	Copper (Cu)	mg/l	3	0.400
9	Zinc (Zn)	mg/l	10	0.500
10	Hexavalent Chromium (Cr ⁶⁺)	mg/l	0.5	<0.10
11	Total Chromium (Cr)	mg/l	1	<0.10
12	Cadmium (Cd)	mg/l	0.1	<0.040
13	Mercury (Hg)	mg/l	0.005	<0.0010
14	Lead (Pb)	mg/l	1	<0.10
15	Tin (Sn)	mg/l	3	<2.0
16	Arsenic (As)	mg/l	0.5	<0.002
17	Selenium (Se)	mg/l	0.5	<0.002
18	Nickel (Ni)	mg/l	0.2	<0.10
19	Cobalt (Co)	mg/l	0.6	<0.10
20	Cyanide (CN ⁻)	mg/l	0.5	<0.004
21	Sulfide (H ₂ S)	mg/l	1	<0.06
22	Fluoride (F ⁻)	mg/l	3	1.50
23	Free Chlorine (Cl ₂)	mg/l	2	<0.03
24	Ammonia Nitrogen (NH ₃ -N)	mg/l	10	0.54
25	Nitrate (NO ₃ -N)	mg/l	30	1.34
26	Nitrite (NO ₂ -N)	mg/l	3	<0.010
27	Total Nitrogen	mg/l	60	24
28	BOD	mg/l	150	1524
29	COD	mg/l	300	6470
30	MBAS	mg/L	10	1.84
31	Phenol	mg/L	1	<0.20
32	Oil and Grease	mg/L	20	<5
33	Total Coliform	MPN/100 ml	10,000	19,000

The data source is processed from laboratory test results from October 2025 to April 2026. Regulation of the Minister of Environmental Quality Standards No. 5 of 2014, Appendix XLVII Class II.

For chemical parameters, most heavy metals such as Fe, Mn, Ba, Cu, Zn, Cr, Cd, Hg, Pb, and other trace elements were found to be far below the applicable wastewater quality standards. The pH value of 6.86 was also within the neutral range (6.0–9.0), indicating that the wastewater was relatively stable in terms of chemical characteristics. Nutrient-related parameters, including ammonia (0.54 mg/l), nitrate (1.34 mg/l), nitrite (<0.010 mg/l), and total nitrogen (24 mg/l), also complied with the regulatory standards. These nutrients still possess the potential to contribute to eutrophication in receiving water bodies if wastewater is discharged without adequate treatment. Key parameters indicated a high organic pollutant load

typically associated with chocolate-processing wastewater. BOD concentration (1524 mg/l) exceeded the permissible limit of (150 mg/l), while COD concentration (6470 mg/l) surpassed the quality standard of (300 mg/l). From a biological perspective, the total coliform concentration (19000 MPN/100 mL) also exceeded the allowable standard of 10000 MPN/100 mL. Under these conditions, further analysis is required to determine an effective and efficient treatment method capable of reducing pollutant concentrations to comply with the established environmental quality standards and ensure safe discharge into receiving water bodies.

3.2. Characteristics of main parameters of chocolate industry wastewater.

Based on the laboratory analysis of WWTP influent wastewater, several key parameters indicate a high level of pollution, particularly BOD, COD, and Total Coliform. These three parameters are primary indicators used to evaluate the organic and biological pollutant load in industrial wastewater, including the chocolate industry. Figure 1 shows characteristics of major pollutant parameters in chocolate industry WWTP influent.

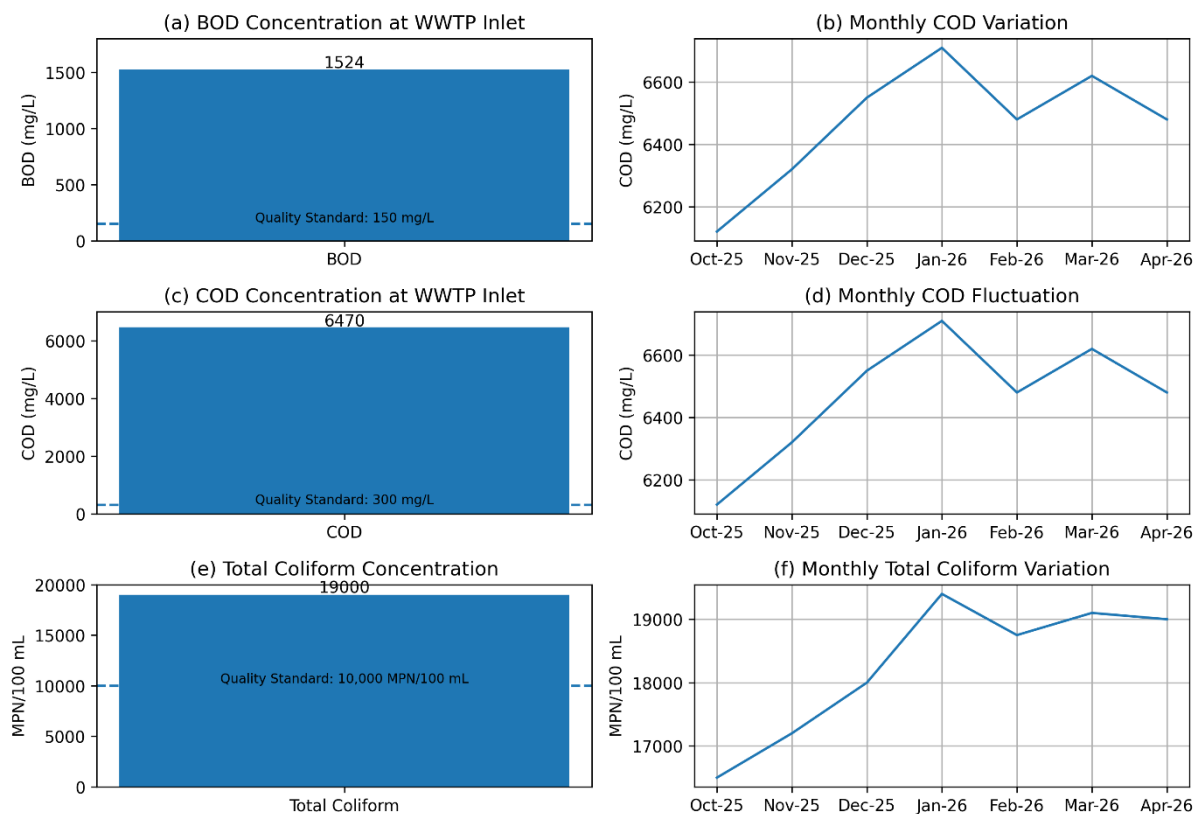


Figure 1. Characteristics of major pollutant parameters in chocolate industry WWTP influent: (a) BOD concentration compared with the quality standard; (b) monthly variation of COD concentration from October 2025 to April 2026; (c) COD concentration compared with the quality standard; (d) monthly fluctuation of COD concentration; (e) total coliform concentration compared with the quality standard; and (f) monthly variation of total coliform concentration.

3.2.1. BOD.

Based on Figure 1a, the concentration of BOD in the influent was 1524 mg/l, which is higher than the applicable regulatory standard of 150 mg/l. This indicates that the incoming

wastewater still contains a relatively high organic load. The elevated BOD value at the influent stage suggests that the organic burden in the wastewater remains significant and has the potential to reduce dissolved oxygen levels in the receiving water body. This condition highlights the need to optimize the treatment process to improve BOD removal efficiency and ensure compliance with environmental standards. The high BOD level in chocolate industry wastewater is generally attributed to the presence of sugars, cocoa fats, proteins, and other organic compounds derived from production processes [2, 3].

Previous studies have shown that wastewater generated from chocolate and confectionery industries is characterized by high concentrations of readily biodegradable organic compounds, reflected by elevated COD and BOD levels as well as high biodegradability indices [2]. Elevated BOD levels in wastewater may accelerate oxygen depletion in aquatic environments, resulting in hypoxic conditions that adversely affect aquatic biota and overall ecosystem health [4]. On the other hand, the relatively high BOD/COD ratio indicates that the wastewater is biodegradable, making biological treatment processes such as the activated sludge system an effective method for reducing the pollutant load [15].

The monthly trend of BOD concentration at the WWTP influent demonstrated fluctuations throughout the monitoring period from October 2025 to April 2026 (Figure 1b). Influent BOD concentrations ranged from 1.380 mg/l to 1.580 mg/l, indicating consistently high biodegradable organic loads originating from chocolate-processing industrial activities. The observed increase in BOD concentration during several monitoring periods was likely associated with fluctuations in production capacity, raw material utilization, equipment cleaning processes, and variations in wastewater discharge volume. High BOD concentrations in food-processing wastewater generally indicate the presence of large quantities of biodegradable organic substances such as carbohydrates, proteins, fats, and residual cocoa materials generated during production activities.

Despite the fluctuations, the overall BOD trend remained relatively stable, suggesting that the wastewater characteristics were consistently dominated by biodegradable organic compounds. The stability of influent organic loading is an important factor supporting the effectiveness of activated sludge treatment systems because microbial populations can adapt more efficiently under relatively consistent substrate conditions [21]. The consistently elevated BOD concentrations observed in this study further emphasize the importance of maintaining stable operational conditions within the activated sludge reactor, including dissolved oxygen availability, hydraulic retention time, and microbial biomass activity, to ensure optimal biodegradation performance and compliance with environmental quality standards.

3.2.2. *Chemical Oxygen Demand (COD).*

Based on Figure 1c, the Chemical Oxygen Demand (COD) concentration in the influent wastewater was compared with the applicable wastewater quality standard. The influent COD

concentration reached 6470 mg/l, significantly exceeding the regulatory limit of 300 mg/l, as indicated by the dashed line in the figure. The elevated influent COD concentration reflects the high organic pollutant load present in the wastewater. Such conditions may adversely affect the quality of receiving water bodies if the wastewater is discharged without adequate treatment. Therefore, an effective treatment process is required to reduce the COD concentration to comply with the established environmental standards. The difference between COD and BOD values also provides insight into the fraction of organic compounds that are not readily biodegradable, which in some cases may require additional treatment processes such as chemical oxidation or advanced oxidation processes (AOPs) [15]. High COD concentrations indicate an increased oxygen demand in aquatic environments, potentially leading to dissolved oxygen depletion, deterioration of water quality, and disruption of ecosystem balance if the wastewater is not properly treated prior to discharge [22].

The monthly trend of COD concentration at the WWTP influent showed fluctuations during the observation period from October 2025 to April 2026 (Figure 1d). The COD concentrations ranged from 6.120 mg/l to 6.710 mg/l, indicating relatively high organic pollutant loading originating from chocolate-processing activities. The observed fluctuations were influenced by variations in production intensity, raw material composition, cleaning activities, and wastewater discharge volume during the operational process. Despite the fluctuations, the COD concentrations consistently exceeded the applicable wastewater quality standard of 300 mg/l, confirming that the wastewater generated by the chocolate-processing industry contained substantial amounts of organic matter requiring intensive treatment prior to environmental discharge. High COD concentrations in food industry wastewater are commonly associated with the presence of sugars, fats, proteins, and other biodegradable organic compounds derived from production residues. The relatively stable trend pattern also indicates that the wastewater characteristics remained consistently high-strength throughout the monitoring period, thereby emphasizing the importance of maintaining operational stability in the activated sludge treatment system to ensure optimal pollutant removal performance.

3.2.3. *Total coliform.*

Based on Figure 1e presents the Total Coliform concentration in the influent wastewater compared with the applicable wastewater quality standard. The influent Total Coliform concentration reached 19,000 MPN/100 mL, exceeding the regulatory limit of 10,000 MPN/100 mL, as indicated by the dashed line in the figure. This condition indicates a potential environmental health risk if the wastewater is discharged into receiving water bodies without adequate treatment. Therefore, an effective treatment process, particularly disinfection, is required to reduce microbial concentrations to comply with the established standards. In the context of the food industry, including chocolate processing industries, the high organic content in wastewater can support microbial growth, thereby significantly increasing coliform concentrations. The presence of these microorganisms may not only deteriorate water quality but also pose public health risks if the wastewater is directly discharged into the environment without proper disinfection treatment.

The monthly trend of Total Coliform concentration at the WWTP influent demonstrated fluctuating microbiological contamination levels throughout the observation period from

October 2025 to April 2026 (Figure 1f). Influent Total Coliform concentrations ranged from 16.500 to 19.400 MPN/100 mL, indicating substantial microbiological loads associated with chocolate-processing industrial wastewater. The fluctuations in Total Coliform concentrations were likely influenced by variations in raw material handling, sanitation practices, wastewater retention conditions, production activities, and organic matter accumulation during industrial operations. High concentrations of Total Coliform in food-processing wastewater commonly indicate the presence of microbial contamination originating from biodegradable organic residues and production-related wastewater streams.

Despite the fluctuations, the overall trend pattern remained relatively stable and consistently exceeded the applicable environmental quality standards. These findings indicate that microbiological contamination represented one of the major environmental concerns associated with untreated wastewater generated by the chocolate-processing industry. The elevated Total Coliform concentrations further emphasize the importance of effective biological treatment and disinfection processes within the WWTP system. Proper operational control of activated sludge treatment, combined with adequate chlorination or disinfection processes, is essential to minimize pathogenic microorganism contamination prior to wastewater discharge into receiving water bodies. The reduction of Total Coliform concentrations after treatment also demonstrates the effectiveness of the integrated wastewater treatment system in improving environmental sanitation and reducing potential public health risks associated with industrial wastewater disposal.

3.3. *Biodegradability characteristics of wastewater.*

The obtained BOD/COD ratio of 0.24 indicates that the wastewater was moderately biodegradable. Wastewater with BOD/COD ratios above 0.3 is generally considered readily biodegradable, whereas lower ratios indicate the presence of slowly degradable or refractory organic compounds [15]. The relatively low ratio observed in this study suggests that the wastewater contained complex organic substances derived from cocoa fats, proteins, and polyphenolic compounds [2, 7], which may require combined physicochemical and biological treatment processes for optimal degradation. Nevertheless, the activated sludge system combined with coagulation–flocculation treatment demonstrated excellent performance in reducing both BOD and COD concentrations, indicating that the integrated treatment process was capable of effectively degrading biodegradable organic fractions while simultaneously reducing more resistant compounds.

3.4. *Effluent WWTP test results (after processing).*

Table 2 presents the wastewater quality analysis results at the outlet of the WWTP, evaluated based on physical and chemical parameters and compared with the applicable water quality standards (Class II). In general, the analytical results indicate that most parameters complied with the established quality standards, reflecting the effectiveness of the wastewater treatment process prior to discharge into receiving water bodies.

Table 2. Laboratory test results of WWTP effluent from chocolate industry.

No	Parameter	Unit	Quality Standard	Analysis Results
1	Temperature	°C	40	29.8
2	TDS	mg/l	4000	452
3	TSS	mg/l	400	16
4	pH	–	6–9	7.19
5	Dissolved Iron (Fe)	mg/l	10	0.300
6	Dissolved Manganese (Mn)	mg/l	5	<0.040
7	Barium (Ba)	mg/l	3	<0.50
8	Copper (Cu)	mg/l	3	0.100
9	Zinc (Zn)	mg/l	10	0.200
10	Hexavalent Chromium (Cr ⁶⁺)	mg/l	0.5	<0.10
11	Total Chromium (Cr)	mg/l	1	<0.10
12	Cadmium (Cd)	mg/l	0.1	<0.040
13	Mercury (Hg)	mg/l	0.005	<0.0010
14	Lead (Pb)	mg/l	1	<0.10
15	Tin (Sn)	mg/l	3	<2.0
16	Arsenic (As)	mg/l	0.5	<0.002
17	Selenium (Se)	mg/l	0.5	<0.002
18	Nickel (Ni)	mg/l	0.2	<0.10
19	Cobalt (Co)	mg/l	0.6	<0.10
20	Cyanide (CN ⁻)	mg/l	0.5	<0.004
21	Sulfide (H ₂ S)	mg/l	1	<0.06
22	Fluoride (F ⁻)	mg/l	3	0.40
23	Free Chlorine (Cl ₂)	mg/l	2	<0.03
24	Ammonia Nitrogen (NH ₃ -N)	mg/l	10	0.40
25	Nitrate (NO ₃ -N)	mg/l	30	0.48
26	Nitrite (NO ₂ -N)	mg/l	3	<0.010
27	Total Nitrogen	mg/l	60	6
28	BOD	mg/l	150	12.94
29	COD	mg/l	300	54.70
30	MBAS	mg/l	10	0.36
31	Phenol	mg/l	1	<0.20
32	Oil and Grease	mg/l	20	<5
33	Total Coliform	MPN/100 ml	10000	560

The data source is processed from laboratory test results from October 2025 to April 2026. Regulation of the Minister of Environmental Quality Standards No. 5 of 2014, Appendix XLVII Class II

Physical parameters such as temperature (29.8°C), TDS = 452 mg/l, and TSS = 16 mg/l) were considerably below the permissible limits. These results indicate that the sedimentation and filtration processes within the WWTP operated effectively. TSS is widely used as a key indicator of sedimentation performance and wastewater treatment efficiency due to its close relationship with particulate pollution and water quality degradation [23]. The relatively low TSS concentration suggests that both primary and secondary treatment units performed efficiently. Regarding chemical parameters, the pH value of 7.19 was within the neutral range (6–9), indicating relatively stable wastewater conditions without extreme acidic or alkaline characteristics. Stable pH conditions are essential because they influence microbial activity during biological wastewater treatment processes. Heavy metal concentrations, including Fe, Mn, Cu, Zn, Cr, Cd, Hg, and Pb, were generally far below the regulatory standards, indicating that the treatment system effectively reduced the potential toxicity of the wastewater. Heavy

metals are considered critical pollutants due to their bioaccumulative properties and potential adverse effects on aquatic organisms and human health. In addition, nutrient-related parameters such as ammonia (0.40 mg/l), nitrate (0.48 mg/l), and total nitrogen (6 mg/l) were within acceptable limits. This is particularly important because excessive nutrient concentrations may trigger eutrophication in receiving water bodies.

Organic parameters, including BOD = 12.94 mg/l and COD = 54.70 mg/l, also showed relatively low concentrations compared with the applicable quality standards. BOD and COD are key indicators of organic pollution load in wastewater. Their low concentrations indicate that most organic matter had been effectively degraded during the biological treatment process. Previous studies have demonstrated that elevated BOD and COD levels are strongly associated with increased microbial activity required to decompose organic compounds; therefore, lower concentrations reflect a reduced pollution load. In untreated wastewater, however, BOD and COD concentrations are typically much higher and often exceed environmental quality standards.

Microbiological parameters such as Total Coliform (560 MPN/100 mL) were also significantly below the regulatory limit, indicating that the disinfection process, such as chlorination, was effective in reducing pathogenic microorganisms. Overall, the analytical results demonstrate that the WWTP effluent complied with the applicable wastewater quality standards and was therefore relatively safe for environmental discharge. These findings are consistent with previous studies stating that the effectiveness of wastewater treatment systems can be evaluated based on the compliance of effluent parameters with environmental standards, where an optimized treatment system is capable of reducing most pollutant concentrations below the permissible thresholds.

3.5. Wastewater treatment technology from the chocolate industry.

The wastewater treatment system applied in the chocolate-processing industry in this study was designed using an integrated combination of physicochemical and biological processes, consisting of an equalization unit, chemical treatment, and an aerobic biological process employing activated sludge technology. This approach was selected because chocolate industry wastewater is generally characterized by a high concentration of biodegradable organic compounds and significant fluctuations in pollutant loading.

The initial treatment stage was carried out in an equalization tank, which functions to stabilize wastewater flow rate and pollutant concentration, thereby preventing shock loading in subsequent treatment units. Equalization processes are essential to maintain stable influent characteristics, including pH, temperature, and organic loading fluctuations, thereby enhancing the stability and efficiency of biological wastewater treatment systems [24]. Subsequently, the wastewater was directed to the chemical treatment unit through a coagulation–flocculation process. At this stage, coagulants such as polyaluminum chloride (PAC) were added to neutralize the electrical charges of colloidal particles, allowing the formation of larger flocs that could be more easily settled [25, 26].

The WWTP flow diagram shown in Figure 2 illustrates an integrated wastewater treatment system that combines physical, chemical, and biological treatment processes to reduce pollutant concentrations before the treated effluent is discharged into the environment

or reused. Integrated wastewater treatment systems are widely recognized as effective approaches for controlling industrial wastewater pollution because they are capable of treating complex contaminants through sequential treatment stages. According to [27], integrated treatment systems are designed to optimize pollutant removal efficiency while maintaining operational stability in industrial wastewater treatment processes.

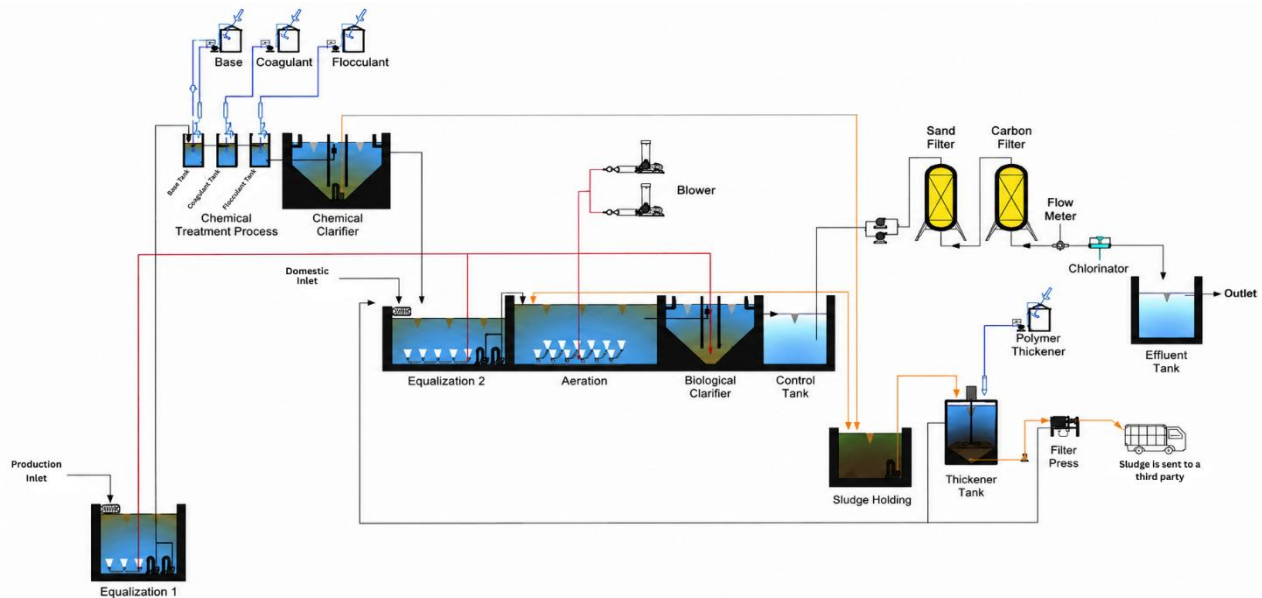


Figure 2. WWTP flow chart.

The treatment process begins at Equalization Tank 1, which receives wastewater from the production process (production inlet). This unit functions as an initial holding basin to stabilize flow rate, pollutant concentration, and the physical and chemical characteristics of the wastewater. Equalization is considered a crucial pretreatment stage because fluctuations in hydraulic and organic loading may reduce the efficiency of downstream biological processes. A study conducted by [28] reported that equalization tanks significantly improve process stability and reduce shock loading in industrial wastewater treatment systems. In addition, homogenization within the equalization tank minimizes sudden variations in pH, temperature, and organic matter concentration.

The wastewater is subsequently directed to the Chemical Treatment Process, which consists of the addition of chemicals such as base, coagulant, and flocculant. Chemical dosing is performed sequentially to optimize the coagulation–flocculation mechanism. The addition of alkaline substances aims to maintain optimum pH conditions, while coagulants destabilize suspended colloidal particles and flocculants promote larger floc formation for easier sedimentation. Previous studies have demonstrated the effectiveness of coagulation flocculation processes in reducing suspended solids and organic pollutants in industrial wastewater. [25] Reported that coagulation–flocculation treatment could remove more than 80% of suspended solids and significantly reduce COD concentrations in industrial effluents. Similarly, research by [26] showed that the application of aluminum- and iron-based coagulants effectively improved wastewater clarity and reduced turbidity levels.

The formed flocs are separated in the Chemical Clarifier through gravitational sedimentation. In this process, dense particles settle at the bottom of the clarifier, producing chemical sludge, while clarified supernatant flows toward biological treatment units. The efficiency of sedimentation depends on hydraulic retention time (HRT), settling velocity, and floc characteristics. According to [29], properly designed clarifiers can substantially improve suspended solids removal and reduce the pollutant load entering biological treatment systems.

The wastewater then enters Equalization Tank 2, which also receives domestic wastewater inflow. The combination of industrial and domestic wastewater is intended to achieve a balanced nutrient composition of carbon, nitrogen, and phosphorus required for biological treatment processes. This unit serves to stabilize organic loading before the wastewater undergoes aerobic biological treatment in the aeration tank. Furthermore, the mixing system within the equalization tank prevents premature sedimentation and maintains homogeneous wastewater conditions.

The core biological treatment process takes place in the Aeration Tank, where oxygen is supplied through blowers to support aerobic microbial activity. In activated sludge systems, microorganisms degrade dissolved and suspended organic matter into simpler and more stable compounds. Several previous studies have confirmed the high efficiency of aerobic biological treatment for reducing organic pollutants. Research by [30] reported that conventional activated sludge systems generally achieve COD removal efficiencies ranging from 75–85% under stable operating conditions. Explained that dissolved oxygen concentration, MLSS, sludge age, and Food to Microorganism (F/M) ratio are critical operational parameters influencing biological treatment performance.

The mixture of treated water and activated sludge from the aeration tank is then transferred to the Biological Clarifier for biomass separation. In this unit, activated sludge settles by gravity, producing two main streams: clarified effluent at the upper section and settled sludge at the bottom. A portion of the sludge is recirculated back to the aeration tank as Return Activated Sludge (RAS) to maintain microbial populations, while excess sludge is directed to the sludge treatment system.

The clarified effluent from the biological clarifier is subsequently collected in the Control Tank, which functions as a quality control and balancing unit prior to tertiary treatment. This tank also serves as a monitoring point to evaluate wastewater quality and ensure the optimal performance of previous treatment processes.

Tertiary treatment is carried out using a Sand Filter and Carbon Filter. The sand filter removes fine suspended particles that may still remain after sedimentation, while the carbon filter adsorbs dissolved organic compounds, color, odor, and residual contaminants. The combination of these filtration units significantly improves the final effluent quality, resulting in clearer and more stable treated water.

Following filtration, the treated wastewater passes through a Flow Meter to measure the effluent discharge rate. Flow monitoring is important for operational evaluation and regulatory compliance. The final treatment stage involves chlorination using a chlorinator. This disinfection process aims to reduce pathogenic microorganisms such as total coliform and fecal coliform before the treated wastewater is discharged into receiving water bodies or reused for applications such as landscape irrigation [16].

The final treated effluent is then stored in the Effluent Tank prior to discharge or reuse. At this stage, the effluent quality is expected to comply with environmental discharge standards and applicable regulations.

Meanwhile, sludge generated from both the chemical and biological clarification processes is transferred to the Sludge Holding Tank for temporary storage. The sludge is further processed in the Thickener Tank, where polymer addition enhances sludge thickening through particle aggregation. After reducing the water content, the sludge undergoes dewatering using a Filter Press to produce sludge cake. The dewatered sludge is subsequently transported to a licensed third party for further treatment or disposal in accordance with environmental regulations. Overall, the WWTP system presented in the diagram applies an integrated wastewater treatment approach by combining physical, chemical, and biological processes in sequential stages. The integration of these treatment units is designed to maximize pollutant removal efficiency, maintain operational stability, and ensure that the final effluent consistently meets environmental quality standards.

3.6. Processing efficiency.

BOD removal efficiency of 99.15% (Table 3) indicates that the biological treatment process in the WWTP was highly effective in reducing the biodegradable organic load. Microbial activity within the biological reactor (activated sludge system) plays a crucial role in decomposing organic matter into simpler compounds through aerobic biodegradation processes [21, 15]. The high removal efficiency suggests that operational conditions such as dissolved oxygen concentration, microbial activity, and hydraulic retention time were maintained under optimal conditions throughout the treatment process. Previous studies on biological treatment of high-strength food industry wastewater reported BOD removal efficiencies of approximately 70–85%, depending on operational conditions and organic loading rates [31]. The efficiency and stability of biological wastewater treatment processes are highly dependent on operational conditions, particularly the F/M ratio, dissolved oxygen availability, and hydraulic retention time, which regulate microbial metabolism and organic matter degradation performance [21].

Table 2. Efficiency of main parameters of treatment after treatment using activated sludge system.

Parameter	Inlet	Outlet	Removal
BOD	1524	12.94	99.15
COD	6470	54.70	99.15
Total Coliform	19000	560	97.05

COD removal efficiency of 99.15% (Table 3) indicates that most organic compounds, including fractions that are relatively resistant to biological degradation, were successfully reduced through the combined physicochemical and biological treatment processes. Food industry wastewater often contains complex organic compounds that contribute to elevated COD concentrations relative to BOD values due to the presence of refractory and slowly degradable organic substances [32]. The high COD removal observed in this study demonstrates the effectiveness of the integrated treatment system in reducing the overall organic pollution load. Conventional activated sludge systems are commonly reported to

achieve COD removal efficiencies of approximately 75–85% under stable operating conditions, suggesting that the higher removal efficiency observed in this study indicates optimal biological treatment performance [33].

Total Coliform removal efficiency of 97.05% (Table 3) also represents an excellent treatment performance and demonstrates the effectiveness of the disinfection process as well as the unfavorable environmental conditions for pathogenic bacterial growth within the treatment system. Significant reductions in coliform concentrations may occur through several mechanisms, including microbial competition, environmental fluctuations such as pH and temperature changes, sedimentation processes, and biological oxidation within wastewater treatment reactors [16]. Food industry WWTP have also reported coliform removal efficiencies exceeding 95% through the combination of biological treatment and chlorination disinfection processes.

These findings indicate that the WWTP system applied in this study was effective not only in reducing organic pollutants but also in minimizing microbiological contamination prior to environmental discharge. The results presented in Table 3 confirm the high overall treatment performance, while Figure 3 illustrates the stability of pollutant removal trends and supporting operational conditions throughout the monitoring period. Furthermore, the substantial reduction in pollutant concentrations suggests that the treatment processes operated effectively in minimizing the potential adverse impacts of wastewater on aquatic ecosystems and overall environmental quality. The monthly removal efficiency trends demonstrated in Figure a show that the WWTP system consistently achieved excellent pollutant reduction performance throughout the monitoring period. The removal efficiencies of BOD and COD remained relatively stable and consistently exceeded 97%, while Total Coliform removal efficiencies remained above 95% during all observation periods. The BOD removal efficiency increased gradually from 98.4% in October 2025 to 99.15% in April 2026, indicating highly stable aerobic biodegradation performance within the activated sludge reactor. Similarly, COD removal efficiency improved from 97.8% to 99.15%, demonstrating the effectiveness of the combined physicochemical and biological treatment processes in reducing both biodegradable and more refractory organic compounds.

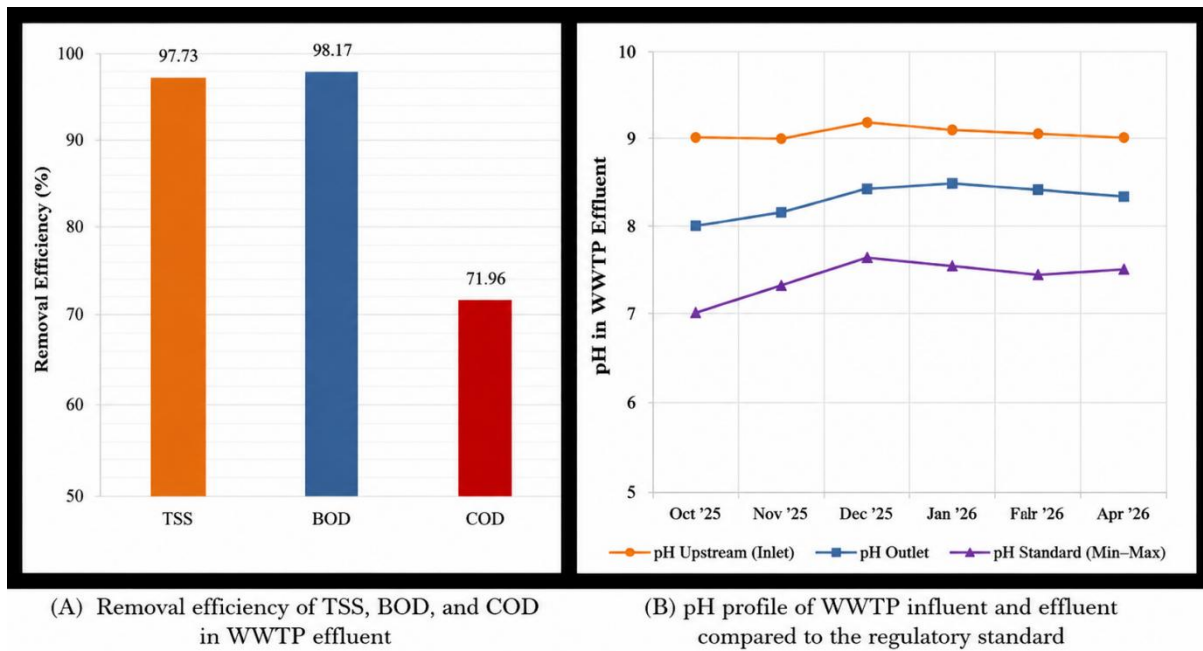


Figure 3. (A) Removal efficiency of TSS, BOD, and COD in WWTP effluent; (B) pH profile of WWTP influent and effluent compared with regulatory standards (October 2025–April 2026).

The Total Coliform removal efficiency also showed stable performance, ranging from 95.2% to 97.05% (Table 3 and Figure a). The high microbiological removal efficiency indicates that the biological treatment and disinfection processes operated effectively in reducing pathogenic contamination within the treated wastewater. The relatively stable trend patterns observed throughout the monitoring period (Figure a) indicate that the WWTP system maintained favorable operational conditions, including stable microbial activity, adequate dissolved oxygen availability, and effective sludge settling performance. Stable removal efficiency is an important indicator of operational reliability and treatment sustainability in industrial wastewater management systems. These findings further demonstrate that the integration of activated sludge technology with physicochemical treatment processes can provide highly effective and sustainable pollutant removal performance for high-strength wastewater generated by chocolate-processing industries.

The Total Coliform removal efficiency also showed stable performance, ranging from 95.2% to 97.05%. The high microbiological removal efficiency indicates that the biological treatment and disinfection processes operated effectively in reducing pathogenic contamination within the treated wastewater. The relatively stable trend patterns observed throughout the monitoring period indicate that the WWTP system maintained favorable operational conditions, including stable microbial activity, adequate dissolved oxygen availability, and effective sludge settling performance. Stable removal efficiency is an important indicator of operational reliability and treatment sustainability in industrial wastewater management systems. These findings further demonstrate that the integration of activated sludge technology with physicochemical treatment processes can provide highly effective and sustainable pollutant removal performance for high-strength wastewater generated by chocolate-processing industries.

3.7. Environmental, social, and economic aspects of wastewater treatment results.

Based on the treatment efficiency results obtained, the WWTP system applied in the chocolate-processing industry demonstrated excellent performance in reducing major pollutant parameters, namely BOD, COD, and Total Coliform. The successful reduction of these parameters not only improved wastewater quality but also provided positive impacts on environmental, social, and economic aspects in a sustainable manner. From an environmental perspective, the significant reduction in BOD, COD, and Total Coliform concentrations indicates that the treatment system effectively minimized the potential pollution load discharged into receiving water bodies. The reduction of BOD from 1,524 mg/l to 12.94 mg/l and COD from 6,470 mg/l to 54.70 mg/l demonstrates a substantial decrease in organic matter capable of consuming dissolved oxygen in aquatic environments. The reduction of organic pollutants is essential because untreated food industry wastewater with high organic and nutrient content may lead to dissolved oxygen depletion, eutrophication, and ecological imbalance in aquatic environments [5]. Total Coliform removal efficiency of 97.05% indicates that the treatment and disinfection processes were effective in minimizing the risk of pathogenic microorganism contamination in receiving waters. The reduction of microbiological contaminants in food industry wastewater directly contributes to improved environmental sanitation and the protection of aquatic biodiversity.

From a social perspective, the implementation of an effective wastewater treatment system provides significant benefits to public health and the overall environmental quality surrounding the industrial area. Improperly treated wastewater may become a source of pollution that can lead to various public health problems, including waterborne diseases, skin irritation, and environmental sanitation issues. The reduction of Total Coliform concentrations to levels below the regulatory standard indicates that the risk of microbiological contamination affecting nearby communities can be substantially minimized. Effective wastewater management is essential to reduce environmental pollution and prevent the spread of waterborne and environmentally related diseases among populations living near industrial activities [34]. From an economic perspective, effective wastewater treatment provides long-term benefits for the company. The reduction of organic pollutant loads through the activated sludge system demonstrates that the biological process operated efficiently, thereby reducing the need for more expensive advanced treatment technologies. The BOD and COD removal efficiencies, both reaching 99.15%, indicate that most organic compounds were successfully treated biologically without requiring high-cost advanced treatment processes. Previous studies demonstrated that optimizing biological treatment systems in wastewater management may reduce operational costs and carbon emissions while maintaining high pollutant removal efficiency, making them more sustainable than intensive chemical treatment processes [35]. Overall, the findings of this study demonstrate that the application of activated sludge technology combined with chemical treatment processes in the chocolate-processing industry was not only effective in reducing major pollutant parameters but also provided multidimensional environmental, social, and economic benefits. Optimal wastewater management therefore represents an essential component in supporting sustainable industrial

development, environmentally friendly production practices, and the implementation of green industry principles in the modern industrial era.

3.8. Environmental compliance assessment.

Based on the analytical results, all major effluent parameters complied with the wastewater quality standards stipulated under the Indonesian Ministry of Environment and Forestry Regulation No. 5 of 2014. Compliance with these standards indicates that the treated wastewater was environmentally acceptable for discharge into receiving water bodies. The achievement of regulatory compliance also reflects the operational reliability of the WWTP system in maintaining stable pollutant removal performance under varying industrial wastewater conditions.

3.9. Study limitation and future research.

This study was limited to wastewater characterization and treatment performance evaluation under existing operational conditions without detailed investigation of operational parameters such as sludge retention time (SRT), mixed liquor suspended solids (MLSS), dissolved oxygen (DO), and microbial community dynamics. Future studies are recommended to investigate kinetic modeling, operational optimization, sludge characteristics, energy efficiency, and advanced treatment integration to improve wastewater treatment sustainability in food-processing industries.

4. Conclusions

This study demonstrated that wastewater generated from the chocolate-processing industry is predominantly characterized by high organic and microbiological pollutant loads, making effective treatment essential before environmental discharge. The influent wastewater was mainly dominated by biodegradable organic matter originating from production residues such as sugars, fats, proteins, and cocoa-derived compounds. The biodegradability assessment indicated that the wastewater contained both readily degradable and more complex organic fractions, highlighting the need for an integrated treatment approach capable of addressing diverse pollutant characteristics. These findings confirm that chocolate-processing wastewater represents a high-strength industrial effluent requiring comprehensive management to prevent adverse impacts on receiving water bodies. The combined physicochemical treatment and activated sludge system proved highly effective in reducing organic and microbiological contaminants, resulting in effluent quality that complied with the applicable wastewater discharge standards. The stable treatment performance observed throughout the monitoring period indicates that the WWTP operated reliably under actual industrial conditions. Beyond achieving regulatory compliance, the treatment system contributed to environmental protection, reduced potential public health risks, and supported sustainable industrial operations. Therefore, the integration of coagulation–flocculation and activated sludge processes can be considered a suitable and sustainable wastewater management strategy for chocolate-processing industries and other food-processing sectors with similar wastewater characteristics.

Acknowledgments

The author gratefully acknowledges Almighty God for His blessings and guidance throughout this research. Sincere appreciation is extended to Universitas Sultan Ageng Tirtayasa for its academic support and facilities. The author also thanks the supervisors, examiners, industry representatives, and all parties who contributed valuable guidance and assistance during this study. It is hoped that the findings of this research will contribute to the development of industrial wastewater management and environmental sustainability.

Author Contribution

Rizal Aulia Ahadi Putra Karim: Conceptualization, methodology, investigation, data curation, formal analysis, funding acquisition, resources, writing, original draft preparation. Rida Oktorida Khastini: Supervision, methodology, writing, review and editing. Najmi Firdaus: Supervision, methodology, writing, review and editing. All authors have read and approved the final version of the manuscript.

Competing Interest

The authors declare that there are no competing financial or personal interests that could have influenced the work reported in this study.

Data Availability

All data generated and analyzed during this study are included in this published article. Additional raw data supporting the findings are available from the corresponding author upon reasonable request.

References

- [1] Abdulla, H.; Zamorano, M.; Rodríguez, M.L.; El Shahawy, A.; et al. (2023). An overview of agro-food industry wastewater treatment: A bibliometric analysis and literature review. *Applied Water Science*, 13, 47. <https://doi.org/10.1007/s13201-022-01857-3>.
- [2] García-Orozco, V.M.; Roa-Morales, G.; Linares-Hernández, I.; Serrano-Jiménez, I.J.; Salgado-Catarino, M.A.; Natividad, R. (2021). Electrocoagulation of a chocolate industry wastewater in a downflow column electrochemical reactor. *Journal of Water Process Engineering*, 42, 102057. <https://doi.org/10.1016/j.jwpe.2021.102057>.
- [3] He, L.; Zhang, Y.; Song, D.; Ou, Z.; Xie, Z.; Yang, S.; et al. (2022). Influence of pretreatment system on inorganic suspended solids for influent in wastewater treatment plant. *Journal of Environmental and Public Health*, 2022, 2768883. <https://doi.org/10.1155/2022/2768883>.
- [4] Kiatkittipong, W.; Phalakornkule, C.; Nuchdang, S.; Pavasant, P. (2021). Performance of dynamic anaerobic membrane bioreactor (DAnMBR) with phase separation in treating high strength food processing wastewater. *Journal of Environmental Chemical Engineering*, 9(3), 105245. <https://doi.org/10.1016/j.jece.2021.105245>.
- [5] Luo, Y.; Guo, W.; Ngo, H.H.; Nghiem, L.D.; Hai, F.I.; Zhang, J.; Liang, S.; Wang, X.C. (2022). A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment. *Science of the Total Environment*, 473–474, 619–641. <https://doi.org/10.1016/j.scitotenv.2013.12.065>.

- [6] Lieske, C.; Leutnant, D.; Uhl, M. (2021). Assessing the TSS removal efficiency of decentralized stormwater treatment systems by long-term in-situ monitoring. *Water*, 13(7), 908. <https://doi.org/10.3390/w13070908>.
- [7] Lin, L.; Yang, H.; Xu, X. (2022). Effects of water pollution on human health and disease heterogeneity: A review. *Frontiers in Environmental Science*, 10, 880246. <https://doi.org/10.3389/fenvs.2022.880246>.
- [8] Liang, Y.; Huang, Z.; Pan, Z.; Xu, M.; Shen, Y.; Li, J. (2023). A municipal wastewater treatment plant “drinking beer” for reduction of cost and carbon emission. *RSC Advances*, 13(29), 20113–20123. <https://doi.org/10.1039/D3RA02213G>.
- [9] Lian, Y.; Coggins, L. X.; Hay, J.; van de Ven, A.; Ghadouani, A. (2022). Effect of attached growth on treatment performance in waste stabilization ponds. *Water*, 14(20), 3245. <https://doi.org/10.3390/w14203245>.
- [10] Muleta, T.N.; Knolmar, M. (2025). Ecological impacts of combined sewer overflows on receiving waters. *Discover Water*, 5, 24. <https://doi.org/10.1007/s43832-025-XXXXX>.
- [11] Mannina, G.; Capodici, M.; Cosenza, A.; Di Trapani, D.; Viviani, G. (2022). Performance evaluation of activated sludge systems treating industrial wastewater under different operational conditions. *Journal of Water Process Engineering*, 45, 102944. <https://doi.org/10.1016/j.jwpe.2022.102944>.
- [12] Makowska, M.; Sychała, M.; Pawlak, M. (2021). Efficacy and reliability of wastewater treatment technology in small meat plants. *Desalination and Water Treatment*, 221, 1–10. <https://doi.org/10.5004/dwt.2021.27107>.
- [13] Muhamad Ng, S.N.; Idrus, S.; Ahsan, A.; Marzuki, T.N.T.M.; Mahat, S.B. (2021). Treatment of wastewater from a food and beverage industry using conventional wastewater treatment integrated with membrane bioreactor system: A pilot-scale case study. *Membranes*, 11(6), 456. <https://doi.org/10.3390/membranes11060456>.
- [14] Naveen, B.P.; Mahapatra, D.M.; Sitharam, T.G.; Sivapullaiyah, P.V. (2021). Physico-chemical and biological characterization of food industry wastewater and its treatment potential. *Environmental Technology & Innovation*, 21, 101318. <https://doi.org/10.1016/j.eti.2020.101318>.
- [15] Pervez, M.N.; Balakrishnan, M.; Hasan, S.W.; Rashid, T.U. (2021). Wastewater characteristics and treatment technologies for food processing industries: A review. *Journal of Environmental Chemical Engineering*, 9(5), 106063. <https://doi.org/10.1016/j.jece.2021.106063>.
- [16] Paulo, A.M.S.; Amorim, C.L.; Costa, J.; Mesquita, D.P.; Ferreira, E.C.; Castro, P.M.L. (2021). High carbon load in food processing industrial wastewater is a driver for metabolic competition in aerobic granular sludge. *Frontiers in Environmental Science*, 9, 735607. <https://doi.org/10.3389/fenvs.2021.735607>.
- [17] Pervez, M.N.; Mishu, M.R.; Stylios, G.K.; Hasan, S.W.; Zhao, Y.; Cai, Y.; et al. (2021). Sustainable treatment of food industry wastewater using membrane technology: A short review. *Water*, 13(23), 3450. <https://doi.org/10.3390/w13233450>.
- [18] Pambudi, N.A.; Wibowo, H.; Prasetyo, A. (2021). Characterization and treatment strategies of industrial wastewater: A review. *IOP Conference Series: Earth and Environmental Science*, 623(1), 012012. <https://doi.org/10.1088/1755-1315/623/1/012012>.
- [19] Ravndal, K.T.; Yang, Y.; Zhang, Y.; Ødegaard, H. (2022). Operational parameters governing biological wastewater treatment performance and microbial stability: A review. *Journal of Environmental Management*, 317, 115525. <https://doi.org/10.1016/j.jenvman.2022.115525>.
- [20] Ren, F.; Sun, Y.; Liu, J.; Chen, K.; Shi, N. (2022). A modified dynamic DEA model to assess the wastewater treatment efficiency: Perspective from Yangtze River and Non-Yangtze River Basin. *Scientific Reports*, 12, 9931. <https://doi.org/10.1038/s41598-022-14105-0>.

- [21] Saralate, G.D.; Saratale, R.G.; Kim, D.S.; Shin, H.S. (2020). Treatment of high strength food and food processing wastewater using biological approaches: A review. *Science of the Total Environment*, 709, 136073. <https://doi.org/10.1016/j.scitotenv.2019.136073>.
- [22] Shrivastava, V.; Ali, I.; Marjub, M.M.; Rene, E.R.; et al. (2022). Wastewater in the food industry: Treatment technologies and reuse potential. *Chemosphere*, 293, 133553. <https://doi.org/10.1016/j.chemosphere.2022.133553>.
- [23] Sirohi, R.; Joun, J.; Lee, J. Y.; Yu, B. S.; Sim, S. J. (2022). Waste mitigation and resource recovery from food industry wastewater employing microalgae bacterial consortium. *Bioresource Technology*, 352, 127129. <https://doi.org/10.1016/j.biortech.2022.127129>.
- [24] Tchobanoglous, G.; Stensel, H.D.; Tsuchihashi, R.; Burton, F.L.; Abu-Orf, M.; Bowden, G.; Pfrang, W. (2021). *Wastewater engineering: Treatment and resource recovery*, 6th ed.; McGraw-Hill Education: New York, USA.
- [25] Usman, M.; Farooq, M.; Hanna, K.; Haderlein, S.B. (2021). Bacterial pathogens, antibiotic resistance, and wastewater treatment: Mechanisms and environmental implications. *Science of the Total Environment*, 796, 145132. <https://doi.org/10.1016/j.scitotenv.2021.145132>.
- [26] Metcalf & Eddy. (2014). *Wastewater Engineering: Treatment and Resource Recovery*, 5th ed.; McGraw-Hill Education: New York, USA.
- [27] Wondim, T.T.; Dzwayiro, R.B.; Aklog, D.; Janka, E.; Samarakoon, G.; Dereseh, M.M. (2023). Wastewater treatment plant performance assessment using time-function-based effluent quality index and multiple regression models: The case of Bahir Dar textile factory. *Environmental Monitoring and Assessment*, 195(11), 1360. <https://doi.org/10.1007/s10661-023-11952-w>.
- [28] Tchobanoglous, G.; Burton, F.L.; Stensel, H.D. (2003). *Wastewater Engineering: Treatment and Reuse*, 4th ed.; McGraw-Hill: New York, USA.
- [29] Zhang, Y.; Li, X.; Chen, G. (2024). Optimization of pH in biological wastewater treatment processes for enhanced organic removal. *Bioresource Technology*, 385, 129012. <https://doi.org/10.1016/j.biortech.2023.129012>.
- [30] Bazrafshan, E.; Mostafapour, F.K.; Hosseini, A.R.; et al. (2016). Application of coagulation process for industrial wastewater treatment. *Journal of Environmental Health Science and Engineering*, 14(1), 1–9. <https://doi.org/10.1186/s40201-016-0251-0>.
- [31] Zagklis, D.P.; Bampos, G. (2022). Tertiary wastewater treatment technologies: A review of technical, economic, and life cycle aspects. *Processes*, 10(11), 2304. <https://doi.org/10.3390/pr10112304>.
- [32] Verma, A.K.; Dash, R.R.; Bhunia, P. (2012). A review on chemical coagulation/flocculation technologies for removal of colour from textile wastewaters. *Journal of Environmental Management*, 93(1), 154–168. <https://doi.org/10.1016/j.jenvman.2011.09.012>.
- [33] Spellman, F.R. (2014). *Handbook of Water and Wastewater Treatment Plant Operations*, 3rd ed.; CRC Press: Boca Raton, USA. <https://doi.org/10.1201/b17376>.
- [34] Kurniawan, S.B.; Abdullah, S.R.S.; Imron, M.F.; et al. (2022). Challenges and opportunities of sustainable industrial wastewater treatment technologies. *Environmental Technology & Innovation*, 25, 102219. <https://doi.org/10.1016/j.eti.2021.102219>.



© 2026 by the authors. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).