sustainability

MDPI

Article

The Effect of Mixing Ratios on the Performance of an Integrated Poultry Slaughterhouse Wastewater Treatment Plant for a Recyclable High-Quality Effluent

Kulyash Meiramkulova [1], Duman Orynbekov [2], Gulnur Saspugayeva [1], Karlygash Aubakirova [3], Sholpan Arystanova [3], Aliya Kydyrbekova [1], Erbolat Tashenov [4], Kartjanov Nurlan [5] and Timoth Mkilima [6,*]

1 Department of Environmental Engineering and Management, L.N. Gumilyov Eurasian National University, Satpayev Street 2, Nur-Sultan 010000, Kazakhstan; kuleke@gmail.com (K.M.); gulnur.er@mail.ru (G.S.); aliyafromkz@gmail.com (A.K.)
2 Department of Sciences and Technology, L.N. Gumilyov Eurasian National University, Satpayev Street 2, Nur-Sultan 010000, Kazakhstan; duman_r@mail.ru
3 Department of Biotechnology, L.N. Gumilyov Eurasian National University, Satpayev Street 2, Nur-Sultan 010000, Kazakhstan; karlanasam2015@gmail.com (K.A.); sholpan1607@mail.ru (S.A.)
4 Department of Chemistry, L.N. Gumilyov Eurasian National University, Satpayev Street 2, Nur-Sultan 010000, Kazakhstan; tashenovyerbolat@gmail.com
5 Department of Thermal Engineering, Faculty of Transport and Energy, L.N. Gumilyov Eurasian National University, Satpayev Street 2, Nur-Sultan 010000, Kazakhstan; nurlanke16@gmail.com
6 Department of Civil Engineering, L.N. Gumilyov Eurasian National University, Satpayev Street 2, Nur-Sultan 010000, Kazakhstan
* Correspondence: tmkilima@gmail.com

Received: 2 July 2020; Accepted: 27 July 2020; Published: 29 July 2020

Abstract: Poultry slaughterhouse wastewater is characterized by high pollution strength, making its treatment before discharge or recycling of great importance. This study investigated the potential influence of mixing ratios on the treatability of poultry slaughterhouse wastewater under three different mixing ratios; 20:80, 50:50, and 80:20 of defeathering and cooling sources, respectively. Wastewater samples were collected from the Izhevski production corporate (PC) poultry farm located in the Akmola region, Kazakhstan. The lab-scale treatment plant, designed to simulate the industrial-scale treatment plant of the poultry farm, consists of electrolysis, membrane filtration, and ultraviolet disinfection as the main units. The general design purpose of the Izhevski PC treatment plant is to treat about 1.25 m^3/h (51.72%) of the total wastewater generated from the defeathering and cooling sections of the slaughterhouse to a recyclable degree. Water quality indices (WQIs) were developed for each of the studied mixing ratios. A comparative analysis was also done with drinking water quality standards set by the World Health Organization (WHO), as well as the government of Kazakhstan. From the analysis results, the defeathering raw wastewater was generally higher in pollution strength than the cooling wastewater. It was also observed that the increase in the ratio of defeathering wastewater reduced treatment efficiency for some physicochemical parameters such as turbidity, total suspended solids (TSS), color, biochemical oxygen demand (BOD), as well as chemical oxygen demand (COD). However, 100% removal efficiency was achieved for the microbial parameters for all the three studied ratios. Based on the computed WQIs, the highest-quality effluent was achieved from the 20:80 (defeathering:cooling) mixing ratio. However, with the fact that all the three mixing ratios produced "excellent" status, the 80:20 (defeathering:cooling) mixing ratio stands to be an ideal option. The selection of 80:20 mixing ratio has the potential to reduce the pollution load in the wastewater discharged to the sewerage system, while achieving high-quality effluent for recycling in the cooling processes of the slaughterhouse.

Keywords: defeathering; cooling; mixing ratio; poultry slaughterhouse; wastewater treatment

1. Introduction

The poultry industry is one of the rapidly growing agricultural and industrial sectors producing affordable food products in the world. The production processes are associated with a high usage of water [1]. An average amount of 26.5 L of water per bird may be required from live birds processing to meat [2]. Also, the processes generate wastewater containing high amounts of proteins, fats, and carbohydrates from meat, blood, skin, as well as feathers [3]. Therefore, efficient treatment systems are required to remove the majority of the soluble and particulate matter before either discharge or recycling [4]. Usually, poultry slaughterhouse wastewater is handled by discharging it into water bodies, municipal wastewater collection and treatment systems, as well as open environment such as grassland. However, the pollutants in the poultry slaughterhouse wastewater pose a significant threat to human health and the environment in general [5], making its treatment before discharge of great importance.

There are many technologies used for poultry slaughterhouse wastewater treatment, which can be categorized as physical [6], chemical [7–9], as well as biological processes [10,11].

However, each wastewater treatment technology has its strengths and weaknesses. Although physical treatment processes such as membrane filtration can be highly efficient in the pollutant removal but are pressure-demanding, the generated sludge has to be separately handled making the processes relatively expensive and less feasible for large-scale treatments [12]. The biological treatment systems offer natural treatment processes with high adaptability of microorganisms to a wide variety of wastewater characteristics. Unfortunately, the biological treatment systems are characterized by slow treatment processes, being space-demanding as well as generating high quantities of sludge [13]. While chemical wastewater treatment processes, such as electrochemical systems, are termed to be robust, space-friendly, as well as flexible to fluctuating wastewater characteristics [14], the risk of by-products formation is among the drawbacks associated with the chemical treatment systems [15]. Therefore, combining different treatment technologies is essential to overcome the weaknesses, which in turn brings the importance of integrated wastewater treatment systems. Integrated technologies for poultry wastewater treatment have also been increasingly gaining interest, for example: using a static granular bed reactor (SGBR) coupled with ultrafiltration (UF) membrane system [16], the combination of ultraviolet light, pulsed electric field and ozone [17], as well as aluminum salts and natural polyelectrolytes [18], are among the integrated treatment technologies. However, despite their applicability for poultry wastewater treatment, the potential response of these technologies to different wastewater mixing ratios has not been comprehensively captured. For a wastewater recycling system that intends to recover only a portion of the generated wastewater from identifiable and accessible sources, it is necessary to understand the response of the treatment system to different mixing ratios for optimization purposes. Therefore, understanding the response of an integrated treatment plant to different mixing ratios of a poultry slaughterhouse wastewater is a key to a profound decision making.

Moreover, for achieving high-quality recyclable effluent, integration of electrochemical (EC) methods, membrane filtration, as well as ultraviolet (UV) disinfection are some of the most promising approaches. The EC methods play an important role as pre-treatment units before the membrane filtration; while the membrane filtration unit removes the majority of the suspended and dissolved solids including microorganisms [19]. The UV disinfection unit eliminates the remaining microorganisms as part of the quality enhancement.

Electrolysis is an electrochemical (EC) process using electrical energy as the driving force for chemical reactions to occur. Water is decomposed to hydrogen and oxygen by passing a current through it in the presence of electrolytes [20]. During the EC process, oxidation occurs in the anode making it electrochemically corroded, while passivation occurs in the cathode, where during the process, amorphous $M(OH)_3$, also known as sweep flocs, are formed. The formed flocs are responsible for the removal of colloidal particles through rapid adsorption of soluble organic compounds [21]. However, the application of the EC treatment methods can be highly affected by the types of electrodes used [22]. This technology has also been reported in many studies in relation to poultry wastewater treatment [23–25].

Membrane filtration is a treatment technology using a thin layer of semi-permeable material that separates substances when a driving force is applied across the membrane. Membrane filtration removes microorganisms, particulates, and natural organic materials; of which the filter pore size is an important factor. In general, the membrane filtration technology includes microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) [26]. Value-added products like crude proteins could be separated through ultrafiltration from poultry wastewater, subsequently reducing the COD [2].

Ultraviolet disinfection, which is also known as ultraviolet germicidal radiation, is widely used for disinfecting water to inactivate microorganisms by attacking their genetic core (DNA) and eliminating their ability to reproduce [27]. UV radiation technology has been used to treat water since 1909 and offers one of the safest and most effective disinfection approach for drinking water [28]. UV disinfection has also shown to be useful for the elimination of pathogens in poultry wastewater [29].

Studies on the use of water recycling technologies are important as they are likely to facilitate the industrial transformations towards achieving closed-cycle systems of process water. Wastewater recycling has been known for many years [30], however it remains a challenge in many countries including in the European countries where water is a scarce resource [31]. The lack of full knowledge on the potential hazards associated with the use of the approach, challenges in the accurate quality assessment and motoring in real-time, bad management of the social aspects related to the practice e.g., acceptability, marketing, as well as disagreements among scientists on the acceptable level of the standards to be applied, are among the factors challenging the implementation of wastewater recycling practices. [32].

In Kazakhstan, several development strategies are currently being implemented, including the increase of the economic affordability of water for agricultural products. These measures are under the framework of the Agribusiness 2020 Program for the Development of the Agro-Industrial Complex in the Republic of Kazakhstan for 2013–2020 [33]. There have been significant efforts to increase the awareness of environmental protection in the country [34,35]. Also, having industrial technologies that are friendly to the environment with a maximum reduction of harmful emissions to the environment is prioritized. The most preferable approach is to achieve almost completely waste-free industrial production systems.

In this study, an integrated wastewater treatment system for a poultry slaughterhouse wastewater is investigated in terms of its response to different mixing ratios of defeathering and cooling sections of a poultry slaughterhouse (defeathering:cooling; 20:80, 50:50, 80:20). The selected mixing ratios take into account both low and higher proportions of the studied sources as well as the average conditions. The lab-scale treatment plant installed in the Water and Environmental Management laboratory of the L.N. Gumilyov Eurasian National University, was used to treat wastewater samples from the Izhevski PC poultry farm in Kazakhstan. The general design purpose of the lab treatment plant is to simulate the full-scale (industrial) treatment plant aimed at treating the poultry slaughterhouse wastewater to a high-quality recyclable effluent, which in turn minimizes the dependency of portable water in the production processes. The main sources of wastewater from the poultry farm are defeathering, evisceration (removal of the birds' internal organs), and cooling processes. However, the evisceration process in the poultry farm uses a very small amount of water, which is highly concentrated with suspended particles leading to a relatively high treatment cost. Therefore, defeathering and cooling sections (accounting for more than 90% of the generated wastewater) were selected as sources of wastewater to be recycled within the industry; while the evisceration wastewater is subjected to microfiltration and then discharged to the village sewerage system. The defeathering and cooling sections generate a total of approximately 2.41 m^3/h (44.8% defeathering and 55.2% cooling), on average. Moreover, design capacity of the Izhevski PC poultry treatment plant is 1.25 m^3/h, equivalent to 51.9% of the total wastewater generated from the defeathering and cooling sections. While the remaining amount of wastewater from defeathering and cooling sections is discharged to the sewerage system, which is then treated within the activated sludge treatment plant of the Izhevsk village. As the treated effluent from the Izhevski PC wastewater treatment plant is expected to be recycled for cooling purposes, drinking water quality standards became the most desirable reference for the effluent quality classification. Water quality indices (WQIs) were developed for each of the studied mixing ratios as well as a comparative analysis with drinking water quality standards set by the government of Kazakhstan and WHO was done.

2. Materials and Methods

2.1. Case Study, Study Design, and Analytical Methods

The water samples used in this study were collected from the Izhevski PC poultry slaughterhouse located in Izhevsk village, Arshalinsky district, in Akmola region of the Republic of Kazakhstan, about 70 km from the capital city Nur-Sultan; located at 51°10′ North latitude and 71°26′ East longitude. Defeathering, evisceration, and cooling processes are the main sources of wastewater in the slaughterhouse (Figure 1). Water samples were collected as grab samples and then stored at 4 °C. The collection of the samples was done using 5 L plastic bottles, which were thoroughly rinsed with deionized water before use. For data quality control, replicate samples were also collected and analyzed; the replicate samples were essential to establish the amount of data variability, which could have been led by some part of the collection processes as well the analytical procedures. Each study session used a total of 1 L as an influent to the treatment plant. A well-rinsed measuring cylinder was used to measure the required quantity of wastewater as determined by the mixing ratios; where, the 20% ratio corresponded to 0.2 L, 50% to 0.5 L, as well as 80% to 0.8 L. The selection of the mixing ratios intended to capture the influence of the mixing ratios under both low and high proportions from the studied sources, including the average conditions. The study was conducted within the two years of the project timeline.

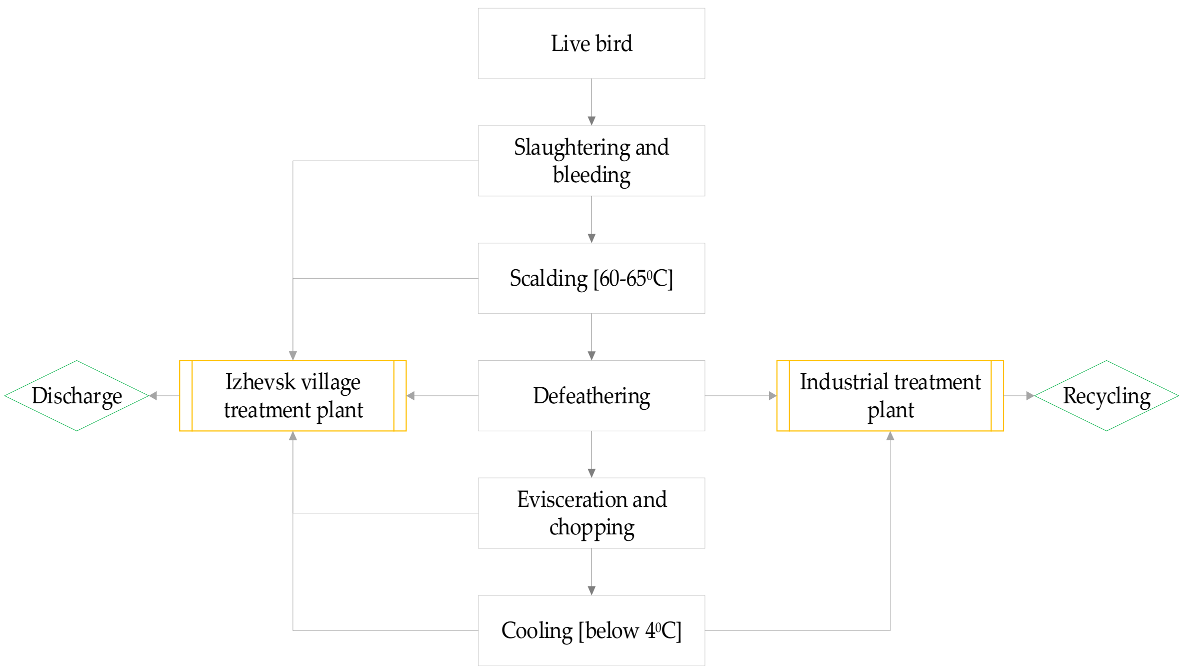

Figure 1. Main units process flowchart.

The measurements of COD, free chlorine, total chlorine, nitrites, nitrates, total phosphorous, and ammonia before and after the treatment were achieved using the combination of Spectrophotometer (Hach DR3900, HACH/LANGE, Germany), Colorimeter (Hach DR900), with standard reagents as well as the test kits. The U.S. Environmental Protection Agency Great Lakes National Program Office (GLNPO), Standard Operating Procedure for Turbidity was used for the analysis of turbidity [36]; as well as the American Public Health Association (APHA) 4500-Nor that was used for the analysis of total phosphorous [37]. Moreover, the lab pH-meter (Hach Co) was used for pH measurements. Color measurements were achieved using the UV-V Spectrophotometer (PE-5400UV) [38], as well as TSS was measured using the Hach TSS portable hand-held turbidity meter, while the microbiological analysis was achieved using the membrane filtration method [39]. In this method, the samples were passed through a membrane filter with a pore size of 0.45 µm and incubated on an agar plate at 37 °C for 48 h. Bacterial cells trapped on the membrane filter grew into countable colonies, of which facilitated the calculation of bacterial density. Generally, the analyses of the samples were accomplished following the recommendations in the APHA, Standard Methods for the Examination of Water and Wastewater [40]. Generally, between the two studied sources of wastewater within the poultry farm, wastewater from the defeathering section is characterized by higher pollution strength than the cooling section (Table 1). The minimum and maximum recorded concentrations from defeathering wastewater are relatively higher than those from the cooling section. Table 2 presents the studied microbial parameters in the raw wastewater from the three studied mixing ratios.

Table 1. General physicochemical raw wastewater characteristics (number of samples = 12).

Indicator	Min		Max		AM		Med		SD	
	D	C	D	C	D	C	D	C	D	C
pH	5.5	6.5	7.4	7.2	6.7	6.7	6.9	6.6	0.7	0.3
Turbidity	62.6	9.7	196.0	172.0	121.7	71.7	114.0	52.6	47.8	65.7
Color	865.0	193.0	2369.0	1840.0	1775.3	802.3	1933.5	588.0	564.1	668.8
TSS	113.0	25.0	337.0	266.0	216.5	119.5	208.0	93.5	79.7	97.6
Free chlorine	0	0.0	0.4	0.2	0.1	0.1	0.0	0.1	0.2	0.1
Total chlorine	0	0	0.6	0.3	0.1	0.1	0	0.1	0.3	0.2
Nitrites	0.0	0.1	0.3	0.6	0.2	0.3	0.2	0.2	0.1	0.2
Nitrate	10.0	2.0	67.8	49.3	29.5	17.7	20.1	9.8	22.9	18.6
Total phosphorous	3.3	0.0	5.9	5.2	4.8	3.0	4.9	3.3	1.0	2.1
Ammonium	1.7	1.6	2.6	2.5	2.0	2.0	1.9	2.0	0.4	0.3
COD	651.0	155.0	2009.0	1646.0	1367.3	702.2	1404.5	503.5	484.6	600.1
Total iron	0.2	0.2	1.3	0.7	0.8	0.4	0.8	0.3	0.6	0.2
Aluminum	2.1	0.7	4.5	6.6	3.0	4.3	3.2	5.0	1.1	2.2
BOD	833.2	139.6	1557.0	1287.0	1236.8	820.9	1278.5	928.5	259.3	490.3
Manganese	0.1	0.2	0.5	0.3	0.3	0.2	0.2	0.2	0.1	0.1
Nickel	3.7	5.6	8.6	8.2	6.5	6.9	6.9	6.9	2.0	1.3
Chromium	0.6	1.3	2.2	2.2	1.2	1.7	1.0	1.7	0.6	0.4

D = defeathering; C = cooling; Min = minimum; max = maximum; AM = arithmetic mean; med = median; SD = standard deviation. pHunitless, turbidity in nephelometric turbidity units (NTU), color in degree, all other parameters in mg/dm^3.

Table 2. Microbial raw wastewater characteristics (average).

Parameter (CFU/mL)	D	C
Total number of bacteria (TNB)	1.4×10^5	2.2×10^5
Total coliform bacteria (TCB)	3.5×10^4	2.6×10^4
Thermo-tolerant coliform bacteria (TTCB)	7.1×10^4	6.6×10^4
Salmonella typhi	120	215
Enterococcus faecalis	2.8×10^4	5.3×10^4
Pseudomonas aeruginosa	3.2×10^7	7.4×10^7

D = defeathering; C = cooling.

2.2. Treatment Plant Setup

The principal units of the integrated treatment plant are; electrolysis, membrane filtration, and ultraviolet disinfection (Figure 2 and Table 3). Firstly, wastewater to the treatment plant is received by a reservoir consisting of a macro-filter responsible for trapping feathers and organic components. Thereafter, the wastewater is subjected to the EC process, which takes place within a reactor of 15 × 13 × 11 cm dimensions made of polypropylene material. Direct current is supplied to the electrodes through a power supply with a range of 0–50 V (voltage) and 0–10 A (current density). The purified water from the EC process enters a sedimentary cylinder where the particles in suspension settle down and come to rest against the barrier. Moreover, a pump of 5.5 bar is then utilized to transfer water from the sedimentary cylinder to the ultra-filter, which has a pore size of 0.02 μm, enough to trap sediments not smaller than its pore size, including most bacteria and viruses. Next, the ultra-filtered water flows to another small reservoir where it is pumped to the UV sterilizer to eliminate the remaining microorganisms. The UV sterilizing unit has a quartz tube with a germicidal lamp installed. The purpose of the quartz tube is to avoid direct contact of water and lamp, which in turn facilitates easy replacement without any need for draining water from the UV container. The UV water sterilization process is designed in such a way it can sustain pressure as the purification process continues. The water circulates in the UV sterilizer for about 10 min before the treatment process ends. Cleaning of the reservoirs and electrolyte cell is done manually.

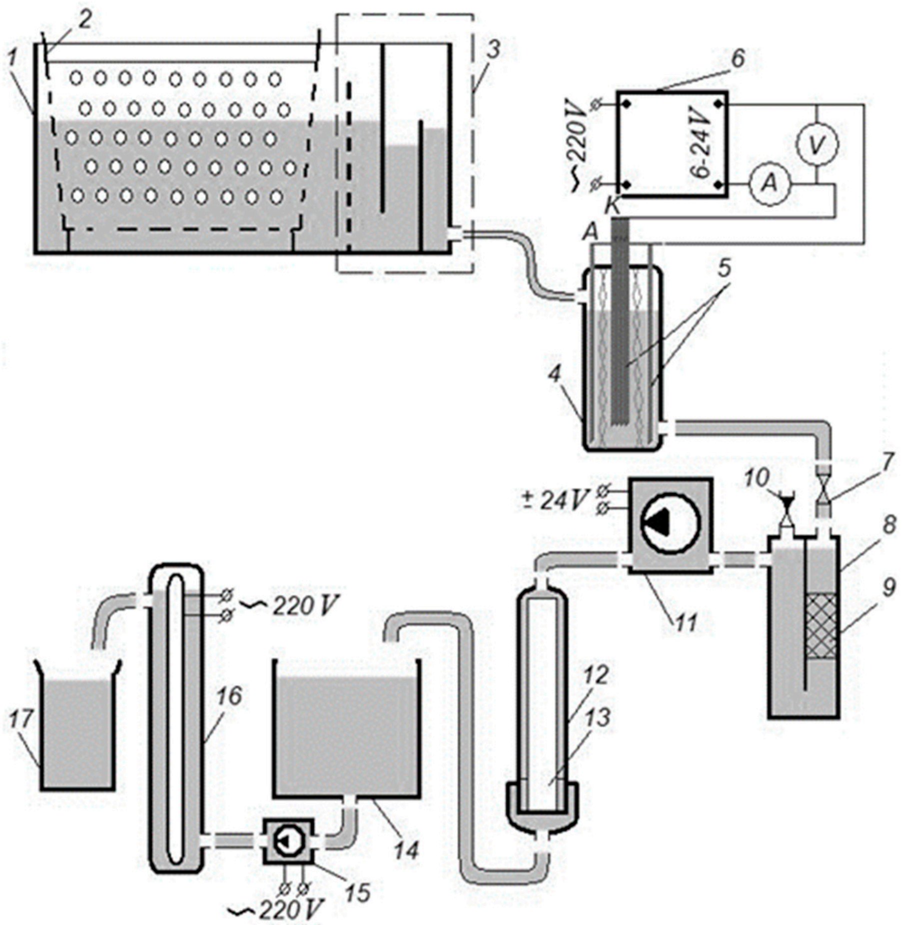

Figure 2. Plant setup: 1—wastewater reservoir; 2—removable macro-filter; 3—fat catcher; 4—electrolyte cell; 5—electrodes (A—anode, K—cathode); 6—power supply; 7—valve; 8—sedimentary tank; 9—filter; 10—air vent valve; 11—pump; 12—ultra-filter; 13—ultra-filtration membrane; 14—reservoir; 15—circulatory pump; 16—UV lamp; 17—reservoir for treated effluent.

Table 3. Treatment plant specifications.

Performance	Unit	Value
Influent	L/h	1
Effluent	L/h	0.55
Total power supply	kW	0.3–0.6
	Feather catcher	
Length	mm	80
Width	mm	60
Height	mm	50
	Fat catcher	
Length	mm	100
Width	mm	40
Height	mm	80
	Electrolysis	
Length	mm	150
Width	mm	130
Height	mm	110
Cathode	Material	Titanium alloy BT1
Anode	Material	Aluminum
Supply voltage	V	12
Hydraulic retention time	min	10
	Membrane filtration	
Nominal filtration fineness	µm	0.02
Pump supply voltage	V	24
Pump power	kW	0.2–0.4
	UV lamp for disinfection	
Power	W	30
Operating pressure	bar	1.1
Supply voltage	V	220
Hydraulic retention time	min	5–20

2.3. Statistical Methods

The analysis results from raw wastewater and the purified water were used to compute treatment efficiencies in percentage. The approach used for the treatment efficiency computation is illustrated in Equation (1).

$$T_e(\%) = \left(\frac{C_b - C_a}{C_b}\right) \times 100 \quad (1)$$

where:

T_e, treatment efficiency,

C_b, concentration before treatment,

C_a, concentration after treatment.

Percentage compliance computations were performed for some of the studied parameters as part of the comparative analysis with drinking water quality guidelines set by the government of Kazakhstan and WHO. Equation (2) gives a summary of the percent compliance computation approach used.

$$C_p(\%) = \left(\frac{S_i - C_i}{S_i}\right) \times 100 \quad (2)$$

where:

C_p, percent compliance,

S_i, recommended standard for *i*th parameter,

C_i, concentration of *i*th parameter.

Also, the weighted arithmetic water quality index method was used to present the analysis results by aggregating information from several water quality parameters to get an overall picture of the water quality from the studied mixing ratios. The drinking water quality guidelines, set by the government of Kazakhstan [41], were used for the computation of the quality rating scale. The procedures for WQIs development are summarized in the five steps below, and also presented in Equations (3)–(6):

i. Assigning weights to each of the studied parameters (w_i) (Table 4). This was the first step at which different weights to each of the studied parameters were assigned on a scale of 0 to 6, where 0 represents the lowest effect on water quality while 6 is for the highest perceived effect. The weighting process is based on the perceived effects of the water quality parameters on drinking water suitability and is validated by the water quality experts [42].

Table 4. Weight of the parameters with guidelines (Kazakhstan).

Parameter	Weight	Guideline
Turbidity	4	1.5 NTU
Color	4	20 degrees
TSS	4	500 mg/dm^3
Free chlorine	5	0.3–0.5 mg/dm^3
Total chlorine	5	0.8–1.2 mg/dm^3
Nitrite	5	3.0 mg/dm^3
Nitrate	5	45.0 mg/dm^3
Total phosphorous	4	3.5 mg/dm^3
Ammonium	4	0.5 mg/dm^3
Total iron	4	0.3 mg/dm^3
Aluminum	4	0.5 mg/dm^3
COD	5	5 mg/dm^3
BOD	5	3 mg/dm^3
Total coliform (100 mL)	6	0 CFU/mL
Total	64	

ii. Computation of relative weights (W_i)

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{3}$$

iii. Calculation of a quality rating scale (q_i)

$$q_i = \frac{C_i}{S_i} \times 100 \tag{4}$$

iv. Computation of sub-indices (SI_i)

$$SI_i = W_i \times q_i \tag{5}$$

v. Summation of sub-indices

$$WQI = \sum_{i=1}^{n} Sub - indices\ (SI_i) \tag{6}$$

where:

w_i is the weight of individual parameters,
W_i (with capital W) is referred to as relative weight,
n accounts for the number of parameters being studied,
q_i is the quality rating,
C_i is the average concentration of individual parameters,
S_i is the recommended water standard,
SI_i is the sub-index of an ith parameter.

The definition of the aggregated WQIs based on the five categories: <50 "excellent water", 50–100 "good water", 100–200 "poor water", 200–300 "very poor water", >300 "water unsuitable for drinking" [43,44].

The statistical analysis of the results presented in this study was achieved using Microsoft Excel 2019.

3. Results and Discussion

3.1. Physicochemical Parameters

The collected samples were successfully analyzed for physical, chemical, as well as biological water quality parameters. Tables 5–7 present the lab analysis results in terms of minimum (min), maximum (max), arithmetic mean (AM), median (med), as well as standard deviation (SD).

Table 5. Analysis results for 20:80 (defeathering:cooling) mixing ratio.

Parameter	Defeathering:Cooling (20:80)					Units
	Min	**Max**	**AM**	**Med**	**SD**	
pH	5.40	8.42	7.07	7.11	1.11	
Turbidity	0.00	0.40	0.07	0.00	0.15	NTU
Color	0.00	38.60	12.27	7.00	12.70	degree
TSS	0.00	1.40	0.53	0.40	0.56	mg/dm^3
Free chlorine	0.00	0.03	0.01	0.01	0.01	mg/dm^3
Total chlorine	0.00	0.04	0.02	0.01	0.02	mg/dm^3
Nitrites	0.00	0.05	0.02	0.01	0.02	mg/dm^3
Nitrate	0.00	5.30	1.76	0.51	2.16	mg/dm^3
Total phosphorous	0.00	0.19	0.06	0.02	0.07	mg/dm^3
Ammonium	0.00	2.10	1.00	1.13	0.81	mg/dm^3
COD	2.02	26.88	8.88	5.46	8.36	mg/dm^3
Total iron	0.04	0.16	0.07	0.06	0.04	mg/dm^3
Aluminum	0.01	0.04	0.02	0.02	0.01	mg/dm^3
BOD	0.86	4.80	2.48	2.17	1.48	mg/dm^3
Manganese	0.02	0.26	0.10	0.04	0.10	mg/dm^3
Nickel	0.04	0.92	0.59	0.74	0.36	mg/dm^3
Chromium	0.02	0.46	0.29	0.41	0.19	mg/dm^3

Table 6. Analysis results for 50:50 (defeathering:cooling) mixing ratio.

Indicator	Defeathering:Cooling (50:50)					Units
	Min	**Max**	**AM**	**Med**	**SD**	
pH	5.40	8.04	6.94	7.33	1.11	
Turbidity	0.00	1.01	0.27	0.00	0.40	NTU
Color	10.00	41.00	26.50	27.50	10.72	degree
TSS	0.00	4.20	1.87	2.00	1.30	mg/dm^3
Free chlorine	0.00	0.01	0.01	0.01	0.01	mg/dm^3
Total chlorine	0.00	0.03	0.01	0.01	0.01	mg/dm^3
Nitrites	0.00	0.13	0.03	0.01	0.05	mg/dm^3
Nitrate	0.01	0.40	0.18	0.16	0.16	mg/dm^3
Total phosphorous	0.01	4.60	0.79	0.03	1.71	mg/dm^3
Ammonium	0.00	1.37	0.31	0.06	0.48	mg/dm^3
COD	7.46	39.60	15.73	8.94	11.67	mg/dm^3
Total iron	0.01	0.05	0.03	0.04	0.01	mg/dm^3
Aluminum	0.01	0.04	0.03	0.03	0.01	mg/dm^3
BOD	4.42	9.06	6.55	5.76	1.77	mg/dm^3
Manganese	0.02	0.49	0.19	0.15	0.17	mg/dm^3
Nickel	0.01	2.48	0.51	0.13	0.89	mg/dm^3
Chromium	0.04	0.26	0.19	0.24	0.09	mg/dm^3

Table 7. Analysis results for 80:20 (defeathering:cooling) mixing ratio.

Indicator	Defeathering:Cooling (80:20)					Units
	Min	Max	AM	Med	SD	
pH	5.65	8.04	6.65	6.55	0.75	
Turbidity	0.00	1.61	0.44	0.00	0.65	NTU
Color	12.00	43.40	27.90	28.00	10.75	degree
TSS	2.60	5.00	3.57	3.50	0.84	mg/dm^3
Free chlorine	0.00	0.02	0.01	0.01	0.01	mg/dm^3
Total chlorine	0.00	0.03	0.01	0.01	0.01	mg/dm^3
Nitrites	0.00	0.07	0.03	0.02	0.02	mg/dm^3
Nitrate	0.01	6.90	1.84	0.16	2.64	mg/dm^3
Total phosphorous	0.01	4.20	0.78	0.12	1.53	mg/dm^3
Ammonium	0.16	2.80	1.82	2.12	0.87	mg/dm^3
COD	21.20	52.32	32.85	29.80	11.18	mg/dm^3
Total iron	0.02	0.04	0.03	0.02	0.01	mg/dm^3
Aluminum	0.02	0.05	0.03	0.02	0.01	mg/dm^3
BOD	8.08	13.00	10.39	10.21	1.79	mg/dm^3
Manganese	0.02	0.42	0.13	0.04	0.15	mg/dm^3
Nickel	0.01	2.04	0.43	0.13	0.73	mg/dm^3
Chromium	0.01	0.40	0.23	0.24	0.14	mg/dm^3

3.1.1. Turbidity, TSS, Color, BOD, and COD

The integrated treatment plant achieved a minimum value of 0 NTU of turbidity from all three mixing ratios, which is 100% removal efficiency, with the maximum recorded value being 1.61 NTU from 80:20 (defeathering:cooling) mixing ratio. The minimum, average, and maximum values of turbidity in the wastewater are observed to be increasing with the increase in the ratio of defeathering wastewater; a fact that can also be observed in the turbidity boxplot in Figure 3. The raw wastewater from the defeathering process is characterized by a relatively high pollution strength in terms of turbidity compared to the wastewater from the cooling process (see Table 1). The high pollution strength from the defeathering process is due to the fact that the process results in high organic load [45], affecting the level of turbidity in the wastewater.

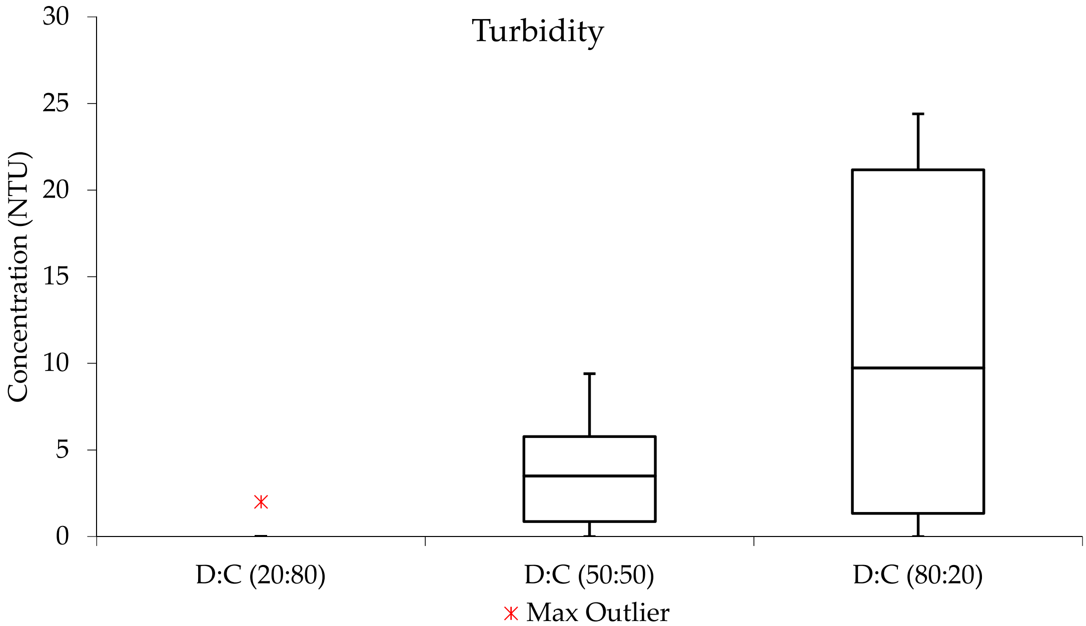

Figure 3. Turbidity boxplot.

Minimum concentration value of 0 mg/dm^3 (100% removal efficiency) of TSS was achieved from the 20:80 and 50:50 (defeathering:cooling) mixing ratios, with 2.60 mg/dm^3 being the minimum recorded concentration value from the 80:20 (defeathering:cooling) mixing ratio. The highest maximum TSS concentration value of 5 mg/dm^3 was also recorded from the 80:20 (defeathering:cooling) mixing ratio. Despite the high TSS removal efficiency, the concentration levels of TSS in the treated effluent were also observed to be increasing with the increase in the ratio of defeathering wastewater. From the treated effluent, the average concentration of TSS from 20:80 (defeathering:cooling) mixing ratio was approximately 8.9% of the total average TSS concentrations from the three mixing ratios; as well as 31.3% from 50:50, and 59.8% from 20:80. A high concentration of TSS makes water not aesthetically appealing for use especially for drinking purposes [46].

Noticeable color in drinking water is objectionable; from the analysis results, 0 degree of color was recorded as a minimum value achieving 100% removal efficiency when the treatment plant was subjected to the 20:80 (defeathering:cooling) mixing ratio with 38.60 degrees being the maximum value for the same ratio. For the 50:50 (defeathering:cooling) mixing ratio, 10 degrees of color was the minimum recorded value, with 41.00 being the maximum recorded value. While, for the 80:20 (defeathering:cooling) mixing ratio, 12.00 degrees was recorded as the minimum value with 43.40 degrees being the maximum value. Color in water can be caused by dissolved and suspended materials [47]. Also, as in turbidity and TSS, the degree of color in the treated effluent was observed to be increasing with the increase in the ratio of defeathering wastewater (Tables 5–7).

The minimum initial concentration of BOD was 833.2 mg/dm^3 from the raw defeathering wastewater, while 139.6 mg/dm^3 was the minimum initial concentration value from the raw cooling wastewater. From the treated effluent, the lowest minimum concentration value of 0.86 mg/dm^3 was recorded from the 20:80 (defeathering:cooling) mixing ratio, with the highest concentration value of 13 mg/dm^3 observed from the 80:20 (defeathering:cooling) mixing ratio. The results show a similar phenomenon as in turbidity, TSS, and color. From the treated effluent, the BOD average concentration from 20:80 (defeathering:cooling) mixing ratio was approximately 12.8% of the total average BOD concentrations from the three mixing ratios; as well as 33.7% from 50:50, and 53.5% from 20:80.

The minimum recorded concentration of COD from the defeathering wastewater before treatment was 651.0 mg/dm^3 while that of cooling was 155.0 mg/dm^3. The maximum recorded concentration of COD from the defeathering wastewater before treatment was 2009.0 mg/dm^3 while that of the cooling section being 1646.0 mg/dm^3, with 1367.3 mg/dm^3 and 702.2 mg/dm^3 being the average concentrations for defeathering and cooling wastewater, respectively. After treatment, the lowest minimum concentration value of 2.02 mg/dm^3 was achieved from the 20:80 (defeathering:cooling) mixing ratio while the highest maximum concentration was recorded from the 80:20 (defeathering:cooling) mixing ratio with 52.32 mg/dm^3. Referring to the analysis results of treated effluent; the average concentration of COD from 20:80 (defeathering:cooling) mixing ratio was approximately 15.4% of the total average COD concentrations from the three mixing ratios; as well as 27.4% from 50:50, and 57.2% from 20:80. From the boxplot in Figure 6, it can be observed that the proportional increase in the defeathering wastewater also affected the COD removal performance; which can be linked to the high pollution strength from the defeathering wastewater.

Moreover, from the results, a similar trend (increase with the increase in the defeathering ratio) can be observed among turbidity, TSS, color, BOD, and COD (Figures 3–6). Some studies have indicated the potential existence of a strong linear relationship between turbidity and TSS in water [48], as well as the potential influence of turbidity and TSS on color, BOD, and COD [49].

3.1.2. Nitrate, Nitrite, Total Phosphorous, and Ammonium

Nitrate and nitrite did not appear to be perfectly following the trend observed from turbidity, TSS, color, BOD, and COD when the wastewater samples were subjected to different mixing ratios. The initial (before treatment) maximum nitrate concentration value of 67.8 mg/dm^3 was observed from the defeathering wastewater, with 49.3 mg/dm^3 being the maximum from the cooling section.

From the 20:80 (defeathering:cooling) mixing ratio, 0 mg/dm^3 of nitrate was recorded as the minimum concentration in the treated effluent, which is 100% removal efficiency with 5.30 mg/dm^3 being the maximum concentration value. From the 50:50 (defeathering:cooling) mixing ratio, a minimum concentration value of 0.01 mg/dm^3 of nitrate was achieved from the treated effluent with 0.4 mg/dm^3 being the maximum. Also, as in the 50:50 (defeathering:cooling) mixing ratio, 0.01 mg/dm^3 of nitrate was recorded as the minimum concentration value from the treated effluent from 80:20 (defeathering:cooling) mixing ratio, with 6.9 mg/dm^3 being the maximum concentration. However, all the maximum nitrate concentration values were within the guidelines set by the WHO. In higher concentrations, nitrate may lead to a Methemoglobinemia disease, which is also known as a blue baby syndrome, generally affecting bottle-fed infants [50].

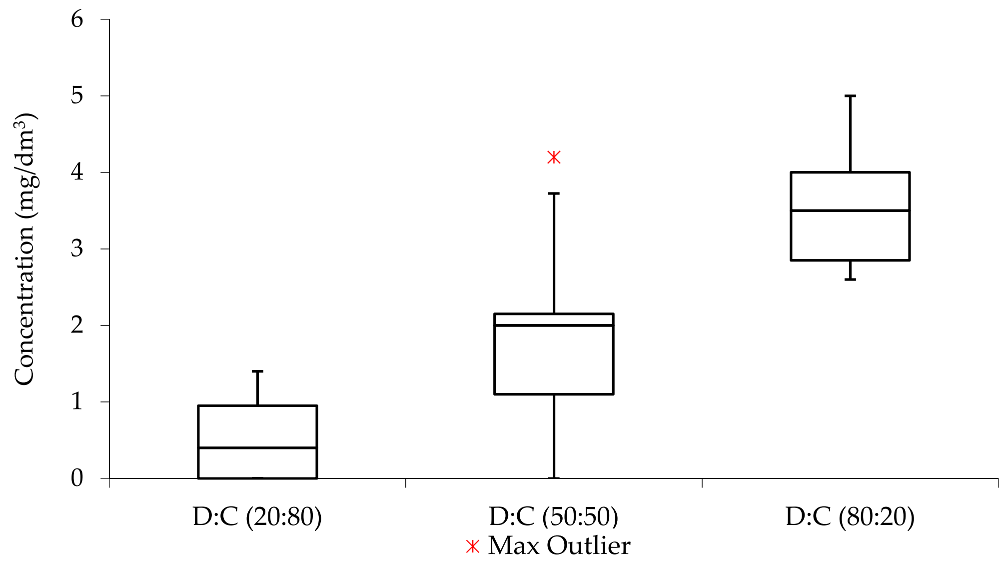

Figure 4. TSS boxplot.

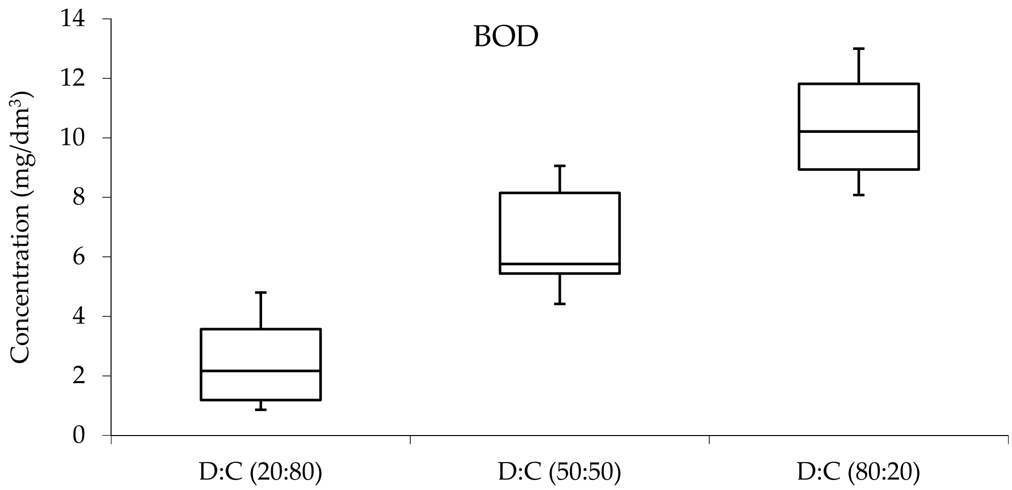

Figure 5. BOD boxplot.

The minimum concentration value of 0 mg/dm^3 of nitrites (100% removal efficiency) was achieved from all the three mixing ratios. Meanwhile, 0.05 mg/dm^3 being the maximum recorded concentration value from 20:80 (defeathering:cooling) mixing ratio, 0.13 mg/dm^3 from 50:50, as well as 0.07 mg/dm^3 from 80:20, which were also within the recommended standards set by the government of Kazakhstan. However, low concentrations of nitrites were also observed from the defeathering and cooling raw wastewater. This fact is probably due to the nature of its occurrence, where nitrite anions (NO_2^-) occur as metastable intermediates in the oxidation process resulting from nitric oxide (NO) radicals to the stable metabolite nitrate (NO_3^-) [51].

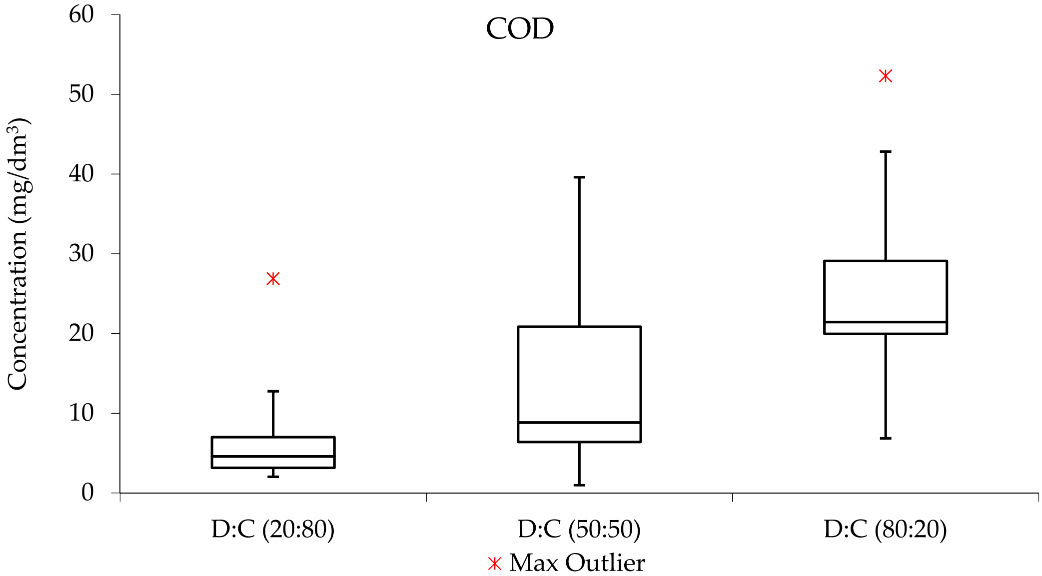

Figure 6. COD boxplot.

On average, the concentration of total phosphorous in the defeathering raw wastewater was 37.5% higher than that of cooling raw wastewater. The phenomenon is also reflected in the treated effluent under different mixing ratios. From the 20:80 (defeathering:cooling) mixing ratio, an average of 0.06 mg/dm^3 was achieved. However, when the defeathering wastewater ratio was increased to 50%, an average concentration of 0.79 mg/dm^3 was achieved, which is an increase of about 92.4% from the 20% ratio. As for nitrate and nitrite, total phosphorous concentrations in the treated effluent were also observed to be highly fluctuating with no complete specific pattern. In the 80% ratio of the defeathering wastewater, an average concentration of 0.78 mg/dm^3 of total phosphorous was achieved, which is approximately 92.3% increase from the 20% ratio of defeathering wastewater as well as 0.1% decrease from the 50% ratio of defeathering wastewater.

Despite the differences in minimum and maximum recorded concentrations of ammonium in the defeathering and cooling raw wastewater, their average concentrations were approximately equal, of which meat and blood are among the sources of ammonium in the wastewater. However, ammonium is among the parameters that the treatment plant faced a significant challenge in their removal, especially when the ratio of defeathering wastewater increased. From the 80:20 (defeathering:cooling) ratio, an average concentration of 1.82 mg/dm^3 was achieved, which is still 3.64 times higher than the recommended guideline according to the Kazakhstan drinking water quality standards. In this study, the membrane filtration treatment process was the main unit that can be associated with difficulty in the removal of ammonium; similar challenges of ammonium removal using membrane filtration processes have been observed in some other studies [52]. Although there is no evidence that ammonia is carcinogenic, ammonia has a toxic effect on healthy humans only if the intake becomes higher than the capacity to detoxify [53].

3.1.3. Free and Total Chlorine

Low concentrations of free and total chlorine were observed in the raw wastewater. The phenomenon can be highly linked to the fact that the poultry farm is working hard to achieve a chlorine-free production process. In the treated effluent, 0 mg/dm^3 was achieved for both free and total chlorine from all the three mixing ratios, while the maximum recorded concentrations for both parameters ranged from 0.01 mg/dm^3 to 0.04 mg/dm^3. A 98% compliance was achieved from the free chlorine average concentrations according to the Kazakhstan standards, and 99.33% according to the WHO standards. In general, free and total chlorines were not observed to have a specific response to the mixing ratios. The unpredictable behavior of chlorine from the mixing ratios may have been contributed by the fact that chlorine is an extremely reactive element, and it combines with all elements except the noble gases [54].

3.1.4. Potentially Toxic Elements (PTEs)

PTEs include trace element and heavy metals that are naturally present in the environment; however, anthropogenic activities such as industrial food productions have been leading to their increase in concentration [55]. In this study, manganese, nickel, chromium, and total iron were studied.

The maximum initial (before treatment) manganese concentration value of 0.5 mg/dm^3 was observed from the defeathering wastewater, while 0.3 mg/dm^3 being the maximum from the cooling section. However, the maximum concentration of manganese from the defeathering wastewater is above the 0.05 mg/dm^3 limit set by the WHO for drinking water standards. The average concentration of manganese in the defeathering wastewater is 6 times higher than the WHO guideline, as well as 4 times higher in the cooling wastewater. After the treatment, a minimum concentration of 0.02 mg/dm^3 was achieved for all the three mixing ratios. The highest maximum value of 0.49 mg/dm^3 was obtained from the 50:50 mixing ratio. Still, the average manganese concentration in the treated effluent is 2 times higher than the WHO guideline from 20:80 (defeathering:cooling) ratio, as well as 3.8 and 2.6 from 50:50 and 80:20, respectively. Manganese toxicity upon overexposure to humans can lead to diverse effects including permanent neurological disorder (manganism) associated with several symptoms such as tremors, difficulty walking, as well as facial muscle spasms [56].

The average chromium concentration in defeathering wastewater was 1.2 mg/dm^3, while in cooling wastewater was 1.7 mg/dm^3. After treatment, average chromium concentrations of 0.29 mg/dm^3, 0.19 mg/dm^3 and 0.23 mg/dm^3 were achieved from 20:80, 50:50, and 80:20 (defeathering:cooling) mixing ratios, respectively. On average, more than 90% removal efficiency was achieved from all the three mixing ratios. However, the remaining concentrations in the treated were not sufficient enough to comply with the guidelines set by the government of Kazakhstan and WHO. Moreover, drinking water supplies in many parts of the world contain chromium in the oxidation states of +3 and +6. However, the biggest concerns for public health are focused on the presence of hexavalent Cr. The hexavalent Cr is classified as a known human carcinogen through inhalation. Sources of Cr (VI) can range from anthropogenic to natural sources and characterized by high environmental mobility [57].

Iron also makes in the list of PTEs, which is mainly present in water in either soluble ferrous iron or the insoluble ferric iron. From the treated effluent, the minimum total iron concentration values ranged from 0.01 mg/dm^3 to 0.04 mg/dm^3, while the maximum values ranged from 0.04 mg/dm^3 to 0.16 mg/dm^3. Average concentrations ranged from 0.03 mg/dm^3 to 0.07 mg/dm^3. On average, more than 94% removal efficiency was achieved for total iron from all the three mixing ratios. Also, the average concentrations of total iron in the treated effluent were observed to be complying with the guidelines set by the government of Kazakhstan and WHO. Normally, water that contains ferrous iron is observed to be clear and colorless since iron is completely dissolved. According to the WHO, iron concentrations of 1 to 3 mg/dm^3 can be acceptable for people drinking anaerobic well-water. However, no health-based guideline value for iron is proposed [58].

Nickel is another element in the PTEs group in this study, which is a metal of widespread distribution in the environment [59]. According to the average concentrations, very little difference in terms of concentration was observed between wastewater from defeathering and the one from the cooling process; where a similar phenomenon was also reflected in the mixing ratios. An average concentration of 0.43 mg/dm^3 of nickel was achieved from the 80:20 purified water, which is also the lowest average concentration value among the three mixing ratios. Although more than 95% removal efficiency was achieved from all the three mixing ratios, on average, the average concentrations of nickel in the treated effluent were not sufficient enough in terms of compliance with both the Kazakhstan and WHO guidelines.

Some reports have shown that short-term exposures to high aluminum levels in drinking water results in clinical diagnoses of dementia [60]. The average concentration of aluminum in the defeathering wastewater was 3.0 mg/dm^3, while that cooling wastewater was 4.3 mg/dm^3. However, the recommended guideline for aluminum in drinking water according to Kazakhstan is 0.5 mg/dm^3. This means, on average, the defeathering process generates wastewater with aluminum concentration 6 times higher than the recommended guideline, as well as 8.6 times higher from the cooling processes. After the treatment, high removal efficiency was observed, with average concentrations ranging from 0.02 to 0.03 mg/dm^3 of aluminum. The achieved removal efficiency is equivalent to drinking water quality compliance ranging 94–96% according to the guidelines set by the government of Kazakhstan.

In general, the PTEs did not show significant variations in terms of concentration between the samples collected from defeathering and cooling processes. The phenomenon also affected the sensitivity of the mixing ratios as reflected in the analysis results of the treated effluent. Except for total iron and aluminum, there was a little challenge in the removal of manganese, nickel, and chromium to the required level as recommended by the government of Kazakhstan and WHO. However, it should also be noted that an operating scale may have a significant influence on the general performance of a treatment system [61].

3.2. *Physicochemical Parameters Compliance with Drinking Water Standards*

The compliance of the physicochemical parameters to the guidelines set by the government of Kazakhstan and WHO for drinking water suitability was computed and the results are summarized in Table 8 as well as in Figures 4 and 5. The highest percent compliance of 99.89% is observed from TSS under 20:80 mixing ratio referring to the guidelines set by the government of Kazakhstan, while the lowest compliance value being −1840% from chromium under 50:50 mixing ratios with 0.05 mg/dm^3 being the guideline as recommended by the WHO. The percent compliance of turbidity, color, and TSS can be observed to be decreasing with the increase in the ratio of defeathering wastewater. From Figure 7, it can be observed that most of the minimum recorded concentration values are within the positive region. Also, Figure 8 shows that some of the recorded maximum values are within the positive region, with an interpretation of being within the recommended guidelines. The negative values in the percent compliance indicate that the concentration values of the parameters exceeded the recommended limit.

Table 8. Percent compliance with WHO standards (average concentrations).

Parameter	Guideline		Percent Compliance (%)					
			D:C (20:80)		D:C (50:50)		D:C (80:20)	
	KZ	WHO	KZ	WHO	KZ	WHO	KZ	WHO
Turbidity	1.50	5.00	95.33	98.60	82.00	94.60	70.67	91.20
Color	20.00	5.00	38.65	−145.40	−32.50	−430.00	−39.50	−458.00
TSS	500.00	-	99.89	-	99.63	-	99.29	-
Free chlorine	0.50	1.50	98.00	99.33	98.00	99.33	98.00	99.33
Total chlorine	1.20	-	98.33	-	99.17	-	99.17	-
Nitrite	3.00	3.00	99.33	99.33	99.00	99.00	99.00	99.00
Nitrate	45.00	50.00	96.09	96.48	99.60	99.64	95.91	96.32
Total phosphorous	3.50	-	98.29	-	77.43	-	77.71	-
Ammonium	0.50	-	−100.00	-	38.00	-	−264.00	-
Total iron	0.30	0.10	76.67	30.00	90.00	70.00	90.00	70.00
Aluminum	0.50	0.10	96.00	80.00	94.00	70.00	94.00	70.00
Manganese	0.10	0.05	0.00	−100.00	−90.00	−280.00	−30.00	−160.00
Nickel	0.10	0.07	−490.00	−1485.71	−410.00	−628.57	−330.00	−1771.43
Chromium	0.10	0.05	−190.00	−480.00	−90.00	−1840.00	−130.00	−520.00

KZ = drinking water quality guidelines set by the government of Kazakhstan; D = defeathering; C = cooling; turbidity in NTU, color in degree, all other parameters in mg/dm^3.

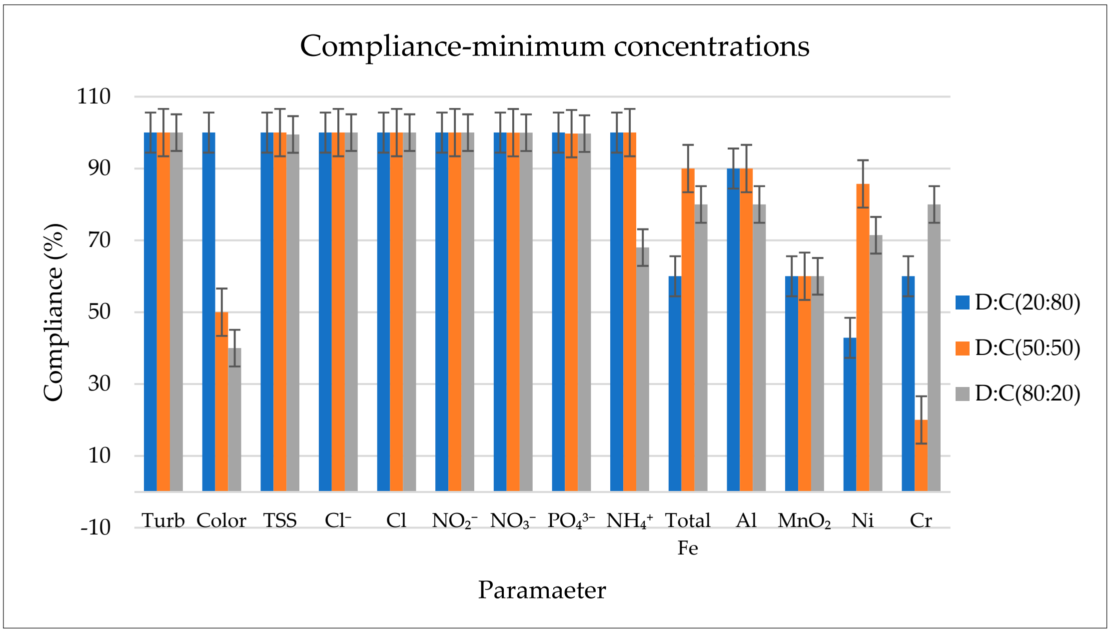

Figure 7. Percent compliance from minimum concentrations (D = defeathering; C = cooling). TSS, total chlorine, total phosphorous, and ammonium according to the Kazakhstan guidelines, all other parameters according to WHO guidelines.

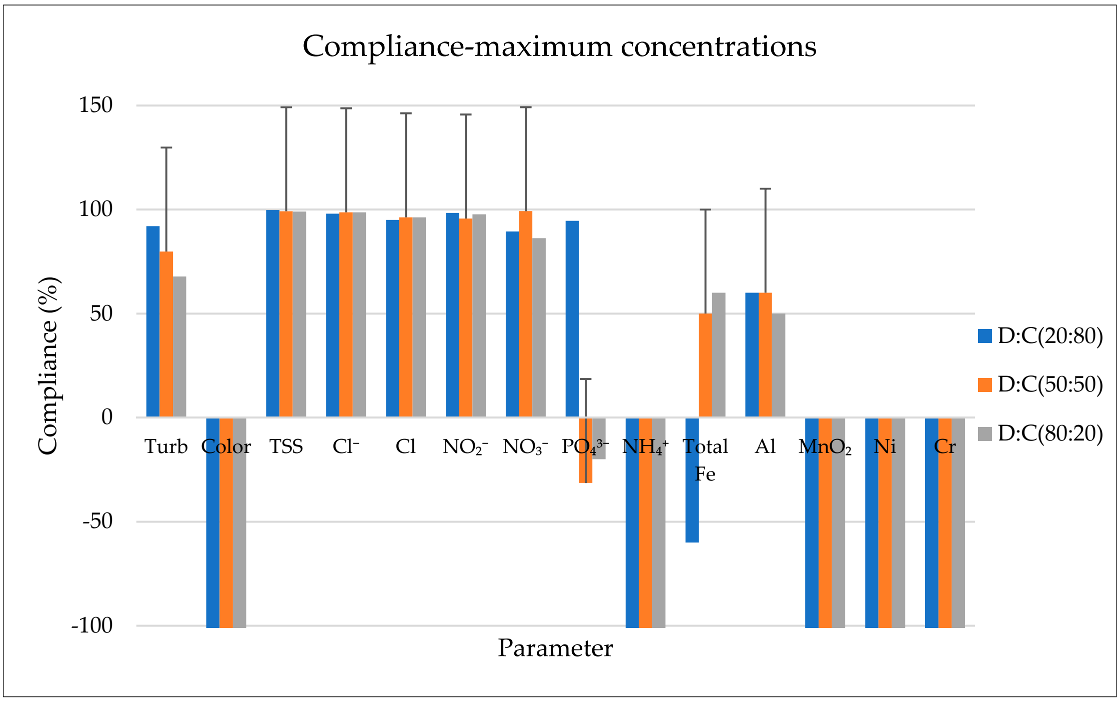

Figure 8. Percent compliance from maximum concentrations (D = defeathering; C = cooling). TSS, total chlorine, total phosphorous, and ammonium according to Kazakhstan guidelines, all other parameters according to WHO guidelines.

3.3. WQI

WQIs from each of the studied mixing ratios were successfully developed based on drinking water quality standards (Tables 9–11). The 20:80 (defeathering:cooling) mixing ratio presented the highest water quality with 26 as an aggregated WQI value (see Table 8). From the 50:50 mixing ratio, WQI of 27.88 was achieved (see Table 9), while 43.09 was achieved from 80:20 (defeathering:cooling) mixing ratio (see Table 10). Being below 50, the WQIs from all the three mixing ratios fall under the "excellent" water quality status. Despite the total coliform having the highest weight in the list, it had 0 SI_i for all the three mixing ratios, and an average of 100% removal efficiency was achieved from the treated effluent. From Table 9 to Table 11, it can be observed that 57.9% of the general WQI from 20:80 (defeathering:cooling) mixing ratio was contributed by ammonium. High ammonium contributions are also observed from 50:50 and 80:20 (defeathering:cooling) mixing ratios, respectively. The phenomenon is highly linked to the fact that ammonium had the lowest percent compliance among the parameters included in the WQIs development.

Table 9. Water quality indices (WQIs) results for 20:80 (defeathering:cooling) mixing ratio.

Parameter	W_i	q_i	SI_i
Turbidity	0.06	0.17	0.01
Color	0.06	61.33	3.83
TSS	0.06	1.33	0.08
Free chlorine	0.08	2.00	0.16
Total chlorine	0.08	2.00	0.16
Nitrite	0.08	0.63	0.05
Nitrate	0.08	3.90	0.30
Total phosphorous	0.06	1.45	0.09
Ammonium	0.06	240.72	15.05
Total iron	0.06	53.33	3.33
Aluminum	0.06	18.59	1.16
COD	0.08	17.76	1.39
BOD	0.08	4.97	0.39
Total coliform (100 mL)	0.09	0.00	0.00
Total	1.00		26.00

Table 10. WQI results for 50:50 (defeathering:cooling) mixing ratio.

Parameter	W_i	q_i	SI_i
Turbidity	0.06	9.27	0.58
Color	0.06	53.25	3.33
TSS	0.06	19.35	1.21
Free chlorine	0.08	24.33	1.90
Total chlorine	0.08	159.11	12.43
Nitrite	0.08	2.15	0.17
Nitrate	0.08	7.14	0.56
Total phosphorous	0.06	34.29	2.14
Ammonium	0.06	160.00	10.00
Total iron	0.06	13.24	0.83
Aluminum	0.06	150.00	9.38
COD	0.08	6.40	0.50
BOD	0.08	2.40	0.19
Total coliform (100 mL)	0.09	0.00	0.00
Total	1.00		27.88

3.4. Microbial Parameters

In this study, the total number of bacteria (TNB), total coliform bacteria (TCB), thermo-tolerant coliform bacteria (TTCB), Pseudomonas aeruginosa, as well as pathogenic flora, including Salmonella and Enterococcus faecalis indicators were studied. Unlike the physicochemical parameters, the treatment plant achieved an average of 100% microbial removal efficiency from all the three mixing ratios. Several factors may have influenced the impressive performance of the treatment plant in terms of microbial removal, including the fact that each of the sub-units within the integrated treatment plant can eliminate some microbes in the wastewater. During the electrolysis process, microbes are killed by a variety of oxidants that are produced within the process [62]. Depending on the filter pore size, some microorganisms are also retained from the membrane filtration process [63], as well as the UV disinfection unit, which is mainly for the microbes elimination. From the results, it is further revealed that the treatment approach is highly efficient for microbial elimination in the poultry slaughterhouse wastewater.

Table 11. WQI results 80:20 (defeathering:cooling) mixing ratio.

Parameter	W_i	q_i	SI_i
Turbidity	0.06	28.47	1.78
Color	0.06	84.83	5.30
TSS	0.06	31.91	1.99
Free chlorine	0.08	31.53	2.46
Total chlorine	0.08	100.00	7.81
Nitrite	0.08	1.33	0.10
Nitrate	0.08	4.09	0.32
Total phosphorous	0.06	71.43	4.46
Ammonium	0.06	320.00	20.00
Total iron	0.06	25.38	1.59
Aluminum	0.06	18.59	1.16
COD	0.08	6.01	0.47
BOD	0.08	13.21	1.03
Total coliform (100 mL)	0.09	0.00	0.00
Total	1.00		43.09

4. Conclusions

The potential influence of mixing ratios on the performance of an integrated treatment system subjected to a poultry slaughterhouse wastewater under three different mixing ratios; 20:80, 50:50, and 80:20 (defeathering:cooling) for a high-quality recyclable wastewater effluent has been studied. The wastewater samples collected from the defeathering and cooling sections of the Izhevski PC poultry farm in Kazakhstan were treated using the lab-scale treatment plant. The traditional and WQI-based techniques were used to evaluate the quality of treated effluent. From the analysis results, it was observed that the mixing ratios affected the performance of the treatment plant for some physicochemical parameters. Quality of the treated effluent decreased with the increase in defeathering wastewater ratio; mainly for parameters such as turbidity, TSS, color, BOD, as well as COD. The phenomenon was also reflected in the percent compliance under the guidelines set by the government of Kazakhstan, and WHO. However, 100% removal efficiency was achieved from all the studied microbiological parameters under the three mixing ratios. In the group of PTEs, little differences in terms of concentrations were observed between the defeathering and cooling raw wastewater, which in turn affected the sensitivity of the mixing ratios in the treated effluent for the particular parameters. Moreover, despite the quality deterioration when the ratio of the defeathering wastewater increased, the integrated treatment plant was able to produce impressive results as characterized by the computed WQIs. Generally, the highest quality effluent was achieved from the 20:80 (defeathering:cooling) mixing ratio. However, with the fact that all the three mixing ratios produced "excellent" status based on the WQIs, the 80:20 (defeathering:cooling) mixing ratio stands to be an ideal option. The selection of 80:20 mixing ratio has the potential to reduce the pollution load in the wastewater discharged to the sewerage system, while achieving high-quality effluent for recycling in the cooling processes of the slaughterhouse.

Author Contributions: Conceptualization, K.M.; methodology, K.M., and T.M.; software, D.O., A.K., K.A., and E.T.; validation, E.T., K.A., and S.A.; formal analysis, A.K.; investigation, resources, and data curation, K.M., K.A., S.A., K.N., G.S., and T.M.; writing—original draft preparation, T.M.; writing—review and editing, K.M., A.K., G.S.,

and T.M.; visualization, K.N., E.T., and D.O.; supervision, project administration, and funding acquisition, K.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Education and Science, the Republic of Kazakhstan to support "Reducing the technogenic impact on water resources with using water recycling technology", № BR05236844 /215 for 2018–2020 years.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Meiramkulova, K.; Userbayev, M.; Aubakirova, K.; Saiyabayev, K.; Suleimenova, B. Electrochemical treatment of poultry industry wastewater. *Int. J. Mech. Eng. Technol.* **2018**, *9*, 1285–1293.
2. Avula, R.Y.; Nelson, H.M.; Singh, R.K. Recycling of poultry process wastewater by ultrafiltration. *Innov. Food Sci. Emerg. Technol.* **2009**, *10*, 1–8. [CrossRef]
3. Rajakumar, R.; Meenambal, T.; Banu, J.R.; Yeom, I.T. Treatment of poultry slaughterhouse wastewater in upflow anaerobic filter under low upflow velocity. *Int. J. Environ. Sci. Technol.* **2011**, *8*, 149–158. [CrossRef]
4. De Nardi, I.R.; Del Nery, V.; Amorim, A.K.B.; dos Santos, N.G.; Chimenes, F. Performances of SBR, chemical–DAF and UV disinfection for poultry slaughterhouse wastewater reclamation. *Desalination* **2011**, *269*, 184–189. [CrossRef]
5. Yetilmezsoy, K.; Sakar, S. Improvement of COD and color removal from UASB treated poultry manure wastewater using Fenton's oxidation. *J. Hazard. Mater.* **2008**, *151*, 547–558. [CrossRef] [PubMed]
6. Coskun, T.; Debik, E.; Kabuk, H.A.; Manav Demir, N.; Basturk, I.; Yildirim, B.; Temizel, D.; Kucuk, S. Treatment of poultry slaughterhouse wastewater using a membrane process, water reuse, and economic analysis. *Desalin. Water Treat.* **2016**, *57*, 4944–4951. [CrossRef]
7. Gomes, A.J.G.; Atambo, D.O.; Das, K.K.; Cocke, D.L.; Das, K.P. Electrochemical remediation of chicken processing plant wastewater. *J. Environ. Chem. Eng.* **2018**, *6*, 6028–6036. [CrossRef]
8. Wang, M.; Cao, W.; Wu, Y.; Zhou, H.; Li, B.; Lu, H. Electrochemical disinfection of effluents from poultry waste anaerobic digestion. *Environ. Eng. Manag. J.* **2017**, *16*, 329–335.
9. Paulista, L.O.; Presumido, P.H.; Theodoro, J.D.P.; Pinheiro, A.L.N. Efficiency analysis of the electrocoagulation and electroflotation treatment of poultry slaughterhouse wastewater using aluminum and graphite anodes. *Environ. Sci. Pollut. Res.* **2018**, *25*, 19790–19800. [CrossRef]
10. Debik, E.; Coskun, T. Use of the Static Granular Bed Reactor (SGBR) with anaerobic sludge to treat poultry slaughterhouse wastewater and kinetic modeling. *Bioresour. Technol.* **2009**, *100*, 2777–2782. [CrossRef]
11. Rajakumar, R.; Meenambal, T.; Saravanan, P.M.; Ananthanarayanan, P. Treatment of poultry slaughterhouse wastewater in hybrid upflow anaerobic sludge blanket reactor packed with pleated poly vinyl chloride rings. *Bioresour. Technol.* **2012**, *103*, 116–122. [CrossRef]
12. Nur Hazirah, R.; Nurhaslina, C.R.; Ku Halim, K.H. Enhancement of biological approach and potential of Lactobacillus delbrueckii in decolorization of textile wastewater—A review. *IOSR J. Environ. Sci. Toxicol. Food Technol.* **2014**, *8*, 6–10. [CrossRef]
13. Mickova, I. Advanced Electrochemical Technologies in Wastewater Treatment Part I: Electrocoagulation. *Am. Sci. Res. J. Eng. Technol. Sci.* **2015**, *14*, 233–257.
14. Muddemann, T.; Haupt, D.; Sievers, M.; Kunz, U. Electrochemical Reactors for Wastewater Treatment. *ChemBioEng Rev.* **2019**, *6*, 142–156. [CrossRef]
15. Woisetschläger, D.; Humpl, B.; Koncar, M.; Siebenhofer, M. Electrochemical oxidation of wastewater—Opportunities and drawbacks. *Water Sci. Technol.* **2013**, *68*, 1173–1179. [CrossRef] [PubMed]
16. Basitere, M.; Rinquest, Z.; Njoya, M.; Sheldon, M.S.; Ntwampe, S.K.O. Treatment of poultry slaughterhouse wastewater using a static granular bed reactor (SGBR) coupled with ultrafiltration (UF) membrane system. *Water Sci. Technol.* **2017**, *76*, 106–114. [CrossRef] [PubMed]
17. Ngadi, M.; Jun, X.; Smith, J.; Raghavan, G.S.V. Inactivation of Escherichia coli O157:H7 in Poultry Chiller Water Using Combined Ultraviolet Light, Pulsed Electric Field and Ozone Treatments. *Int. J. Poult. Sci.* **2004**, *3*, 733–737.
18. Ikeda, E.; Rodrigues, D.G.; Nozaki, J. Treatment of Effluents of Poultry Slaughterhouse with Aluminum Salts and Natural Polyelectrolytes. *Environ. Technol.* **2002**, *23*, 949–954. [CrossRef]

19. Melin, T.; Jefferson, B.; Bixio, D.; Thoeye, C.; De Wilde, W.; De Koning, J.; van der Graaf, J.; Wintgens, T. Membrane bioreactor technology for wastewater treatment and reuse. *Desalination* **2006**, *187*, 271–282. [CrossRef]
20. Zoulias, E.; Varkaraki, E. A review on water electrolysis. *Tcjst* **2004**, *4*, 41–71.
21. Cerqueira, A.; Russo, C.; Marques, M.R.C. Electroflocculation for textile wastewater treatment. *Braz. J. Chem. Eng.* **2009**, *26*, 659–668. [CrossRef]
22. Meiramkulova, K.; Jakupova, Z.; Orynbekov, D.; Tashenov, E.; Kydyrbekova, A.; Mkilima, T.; Inglezakis, V.J. Evaluation of Electrochemical Methods for Poultry Slaughterhouse Wastewater Treatment. *Sustainability* **2020**, *12*, 5110. [CrossRef]
23. Yousefi, Z.; Sahebian, H.; Amouei, A.; Mohammadpour, R.A.; Zarei, E. Process performance with DC current in treatment of poultry slaughterhouse wastewater using aluminum electrodes. *J. Maz. Univ. Med. Sci.* **2019**, *29*, 53–66.
24. Zarei, A.; Biglari, H.; Mobini, M.; Dargahi, A.; Ebrahimzadeh, G.; Narooie, M.; Mehrizi, E.; Yari, A.; Mohammadi, M.J.; Baneshi, M.M.; et al. Disinfecting Poultry Slaughterhouse Wastewater Using Copper Electrodes in the Electrocoagulation Process. *Pol. J. Environ. Stud.* **2018**, *27*, 1907–1912. [CrossRef]
25. Bayar, S.; Yildiz, Y.; Yilmaz, A.; Koparal, A.S. The effect of initial pH on treatment of poultry slaughterhouse wastewater by electrocoagulation method. *Desalin. Water Treat.* **2014**, *52*, 3047–3053. [CrossRef]
26. Minnesota Rural Water Association. Chapter19: Membrane Filtration. In *Minnesota Water Work*; Minnesota Rural Water Association: Elbow Lake, MN, USA, 2001.
27. Clancy, J.L.; Bukhari, Z.; Hargy, T.M.; Bolton, J.R.; Dussert, B.W.; Marshall, M.M. Using UV to inactivate Cryptosporidium. *J. Am. Water Works Assoc.* **2000**, *92*, 97–104. [CrossRef]
28. Gray, N.F. Ultraviolet Disinfection. In *Microbiology of Waterborne Diseases: Microbiological Aspects and Risks*, 2nd ed.; Academic Press: Cambridge, MA, USA, 2014; ISBN 9780124158467.
29. Diaz, M.E.; Law, S.E.; Birt, D.M. Microbiological Benefits of Removing Foam Formed After UV-Enhanced Ozonation of Poultry-Processing Chiller Water for Recycling. *J. Food Sci.* **2002**, *67*, 1036–1042. [CrossRef]
30. Angelakis, A.; Gikas, P. Water reuse: Overview of current practices and trends in the world with emphasis on EU states. *Water Util. J.* **2014**, *8*, e78.
31. Bixio, D.; Thoeye, C.; De Koning, J.; Joksimovic, D.; Savic, D.; Wintgens, T.; Melin, T. Wastewater reuse in Europe. *Desalination* **2006**, *187*, 89–101. [CrossRef]
32. Salgot, M. Water reclamation, recycling and reuse: Implementation issues. *Desalination* **2008**, *218*, 190–197. [CrossRef]
33. Kaiyrbayeva, A.; Kalykova, B.; Nurmanbekova, G.; Kaiyrbayeva, A.; Rakhimzhanova, G. Agro-industrial formations as economic agents: The influence of education on the economic performance of the agro-industrial enterprise. *J. Entrep. Educ.* **2018**, *21*, 1–8.
34. Stabler, M.J.; Goodall, B. Environmental awareness, action and performance in the Guernsey hospitality sector. *Tour. Manag.* **1997**, *18*, 19–33. [CrossRef]
35. Stern, P.C.; Dietz, T.; Black, J.S. Support for environmental protection: The role of moral norms. *Popul. Environ.* **1985**, *8*, 204–222. [CrossRef]
36. Palmer, M.; States, U.; Protection, E.; Lakes, G.; Program, N. Standard Operating Procedure for GLNPO Total Alkalinity Titration. United States Environmental Protection Agency: Chicago, IL, USA, 1992; pp. 5–10.
37. Walter, W.G. STANDARD METHODS FOR THE EXAMINATION OF WATER AND WASTEWATER (11th ed.). *Am. J. Public Health Nations Health* **1961**, *51*, 940. [CrossRef]
38. Lalanne, J.-R.; Carmona, F.; Servant, L. *UV-Visible Absorption Spectroscopy*; World Scientific Pub: Singapure, 1999; Volume 17, pp. 117–217.
39. Mulvany, J.G. Chapter VII Membrane Filter Techniques in Microbiology. *Methods Microbiol.* **1969**, *1*, 205–253.
40. American Public Health Association (APHA). Standard Methods for the Examination of Water & Wastewater 21st Edition. Washington, DC, USA, 2005. Available online: http://www.who.int/water_sanitation_health/dwq/che (accessed on 12 May 2020).
41. Tyuryaev, A.; Nikolayenko, A.; Mirkhashimov, I. *Water Quality Standards and Norms in the Republic of Kazakhstan*; CAWater-Info: Almaty, CA, USA, 2009; ISBN 9965659907.
42. Pesce, S.F.; Wunderlin, D.A. Use of water quality indices to verify the impact of Cordoba City (Argentina) on Suquia River. *Water Res.* **2000**, *34*, 2915–2926. [CrossRef]

43. Bhatnagar, A.; Devi, P.; George, M.P. Impact of mass bathing and religious activities on water quality index of prominent water bodies: A multilocation study in Haryana, India. *Int. J. Ecol.* **2016**, *2016*, 1–8. [CrossRef]
44. Alobaidy, A.H.M.J.; Abid, H.S.; Maulood, B.K. Application of Water Quality Index for Assessment of Dokan Lake Ecosystem, Kurdistan Region, Iraq. *J. Water Resour. Prot.* **2010**, *2*, 792–798. [CrossRef]
45. Kiepper, B. Characterisation of Poultry Processing Operations, Wastewater Generation and Wastewater Treatment. Ph.D. Thesis, University of Georgia, Athens, GA, USA, 2003; pp. 1–141.
46. Md, S.; Md.AI, C.; Haque, M.M.; Haque, M.E. Using Turbidity to Determine Total Suspended Solids in an Urban Stream: A Case Study. *Int. J. Eng. Trends Technol.* **2019**, *67*, 83–88. [CrossRef]
47. Pala, A. Color removal from cotton textile industry wastewater in an activated sludge system with various additives. *Water Res.* **2002**, *36*, 2920–2925. [CrossRef]
48. Hannouche, A.; Chebbo, G.; Ruban, G.; Tassin, B.; Lemaire, B.J.; Joannis, C. Relationship between turbidity and total suspended solids concentration within a combined sewer system. *Water Sci. Technol.* **2011**, *64*, 2445–2452. [CrossRef]
49. Nikoonahad, A.; Ebrahimi, A.A. Evaluation the Correlation between Turbidity and Total Suspended Solids with other Chemical Parameters in Yazd Wastewater Treatment Effluent Plant. *J. Environ. Health Sustain. Dev.* **2016**, *1*, 66–74.
50. Fan, A.M. Nitrate. In *Encyclopedia of Toxicology*, 3rd ed.; Elsevier: Amsterdam, The Netherlands, 2014; ISBN 9780123864543.
51. van Faassen, E.; Vanin, A.F.; Slama-Schwok, A. Nitrite as endothelial NO donor under anoxia. In *Radicals for Life*; Elsevier: Amsterdam, The Netherlands, 2007; pp. 291–312. ISBN 9780444522368.
52. Ferreiro, C.; Gómez-Motos, I.; Lombraña, J.I.; de Luis, A.; Villota, N.; Ros, O.; Etxebarria, N. Contaminants of Emerging Concern Removal in an Effluent of Wastewater Treatment Plant under Biological and Continuous Mode Ultrafiltration Treatment. *Sustainability* **2020**, *12*, 725. [CrossRef]
53. World Health Organization (WHO). Ammonia in Drinking-water. *San Fr.* **2003**, *2*. Available online: http://www.who.int/water_sanitation_health/dwq/che (accessed on 14 May 2020).
54. Eggenkamp, H. Chlorine. In *Advances in Isotope Geochemistry*; Springer: Berlin, Germany, 2014; pp. 15–19.
55. Atamaleki, A.; Sadani, M.; Raoofi, A.; Miri, A.; Bajestani, S.G.; Fakhri, Y.; Heidarinejad, Z.; Mousavi Khaneghah, A. The concentration of potentially toxic elements (PTEs) in eggs: A global systematic review, meta-analysis and probabilistic health risk assessment. *Trends Food Sci. Technol.* **2020**, *95*, 1–9. [CrossRef]
56. O'Neal, S.L.; Zheng, W. Manganese Toxicity Upon Overexposure: A Decade in Review. *Curr. Environ. Health Rep.* **2015**, *2*, 315–328. [CrossRef] [PubMed]
57. Zhitkovich, A. Chromium in drinking water: Sources, metabolism, and cancer risks. *Chem. Res. Toxicol.* **2011**, *24*, 1617–1629. [CrossRef]
58. World Health Organization. Iron in drinking-water. In *WHO Guidelines for Drinking-Water Quality*; Who/Sde/Wsh/03.04/08; World Health Organization: Geneva, Switzerland, 2003.
59. Cempel, M.; Nikel, G. Nickel: A review of its sources and environmental toxicology. *Pol. J. Environ. Stud.* **2006**, *15*, 375–382.
60. Wisconsin Department of Health Services State of Wisconsin. *Aluminum in Drinking Water*; Wisconsin Department of Health Services State of Wisconsin: Madison, WI, USA, 2011; pp. 1–2.
61. Meiramkulova, K.; Zorpas, A.A.; Orynbekov, D.; Zhumagulov, M.; Saspugayeva, G.; Kydyrbekova, A.; Mkilima, T.; Inglezakis, V.J. The Effect of Scale on the Performance of an Integrated Poultry Slaughterhouse Wastewater Treatment Process. *Sustainability* **2020**, *12*, 4679. [CrossRef]
62. Huang, X.; Qu, Y.; Cid, C.A.; Finke, C.; Hoffmann, M.R.; Lim, K.; Jiang, S.C. Electrochemical disinfection of toilet wastewater using wastewater electrolysis cell. *Water Res.* **2016**, *92*, 164–172. [CrossRef]
63. Bobbitt, J.A.; Betts, R.P. The removal of bacteria from solutions by membrane filtration. *J. Microbiol. Methods* **1992**, *16*, 215–220. [CrossRef]

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. 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/).