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Evaluation of Multi-Stage Treatment Processes for Wastewater Containing Compounds Derived from Coffee Processing

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Highlights

- An integrated treatment train for coffee-related wastewater was systematically evaluated.
- Synergistic effects enhanced the performance of sequential treatment processes.
- Selected HRT and ozone time improved overall treatment efficiency.
- High removal of turbidity, TOC, and ammonium nitrogen was achieved.
- The treatment concept supports sustainable industrial wastewater management.

Abstract

Growing demand for water resources and the need to reduce wastewater discharge are driving the development of integrated treatment technologies, particularly in the coffee processing sector, where wastewater has a high organic pollutant load and contains compounds that are difficult to biodegrade. The research aimed to evaluate the effectiveness of an integrated, multi-stage treatment system for synthetic wastewater containing coffee bean extract as a model contaminant. The system included biological treatment, activated carbon sorption, membrane filtration, and two-stage disinfection using ozonation and UV-C radiation. The effectiveness of removing selected pollution indicators, interactions between successive processes, and the impact of operating parameters on system efficiency were evaluated. The best results were obtained for variant D8, involving alternating aeration and mixing phases and an HRT of 8 days. Turbidity removal reached 97.0%, TOC removal 90.2%, and ammonium nitrogen removal 58.8%, with a final pH of 7.05 and complete elimination of microorganisms. The use of 30 min ozonation and 15 min UV-C irradiation ensured effective disinfection. The results indicate the potential of the developed system for industrial wastewater treatment and water recovery; however, further research using actual coffee industry wastewater is necessary, including refinement of process parameters and assessment of energy, economic, and environmental efficiency.

Keywords: coffee wastewater; biological treatment; activated carbon; membrane filtration; disinfection; wastewater treatment

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1. Introduction

Water and wastewater management in industry requires solutions aimed at reducing water consumption and effectively treating the resulting wastewater. According to data from the Central Statistical Office, the volume of industrial wastewater discharged in Poland decreased from 8.04 billion m^3 in 2010 to 6.51 billion m^3 in 2021 [1,2]. These data indicate a downward trend, which can be attributed to reduced water consumption as well as the modernization and optimization of technological processes. Despite this decline, the quality

of discharged wastewater remains a significant issue, as it depends on its composition and the effectiveness of the treatment processes used. These trends should also be considered in the context of changes in the structure of the economy and the gradual implementation of solutions aimed at more rational water resource management [3].

In the food industry, the selection of technologies appropriate to the specific characteristics of raw materials and production processes is of particular importance [4]. The evaluation of such solutions should be based on both the effectiveness of contaminant removal and the quality of the final effluent. It is therefore important to consider the possibility of combining processes that complement each other and allow for the removal of contaminants with different properties [5,6]. This approach can also support water recovery, provided that the quality meets the requirements of the intended use. Reducing the volume of discharged wastewater should therefore go hand in hand with efforts to improve wastewater treatment and ensure the rational use of water resources.

Regulatory changes at the European Union level also influence the development of water and wastewater management [7]. Directive (EU) 2024/3019 of the European Parliament and of the Council expands requirements regarding wastewater treatment, water reuse, and energy recovery, and supports the implementation of circular economy principles. It also addresses the control of industrial wastewater discharged into municipal wastewater systems, emphasizing the importance of selecting appropriate pre-treatment methods. Changes in legal regulations are therefore a significant factor stimulating the development of the water and wastewater management sector in industry. They promote the modernization of existing facilities and the implementation of more effective treatment technologies [7–9].

One of the sectors of the food industry that generates wastewater is coffee processing. Wastewater is produced both during the wet processing of coffee fruit and during the processing of roasted coffee, including the production of instant coffee. These are distinct streams, and their characteristics must be considered in relation to the production technology used [10]. It is estimated that in 2016, global coffee production generated approximately 16.6 billion liters of wastewater. Depending on the technology used, the production of 1 kg of green coffee consumes between 1 and 15 L of water, while washing and processing generate between 20 and as much as 45 L of wastewater per kilogram of raw material [11,12]. The scale of water consumption and the volume of wastewater generated indicate that coffee processing poses a significant challenge in terms of reducing environmental impact. For this reason, it is crucial to seek solutions that enable the efficient management of water resources [13,14].

Coffee wastewater can contain significant levels of organic pollutants. Depending on the type of production process and coffee processing method, chemical oxygen demand (COD) values can range from approximately 1185 to 32,459 mg O_2/L, while biological oxygen demand (BOD) values can range from approximately 3450 to 15,200 mg O_2/L [11–13]. The high organic load is often accompanied by an acidic pH of the wastewater, typically in the range of 3.0–5.0, and a significant content of total suspended solids, whose concentration can reach approximately 7000–10,900 mg/L [13,14]. This wastewater also contains biogenic compounds, including nitrogen at concentrations of approximately 37–279 mg/L and phosphorus in the range of 4.4–70 mg/L [13,14]. It may also contain compounds such as caffeine, tannins, pectins, and phenolic compounds, as well as melanoidins and polyphenols, which are responsible for the dark brown color and the increased resistance of some organic matter to biodegradation [13–15]. For example, in wastewater from instant coffee production, a tannin concentration of 333.1 ± 45.4 mg/L was measured, with an average COD of 6124.8 ± 2608.2 mg O_2/L and a BOD of 3397.8 ± 1090.3 mg O_2/L [15]. The complex composition and the presence of substances that are difficult to biodegrade

hinder treatment, while the discharge of untreated wastewater can degrade the quality of surface waters due to the introduction of significant amounts of organic matter, suspended solids, and biogenic compounds [10,13]. For this reason, it is necessary to employ effective treatment methods adapted to the specific properties of this type of wastewater.

The methods used and studied in coffee wastewater treatment include biological processes carried out under aerobic and anaerobic conditions. Among others, lagoons and anaerobic reactors such as UASB (Up-Flow Anaerobic Sludge Blanket) and EGSB (Expanded Granular Sludge Bed) are utilized. The advantages of lagoons include simple operation and relatively low capital costs, while their limitations include significant space requirements and the potential for odor nuisance [16]. Anaerobic reactors allow for the treatment of wastewater with high organic loading, while also enabling biogas production. However, the effectiveness of biological processes depends on maintaining appropriate operating conditions and the adaptation of microorganisms. Their performance can be disrupted by variations in wastewater composition, acidic pH, and the presence of substances that inhibit biomass activity [16,17].

Among the physicochemical methods considered are coagulation and flocculation, electrocoagulation, and adsorption. Coagulation and flocculation make it possible to reduce the content of suspended solids and some colored substances, but they do not ensure the complete decomposition of complex organic compounds. Electrocoagulation can aid in the removal of color and organic pollutants; however, it requires a supply of electricity, and its effectiveness may be limited by electrode passivation, which restricts further current flow. Adsorption on activated carbon or plant-based materials allows for the removal of some of the compounds remaining in the wastewater, but involves the costs of preparing the sorbent and the need to manage the spent material [16,17].

Membrane processes and advanced oxidation complement these solutions. Membrane separation enables the further treatment of wastewater; however, it retains contaminants without breaking them down, and its operation is hampered by fouling and membrane blockage. In turn, processes utilizing ozone, hydrogen peroxide, or the Fenton reaction can aid in the degradation of poorly biodegradable organic compounds and the removal of color. Their limitations include the costs of reagents and energy, as well as the need to carefully select the appropriate process conditions [12,16].

The limitations of individual methods justify the development of integrated coffee wastewater treatment technologies that combine biological processes with physicochemical methods. This approach allows for leveraging the advantages of individual processes at successive treatment stages, thereby increasing the efficiency of removing various types of pollutants [12,18].

An example of such solutions is the combination of an anaerobic partitioned reactor with microfiltration, which reduces the organic matter content and retains suspended solids. More complex configurations include biological treatment, ultrafiltration, and reverse osmosis, which enable the additional removal of dissolved substances. The selection of individual stages should take into account the composition of the wastewater, process operating conditions, and the required effluent quality, which depends on the planned method of discharge or reuse [19,20].

The use of integrated technologies can also support the implementation of circular economy (CE) principles, aimed at reducing resource consumption and reusing treated water streams [21,22]. In coffee processing, the recovery and recirculation of process water help reduce the demand for fresh water and the volume of wastewater discharged outside the facility. However, the possibility of partially closing the circle depends on achieving water quality suitable for use in selected stages of the technological process [23].

In light of the challenges outlined regarding the treatment of industrial wastewater, and in particular wastewater generated in the coffee processing sector, the objective of this research was to evaluate the effectiveness of an integrated, multi-stage treatment system for synthetic wastewater containing coffee bean extract, used as a model contaminant characteristic of wastewater generated, among other things, during the extraction of roasted coffee and the washing and cleaning of process equipment used in instant coffee production. The developed process system included, in sequence, biological wastewater treatment, activated carbon sorption, membrane filtration, and two-stage disinfection using ozonation and UV-C radiation.

The research was focused not only on determining the effectiveness of removing selected pollution indicators at individual stages of the process, but also on evaluating the interactions between the unit processes used and identifying the operating parameters that influence the efficiency of the entire integrated system. Particular attention was paid to assessing the extent to which the application of successive treatment stages affects the quality of wastewater directed to subsequent processes, and whether the appropriate combination and sequence of individual methods can increase the overall treatment efficiency and improve the quality of the final treated wastewater stream. An additional objective was to determine the potential of the developed process system in the context of current trends in wastewater treatment technology, which focus on the integration of unit processes, increasing the efficiency of pollutant removal, and the possibility of recovering and reusing treated water.

A key aspect of this research is the evaluation of interactions between individual treatment stages and the importance of their proper sequencing. The results provide insights into the performance of the integrated system and support the development of more efficient industrial wastewater treatment technologies, contributing to improved water management and reduced water consumption in line with circular economy principles.

2. Materials and Methods

The research described in this paper involved an analysis of a multi-stage integrated treatment process for synthetic wastewater containing model pollutants.

In the first stage of the research, synthetic wastewater containing model pollutants underwent biological treatment using the activated sludge process. The next two stages of wastewater treatment following biological treatment were based on physicochemical methods and involved the further removal of key pollutants using activated carbon and a membrane. After selecting the most favorable process conditions during the initial stages of the research, the treated wastewater was subjected to the final stage—disinfection with ozone, followed by UV irradiation. After each stage, a series of laboratory analyses was conducted to evaluate the effectiveness of the individual processes. A simplified diagram of the research is shown in Figure 1.

The methods used in this research were selected because they are well-documented in the scientific literature and frequently employed in engineering practice, both on a laboratory and industrial scale. Numerous experimental studies and technological implementations confirm their high effectiveness in removing organic, biogenic, and microbiological contaminants [8,12–17].

The selection of well-known and thoroughly characterized technological processes made it possible not only to evaluate their effectiveness with respect to the type of wastewater under research, but also to analyze the possibility of integrating them within a single process line. This approach enhances the practical application potential of the proposed solution.

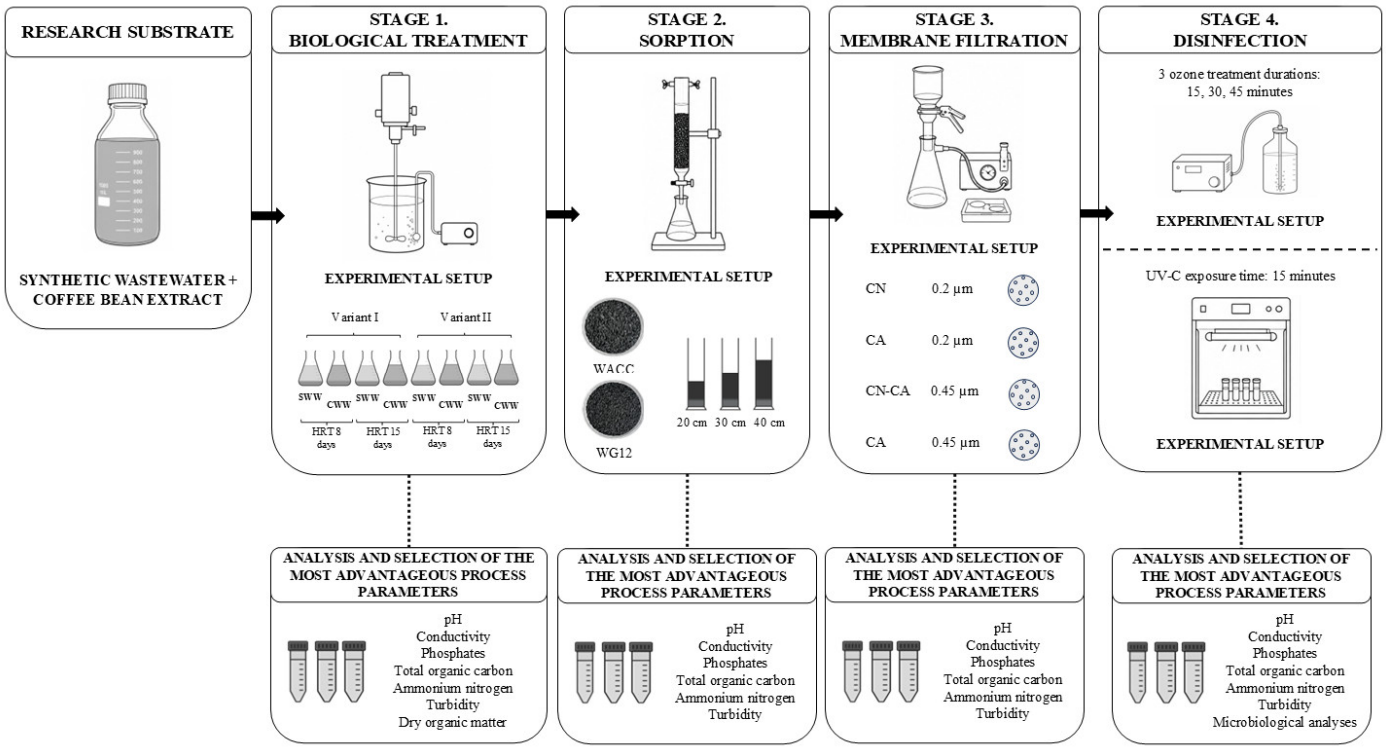


Figure 1. General scheme of the research being conducted (own elaboration).

The Gemini 3 Flash Image model (Google) was used to generate graphical representations of the experimental setups based on original photographs taken by the authors. These photographs served as visual references for creating illustrations included in Figure 1 and Figure 25. The same AI tool was also used to generate selected illustrative elements for the graphical abstract, depicting sources of wastewater containing compounds derived from coffee processing and the associated environmental risks, based on textual descriptions provided by the authors.

2.1. Research Substrate

The research used synthetic wastewater prepared in accordance with the Polish Standard PN-72/C-04550/09, entitled "Determination of the Efficiency of Biochemical Oxidation of Anionic and Non-Ionic Synthetic Surface-Active Agents by the Activated Sludge Method under Kinetic Conditions" [24], supplemented with a model contaminant in the form of a coffee bean extract. The extract was prepared based on the procedure described by Shanmugam and Gummadi [25], using a mixture of Arabica and Robusta coffees in a 60:40 ratio. In this research, a single concentration of coffee bean extract of 1 g/L was used, which was selected as representative of a moderate load in wastewater from the coffee industry. In contrast to previous studies [8], which analyzed the effect of different extract concentrations (1, 10, and 20 g/L) on the efficiency of treatment processes, the aim of this research was to conduct a detailed assessment of the effectiveness of a multi-stage treatment system under constant loading conditions. Using a single concentration helped minimize the impact of variations in wastewater composition on the results and allowed for a more precise analysis of the performance of individual stages of the treatment process. Table 1 presents the general characteristics of freshly prepared synthetic wastewater and synthetic wastewater with model contamination.

Table 1. General characteristics of synthetic wastewater and synthetic wastewater with the addition of coffee extract at a concentration of 1 g/L (own elaboration).

Indicator	Unit	Synthetic Wastewater with Coffee Extract (1 g/L)	Synthetic Wastewater
pH	-	6.31	6.47
Conductivity	µS/cm	254.9	219.2
Turbidity	NTU	18.0	15.4
Phosphates	mg P-PO_4/L	13.34	12.71
Ammonium nitrogen	mg N-NH_4^+/L	8.5	8.4
Total organic carbon	mg C/L	176.2	90.26

Actual wastewater from coffee processing is characterized by significant variability in composition, resulting, among other things, from the type of beans used (Arabica or Robusta), their origin, the processing method employed (dry, wet, or semi-dry), the degree of roasting, and the seasonality of production. In addition, this wastewater may contain varying amounts of phenolic compounds, caffeine, and other substances that could potentially inhibit biological processes. Such a wide range of composition makes it difficult to conduct research under controlled conditions and to interpret the results unambiguously [26,27].

The use of synthetic wastewater with the addition of a model contaminant was a deliberate and methodologically justified decision. The main advantage of this approach is the ability to fully control the physicochemical composition of the wastewater, including the concentrations of organic compounds and biogenic components. This made it possible to conduct the studies under repeatable conditions and to directly compare results across individual experimental series. This approach also facilitates the interpretation of results and the assessment of the impact of specific factors on the effectiveness of treatment processes.

It should be emphasized, however, that the use of synthetic wastewater also has certain limitations. It does not fully replicate the complex nature of actual wastewater, which contains a variety of components, such as suspended solids, colloidal substances, and naturally occurring microflora. Additionally, the absence of certain specific pollutants may affect the effectiveness of the treatment processes.

Despite these limitations, the adopted approach is justified at the proof-of-concept stage, the purpose of which was to evaluate the effectiveness of the proposed process under controlled experimental conditions.

2.2. Biological Treatment

In the first stage of the research, the prepared synthetic wastewater underwent biological treatment using activated sludge in sequential batch reactors (SBRs). Eight laboratory reactor models in the form of cylindrical plastic tanks were used in the research, each with a working volume of 2.5 L. Aeration was provided by an aeration pump (TD Stones, TB Trade Ltd., Warsaw, Poland), with a capacity of 420 L/h and a power consumption of 6 W, while mixing was ensured by mechanical agitators (model 791-OSC-20L; Alchem Grupa Ltd., Toruń, Poland), operating at a constant speed of 100 rpm.

The activated sludge used in the research came from the sludge stabilization tank of a municipal wastewater treatment plant equipped with the SUPERBOS system, which is based on zoned activated sludge technology. Before the actual testing phase began, the activated sludge microorganisms were acclimated to laboratory conditions. This process was conducted using synthetic wastewater without the addition of coffee bean extract until stable reactor operation was achieved.

Once stable operating conditions were achieved, coffee bean extract was added to the synthetic wastewater supplied to the reactors at a concentration of 1 g/L.

Based on the results of preliminary research [8,28,29], hydraulic retention times (HRT) of 8 and 15 days were adopted. For the adopted HRT values, the daily volume of wastewater discharged from each reactor after sedimentation was 0.312 and 0.167 L, respectively. After the biologically treated wastewater was discharged, the reactors were replenished with freshly prepared synthetic wastewater—both with and without the addition of coffee bean extract (control samples).

All reactors operated on a 24 h cycle. Two reactor operation variants were used (Variant I and Variant II). Four reactors operated according to the first variant, while the remaining four operated according to the second. A schematic of the biological treatment setup is shown in Figure 2.

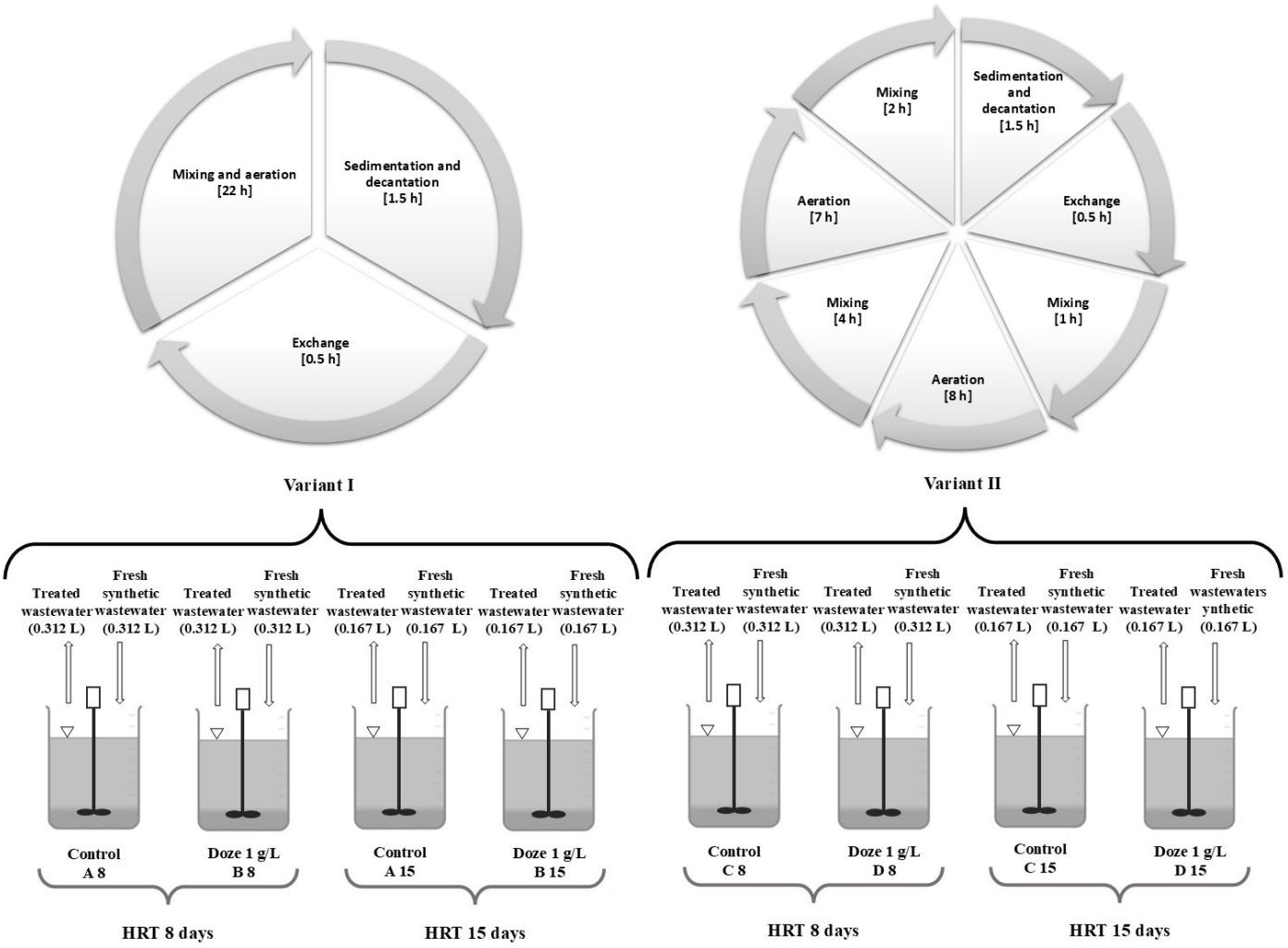


Figure 2. A schematic diagram illustrating the operating principle of SBR reactors and the method of dosing a model contaminant into individual reactors, along with their designations (own elaboration).

In the first variant, the reactor contents were aerated and mixed for 22 h, after which aeration and mixing were shut off and sedimentation was carried out for 1.5 h. The reactor's working volume was then replaced, and the next operating cycle began.

In the second variant, alternating aeration and mixing phases were carried out for 22 h, followed by a 1.5 h sedimentation period and replacement of the working volume, similar to the first variant. Detailed parameters of the reactor operating cycles are presented in Table 2.

Table 2. The specified reactor operating phases for variants I and II (own elaboration).

Names of the Individual Phases for Variant I of the Reactor Operating Cycle	Duration of Each Phase of the Cycle	Names of the Individual Phases for Variant II of the Reactor Operating Cycle	Duration of Each Phase of the Cycle
Mixing and aeration	22 h	Mixing	1 h
Sedimentation and decantation	1.5 h	Aeration	8 h
Exchange	0.5 h	Mixing	4 h
		Aeration	7 h
		Mixing	2 h
		Sedimentation and decantation	1.5 h
		Exchange	0.5 h

One day after the start of dosing synthetic wastewater containing coffee bean extract into the individual reactors, analyses were conducted to determine the following parameters: pH, conductivity, turbidity, total organic carbon (TOC), ammonium nitrogen, and phosphates. Subsequent analyses were conducted every 7 days to evaluate changes in the physicochemical parameters of the treated wastewater and the effectiveness of the biological process as it progressed.

2.3. Further Purification of Samples After Biological Treatment via Sorption on Activated Carbon

Biologically treated wastewater underwent a further stage of purification using a sorption process. Activated carbon was used as the sorbent material; it is widely used in water treatment and wastewater treatment technologies due to its large specific surface area and highly developed porous structure, which facilitates the adsorption of organic and inorganic compounds. The research compared the effectiveness of two commercial carbon sorbents with the trade names WG-12 (manufactured by Gryfskand, Gryfino, Poland) and WACC (manufactured by Elbar—Katowice, Ltd., Katowice, Poland). Figure 3 shows photographs of the activated carbons used, while Table 3 presents the characteristics of the activated carbons used.

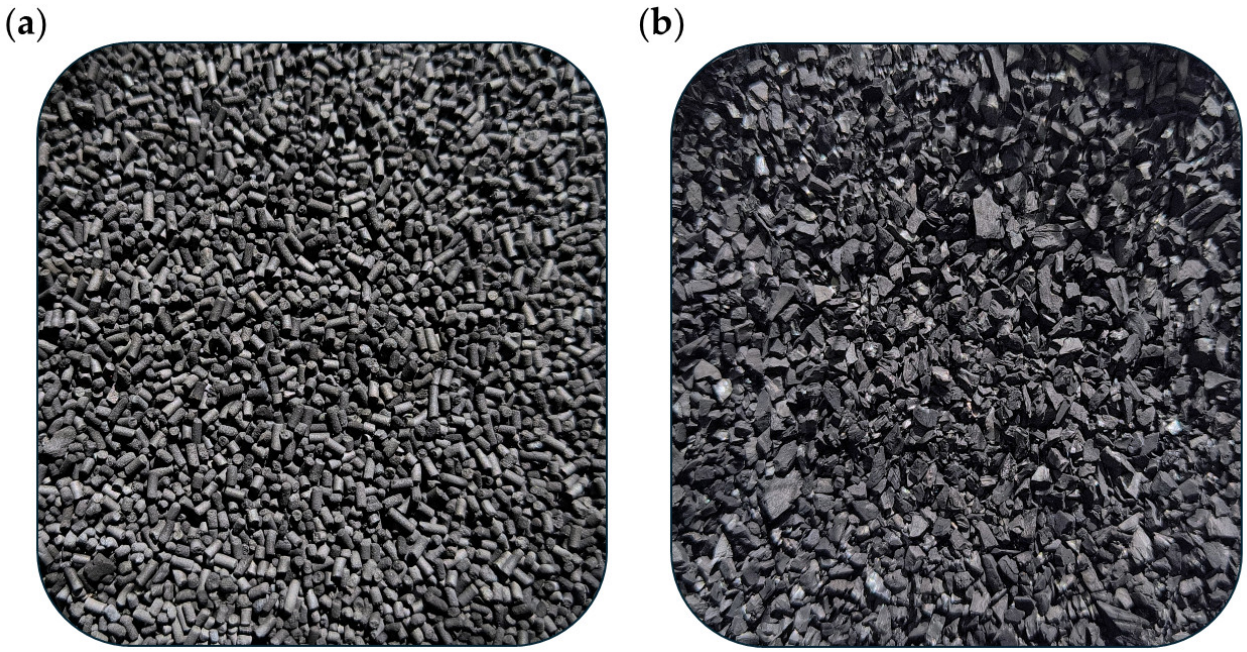


Figure 3. Photos of the activated carbons used in the research: (**a**) activated carbon known as WG-12; (**b**) activated carbon known as WACC (own elaboration).

Table 3. Parameters of the activated carbons used in the research [30,31].

	WG-12	WACC
Manufacturer's name, city, country	Gryfskand, Gryfino, Poland	Elbar—Katowice, Ltd., Katowice, Poland
Specific surface area, minimum	800–1100 m^2/g	1000 m^2/g
Iodine value, minimum	1000 mg/g	1000 mg/g
Dechlorination capacity		<5 cm
Humidity, maximum	2%	5%
Ash content, maximum	15%	5%
pH	~7	~8
Hardness, minimum	95%	98%
Bulk density	450 ± 30 g/L	480 ± 30 g/L
Grain size	1.0–1.5 mm	0.6–2.4 mm

The sorption process was conducted under dynamic conditions using a filter column filled with activated carbon as the sorbent. To evaluate the effect of the sorption bed height on contaminant removal efficiency, three different activated carbon layer heights were tested: 20, 30, and 40 cm. The diameter of the filtration column used was 3 cm^3.

Biologically treated wastewater was passed through a stationary sorption bed in the filtration column. As the solution flowed through the activated carbon layer, dissolved compounds were adsorbed onto the surface and within the pores of the sorption material. The average linear flow rate of the solution (100 mL) through the bed was estimated at approximately 0.2 cm/min, which ensured an adequate contact time between the liquid phase and the sorbent.

After the sorption process was completed, the following measurements were performed: pH, conductivity, turbidity, and TOC.

The use of a dynamic system allowed for an assessment of the sorption process's effectiveness under conditions similar to those of actual technological solutions used in engineering systems. The research made it possible to compare the effectiveness of two types of activated carbon (WG-12 and WACC) and to assess the impact of the sorption bed height on the efficiency of contaminant removal from wastewater following biological treatment.

2.4. Further Purification of Samples After Biological Treatment via Membrane Filtration

In parallel with the sorption process, membrane filtration was performed on samples of biologically treated wastewater (sample volume: 100 mL). The purpose of this procedure was to investigate the possibility of further treating the wastewater after the biological process and to evaluate the effectiveness of membrane filtration alone in removing residual dissolved and colloidal contaminants. Membrane filtration produces high-quality permeate, and conducting the experiment simultaneously with post-sorption samples allows for a direct comparison of the effectiveness of both stages and an assessment of the potential benefits of integrating them.

The filtration efficiency was compared using four types of membranes:

- CN (cellulose nitrate)—0.2 µm (manufactured by Sartorius, Germany);
- CA (cellulose acetate)—0.2 µm (manufactured by Ahlstrom-Munksjö Germany GmbH, Bärenstein, Germany);
- CN-CA (mixed cellulose esters)—0.45 µm (manufactured by Ahlstrom-Munksjö Germany GmbH, Bärenstein, Germany);
- CA (cellulose acetate)—0.45 µm (manufactured by Ahlstrom-Munksjö Germany GmbH, Bärenstein, Germany).

The use of four types of membranes, differing in both material and pore size, had a direct impact on their filtration properties. The diameter of all membranes used was 47 mm.

The membranes with 0.2 µm pores (CA; CN) exhibited similar water flow rates of approximately 24–25 mL/min/cm^2/bar, but differed significantly in terms of bubble point. The CN membrane exhibited a significantly higher value (4.2 bar) compared to the CA membrane (2.9 bar), indicating a more uniform pore structure and higher filtration efficiency. The 0.2 µm CN membrane is hydrophilic and has a thickness of 130 µm, while the 0.2 µm CA membrane, also hydrophilic, has a thickness of 120 µm.

Membranes with a larger pore diameter (0.45 µm) exhibit significantly higher water flux. The CA membrane achieves approximately 65 mL/min/cm^2/bar at a burst pressure of 2.4 bar, while the CN-CA membrane exhibits a similar, slightly more varied range of water flow rates (approx. 60–70 mL/min/cm^2/bar) and a burst pressure of 2.1–2.4 bar. Both the 0.45 µm CA membrane and the 0.45 µm CN-CA membrane are hydrophilic. The 0.45 µm CA membrane has a thickness of 120 µm, while the 0.45 µm CN-CA membrane has a thickness ranging from 120 to 150 µm.

The use of membranes with two pore diameters (0.2 and 0.45 µm) made it possible to evaluate the effect of separation precision on permeate quality, while the use of different polymer materials allowed for an analysis of how the membranes' physicochemical properties affect process efficiency.

Filtration was performed using a glass filtration setup (model 258.202.01, Glassco Laboratory Equipments Pvt. Ltd., Ambala Cantt, India) connected to a pressure pump (model PL2/2; AGA LABOR, Warsaw, Poland). The average operating pressure was 0.08 MPa, which ensured a stable flow through the membrane and reproducibility of the experimental conditions.

In the post-filtration samples, pH, conductivity, turbidity, and TOC were measured as key indicators of process effectiveness.

2.5. Disinfection of Samples After Biological Treatment, Sorption, and Membrane Filtration

An analysis of the results regarding the post-treatment of biologically treated wastewater samples showed that the most effective approach is to first subject the samples to sorption on activated carbon, followed by membrane filtration. Sorption effectively removes most dissolved and colloidal contaminants, reducing the load on the membrane and minimizing the risk of rapid clogging. This approach demonstrates that integrating both stages—sorption and membrane filtration—constitutes an effective strategy for the post-treatment of wastewater following biological treatment, improving its quality and potential for further reuse or discharge.

Accordingly, samples from the biological treatment stage—which had undergone activated carbon sorption and membrane filtration—were directed to the final stage of wastewater treatment, involving a two-stage disinfection process. The use of an integrated O_3/UV system was intended not only to inactivate microorganisms but also to further oxidize the remaining organic compounds in the wastewater after the previous treatment stages.

The disinfection process involved ozonation followed by exposure of the samples to UV radiation. The ozonation process was carried out using the IMPOZ MINI 2 ozone generator, a portable ozone generator manufactured by OPTEL Ltd. (manufactured in Wrocław, Poland), designed to produce a mixture of ozone and air with a maximum concentration of 10 g O_3/m^3. Ozonation of the treated wastewater samples was carried out at a constant flow rate of ozonated air of 10 L/h. To evaluate the process's effectiveness, disinfection efficiency was compared at three ozonation times: 15, 30, and 45 min. After ozonation, the samples were irradiated with UV-C radiation at a wavelength of 253.7 nm for 15 min using

a germicidal UV-C lamp installed in a laminar flow chamber (LabGard ES Energy Saver, Class II, Type A2, NuAire, Inc., Plymouth, MN, USA). According to the manufacturer's specifications, approximately 95% of the emitted radiation was at a wavelength of 253.7 nm, with an irradiance of approximately 100 $\mu W/cm^2$ at the working surface for a new lamp. The parameters of the disinfection process, including the duration of ozonation and UV exposure, were selected based on the results of preliminary research [8].

After each stage of wastewater treatment, the collected samples were subjected to the following analyses:

- pH was determined potentiometrically using a CP-411 pH meter (Elmetron, Zabrze, Poland), in accordance with the methodology described by Hermanowicz et al. [32];
- Conductivity was measured using a CC-505 conductivity meter (Elmetron, Zabrze, Poland), in accordance with the methodology described by Hermanowicz et al. [32];
- Phosphates concentration was determined spectrophotometrically using the ascorbic acid method, in accordance with the methodology described by Hermanowicz et al. [32], with a DR3900 laboratory spectrophotometer (Hach Lange GmbH, Düsseldorf, Germany);
- Total organic carbon (TOC) was determined in accordance with the Polish Standard PN-EN 1484:1999, entitled "Water Analysis—Guidelines for the Determination of Total Organic Carbon (TOC) and Dissolved Organic Carbon (DOC)" [33] using a Multi N/C 3100 TOC analyzer (Analytik Jena GmbH+Co. KG, Jena, Germany);
- Ammonium nitrogen was determined spectrophotometrically using the salicylate method (HACH Method 8155), with Ammonia Salicylate Reagent Powder Pillows (product no. 2653299) and Ammonia Cyanurate Reagent Powder Pillows (product no. 2653199) (Hach Company, Loveland, CO, USA), following the manufacturer's analytical procedure;
- Turbidity was measured using a HACH laboratory turbidimeter (Hach Company, Loveland, CO, USA).

In addition, dry organic matter in the SBR reactors was determined at regular intervals according to the methodology described by Hermanowicz et al. [32].

Each sample was subjected to three analytical replicates to assess the repeatability of the measurements. The results showed high consistency among the individual replicates. Accordingly, the results presented in Section 3 are expressed as mean values from the three analytical replicates, with error bars representing a 5% error level. It should be emphasized that these replicates were performed using the same sample and therefore do not represent independent experimental repetitions.

In samples collected after biological treatment, as well as in samples after disinfection, microbiological cultures were performed using the plate method (surface culture) in accordance with the general guidelines provided in PN-EN ISO 8199:2019-01 [34], entitled "Water Quality – General Requirements and Guidance for Microbiological Examinations by Culture". The aim was to assess selected microbiological indicators and evaluate the microbiological quality of the treated wastewater. For this purpose, the following microbiological determinations were performed:

- The total culturable microbial count (bacteria and fungi) was determined using Plate Count Agar (PCA) medium (BTL Ltd., Łódź, Poland), followed by incubation at 37 °C for 48 h;
- The presence of *Escherichia coli* was assessed using Tryptone Bile X-Glucuronide (TBX) medium (BTL Ltd., Łódź, Poland), followed by incubation at 44 °C for 24 h;
- The presence of presumptive *Salmonella* and *Shigella* spp. was assessed using Salmonella-Shigella Agar (BTL Ltd., Łódź, Poland), followed by incubation at 37 °C for 48 h;

- The presence of fungi and yeasts was assessed using Sabouraud Agar (POL-AURA Chemical Reagents, POL-AURA Ltd., Morąg, Poland), followed by incubation at 20–25 °C for 7 days.

3. Results

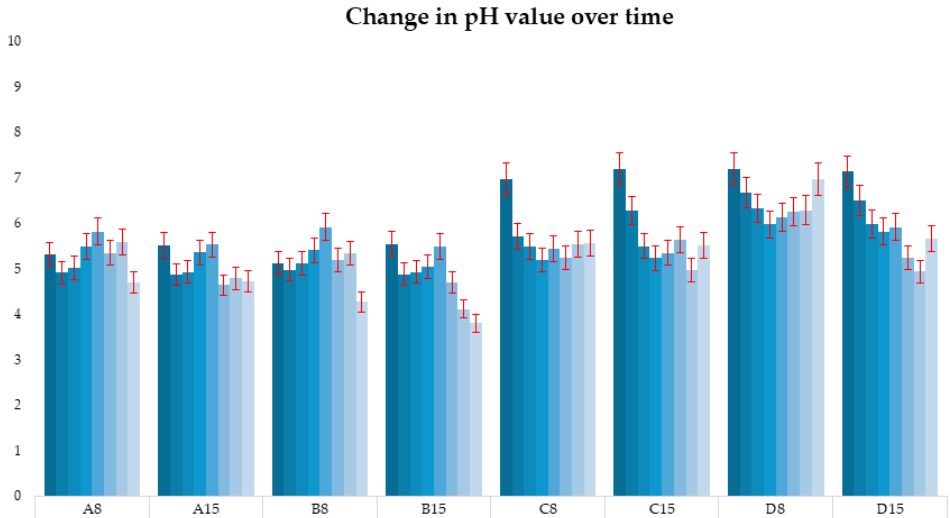
The research included an evaluation of the effectiveness of a multi-stage, integrated wastewater treatment system for synthetic wastewater containing a model contaminant in the form of coffee bean extract. The treatment process included biological treatment, activated carbon sorption, membrane filtration, and final disinfection using ozone and UV-C radiation. At each stage, the optimal operating conditions were determined, and the effectiveness of contaminant removal was evaluated.

Laboratory analyses were performed after the completion of each stage, and following the disinfection stage, additional microbiological tests were conducted to evaluate the effectiveness of the methods used and the sanitary safety of the reclaimed water.

The following subsections present the results obtained at each stage of the treatment process.

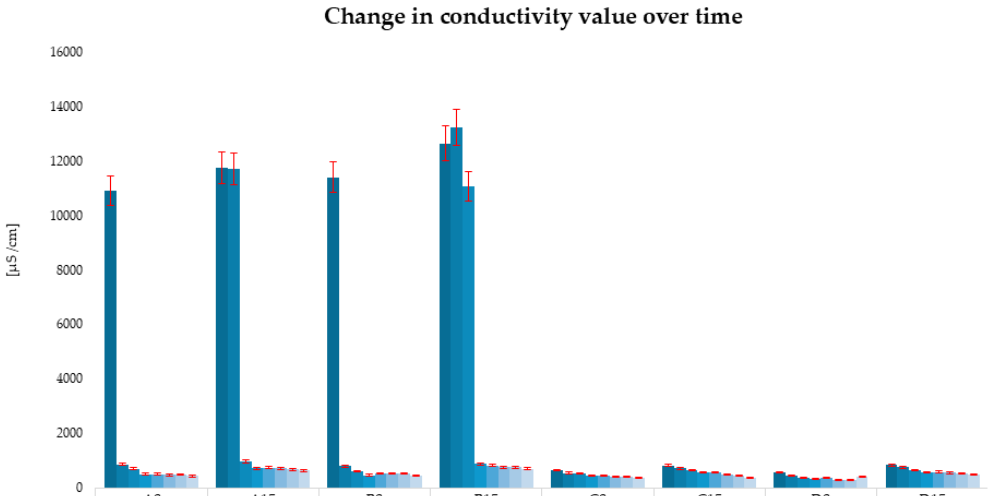
3.1. Biological Treatment

Twenty-four hours after the start of dosing synthetic wastewater containing coffee bean extract at a concentration of 1 g/L into the reactors, measurements were taken of pH, specific electrical conductivity, turbidity, phosphate concentration, ammonium nitrogen, and TOC. Subsequent analyses were conducted at seven-day intervals. The results are presented graphically in Figures 4–9. Additionally, the organic dry matter content was measured once a week in all reactors, and the results are presented in Figure 10.



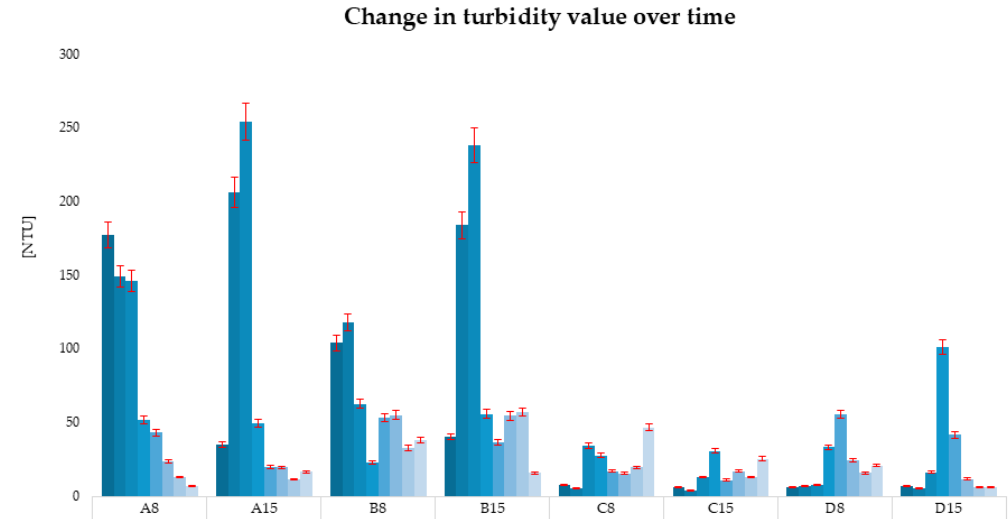
	A8	A15	B8	B15	C8	C15	D8	D15
1 day after adding coffee bean extract to synthetic wastewater	5.32	5.51	5.12	5.55	6.97	7.19	7.18	7.13
8 days after adding coffee bean extract to synthetic wastewater	4.91	4.87	4.98	4.88	5.71	6.28	6.67	6.50
15 days after adding coffee bean extract to synthetic wastewater	5.02	4.93	5.12	4.93	5.49	5.50	6.33	5.98
21 days after adding coffee bean extract to synthetic wastewater	5.49	5.36	5.41	5.04	5.20	5.23	5.97	5.82
28 days after adding coffee bean extract to synthetic wastewater	5.82	5.53	5.91	5.49	5.44	5.35	6.13	5.91
36 days after adding coffee bean extract to synthetic wastewater	5.35	4.64	5.20	4.69	5.24	5.63	6.26	5.24
43 days after adding coffee bean extract to synthetic wastewater	5.59	4.79	5.34	4.12	5.54	4.97	6.29	4.94
54 days (C/D) and 61 days (A/B) after adding coffee bean extract to synthetic wastewater	4.70	4.72	4.27	3.80	5.56	5.51	6.97	5.67

Figure 4. Changes in pH values in the reactors over the course of several weeks (own elaboration).



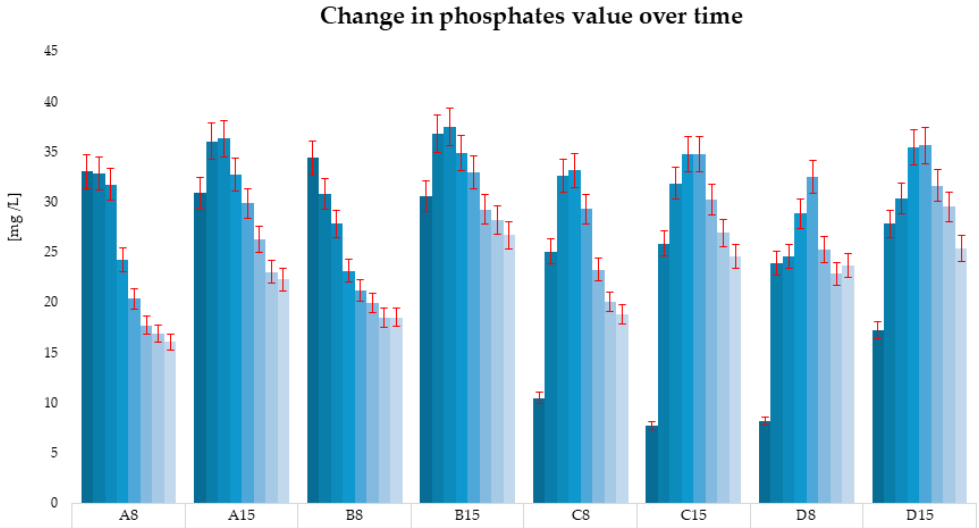
	A8	A15	B8	B15	C8	C15	D8	D15
1 day after adding coffee bean extract to synthetic wastewater	10,920.00	11,769.00	11,411.00	12,654.00	637.10	817.00	575.80	835.60
8 days after adding coffee bean extract to synthetic wastewater	863.00	11,707.00	800.70	13,242.00	544.20	720.70	438.20	750.30
15 days after adding coffee bean extract to synthetic wastewater	705.00	968.40	607.30	11,080.00	517.40	650.90	355.30	652.40
21 days after adding coffee bean extract to synthetic wastewater	503.00	720.80	463.00	869.50	458.70	567.60	340.60	572.90
28 days after adding coffee bean extract to synthetic wastewater	503.80	738.90	510.90	821.70	450.20	559.40	367.90	582.80
36 days after adding coffee bean extract to synthetic wastewater	464.70	707.80	520.20	746.60	398.10	475.90	296.90	548.70
43 days after adding coffee bean extract to synthetic wastewater	469.40	674.80	515.10	751.80	386.50	460.20	289.70	523.60
54 days (C/D) and 61 days (A/B) after adding coffee bean extract to synthetic wastewater	424.60	629.80	450.40	703.80	373.10	351.10	395.90	473.80

Figure 5. Changes in conductivity values in the reactors over the course of several weeks (own elaboration).



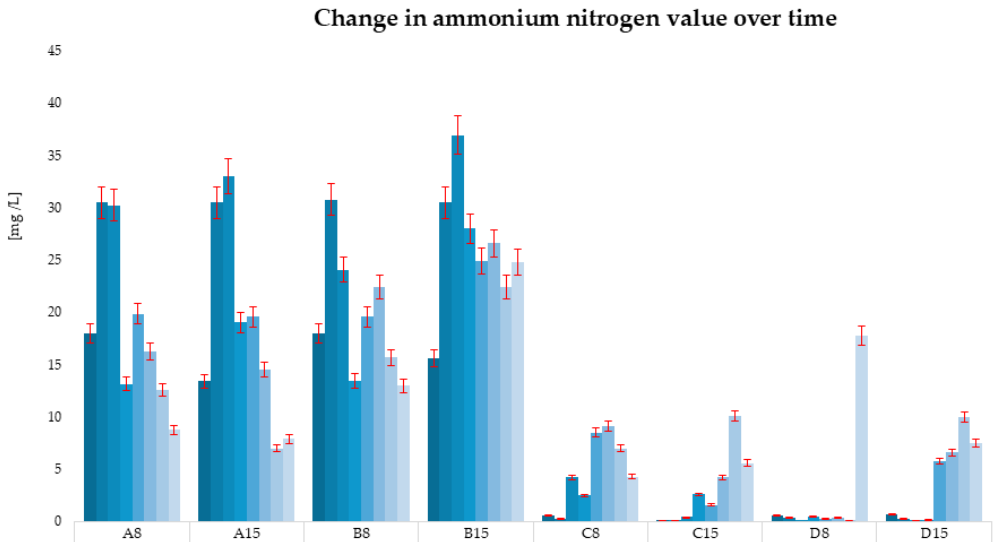
	A8	A15	B8	B15	C8	C15	D8	D15
1 day after adding coffee bean extract to synthetic wastewater	177.00	35.10	104.00	40.40	7.26	5.95	5.98	7.02
8 days after adding coffee bean extract to synthetic wastewater	149.00	206.00	118.00	184.00	5.09	3.89	7.05	5.55
15 days after adding coffee bean extract to synthetic wastewater	146.00	254.00	62.50	238.00	34.10	12.90	7.92	16.10
21 days after adding coffee bean extract to synthetic wastewater	51.70	49.60	23.00	55.90	27.70	30.60	33.20	101.00
28 days after adding coffee bean extract to synthetic wastewater	43.20	20.00	53.60	36.80	17.00	10.90	55.40	41.60
36 days after adding coffee bean extract to synthetic wastewater	23.50	19.50	55.10	54.40	15.30	17.10	24.10	11.60
43 days after adding coffee bean extract to synthetic wastewater	13.00	11.40	32.70	57.00	19.50	12.90	15.70	6.14
54 days (C/D) and 61 days (A/B) after adding coffee bean extract to synthetic wastewater	6.81	16.50	38.30	15.70	46.46	25.40	20.90	6.18

Figure 6. Changes in turbidity values in reactors over the course of several weeks (own elaboration).



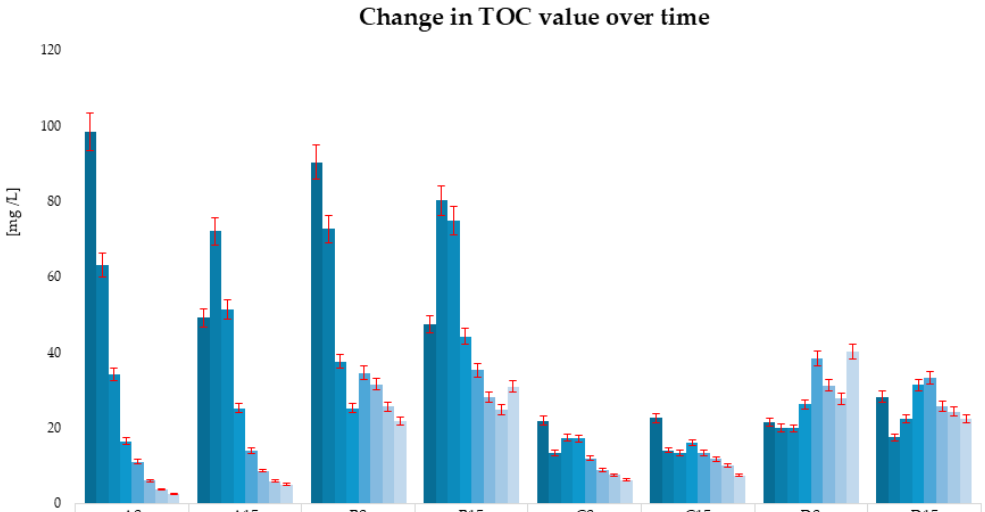
	A8	A15	B8	B15	C8	C15	D8	D15
1 day after adding coffee bean extract to synthetic wastewater	33.01	30.90	34.37	30.61	10.49	7.75	8.21	17.27
8 days after adding coffee bean extract to synthetic wastewater	32.84	36.03	30.84	36.77	25.09	25.88	23.94	27.82
15 days after adding coffee bean extract to synthetic wastewater	31.75	36.31	27.82	37.45	32.61	31.87	24.57	30.38
21 days after adding coffee bean extract to synthetic wastewater	24.23	32.72	23.14	34.83	33.12	34.77	28.84	35.40
28 days after adding coffee bean extract to synthetic wastewater	20.35	29.87	21.21	32.95	29.30	34.77	32.49	35.63
36 days after adding coffee bean extract to synthetic wastewater	17.73	26.28	19.95	29.24	23.26	30.21	25.25	31.64
43 days after adding coffee bean extract to synthetic wastewater	16.87	23.03	18.47	28.16	20.07	26.91	22.86	29.53
54 days (C/D) and 61 days (A/B) after adding coffee bean extract to synthetic wastewater	16.08	22.29	18.53	26.68	18.81	24.57	23.67	25.37

Figure 7. Changes in phosphate values in the reactors over the course of several weeks (own elaboration).



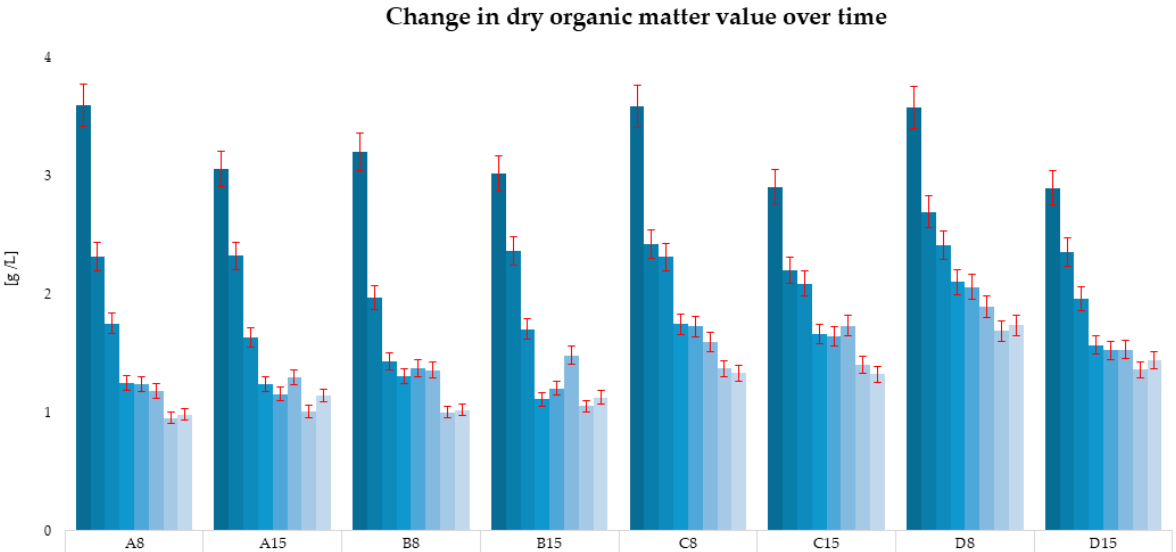
	A8	A15	B8	B15	C8	C15	D8	D15
1 day after adding coffee bean extract to synthetic wastewater	18.00	13.40	18.00	15.60	0.60	0.10	0.60	0.70
8 days after adding coffee bean extract to synthetic wastewater	30.52	30.52	30.80	30.52	0.30	0.10	0.40	0.30
15 days after adding coffee bean extract to synthetic wastewater	30.24	33.04	24.08	36.96	4.20	0.43	0.01	0.05
21 days after adding coffee bean extract to synthetic wastewater	13.16	19.04	13.44	28.00	2.50	2.60	0.45	0.18
28 days after adding coffee bean extract to synthetic wastewater	19.88	19.60	19.60	24.92	8.50	1.60	0.30	5.80
36 days after adding coffee bean extract to synthetic wastewater	16.24	14.56	22.40	26.60	9.10	4.20	0.40	6.60
43 days after adding coffee bean extract to synthetic wastewater	12.60	7.00	15.68	22.40	7.00	10.10	0.11	10.00
49 days after adding coffee bean extract to synthetic wastewater	8.75	7.88	12.98	24.85	4.30	5.60	17.80	7.50

Figure 8. Changes in ammonium nitrogen values in reactors over the course of several weeks (own elaboration).



	A8	A15	B8	B15	C8	C15	D8	D15
1 day after adding coffee bean extract to synthetic wastewater	98.40	49.16	90.42	47.47	21.96	22.62	21.66	28.27
8 days after adding coffee bean extract to synthetic wastewater	63.19	72.05	72.66	80.24	13.42	14.15	20.04	17.54
15 days after adding coffee bean extract to synthetic wastewater	34.18	51.32	37.63	75.00	17.44	13.40	19.92	22.51
21 days after adding coffee bean extract to synthetic wastewater	16.56	25.27	25.28	44.26	17.22	16.15	26.25	31.42
28 days after adding coffee bean extract to synthetic wastewater	11.06	13.96	34.61	35.26	11.98	13.40	38.45	33.30
36 days after adding coffee bean extract to synthetic wastewater	6.03	8.71	31.59	28.24	8.76	11.76	31.26	25.78
43 days after adding coffee bean extract to synthetic wastewater	3.78	6.00	25.68	24.87	7.55	10.13	27.73	24.35
54 days (C/D) and 61 days (A/B) after adding coffee bean extract to synthetic wastewater	2.65	5.07	21.93	30.94	6.26	7.49	40.15	22.39

Figure 9. Changes in total organic carbon values in the reactors over the course of several weeks (own elaboration).



	A8	A15	B8	B15	C8	C15	D8	D15
6 days after the start of the research	3.59	3.05	3.20	3.02	3.58	2.90	3.57	2.90
13 days after the start of the research	2.31	2.32	1.97	2.37	2.42	2.20	2.69	2.35
20 days after the start of the research	1.75	1.63	1.43	1.70	2.31	2.09	2.41	1.96
27 days after the start of the research	1.25	1.24	1.30	1.11	1.75	1.66	2.10	1.57
34 days after the start of the research	1.24	1.15	1.37	1.20	1.72	1.64	2.06	1.52
40 days after the start of the research	1.18	1.29	1.36	1.48	1.59	1.73	1.89	1.53
50 days after the start of the research	0.95	1.01	1.00	1.05	1.37	1.40	1.69	1.36
55 days after the start of the research	0.98	1.14	1.02	1.12	1.33	1.32	1.74	1.44

Figure 10. Changes in dry organic matter values in reactors over the course of several weeks (own elaboration).

Figure 4 shows the changes in pH observed over the course of the research. The results indicate that the use of different hydraulic retention times (HRT of 8 and 15 days) did not significantly affect the pH of the wastewater after the biological treatment process. Higher pH values, closer to the range considered optimal for activated sludge operation, were, however, recorded in reactors operating under an alternating aeration and mixing system (C and D). This may indicate more favorable conditions for biological processes, including more effective stabilization of organic matter and the maintenance of more balanced nitrogen cycles.

A gradual decrease in pH was also observed in all analyzed reactors during the experiment. This phenomenon may have been related to the progressive accumulation of intermediate products of organic compound biodegradation and the course of the nitrification process, during which hydrogen ions are released, causing the pH of the environment to decrease. Additionally, long-term operation of the reactors may have led to a gradual depletion of the wastewater's alkalinity, limiting the system's ability to neutralize the acids produced [35].

No significant differences in pH values were observed between reactors supplied exclusively with synthetic wastewater and reactors supplied with synthetic wastewater supplemented with a model contaminant in the form of coffee bean extract (1 g/L). This may be due to the natural buffering properties of the activated sludge environment and the relatively low load of organic compounds introduced, which did not cause significant disturbances in the acid-base balance in the reactors under study.

Figure 5 shows the changes in specific electrolytic conductivity in wastewater samples after biological treatment, as monitored in all reactors over the course of the research. The results indicate that HRT influenced this parameter—lower conductivity was observed in reactors operating at an HRT of 8 days. This may indicate more effective removal or utilization of dissolved ionic components with more frequent wastewater exchange.

During the initial phase of the experiment, elevated conductivity values were observed in reactors operating under a 22 h continuous mixing and aeration system (A and B). After about two weeks, however, they stabilized and reached a level similar to that recorded in reactors with alternating aeration and mixing (C and D), where they remained at a lower level throughout the research period. This phenomenon may result from the initial adaptation of microorganisms to operating conditions and the gradual stabilization of biological processes, as reflected in studies on biomass stability and adaptation in SBR reactors [36]. Furthermore, in reactors with alternating aerobic and anaerobic phases, more intense transformations of biogenic compounds—including phosphate uptake by the biomass—may have occurred, which could have contributed to a decrease in the concentration of dissolved ions and a reduction in electrical conductivity [37].

Over the following weeks of the research, a gradual decrease in conductivity was observed in all the systems analyzed. This trend may indicate the progressive utilization of dissolved mineral components by the growing biomass and the stabilization of the reactors' operating conditions. Changes in conductivity may, in fact, reflect changes in ion concentration that occur during the biological removal of biogenic components [37]. No significant differences were observed between reactors fed exclusively with synthetic wastewater and systems to which synthetic wastewater was supplied with the addition of coffee bean extract. This is likely because the introduced pollutants consisted mainly of organic compounds, which have little effect on the overall concentration of ions in the solution and, consequently, on the conductivity value.

Figure 6 shows the changes in turbidity values in treated wastewater samples over the course of the research. The results indicate that the reactor's operating mode significantly affected the quality of the treated wastewater. In reactors operating with continuous,

22 h mixing and aeration (A and B), higher initial turbidity values were recorded than in systems operating with alternating mixing and aeration (C and D). This phenomenon can be attributed to more intense resuspension of suspended particles and the fragmentation of activated sludge flocs, leading to an increase in the number of fine particles present in the samples. Das et al. [38] demonstrated similar relationships, pointing to an increase in the concentration of dispersed solid particles as the mixing intensity of the activated sludge increases.

In the subsequent weeks of the research, turbidity values fluctuated across all analyzed variants; however, in most cases, lower values were obtained in reactors operating at an HRT of 15 days. This result suggests that an extended retention time may have a beneficial effect on the stabilization of activated sludge biomass, which may have led to improved flocculation properties and treated wastewater quality [39].

Furthermore, after several weeks of the experiment, slightly lower turbidity values were observed in samples from reactors supplied with wastewater containing coffee bean extract. This effect may suggest that the presence of an additional source of organic compounds influenced the activity of microorganisms and the production of extracellular polymeric substances involved in cell aggregation and the formation of activated sludge flocs [39,40].

Figure 7 shows the changes in phosphate concentration in biologically treated wastewater samples over the course of the research. The results indicate that the way the biological process was conducted had a significant impact on the changes in phosphate concentration in the treated wastewater. During the initial period of the research, higher phosphate concentrations were observed in samples from reactors operating with continuous, 22 h mixing and aeration (A and B) than in systems operating under alternating mixing and aeration (C and D). This phenomenon may result from the limited capacity for biological phosphorus removal under continuous aeration conditions, which do not favor the occurrence of successive anaerobic and aerobic phases necessary for the proper course of processes carried out by phosphorus-accumulating microorganisms [41].

In the following weeks of the research, a systematic decrease in phosphate concentration was observed in the reactors operating with continuous mixing and aeration (A and B), which may indicate a gradual adaptation of the activated sludge biomass to the wastewater composition and a stabilization of the biological processes occurring in the reactors. In contrast, in the systems operating under alternating mixing and aeration (C and D), a gradual increase in phosphate concentration was recorded during the first four weeks of the experiment, after which the values began to decrease slightly. The initial increase may be related to the adaptation period of microorganisms to cyclically changing aerobic and anaerobic conditions, as well as to the temporary release of orthophosphates by phosphorus-accumulating microorganisms during anaerobic phases. Only after microbial activity stabilized could the biological phosphorus removal process proceed more effectively, resulting in a gradual decrease in phosphate concentrations in samples taken from the reactors [41,42].

Despite the differing trends observed during the research, the final phosphate concentrations obtained in both reactor operating modes were similar. These results indicate that the way the reactor cycle is conducted primarily affects the dynamics of phosphorus transformations and the time required to achieve stable operating conditions in the system; however, after an appropriate adaptation period, it is possible to achieve comparable phosphorus removal efficiency.

An analysis of the effect of HRT showed that, ultimately, lower phosphate concentrations were achieved in reactors operating at an HRT of 8 days. This may be due to a higher organic load per unit of biomass, which promotes more intensive microbial growth and greater phosphorus uptake for biomass synthesis. At the same time, a shorter HRT

may have provided more favorable conditions for maintaining a more active microbial community responsible for phosphorus removal.

A comparison of systems supplied with wastewater supplemented with coffee bean extract (B and D) revealed slightly higher phosphate concentrations in the treated wastewater compared to systems without the extract. This phenomenon may result from the presence of additional organic compounds derived from the extract, which influenced the direction of microbial metabolic processes and may have caused partial release of phosphorus into the liquid phase or increased competition between the microorganisms responsible for phosphorus removal and the remaining activated sludge microflora [43,44].

Figure 8 shows the changes in ammonium nitrogen concentration in biologically treated wastewater samples over the course of the research. The results indicate that the way the biological process was conducted significantly affected the efficiency of ammonium nitrogen removal. During most of the research, higher concentrations of ammonium nitrogen were observed in samples from reactors operating with continuous, 22 h mixing and aeration (A and B) than in systems operating under alternating mixing and aeration (C and D). These results suggest that cyclic changes between aerobic and anaerobic conditions promoted more efficient nitrogen compound transformation and better adaptation of the microorganisms responsible for their removal. The use of alternating aeration in SBR reactors may promote the stabilization of biological nitrogen removal processes, as demonstrated by Zhou et al. [45].

After approximately four weeks of research in reactors operating with continuous mixing and aeration (A and B), a gradual decrease in ammonium nitrogen concentration was observed, which may indicate the adaptation of the nitrifying bacterial population and the stabilization of the nitrification process. In contrast, in the systems operating under alternating mixing and aeration (C and D), a temporary increase in ammonium nitrogen concentrations was observed following an initial period of low concentrations. This phenomenon may be related to the adaptation of the nitrifying bacterial population and the stabilization of the nitrification process. Similar relationships were observed by Szabó et al. [46], who demonstrated that complete removal of ammonium nitrogen in the SBR reactors under study occurred after several weeks of the experiment. In contrast, the temporary increase in ammonium nitrogen concentration in systems with intermittent aeration may have resulted from periodic changes in the activity of microorganisms responsible for nitrogen transformation, associated with the adaptation of biomass to changing oxygen conditions [36,45].

Despite the observed changes in the course of the research, the final concentrations of ammonium nitrogen were significantly lower in reactors operating under an alternating mixing and aeration system (C and D) than in systems with continuous mixing and aeration (A and B). The results indicate that the alternating phases of mixing and aeration created more favorable conditions for nitrogen transformation, enabling the microbial communities responsible for removing this nutrient to function more effectively. The influence of aeration conditions and the availability of oxygen and organic substrates on the activity of bacteria involved in nitrogen cycling is also confirmed by Zielińska et al. [47].

An analysis of the effect of HRT showed that in both reactors operating with continuous mixing and aeration (A and B) and in systems with alternating mixing and aeration (C and D), lower final concentrations of ammonium nitrogen were achieved at an HRT of 8 days. This effect may result from a higher loading of the reactors with nitrogen compounds and organic substances, which promotes the maintenance of higher metabolic activity of the biomass and the intensification of the occurring processes. At the same time, a shorter HRT may have provided more favorable conditions for maintaining an active population of microorganisms responsible for nitrogen transformation.

A comparison of systems supplied with wastewater supplemented with coffee bean extract (B and D) showed slightly higher concentrations of ammonium nitrogen in the treated wastewater than in the corresponding systems without the extract. This phenomenon may result from the presence of additional organic compounds derived from the extract, which increased the oxygen demand of heterotrophic microorganisms. Competition for oxygen between heterotrophic and nitrifying bacteria may have periodically limited the intensity of the nitrification process, leading to the persistence of slightly higher concentrations of ammonium nitrogen in the samples [47,48].

Figure 9 shows the changes in TOC levels in biologically treated wastewater samples over the course of the research. The results indicate that the way the biological process was conducted significantly affected the efficiency of organic compound removal. In the initial phase of the research, higher TOC values were recorded in samples from reactors operating with continuous, 22 h mixing and aeration (A and B) than in systems operating with intermittent mixing and aeration (C and D). This may indicate that, in the initial phase of the research, the microorganisms had not yet reached full metabolic activity, and the biodegradation of organic compounds was less efficient. Lochmatter and Holliger [49] observed similar patterns, highlighting the importance of operating conditions and the start-up period for achieving stable efficiency in the biological removal of organic compounds.

In the following weeks of the research, a systematic decrease in TOC values was observed in the reactors operating with continuous mixing and aeration (A and B), indicating the gradual adaptation of the activated sludge biomass to the composition of the wastewater and the stabilization of the biodegradation processes of organic matter. A similar downward trend was also observed in systems operating under alternating mixing and aeration (C and D). The exception was the variant with the addition of coffee bean extract at a concentration of 1 g/L, in which, after approximately four weeks of testing, a temporary increase in TOC values was observed that persisted for about two weeks, after which a decreasing trend resumed. The temporary increase in TOC values may have been related to periodic changes in microbial activity and the partial release of soluble products of cellular metabolism and polymeric substances of microbial origin. The formation and release of soluble microbial products, including proteins, polysaccharides, and cell breakdown products, is a phenomenon that occurs in biological wastewater treatment systems [50,51]. Additionally, the presence of readily biodegradable organic compounds derived from coffee bean extract may have temporarily altered the structure of the microflora and the direction of metabolic processes, leading to a temporary increase in the concentration of dissolved organic compounds in the samples.

An analysis of the effect of HRT showed that in reactors operating with continuous mixing and aeration (A and B), as well as in most systems with alternating mixing and aeration (C and D), lower final TOC values were obtained at an HRT of 8 days. This may be due to a higher organic load in the reactors, which helped maintain high metabolic activity of the microorganisms responsible for the biodegradation of organic matter. An exception was the reactor operating in an alternating mixing and aeration system with the addition of coffee bean extract, in which lower final TOC values were obtained at an HRT of 15 days. In this case, the extended HRT likely provided the microorganisms with longer contact with the more complex organic compounds present in the coffee extract, enabling their more effective biodegradation and more complete mineralization.

A comparison of systems treated with wastewater supplemented with coffee bean extract (B and D) revealed higher TOC values in the treated wastewater than in the corresponding systems without the extract. This is likely related to the introduction of an additional load of organic compounds, including not only readily biodegradable compounds but also more complex substances. Wastewater from coffee processing may contain,

among other things, melanoidins, phenolic compounds, alkaloids, and polysaccharides, some of which are characterized by limited biodegradability [16,52]. These compounds may exhibit greater resistance to biodegradation, which could have resulted in persistently higher TOC values in the treated wastewater despite the ongoing adaptation of the activated sludge biomass.

Figure 10 shows the changes in dry organic matter content in the SBR reactors over the course of the research. The results indicate a clear downward trend in all analyzed systems throughout the entire research period. The most pronounced decrease was observed up to approximately the fourth week of the research, after which the rate of decline in dry organic matter slowed significantly, despite the continuing downward trend. This phenomenon may be related to the endogenous biomass decomposition processes occurring in the activated sludge, including the degradation of cellular components and the gradual decomposition of organic metabolic byproducts. The literature indicates that the initial phase of sludge stabilization is more closely associated with active biomass breakdown, whereas subsequent stages are dominated by slower transformations of cellular residues and partial metabolic products [53,54]. The slower rate of change observed in the later stages of the study may therefore indicate a gradual reduction in the intensity of these processes and the systems' approach toward relative stabilization.

When comparing the two reactor operating cycles analyzed, slightly higher final values of dry organic matter were obtained in systems operating under alternating mixing and aeration (C and D) compared to reactors operating in continuous, 22 h mixing and aeration mode (A and B). These differences may indicate distinct dynamics in the transformation and retention of organic sludge components depending on the operating cycle used. It should be noted that the manner in which the mixing and aeration phases are conducted can affect both the activity of the biomass and its physical properties, as well as its susceptibility to being washed out of the reactor [55,56].

An analysis of the effect of HRT showed that in reactors operating in an intermittent mode (C and D), slightly higher values of dry organic matter were obtained at an HRT of 8 days, whereas in systems with continuous mixing and aeration (A and B), higher values were observed at an HRT of 15 days. The observed differences indicate that the effect of hydraulic retention time on the amount of organic components in the sludge may also depend on how the reactor's operating cycle is managed. Klimiuk and Kulikowska [55] described similar relationships, in which HRT, filling, mixing, and aeration strategies influence the production and degradation of activated sludge. When interpreting these results, however, it should be noted that HRT is not synonymous with sludge age, and changes in biomass quantity also depend on its growth, decay, and losses due to leaching.

A comparison of the treatments with added coffee bean extract (B and D) showed slightly higher values of dry organic matter compared to the treatments without the extract. One possible explanation is the supply of additional organic compounds, which may have served as a substrate for heterotrophic microorganisms and helped retain a greater amount of organic sludge components. At the same time, it cannot be ruled out that metabolic byproducts and cellular residues also influenced the measured value. Therefore, the observed differences should be interpreted as a possible effect of changes in the system's substrate conditions, rather than direct evidence of an increase in biomass abundance.

In summary, the conducted research showed that the method of biological wastewater treatment in SBR systems significantly determined both the efficiency of pollutant removal and the dynamics of changes in the analyzed parameters over time. The addition of coffee bean extract at a concentration of 1 g/L affected the functioning of the biological system, which was manifested primarily by slightly higher values of selected pollutant indicators (TOC, ammonium nitrogen, and phosphates) compared to systems without the extract.

This effect can be attributed to the influx of an additional fraction of organic compounds and a temporary modification of the activity and structure of the activated sludge microflora.

An analysis of the reactors' operation revealed significant differences between the system with continuous, 22 h aeration and mixing and the system with alternating aeration and mixing. The system with alternating aeration and mixing facilitated more efficient removal of nitrogen compounds and a more stable course of biological processes over a longer operating period, which can be attributed to more favorable conditions for the parallel progression of nitrification and denitrification processes. For other parameters, such as phosphates, TOC, and turbidity, both systems achieved similar final efficiency, though they differed in the rate of system stabilization and the course of changes during the initial phase of the research.

HRT had a significant impact on reactor performance and the results obtained. In most of the cases analyzed, more favorable treatment results were observed at a shorter HRT of 8 days, which may be due to a higher biomass loading and the intensification of biological processes. At the same time, the results indicate that further analyses related to HRT should be considered on a case-by-case basis depending on the nature of the influent wastewater and the reactor's operating conditions, as in some cases a longer retention time promotes more complete degradation of organic compounds.

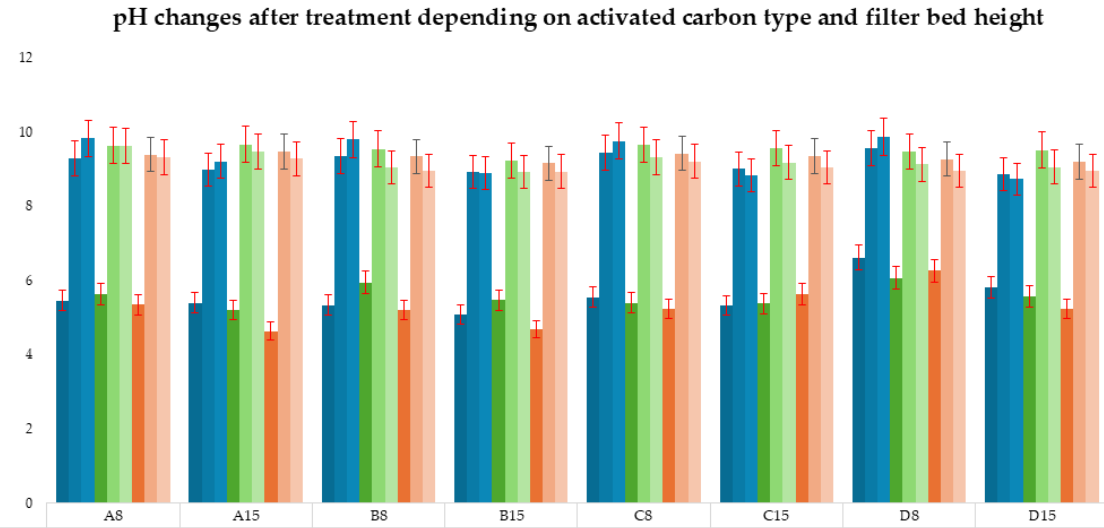
The obtained results unequivocally confirm that the duration of the biological process and the biomass adaptation period play a key role in determining treatment efficiency. The most dynamic changes were observed during the initial phase of operation, after which the system gradually reached a state of relative operational stability, indicating the significant importance of microbial adaptation processes in the long-term operation of SBR reactors.

3.2. Integration of Biological Wastewater Treatment with Activated Carbon Sorption

After completion of the biological wastewater treatment process, the samples underwent post-treatment using an activated carbon sorption process. The research compared the effectiveness of two commercial sorbents—WG-12 and WACC—and evaluated the effect of bed depth in the filtration column (20, 30, and 40 cm) on changes in pH, specific electrical conductivity, turbidity, and TOC in the treated wastewater. The results are presented in Figures 11–14.

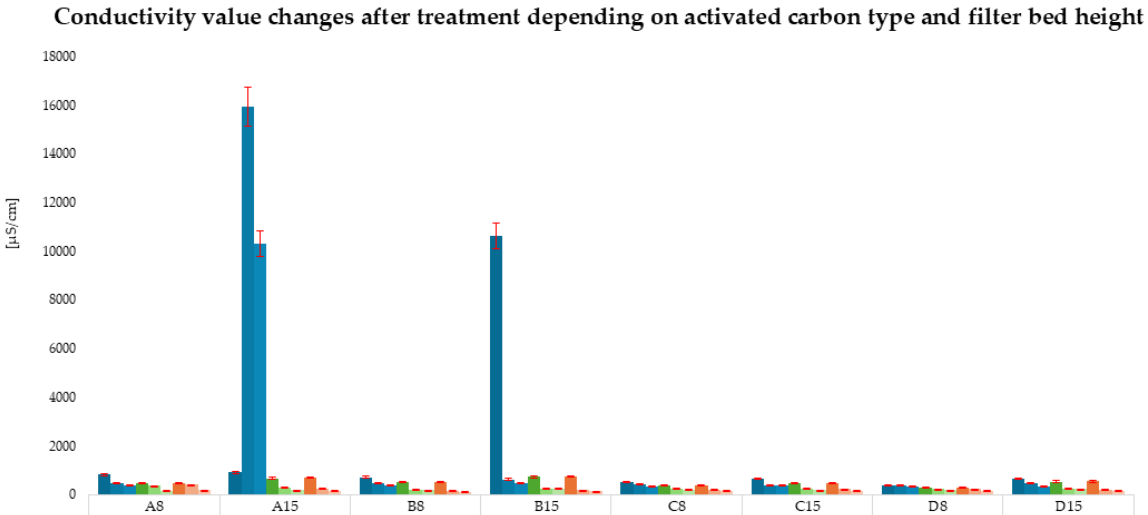
Figure 11 shows changes in the pH of the treated wastewater as a function of the carbon sorbent used (WG-12 and WACC) and the bed depth in the filter column (20, 30, and 40 cm). Regardless of the type of sorbent used and the bed depth, a marked increase in pH was observed in all analyzed variants following the sorption process, compared to samples after biological treatment. The final pH values ranged from approximately 8.7 to as high as 9.9. An increase in pH may be related to the acid-base properties of activated carbon surfaces, which depend on the type and proportion of functional groups, as well as on the presence of mineral components in the sorbent's structure. These interactions can lead to changes in the acid-base equilibrium of the solution, including an increase in its pH [57,58]. The removal of some of the dissolved acidic compounds cannot be ruled out either.

An analysis of the effect of the type of sorbent used revealed only minor differences between the materials tested. At a bed height of 20 cm, slightly higher pH values were obtained for WACC activated carbon, whereas at bed heights of 30 and 40 cm, higher values were recorded for the WG-12 sorbent. These differences may result from the different chemical composition of the surfaces of both materials, the proportion of basic functional groups, and the sorption properties determined by their method of production and activation. As the bed height increased, the contact time between the wastewater and the sorbent increased, which may have allowed for a more complete utilization of the sorption properties of WG-12 carbon and more effective removal of compounds affecting the pH of the wastewater.



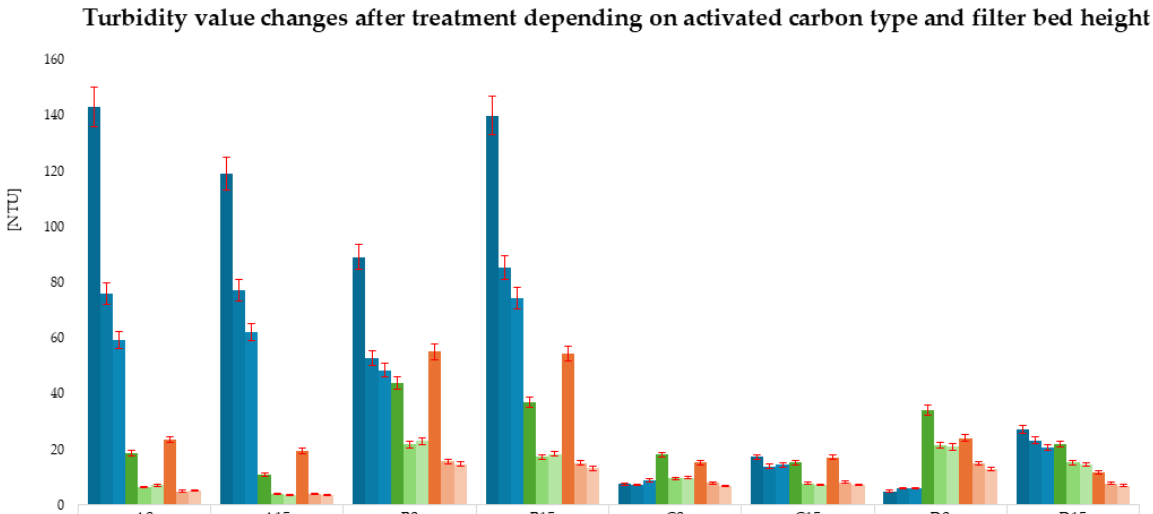
	A8	A15	B8	B15	C8	C15	D8	D15
Before sorption (after biological treatment)	5.46	5.40	5.34	5.08	5.55	5.33	6.62	5.83
WG-12 (20 cm)	9.30	8.99	9.36	8.93	9.46	9.01	9.57	8.86
WACC (20 cm)	9.83	9.21	9.80	8.89	9.76	8.83	9.87	8.73
Before sorption (after biological treatment)	5.64	5.22	5.95	5.47	5.40	5.38	6.07	5.57
WG-12 (30 cm)	9.64	9.67	9.55	9.23	9.66	9.56	9.48	9.52
WACC (30 cm)	9.63	9.47	9.05	8.93	9.32	9.18	9.14	9.06
Before sorption (after biological treatment)	5.35	4.64	5.20	4.69	5.24	5.63	6.26	5.24
WG-12 (40 cm)	9.40	9.47	9.34	9.17	9.43	9.35	9.27	9.20
WACC (40 cm)	9.33	9.28	8.96	8.94	9.21	9.05	8.96	8.96

Figure 11. Changes in pH values before and after further treatment, depending on the type of activated carbon used and its height in the filter column (own elaboration).



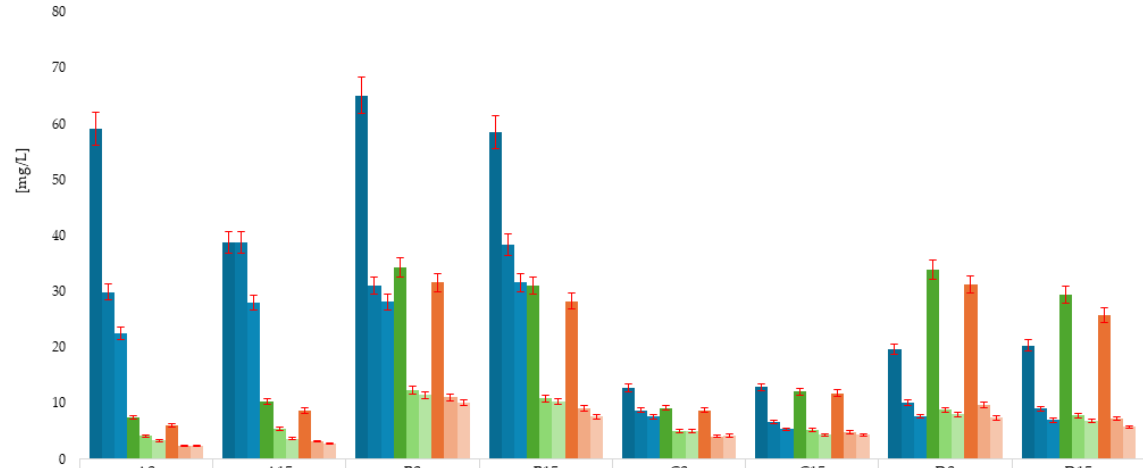
	A8	A15	B8	B15	C8	C15	D8	D15
Before sorption (after biological treatment)	823.80	924.80	725.70	10,618.00	513.10	650.40	395.90	656.10
WG-12 (20 cm)	482.00	15,953.00	482.50	637.10	419.60	396.20	387.80	468.00
WACC (20 cm)	407.20	10,320.00	399.70	482.00	357.50	393.20	329.70	353.00
Before sorption (after biological treatment)	462.10	681.80	508.90	742.30	408.20	486.50	310.90	543.80
WG-12 (30 cm)	369.10	312.40	224.30	268.60	258.40	251.10	234.50	261.60
WACC (30 cm)	180.77	182.58	192.07	246.90	203.60	191.57	190.87	235.20
Before sorption (after biological treatment)	464.70	707.80	520.20	746.60	398.10	475.90	296.90	548.70
WG-12 (40 cm)	412.00	251.80	171.45	191.32	224.50	230.00	229.10	223.40
WACC (40 cm)	193.58	155.26	128.14	138.37	154.42	165.21	164.09	172.33

Figure 12. Changes in conductivity values before and after further treatment, depending on the type of activated carbon used and its height in the filter column (own elaboration).



	A8	A15	B8	B15	C8	C15	D8	D15
Before sorption (after biological treatment)	143.00	119.00	89.10	140.00	7.57	17.30	5.02	27.30
WG-12 (20 cm)	76.10	77.20	52.70	85.30	7.28	13.90	6.12	23.20
WACC (20 cm)	59.30	62.20	48.50	74.40	8.93	14.40	6.07	20.60
Before sorption (after biological treatment)	18.70	10.80	43.90	37.10	18.10	15.30	34.10	21.80
WG-12 (30 cm)	6.47	4.02	21.70	17.30	9.58	7.70	21.40	15.30
WACC (30 cm)	7.15	3.69	23.00	18.40	9.82	7.30	20.90	14.50
Before sorption (after biological treatment)	23.50	19.50	55.10	54.40	15.30	17.10	24.10	11.60
WG-12 (40 cm)	4.99	4.19	15.70	15.10	7.91	8.13	15.00	7.85
WACC (40 cm)	5.25	3.77	14.70	13.20	6.86	7.27	12.90	6.92

Figure 13. Changes in turbidity values before and after further treatment, depending on the type of activated carbon used and its height in the filter column (own elaboration).



	A8	A15	B8	B15	C8	C15	D8	D15
Before sorption (after biological treatment)	59.02	38.73	65.08	58.49	12.75	12.91	19.63	20.31
WG-12 (20 cm)	29.91	38.76	31.03	38.41	8.76	6.62	10.11	9.01
WACC (20 cm)	22.50	28.02	28.18	31.61	7.58	5.35	7.68	6.97
Before sorption (after biological treatment)	7.45	10.26	34.36	31.01	9.16	12.11	33.85	29.38
WG-12 (30 cm)	4.13	5.44	12.35	10.84	5.02	5.22	8.80	7.84
WACC (30 cm)	3.33	3.69	11.44	10.28	4.99	4.37	8.05	6.87
Before sorption (after biological treatment)	6.03	8.71	31.59	28.24	8.76	11.76	31.26	25.78
WG-12 (40 cm)	2.41	3.20	11.03	9.14	4.03	4.84	9.67	7.23
WACC (40 cm)	2.39	2.77	10.11	7.57	4.21	4.35	7.38	5.74

Figure 14. Changes in total organic carbon values before and after further treatment, depending on the type of activated carbon used and its height in the filter column (own elaboration).

At the same time, the results indicate that the height of the activated carbon layer within the tested range did not significantly affect the final pH value of the treated wastewater. This means that effective pH modification was already achieved at a bed height of 20 cm, while further increasing the layer height resulted in only slight changes in pH, indicating that the system was approaching a state of sorption equilibrium.

Figure 12 shows the changes in the specific electrolytic conductivity of wastewater after the sorption process as a function of the type of sorbent used (WG-12 and WACC) and the thickness of the activated carbon layer in the filter column (20, 30, and 40 cm). The results indicate that the sorption process effectively reduced the electrolytic conductivity of the treated wastewater. In all analyzed variants, with the exception of sample A15 at a 20 cm activated carbon bed depth in the filtration column, a marked decrease in conductivity was observed after the sorption process compared to samples following biological treatment. A decrease in conductivity may indicate the partial removal of dissolved ionic components and other substances that affect the electrolytic properties of the solution. However, it should be noted that changes in conductivity may also be related to the leaching of mineral components present in the sorbent material, the quantity and type of which depend on the physicochemical properties of activated carbon [57,59].

The exception was sample A15 with a 20 cm thick layer of activated carbon in the filtration column, in which an increase in conductivity was observed after the sorption process. The observed increase in conductivity may have been related to the release into the solution of small amounts of soluble mineral components present in the sorbent. The possibility of such a phenomenon in the case of activated carbons has also been described in the literature [59]. However, given the isolated nature of the observation, its cause cannot be definitively identified.

The final conductivity values were similar in both systems supplied with synthetic wastewater and those supplied with wastewater containing coffee bean extract, indicating that the sorption stage effectively minimized the differences between the analyzed variants and resulted in comparable wastewater quality after post-treatment.

An analysis of the effect of the type of sorbent used showed that, at all bed heights analyzed, lower conductivity values were obtained when WACC activated carbon was used. This may indicate a higher sorption capacity of this material for dissolved ionic compounds or more favorable surface properties. As a result, the WACC sorbent was able to more effectively reduce the concentration of substances responsible for the electrolytic conductivity of the treated wastewater.

Increasing the height of the activated carbon bed from 20 to 40 cm led to a gradual, albeit slight, decrease in conductivity. The most favorable results were obtained at a bed height of 40 cm, which can be attributed to the prolonged contact time between the wastewater and the sorbent material, as well as an increase in the number of available active sites participating in the adsorption process. However, the small magnitude of the observed differences suggests that a high sorption efficiency was already achieved at a bed height of 20 cm, while further increasing the column height resulted in only a limited improvement in the removal efficiency of substances affecting electrolytic conductivity.

Figure 13 shows the changes in wastewater turbidity after the sorption process as a function of the type of sorbent used (WG-12 and WACC) and the thickness of the activated carbon layer in the filter column (20, 30, and 40 cm). The results indicate that the sorption process effectively reduced the turbidity of biologically treated wastewater. Regardless of the type of sorbent used or the bed depth, a marked decrease in turbidity was observed in all analyzed variants compared to samples after biological treatment. This demonstrates the high effectiveness of the activated carbon bed in improving the clarity of wastewater, resulting both from the retention of fine suspended particles and colloidal aggregates within

the bed structure and from the adsorption of some organic compounds. The literature has shown that granular activated carbon can effectively reduce the turbidity of secondary effluent, although the effectiveness of the process depends on the type of material used and the filtration conditions [60,61].

Slightly higher turbidity values in systems with added coffee extract may be related to the presence of residual organic compounds that were not completely removed during biological treatment and sorption. It is also possible that some of these substances persist in the form of fine aggregates or colloidal systems, the retention of which depends on the properties of the filter bed [62].

An analysis of the effect of sorption layer height showed that the most favorable turbidity reduction results were obtained at bed heights of 30 and 40 cm, with the lowest turbidity values recorded for the 40 cm layer. Increasing the bed height prolonged the contact time between the wastewater and the sorption material and increased the number of available active sites responsible for retaining suspended particles and colloidal compounds. As a result, the adsorption process was more effective, leading to improved clarity of the treated wastewater. However, the slight differences between the 30 cm and 40 cm variants suggest that a significant portion of the treatment effect was already achieved at a bed height of 30 cm, while further increasing the column height resulted in only a limited improvement in process efficiency.

A comparison of the properties of both sorbents showed that, for bed heights of 20 cm, 30 cm, and 40 cm, lower turbidity values were obtained in the vast majority of the analyzed variants when WACC activated carbon was used. This may indicate more favorable sorption properties of this material, resulting from a more developed porous structure and a larger specific surface area, which enable more effective retention of fine suspended particles and colloidal substances. Furthermore, a more developed network of micro- and mesopores may have increased the efficiency of adsorption of organic compounds responsible for maintaining the stability of colloidal systems, which further contributed to a reduction in the turbidity of the treated wastewater.

Figure 14 shows the changes in the TOC values of the wastewater after the sorption process as a function of the type of sorbent used (WG-12 and WACC) and the height of the activated carbon bed in the filter column (20, 30, and 40 cm). The results indicate that the sorption process was an effective stage in the post-treatment of biologically treated wastewater. Regardless of the type of sorbent used or the bed depth, a significant decrease in TOC values was observed in all analyzed variants compared to samples after biological treatment. The results obtained confirm the high effectiveness of activated carbon in removing organic matter residues, including compounds with properties that promote their adsorption onto the surface of the carbon material. The efficiency of this process depends both on the porous structure and surface chemistry of the sorbent and on the properties of the adsorbed compounds [57,62].

Despite the high efficiency of the sorption process, the final TOC values were slightly higher in systems fed with wastewater containing coffee bean extract than in variants without the model contaminant. This phenomenon can be attributed to the presence of an additional fraction of organic compounds, including, among others, substances with varying hydrophobicity and affinity for the activated carbon surface. It has been demonstrated that the effectiveness of adsorption of organic compounds present in coffee wastewater depends on their properties and the type of sorbent used [62].

An analysis of the effect of sorption bed height showed that the most favorable results in terms of TOC reduction were achieved at bed heights of 30 and 40 cm, with the lowest final TOC values recorded at a height of 40 cm. Increasing the bed depth resulted in an increase in the amount of sorbent and a potential extension of the contact time between

the wastewater and the activated carbon, which contributed to a more efficient utilization of available adsorption sites. The relationship between bed depth, contact time, and the efficiency of organic matter removal in granular activated carbon columns has also been described in the literature [63,64]. At the same time, the slight differences between the 30 cm and 40 cm variants suggest that at a height of 30 cm, a significant portion of the bed's sorption capacity was already being effectively utilized, while further increasing the column height provided only a slight improvement in process efficiency.

A comparison of the sorbents used showed that, at all bed heights analyzed, lower TOC values were obtained when WACC activated carbon was used. This may indicate that this material has more favorable sorption properties with respect to the organic compounds present in the wastewater studied. Differences in adsorption efficiency among individual activated carbons may result from both their porous structure and variations in surface chemistry, which influence the availability of adsorption sites and the affinity for specific compounds [57,60].

In summary, the use of an activated carbon sorption process as a post-treatment stage for wastewater following biological treatment significantly improved the quality of the treated wastewater, regardless of the quality parameter analyzed. In all operating modes of the system, a further reduction in electrical conductivity, turbidity, and TOC was observed, as well as stabilization of the pH at a slightly alkaline level. This confirms the high effectiveness of sorption as the next stage in an integrated wastewater treatment system with model pollutants.

A comparison of the sorption materials used showed that WACC activated carbon generally exhibited better efficiency in removing pollutants than WG-12, as evidenced by lower values of conductivity, turbidity, and TOC in the wastewater after sorption. This may be due to the more favorable structural and surface properties of WACC, including a larger available sorption surface area and a more developed pore structure, which promote more effective adsorption.

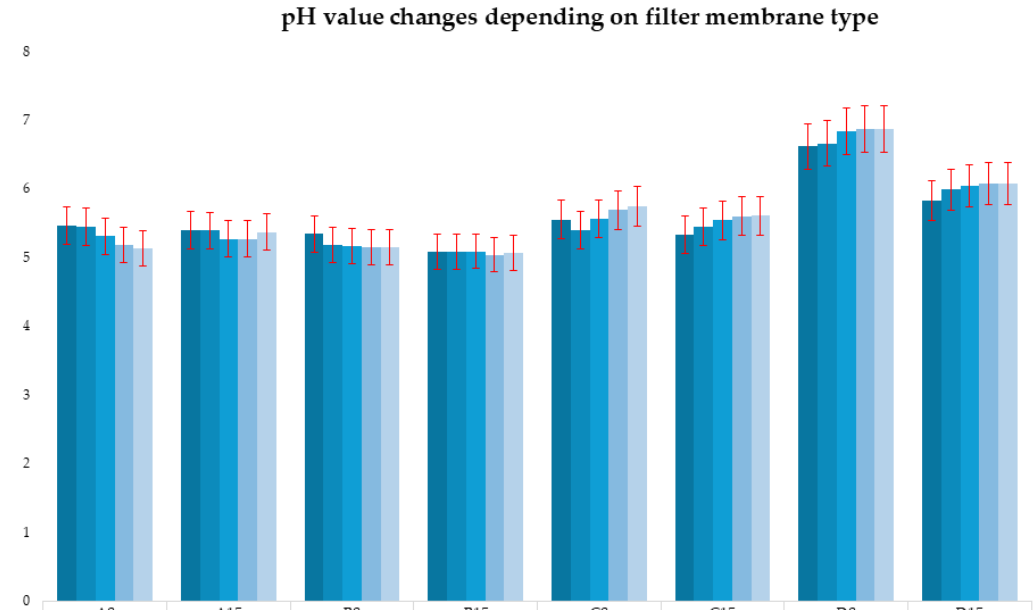
Another important factor affecting the process's efficiency was the height of the bed layer in the filter column. As the bed height increased from 20 to 40 cm, a gradual improvement in the quality of the treated wastewater was observed, which resulted from the extended contact time between the liquid phase and the sorbent material, as well as an increase in the number of available active sites. The best and most stable results were obtained at a bed height of 40 cm, which ensured the highest efficiency of contaminant removal while minimizing variability in the results.

Analysis of the results indicates that the most favorable option in an integrated, multi-stage wastewater treatment system with model pollutants was a system incorporating sorption on WACC activated carbon at a bed height of 40 cm. This combination provided the highest removal efficiency for both organic compounds and components affecting the physicochemical parameters of the wastewater, thus constituting the most effective post-treatment option in the analyzed technological system.

3.3. Integration of Biological Wastewater Treatment with Membrane Filtration Processes

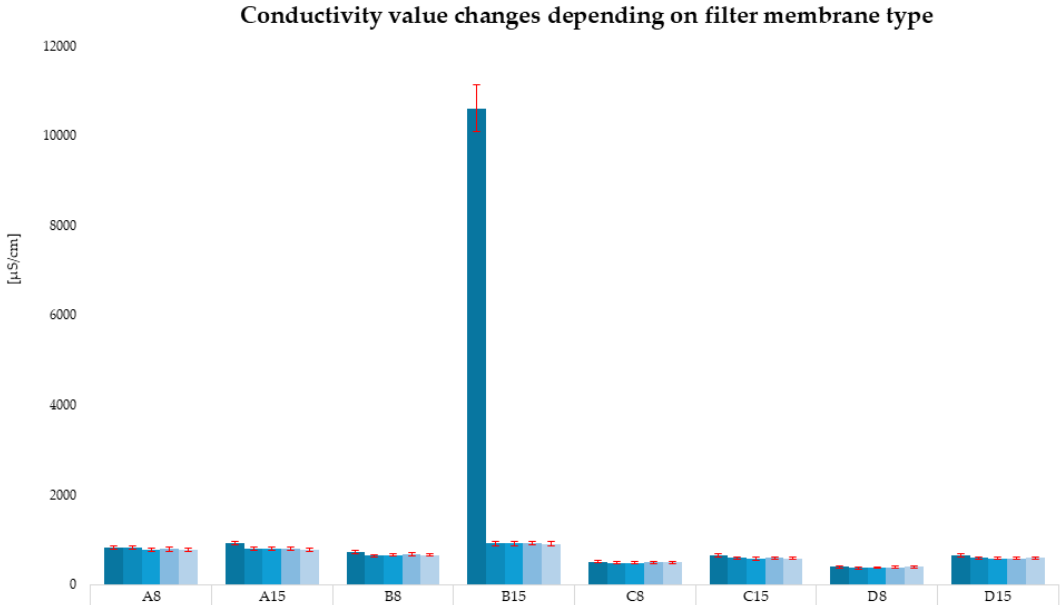
After the biological wastewater treatment was completed, the samples underwent further treatment using pressure membrane filtration. This process was analyzed in parallel with activated carbon sorption to determine which technology should serve as the intermediate step between biological treatment and the final two-stage disinfection process. The research compared the effectiveness of four types of membranes: CN (cellulose nitrate, 0.2 μm), CA (cellulose acetate, 0.2 μm), CN-CA (mixed cellulose esters, 0.45 μm), and CA (cellulose acetate, 0.45 μm), evaluating their impact on pH, specific electrical conduc-

tivity, turbidity, and TOC content in the treated wastewater. The results are presented in Figures 15–18.



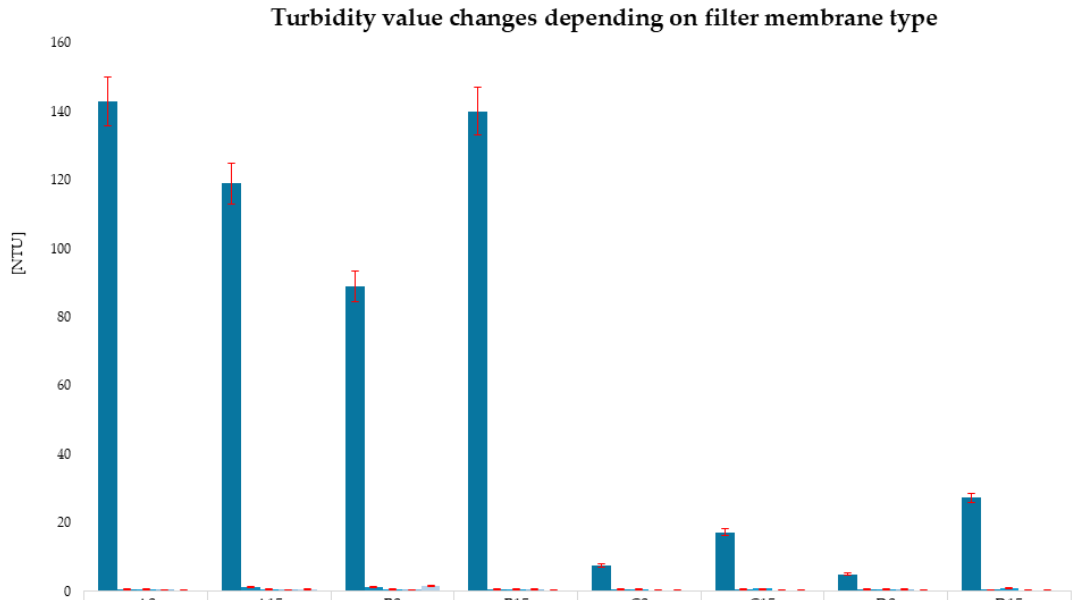
	A8	A15	B8	B15	C8	C15	D8	D15
Before membrane filtration (after biological treatment)	5.46	5.40	5.34	5.08	5.55	5.33	6.62	5.83
CA 0.20 µm	5.45	5.39	5.18	5.08	5.40	5.44	6.66	5.99
CA 0.45 µm	5.31	5.27	5.16	5.09	5.56	5.54	6.83	6.04
CN-CA 0.45 µm	5.18	5.27	5.15	5.04	5.69	5.60	6.87	6.07
CN 0.20 µm	5.13	5.37	5.15	5.07	5.74	5.61	6.87	6.07

Figure 15. Changes in pH values before and after further treatment, depending on the type of filter membrane used (own elaboration).



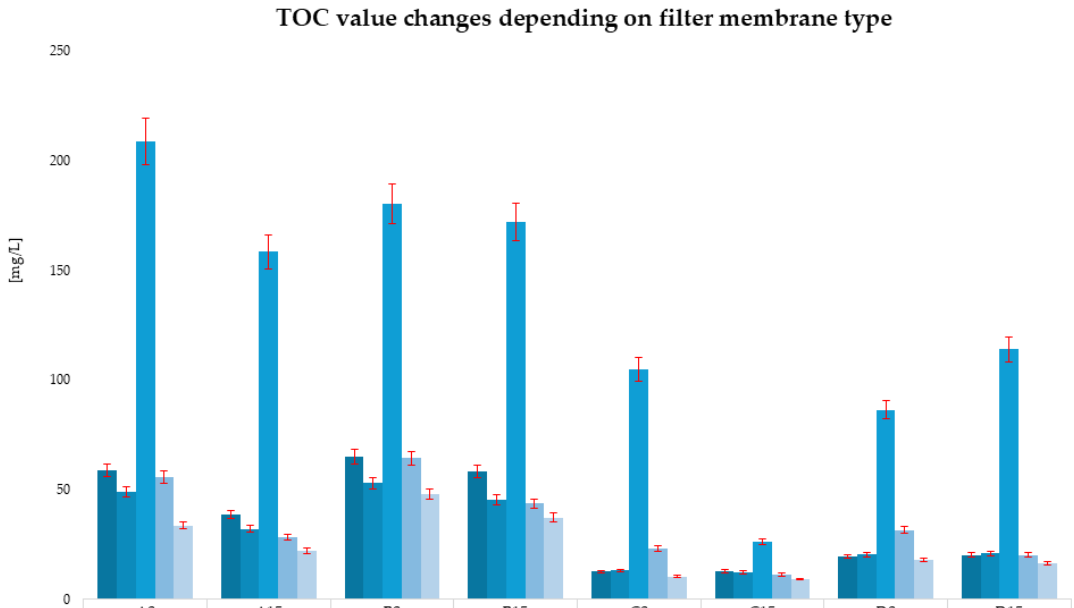
	A8	A15	B8	B15	C8	C15	D8	D15
Before membrane filtration (after biological treatment)	823.80	924.80	725.70	10,618.00	513.10	650.40	395.90	656.10
CA 0.20 µm	833.40	797.00	644.10	916.20	483.00	592.20	367.10	592.00
CA 0.45 µm	785.50	809.00	663.70	915.30	481.10	578.60	382.80	585.20
CN-CA 0.45 µm	789.50	803.70	676.50	923.80	491.20	596.10	387.00	588.60
CN 0.20 µm	767.00	777.80	660.90	910.90	498.80	589.20	393.00	595.60

Figure 16. Changes in conductivity values before and after further treatment, depending on the type of filter membrane used (own elaboration).



	A8	A15	B8	B15	C8	C15	D8	D15
Before membrane filtration (after biological treatment)	143.00	119.00	89.10	140.00	7.57	17.30	5.02	27.30
CA 0.20 µm	0.65	1.37	1.41	0.57	0.62	0.60	0.70	0.55
CA 0.45 µm	0.69	0.68	0.60	0.65	0.62	0.78	0.69	0.93
CN-CA 0.45 µm	0.49	0.51	0.48	0.69	0.34	0.35	0.56	0.35
CN 0.20 µm	0.41	0.58	1.56	0.39	0.32	0.26	0.39	0.33

Figure 17. Changes in turbidity values before and after further treatment, depending on the type of filter membrane used (own elaboration).



	A8	A15	B8	B15	C8	C15	D8	D15
Before membrane filtration (after biological treatment)	59.02	38.73	65.08	58.49	12.75	12.91	19.63	20.31
CA 0.20 µm	48.94	32.08	53.07	45.60	13.15	12.37	20.40	21.04
CA 0.45 µm	208.90	158.50	180.50	172.30	105.00	26.25	86.51	114.10
CN-CA 0.45 µm	55.74	28.31	64.46	43.78	23.16	11.35	31.60	20.17
CN 0.20 µm	33.81	22.18	48.11	37.39	10.45	9.21	18.08	16.65

Figure 18. Changes in total organic carbon values before and after further treatment, depending on the type of filter membrane used (own elaboration).

Figure 15 shows changes in the pH of the wastewater after the membrane filtration process as a function of the type of membrane used. Regardless of the membrane type, samples from systems operating under alternating aeration and mixing conditions (C and D) showed a slight increase in pH after filtration. In contrast, in samples from reactors operating under continuous aeration and mixing conditions (A and B), a slight decrease in pH was observed compared to samples after biological treatment.

The observed differences were likely due to the varying chemical composition of the effluent from the different biological treatment systems. In the systems with alternating aeration and mixing (C and D), the presence of denitrification products and the higher buffer capacity of the effluent may have contributed to a slight increase in pH after filtration. In contrast, in samples from continuously aerated and mixed systems (A and B), a slight decrease in pH may have been associated with a greater contribution from nitrification processes, leading to the consumption of alkalinity and the formation of hydrogen ions. It is worth noting that denitrification can partially restore the alkalinity consumed during nitrification, thereby influencing the acid-base balance of the wastewater [65].

At the same time, the microfiltration process itself should not directly affect the acid-base balance of the solution, since it primarily removes suspended and colloidal particles, rather than the dissolved ions responsible for the pH value. Similar separation limitations are characteristic of microfiltration membranes, whose primary function is to retain particles larger than the effective pore size of the membrane [66]. This is further confirmed by the absence of significant differences between the various types of membranes used, indicating that neither their material nor their pore sizes (0.2 and 0.45 μm) had a significant effect on the pH of the treated wastewater.

Figure 16 shows the changes in the specific electrolytic conductivity of wastewater after membrane filtration, depending on the type of membrane used. Regardless of the type of membrane used, all analyzed samples showed a slight decrease in conductivity after filtration compared to samples after biological treatment. The exception was the sample from reactor B15, which came from a system operating at an HRT of 15 days, with continuous aeration and mixing for 22 h, and treating wastewater with the addition of a model contaminant; for this sample, a more pronounced decrease in conductivity was observed.

A slight decrease in conductivity following membrane filtration may be associated with the retention of fine suspended particles and colloidal matter, as well as with changes in the composition of the filtrate resulting from the formation of a filtration layer on the membrane surface. However, microfiltration is not primarily designed to remove dissolved inorganic ions, which are the main contributors to electrolytic conductivity. In contrast, the removal of dissolved salts is mainly achieved using more selective membrane processes, such as nanofiltration and reverse osmosis [66,67]. Therefore, the relatively minor changes observed in the present study are consistent with the expected separation characteristics of microfiltration membranes with pore sizes of 0.2 and 0.45 μm.

The more pronounced decrease in conductivity observed in sample B15 may be related to differences in the physicochemical composition of the wastewater after biological treatment. A higher content or different size distribution of colloidal particles could have affected the formation and structure of the filtration layer, potentially enhancing the retention of colloidal and associated organic or inorganic matter [67,68]. Nevertheless, since the ionic composition of the samples and the characteristics of the retained material were not determined, this explanation should be considered a possible interpretation rather than a confirmed mechanism. Natural variations in wastewater composition may also have contributed to the observed difference.

No significant differences were found between the various types of membranes used, indicating that neither the membrane material nor the pore size had a significant effect on the change in specific electrolytic conductivity. The results confirm that the microfiltration process is primarily responsible for the removal of suspended solids and colloidal particles, while its effect on the concentration of dissolved ionic components is limited.

Figure 17 shows the changes in wastewater turbidity after the membrane filtration process, depending on the type of membrane used. Regardless of the type of membrane used, a marked decrease in turbidity was observed in all analyzed samples compared to samples after biological treatment. Comparable results were obtained in all filtration variants, and the final turbidity value did not exceed 2 NTU.

The significant reduction in turbidity resulted primarily from the effective retention of suspended solids and colloidal particles responsible for light scattering and reduced wastewater clarity. Microfiltration membranes with pore sizes of 0.2 and 0.45 µm separate particles mainly through a sieving mechanism, retaining particles larger than the effective pore size, as well as a fraction of colloidal matter [66,67]. Consequently, the obtained turbidity values below 2 NTU indicate the high effectiveness of the applied filtration process in removing particulate matter from biologically treated wastewater.

The absence of significant differences between the various membrane types suggests that cellulose nitrate (CN), cellulose acetate (CA), and mixed cellulose ester (CN-CA) membranes provided comparable turbidity reduction under the applied experimental conditions. This indicates that, in the present study, the dominant factor determining turbidity reduction was particle retention during microfiltration rather than the differences in membrane material. The results confirm the suitability of membrane filtration as a post-treatment stage for biologically treated wastewater, ensuring effective removal of suspended solids prior to final disinfection.

Low turbidity in treated wastewater is particularly important for the subsequent UV disinfection stage. Suspended particles can scatter or absorb UV radiation and may shield microorganisms associated with particulate matter, thereby reducing the effectiveness of their inactivation [69,70]. Therefore, the substantial reduction in turbidity achieved during membrane filtration may contribute to more favorable conditions for subsequent UV disinfection.

Figure 18 shows the changes in the TOC values of wastewater after the membrane filtration process, depending on the type of membrane used. Unlike the other parameters analyzed, in the case of TOC, a clear influence of the membrane type on the efficiency of the filtration process was observed.

The lowest efficiency in removing organic compounds was observed for the CA membrane with a pore diameter of 0.45 µm. In all analyzed samples, the TOC value was higher after using this membrane than before the filtration process. A similar effect was observed for the CN-CA membrane with a pore diameter of 0.45 µm in samples from reactors C8 and D8, which represented systems operating at an HRT of 8 days with alternating aeration and mixing, without and with the addition of a model contaminant, respectively. In the remaining experimental variants, the filtration process led to a reduction in TOC values; however, the degree of reduction varied depending on the membrane type.

The increase in TOC values after filtration, observed primarily for the CA membrane with a pore diameter of 0.45 µm, may indicate the release of small amounts of organic compounds from the membrane material or other materials associated with its storage and preparation. Such a possibility should be considered when interpreting organic carbon measurements following membrane filtration. Nevertheless, this explanation cannot be confirmed without additional control tests using the membrane and organic-carbon-free water. Differences in the interactions between dissolved organic matter and the membrane

surface, including adsorption and the formation of an organic fouling layer, may also influence the observed filtration performance [71,72]. Additionally, the larger pore diameter (0.45 µm) may have limited the retention of fine colloidal particles containing organic matter, contributing to the lower TOC removal efficiency [66].

The highest TOC removal efficiency, considering all the biological treatment variants analyzed (A–D), was achieved using a CN membrane with a pore diameter of 0.20 µm. This result suggests that the smaller pore size, combined with the surface properties of the membrane material, favored the retention of fine colloidal particles and organic matter associated with suspended solids. The separation efficiency of microfiltration membranes depends not only on pore size but also on membrane surface characteristics and interactions between the membrane and organic foulants [66,71,72]. The results confirm that the selection of an appropriate membrane material and pore size can influence the removal of particulate and colloidal organic matter. However, microfiltration is not primarily designed to retain dissolved organic compounds with low molecular weights, which may pass through the membrane pores [66].

In summary, the membrane filtration process effectively improved the quality of biologically treated wastewater; however, the effect of the type of membrane used depended on the parameter being analyzed. Neither the membrane material nor its pore size had a significant effect on the pH, specific electrical conductivity, or turbidity of the treated wastewater. Comparable values for these parameters were obtained in all tested variants, confirming that microfiltration primarily removes suspended solids and colloidal particles without significantly affecting the concentration of dissolved ions or the acid-base balance of the solution. Significant differences between the tested membranes were, however, observed for TOC, whose removal efficiency depended on both the membrane material and the pore size. The best results were obtained for the CN membrane with a pore diameter of 0.20 µm, while the CA membrane with a pore diameter of 0.45 µm showed the lowest efficiency in removing organic matter.

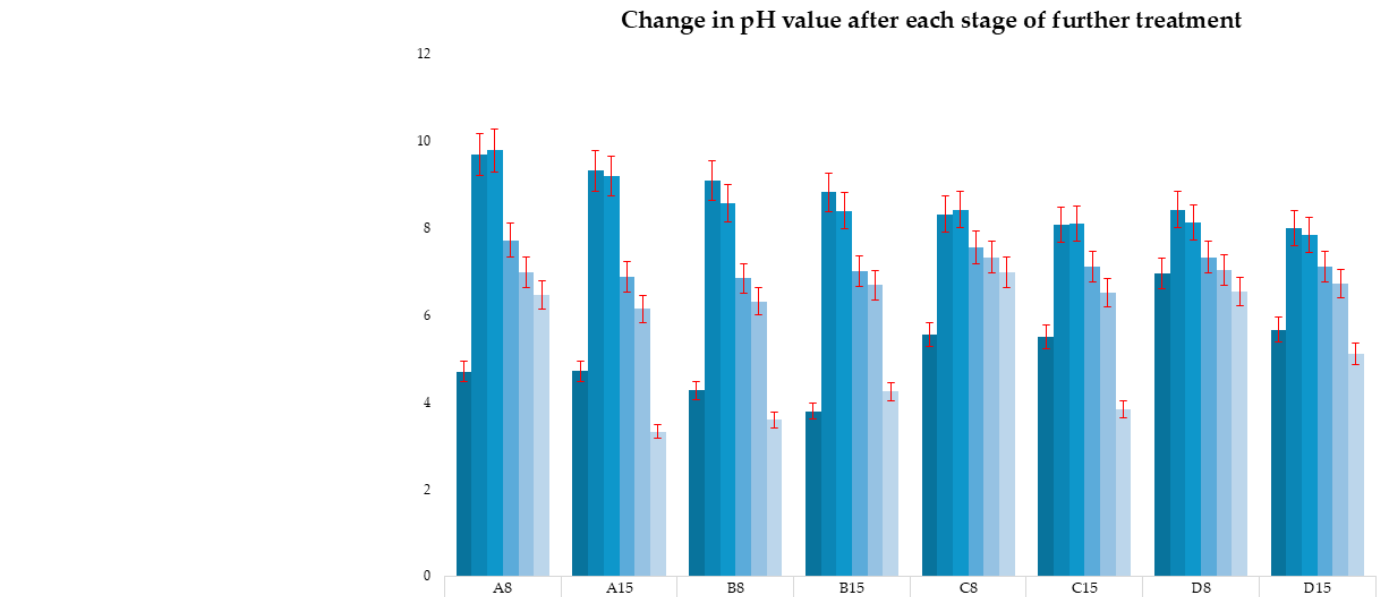
Despite the high efficiency of membrane filtration in removing suspended solids and turbidity, the results obtained in this research indicate that it is more appropriate to use activated carbon sorption before the microfiltration process than the reverse process configuration. Sorption enables the effective removal of a significant portion of dissolved organic compounds, which are not effectively retained by microfiltration membranes and are simultaneously responsible for the formation of precipitates and membrane fouling. Reducing the concentration of organic matter prior to the filtration stage limits the rate of membrane pore clogging, improves process stability, and can extend the service life of the membrane modules. Subsequently, microfiltration effectively removes the remaining suspended solids and fine colloidal particles, ensuring low turbidity in the wastewater, which creates particularly favorable conditions for the final disinfection process, especially when using UV radiation.

Based on the results obtained, a CN membrane with a pore diameter of 0.20 µm was selected for further research using an integrated wastewater treatment system with the addition of a model contaminant. This membrane provided the highest TOC removal efficiency while maintaining high turbidity removal efficiency and having no adverse effect on pH and specific electrical conductivity. The results indicate that, among the analyzed options, this membrane was the best solution for use in the final integrated wastewater treatment system, which includes biological treatment, activated carbon sorption, membrane filtration, and two-stage disinfection.

3.4. Integration of Biological Wastewater Treatment with Sorption, Membrane Filtration, and Two-Stage Disinfection

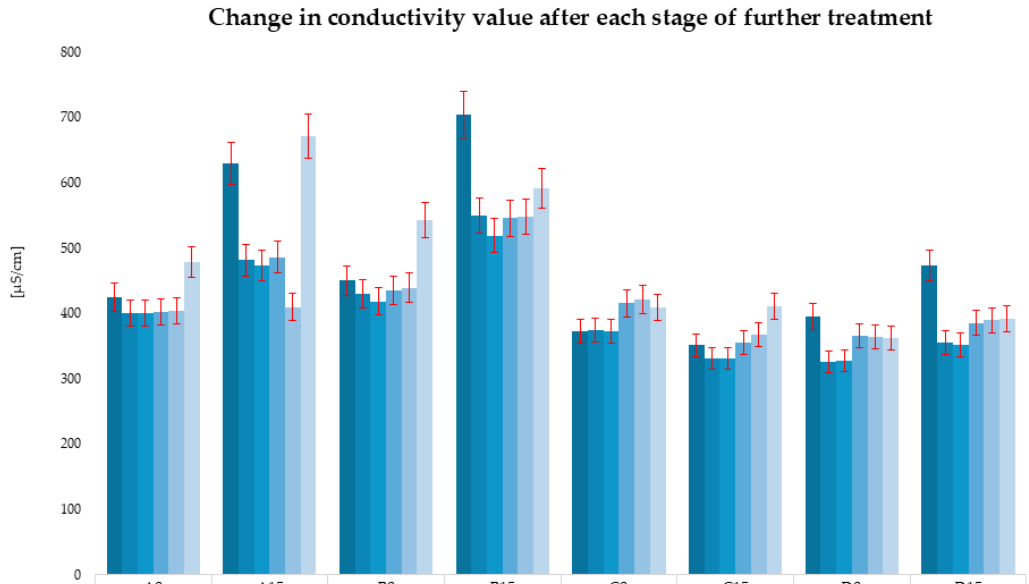
Based on the research results presented in Sections 3.1–3.3, a model integrated wastewater treatment system was developed for wastewater containing coffee bean extract at a concentration of 1 g/L. To comprehensively evaluate the effectiveness of the proposed technology, a complete, multi-stage treatment process was carried out for all analyzed biological treatment variants, including SBR reactors operating under various aeration and mixing conditions, with two HRT variants (8 and 15 days), both in the presence and absence of model pollutants (systems A8–D15).

After biological treatment, the wastewater underwent sorption on WACC activated carbon using a filtration column filled to a height of 40 cm with a sorption bed. The samples were then further treated by membrane filtration using a cellulose nitrate (CN) membrane with a pore diameter of 0.20 µm. After filtration, each sample was divided into three parts, which were subjected to the final stage of the integrated treatment system—a two-stage disinfection process consisting of ozonation for 15, 30, and 45 min, followed by exposure to UV radiation for 15 min. The objective of this stage was to determine the most favorable ozonation duration, ensuring effective disinfection and the sanitary safety of the treated wastewater while preserving its beneficial physicochemical properties. After each stage of the process, the pH, specific electrical conductivity, turbidity, phosphate concentration, ammonium nitrogen concentration, and TOC content were measured. The results are presented in Figures 19–24.



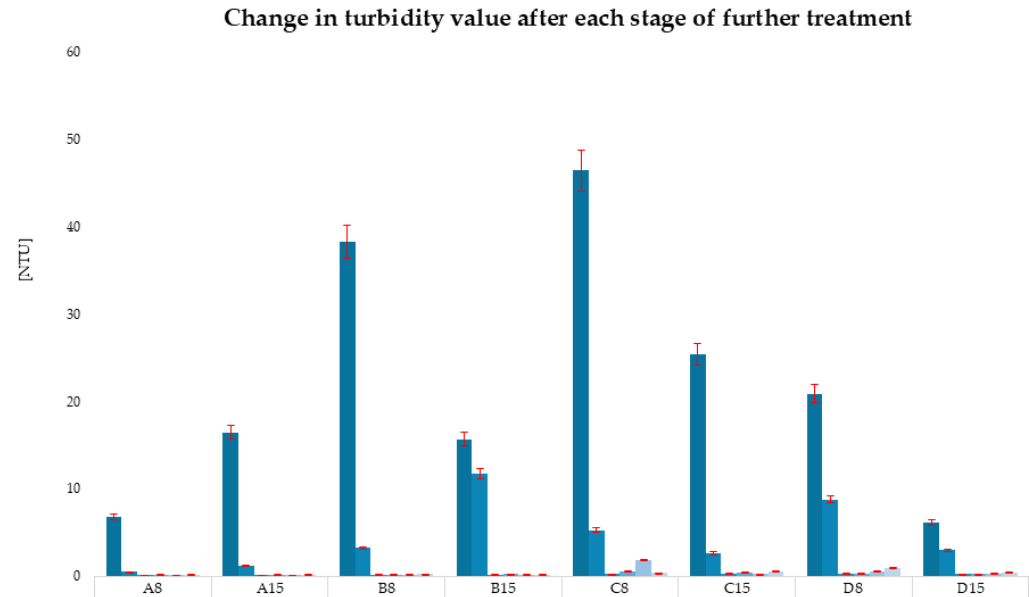
	A8	A15	B8	B15	C8	C15	D8	D15
After biological treatment	4.70	4.72	4.27	3.80	5.56	5.51	6.97	5.67
After biological treatment and sorption	9.70	9.33	9.11	8.83	8.32	8.07	8.43	8.00
After biological treatment, sorption, and filtration	9.79	9.21	8.57	8.40	8.43	8.10	8.14	7.85
After integrated treatment and disinfection (ozone 15 + UV 15)	7.73	6.88	6.85	7.02	7.55	7.12	7.34	7.12
After integrated treatment and disinfection (ozone 30 + UV 15)	6.99	6.15	6.32	6.69	7.33	6.51	7.05	6.73
After integrated treatment and disinfection (ozone 45 + UV 15)	6.47	3.33	3.60	4.25	6.98	3.84	6.54	5.11

Figure 19. Changes in pH values after each stage of further treatment (own elaboration).



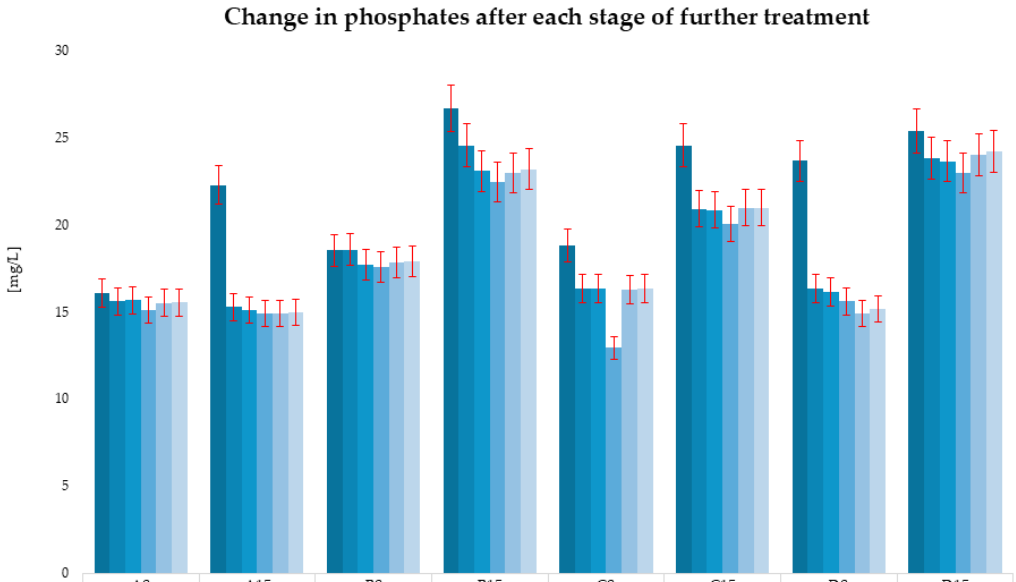
	A8	A15	B8	B15	C8	C15	D8	D15
After biological treatment	424.60	629.80	450.40	703.80	373.10	351.10	395.90	473.80
After biological treatment and sorption	400.90	481.50	429.90	549.60	374.70	331.80	326.10	355.80
After biological treatment, sorption, and filtration	400.10	472.90	418.60	519.10	373.10	331.30	327.10	352.10
After integrated treatment and disinfection (ozone 15 + UV 15)	402.40	486.30	434.40	545.60	416.10	355.40	365.40	385.70
After integrated treatment and disinfection (ozone 30 + UV 15)	404.50	409.70	439.50	548.10	421.60	367.30	363.90	389.40
After integrated treatment and disinfection (ozone 45 + UV 15)	478.80	671.70	543.10	591.40	409.40	410.90	362.80	391.50

Figure 20. Changes in conductivity values after each stage of further treatment (own elaboration).



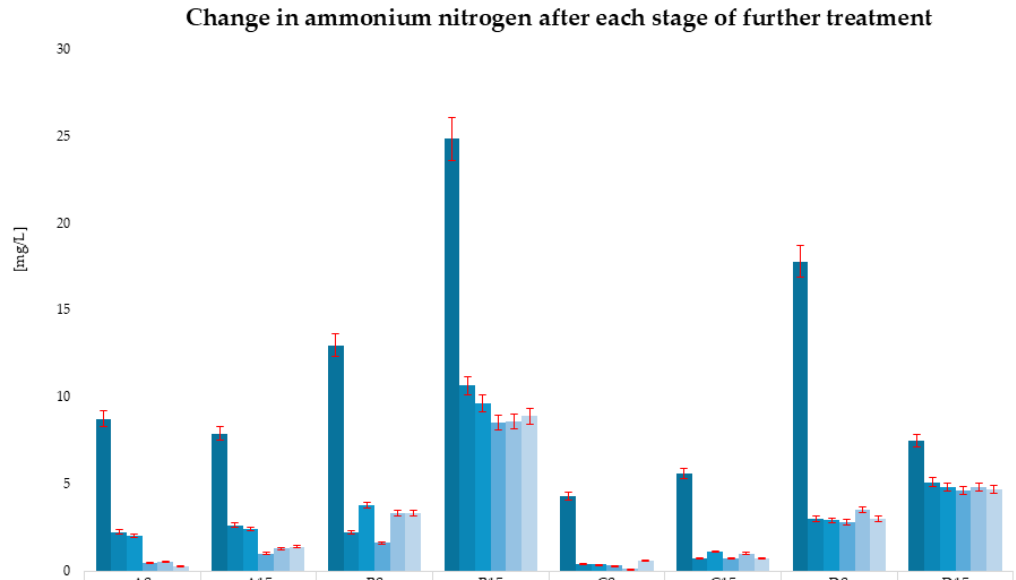
	A8	A15	B8	B15	C8	C15	D8	D15
After biological treatment	6.81	16.50	38.30	15.70	46.46	25.40	20.90	6.18
After biological treatment and sorption	0.51	1.24	3.24	11.80	5.30	2.65	8.83	3.00
After biological treatment, sorption, and filtration	0.13	0.16	0.21	0.20	0.27	0.30	0.31	0.29
After integrated treatment and disinfection (ozone 15 + UV 15)	0.21	0.18	0.19	0.25	0.57	0.46	0.31	0.26
After integrated treatment and disinfection (ozone 30 + UV 15)	0.16	0.14	0.20	0.20	1.88	0.26	0.54	0.30
After integrated treatment and disinfection (ozone 45 + UV 15)	0.21	0.19	0.25	0.21	0.40	0.56	0.93	0.43

Figure 21. Changes in turbidity values after each stage of further treatment (own elaboration).



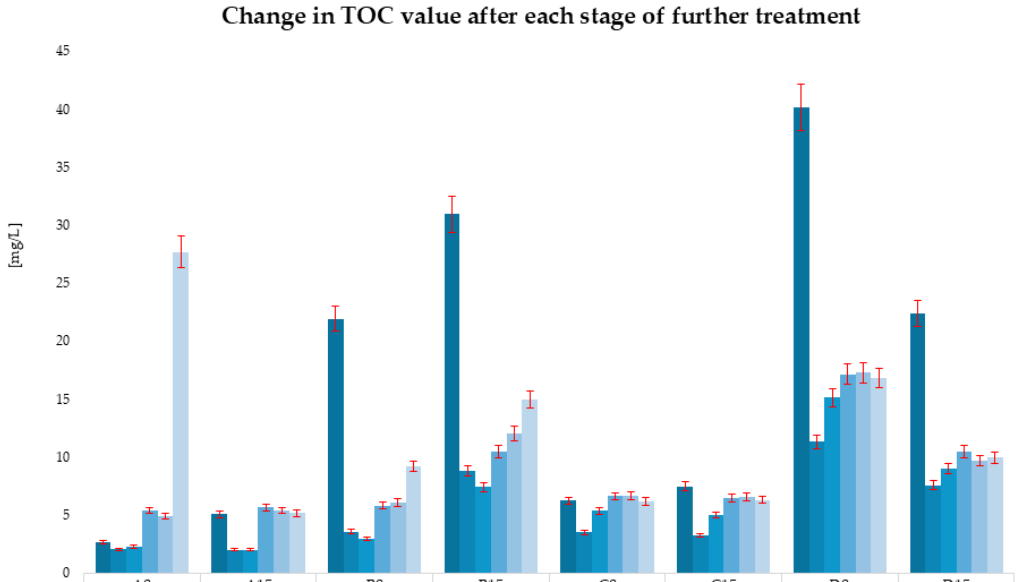
	A8	A15	B8	B15	C8	C15	D8	D15
After biological treatment	16.08	22.29	18.53	26.68	18.81	24.57	23.67	25.37
After biological treatment and sorption	15.62	15.28	18.58	24.57	16.36	20.92	16.36	23.83
After biological treatment, sorption, and filtration	15.68	15.11	17.73	23.09	16.36	20.86	16.13	23.66
After integrated treatment and disinfection (ozone 15 + UV 15)	15.11	14.94	17.61	22.46	12.94	20.07	15.62	22.97
After integrated treatment and disinfection (ozone 30 + UV 15)	15.51	14.94	17.84	22.97	16.30	20.98	14.94	24.00
After integrated treatment and disinfection (ozone 45 + UV 15)	15.56	14.99	17.90	23.20	16.36	20.98	15.16	24.23

Figure 22. Changes in phosphate values after each stage of further treatment (own elaboration).



	A8	A15	B8	B15	C8	C15	D8	D15
After biological treatment	8.75	7.88	12.98	24.85	4.30	5.60	17.80	7.50
After biological treatment and sorption	2.24	2.63	2.23	10.65	0.42	0.70	3.00	5.10
After biological treatment, sorption, and filtration	2.01	2.40	3.78	9.62	0.36	1.10	2.90	4.80
After integrated treatment and disinfection (ozone 15 + UV 15)	0.44	1.00	1.60	8.50	0.30	0.70	2.80	4.60
After integrated treatment and disinfection (ozone 30 + UV 15)	0.52	1.30	3.30	8.60	0.10	1.00	3.50	4.80
After integrated treatment and disinfection (ozone 45 + UV 15)	0.26	1.40	3.30	8.90	0.60	0.70	3.00	4.70

Figure 23. Changes in ammonium nitrogen values after each stage of further treatment (own elaboration).



	A8	A15	B8	B15	C8	C15	D8	D15
After biological treatment	2.65	5.07	21.93	30.94	6.26	7.49	40.15	22.39
After biological treatment and sorption	2.07	2.03	3.59	8.79	3.51	3.28	11.34	7.59
After biological treatment, sorption, and filtration	2.28	2.01	2.97	7.42	5.37	5.01	15.14	8.98
After integrated treatment and disinfection (ozone 15 + UV 15)	5.41	5.68	5.80	10.51	6.63	6.51	17.16	10.49
After integrated treatment and disinfection (ozone 30 + UV 15)	4.94	5.38	6.08	12.04	6.70	6.60	17.30	9.70
After integrated treatment and disinfection (ozone 45 + UV 15)	27.71	5.16	9.20	14.98	6.19	6.32	16.79	9.95

Figure 24. Changes in total organic carbon values after each stage of further treatment (own elaboration).

Figure 19 shows the changes in pH values occurring after successive stages of the integrated wastewater treatment system in all analyzed systems (A8–D15). Regardless of the biological treatment variant, a similar trend in pH changes was observed. The application of activated carbon sorption followed by membrane filtration resulted in a significant increase in pH values. This phenomenon may be associated with the physicochemical properties of activated carbon, particularly its surface functional groups and acid-base characteristics, which can influence the pH of the treated solution [57]. The possible release of mineral components from activated carbon may also contribute to changes in the pH of the wastewater [73]. Additionally, the adsorption of some acidic organic compounds present in the wastewater may have contributed to the observed increase in pH.

A different effect was observed following the disinfection stage. Ozonation, particularly at longer contact times, was accompanied by a gradual decrease in pH. This may be related to the strong oxidizing properties of ozone, which reacts with organic compounds and transforms them into lower-molecular-weight products, including aldehydes and carboxylic acids [74,75]. The formation of such acidic oxidation products may contribute to an increase in hydrogen ion concentration and, consequently, a decrease in pH. Ozonation also changes the molecular structure and properties of dissolved organic matter, reducing its apparent molecular weight and aromaticity [76]. The additional changes observed after UV irradiation may have been associated with further photochemical reactions, potentially involving residual oxidants; however, their individual contribution to the pH variation could not be determined in the present research.

Among the disinfection options analyzed, the most favorable pH values were obtained after 30 min of ozonation followed by 15 min of UV radiation. In this case, the pH of the treated wastewater remained close to neutral (approximately 7.0), which represents a favorable condition from the perspective of the chemical stability of the treated water and its potential further use. In contrast, extending the ozonation time to 45 min resulted in a marked decrease in pH in all analyzed systems. This observation may indicate more extensive formation of acidic oxidation products during prolonged ozone exposure. The

results suggest that extending the ozonation time beyond 30 min did not provide additional benefits in terms of maintaining a near-neutral pH and may adversely affect this parameter.

Figure 20 shows the changes in specific electrolytic conductivity that occur after successive stages of the integrated wastewater treatment system in all analyzed systems (A8–D15).

The application of activated carbon sorption followed by membrane filtration resulted in a decrease in specific conductivity. This decrease may be associated with changes in the ionic composition of the treated wastewater during contact with activated carbon, as well as with the retention of colloidal particles and suspended matter that may contain ion-associated compounds. The physicochemical properties of activated carbon, including its surface functional groups and mineral composition, can influence interactions with dissolved substances. In particular, the potential release or retention of inorganic ions may depend on the properties of the carbon material and the pH of the solution [73]. However, the individual contribution of these processes could not be determined in the present research. Membrane filtration may have additionally contributed to the observed decrease by retaining colloidal particles and suspended matter. Nevertheless, the relatively small changes in conductivity are consistent with the characteristics of the microfiltration process, which primarily removes particles and colloids rather than freely dissolved ions and low-molecular-weight substances [66].

In contrast, an increase in specific conductivity was observed after the disinfection stage. The increase became more pronounced with prolonged ozonation time. This phenomenon may be associated with changes in the chemical composition of the wastewater resulting from ozone-induced oxidation of residual organic compounds. Ozonation can transform complex organic molecules into lower-molecular-weight products, including aldehydes and carboxylic acids [74]. Some of these products may occur in dissociated forms in aqueous solutions and thus contribute to the ionic content of the treated wastewater. Previous studies have also reported increases in conductivity during the ozonation of aqueous solutions of organic compounds, despite a simultaneous reduction in organic matter indicators [8,77]. Nevertheless, the observed increase in conductivity does not directly demonstrate more extensive mineralization of organic matter, nor does it identify the specific ionic species responsible for this change. Their contribution would require additional analyses of the ionic composition of the wastewater.

Among the disinfection variants analyzed, the most favorable conductivity values were obtained after 30 min of ozonation followed by 15 min of UV irradiation. In contrast, extending the ozonation time to 45 min resulted in a further increase in conductivity in all analyzed systems. These results indicate that prolonged ozone exposure was accompanied by less favorable changes in the ionic composition of the treated wastewater, as reflected by the conductivity measurements. Therefore, the combination of 30 min of ozonation and 15 min of UV irradiation may represent a more favorable option in terms of limiting the increase in specific conductivity. However, the observed conductivity changes alone do not allow conclusions to be drawn about the extent of organic matter mineralization or the individual contribution of ozonation and UV irradiation to the formation of ionic products.

Figure 21 shows the changes in turbidity values occurring after successive stages of the integrated wastewater treatment system in all analyzed systems (A8–D15).

In all tested variants, the application of activated carbon sorption followed by membrane filtration resulted in a significant reduction in turbidity, reaching values below 1 NTU. This effect can be attributed to the combined contribution of both treatment processes. The activated carbon bed may reduce turbidity through the retention of suspended and colloidal particles within the filter bed, while adsorption contributes to the removal of selected organic compounds present in the wastewater [60]. Membrane filtration provides an additional physical separation barrier, retaining residual suspended matter and particles

depending on their size and the membrane characteristics [66]. The combined application of these processes therefore resulted in high clarification efficiency, regardless of the biological treatment variant used.

The disinfection stage had only a minor effect on turbidity, which is consistent with its primary purpose of inactivating microorganisms rather than removing suspended particles. Nevertheless, the removal of particles before disinfection is beneficial, particularly for UV treatment, as suspended matter may shield microorganisms from UV radiation and reduce disinfection efficiency [70]. Consequently, after completion of the entire integrated treatment sequence, turbidity values remained below 2 NTU in all analyzed systems. These results confirm the high clarification efficiency of the applied treatment sequence and the maintenance of low turbidity in the final treated wastewater.

Figure 22 shows the changes in phosphate concentration occurring at successive stages of the integrated wastewater treatment system in all analyzed systems (A8–D15).

The application of activated carbon sorption, followed by membrane filtration and two-stage disinfection, resulted in a further, although relatively limited, reduction in phosphate concentrations. The final concentrations at the end of the entire treatment process ranged from 13.0 to 24.0 mg/L, depending on the biological treatment variant applied. Slightly lower final concentrations were observed in the systems operated at an HRT of 8 days. However, this difference should be interpreted as an experimental observation rather than direct evidence of a beneficial effect of shorter HRT on biological phosphorus removal.

The analysis of the results indicated that biological treatment was the main stage associated with phosphate reduction. The subsequent unit processes—activated carbon sorption, membrane filtration, and disinfection—contributed only to a limited additional decrease in phosphate concentrations. This can be explained by the characteristics of the applied treatment methods. Activated carbon may contribute to phosphate removal through adsorption, although its effectiveness depends on the surface properties and chemical composition of the adsorbent [78]. Membrane filtration may additionally retain phosphorus associated with suspended solids and colloidal particles, whereas freely dissolved phosphate ions are generally not effectively removed by microfiltration [79]. The limited changes observed during the final treatment stages are therefore consistent with the predominant role of biological treatment in reducing phosphate concentrations in the analyzed wastewater. Biological phosphorus removal may involve microbial uptake and intracellular phosphorus accumulation; however, the specific contribution of these mechanisms was not determined in the present study [41].

The differences observed between systems with HRT values of 8 and 15 days, as well as between the applied SBR operating configurations, indicate that the phosphate concentrations achieved after biological treatment were influenced by the operating conditions of the biological stage. Nevertheless, the available results do not allow the individual contribution of HRT, aeration and mixing conditions, or specific microbial mechanisms to be distinguished. The findings emphasize the importance of appropriate biological process configuration for phosphate reduction in the investigated treatment system.

Figure 23 shows the changes in ammonium nitrogen concentration occurring at successive stages of the integrated wastewater treatment system in all analyzed systems (A8–D15).

The application of activated carbon sorption, followed by membrane filtration and disinfection, resulted in a further reduction in ammonium nitrogen concentrations in the analyzed samples. Slightly lower final concentrations were observed in the systems operated at an HRT of 8 days. However, this difference should be interpreted as an experimental observation rather than direct evidence of a beneficial effect of shorter HRT on nitrogen removal. At the same time, higher ammonium nitrogen concentrations were observed in systems supplied with wastewater containing the model coffee-derived contaminant

compared with systems without this additive. This may be associated with the higher organic load, which could affect the conditions for nitrification, as well as with the possible release of ammonium ions through the ammonification of organic nitrogen compounds present in the coffee extract. Similar phenomena have been discussed in previous studies on the treatment of wastewater containing coffee-derived compounds [8].

The analysis of the results indicated that biological treatment played an important role in the transformation and reduction of ammonium nitrogen. The subsequent unit processes, particularly activated carbon sorption, contributed to an additional decrease in its concentration. Activated carbon may retain ammonium ions, although the effectiveness of this process depends on the physicochemical properties of the adsorbent and the operating conditions [80]. Membrane filtration may additionally remove nitrogen associated with suspended solids and biomass, whereas freely dissolved ammonium ions are not effectively retained by microfiltration. The observed changes in ammonium nitrogen concentrations therefore reflect the combined effects of biological transformations and subsequent physicochemical treatment processes.

The differences observed between systems with HRT values of 8 and 15 days and between the applied SBR operating configurations indicate that the ammonium nitrogen concentrations achieved were influenced by the biological treatment conditions. Intermittent aeration can create alternating aerobic and anoxic conditions, potentially supporting different stages of nitrogen transformation; however, the individual contributions of nitrification and denitrification could not be determined in the present research without measurements of nitrite and nitrate concentrations [45]. The results indicate the need for further refinement of SBR operating conditions to improve nitrogen removal. Additional investigations, including the determination of nitrite, nitrate, and total nitrogen concentrations, would be necessary to assess the overall nitrogen removal efficiency and the potential of the treated wastewater for discharge or further use.

Figure 24 shows the changes in TOC values occurring at successive stages of the integrated wastewater treatment system in all analyzed systems (A8–D15).

In systems where biological treatment involved continuous aeration and mixing for 22 h (A–B), a systematic decrease in TOC values was observed as the subsequent treatment stages progressed. Activated carbon sorption contributed to the removal of organic matter remaining after biological treatment, while subsequent membrane filtration provided an additional separation step. However, after disinfection using ozone and UV radiation, a slight increase in TOC values was observed. This increase was more pronounced with longer ozonation times. One possible explanation is the transformation of complex organic compounds into smaller oxidation products. Ozonation can reduce the apparent molecular weight and aromaticity of dissolved organic matter without necessarily causing its complete mineralization [74,76]. Moreover, the solubilization of particulate or colloidal organic matter may contribute to an increase in the dissolved organic carbon fraction during ozonation [81]. Therefore, the observed increase may reflect changes in the composition and distribution of organic matter rather than an increase in the total amount of organic carbon.

A different trend was observed in systems where alternating aeration and mixing phases (C–D) were applied during biological treatment. As in systems A–B, activated carbon sorption resulted in a decrease in TOC values. However, subsequent membrane filtration was accompanied by a slight increase in TOC. This observation may be associated with the passage of dissolved organic compounds through the membrane, particularly low-molecular-weight fractions that are not effectively retained by microfiltration membranes [66,82]. Nevertheless, differences in sample composition and analytical variability cannot be excluded. After disinfection, a further slight increase in TOC was observed, with a more pronounced effect at longer ozonation times. As in systems A–B, this trend

may be related to the partial oxidation and solubilization of organic matter, leading to the formation or release of dissolved intermediate products rather than its complete mineralization [74,76,81].

Regardless of the biological treatment variant used, the final TOC values were higher in systems supplied with wastewater containing the added model contaminant than in systems without this addition. This indicates that the additional organic load associated with the coffee extract resulted in a higher residual organic carbon concentration after the integrated treatment process, despite the contribution of the subsequent treatment stages to organic matter removal.

Table 4 presents the results of microbiological analyses of wastewater samples collected after biological treatment and after completion of the entire integrated treatment process, which included biological treatment, activated carbon sorption, membrane filtration, and disinfection using ozonation (15, 30, and 45 min) and final UV radiation for 15 min. Microbiological analyses were performed using the surface plating method on appropriate microbiological media to evaluate the effectiveness of the treatment system in ensuring the sanitary safety of the treated wastewater.

The scope of the research included the determination of the total microbial count (bacteria and fungi), the presence of *Escherichia coli*, the presence of bacteria of the genera *Salmonella* and *Shigella*, and the presence of fungi and yeasts. Each analyzed sample underwent three independent microbiological replicates. A conservative criterion for assessing sanitary safety was adopted, according to which the detection of microbial growth in at least one of the three replicates meant that the sample was considered microbiologically positive. Consequently, such samples were marked in the table as failing to meet the sanitary safety criterion.

All samples collected after biological treatment showed the presence of total microorganisms, *Escherichia coli*, bacteria of the genera *Salmonella* and *Shigella*, as well as fungi and yeasts. These results indicate that the biological treatment process alone, despite its effective removal of physicochemical contaminants, does not ensure adequate elimination of microorganisms, which confirms the need for a final disinfection step. Similar observations have been reported in research on biologically treated wastewater, demonstrating that biological treatment does not necessarily provide sufficient microbial inactivation and that additional disinfection is required to improve the microbiological quality of the effluent [83,84].

In samples subjected to a fully integrated treatment process with disinfection comprising 15 min of ozonation and 15 min of UV radiation, no *Escherichia coli*, bacteria of the genera *Salmonella* and *Shigella*, or fungi and yeasts were detected. However, microbial growth was still observed on PCA medium in half of the analyzed samples, indicating the presence of some microorganisms not detected on selective media. According to the established evaluation criteria, the presence of growth in at least one of the three replicates resulted in the sample being classified as failing to meet sanitary safety requirements. This means that the ozonation time used was insufficient to completely inactivate all microflora present in the treated wastewater. The differences in susceptibility of microbial groups to disinfection processes may contribute to such observations, as previous studies have demonstrated that the effectiveness of UV radiation and ozonation varies depending on the microorganisms present [8,84,85].

Increasing the ozonation time to 30 and 45 min, while maintaining 15 min of UV radiation, led to the complete elimination of microorganisms in all analyzed samples. No increase in the total microbial count on the PCA medium was observed, nor was the presence of *Escherichia coli*, bacteria of the genera *Salmonella* and *Shigella*, or fungi and yeasts detected in any of the three replicates. These results demonstrate the high microbiological effectiveness of the applied treatment under the tested cultivation conditions. This observation is consis-

tent with previous studies indicating that the effectiveness of ozone disinfection depends on the applied ozone dose and exposure conditions [8,85,86]. The results obtained in the present study indicate that extending the ozonation time from 15 to at least 30 min was sufficient to achieve no detectable microbial growth on the applied media.

Table 4. Results of sample analysis after biological treatment and after multi-stage treatment integrated with disinfection (own elaboration).

The Process from Which the Sample Originates	Sample Name	Total Number of Microorganisms (Bacteria and Fungi)	Presence of *Escherichia coli* Bacteria	Presence of *Salmonella* and *Shigella* Bacteria	Presence of Fungi and Yeasts
After biological wastewater treatment	A8	×	×	×	×
	A15	×	×	×	×
	B8	×	×	×	×
	B15	×	×	×	×
	C8	×	×	×	×
	C15	×	×	×	×
	D8	×	×	×	×
	D15	×	×	×	×
After integrated wastewater treatment and disinfection (ozone 15 min + UV radiation 15 min)	A8	×	✓	✓	✓
	A15	✓	✓	✓	✓
	B8	✓	✓	✓	✓
	B15	✓	✓	✓	✓
	C8	✓	✓	✓	✓
	C15	×	✓	✓	✓
	D8	×	✓	✓	✓
	D15	×	✓	✓	✓
After integrated wastewater treatment and disinfection (ozone 30 min + UV radiation 15 min)	A8	✓	✓	✓	✓
	A15	✓	✓	✓	✓
	B8	✓	✓	✓	✓
	B15	✓	✓	✓	✓
	C8	✓	✓	✓	✓
	C15	✓	✓	✓	✓
	D8	✓	✓	✓	✓
	D15	✓	✓	✓	✓
After integrated wastewater treatment and disinfection (ozone 45 min + UV radiation 15 min)	A8	✓	✓	✓	✓
	A15	✓	✓	✓	✓
	B8	✓	✓	✓	✓
	B15	✓	✓	✓	✓
	C8	✓	✓	✓	✓
	C15	✓	✓	✓	✓
	D8	✓	✓	✓	✓
	D15	✓	✓	✓	✓

✓, No microorganisms detected (sample is safe). ×, Microorganisms detected (sample is not safe).

In summary, the conducted research confirmed that the use of an integrated wastewater treatment system enables the effective treatment of model wastewater containing coffee bean extract and the production of wastewater with improved microbiological quality. Regardless of the biological treatment variant used, the successive stages effectively improved wastewater quality; however, the final efficiency depended to a large extent on the operating conditions of the SBR reactors and the ozonation time.

The use of the integrated system had a similar effect on most of the analyzed physicochemical parameters. In most systems, the final pH value approached neutrality (6.15–7.33), which is advantageous from the perspective of the potential reuse of treated wastewater. At the same time, an increase in specific conductivity was observed, which may have been asso-

ciated with changes in the ionic composition of the wastewater during ozonation. However, the observed increase in conductivity should be considered when assessing the suitability of the treated wastewater for specific reuse applications. The use of sorption and membrane filtration, on the other hand, allowed for very effective reduction in turbidity, resulting in a final turbidity of less than 2 NTU in all variants and, in most cases, not exceeding 0.5 NTU, indicating the high clarity of the treated wastewater.

An analysis of biogenic compounds showed that their removal occurred primarily during biological treatment. Subsequent treatment stages had only a slight effect on the final concentrations of phosphates and ammonium nitrogen. The presence of a model contaminant in the form of coffee bean extract resulted in higher final TOC and ammonium nitrogen values than in systems without this additive, indicating a greater load on the biological system from additional organic compounds and potentially less favorable conditions for ammonium nitrogen removal. Nevertheless, the integrated treatment system enabled effective removal of organic matter even in wastewater containing the coffee bean extract. The highest TOC removal efficiency was achieved in systems without the model contaminant, whereas in systems with its addition, the final TOC values remained higher, indicating the presence of a greater residual organic carbon load associated with the added coffee extract.

To provide an overall perspective on the treatment performance, Figure 25 summarizes the percentage changes in all analyzed physicochemical parameters at successive stages of the integrated treatment system for the best-performing variant (D8).

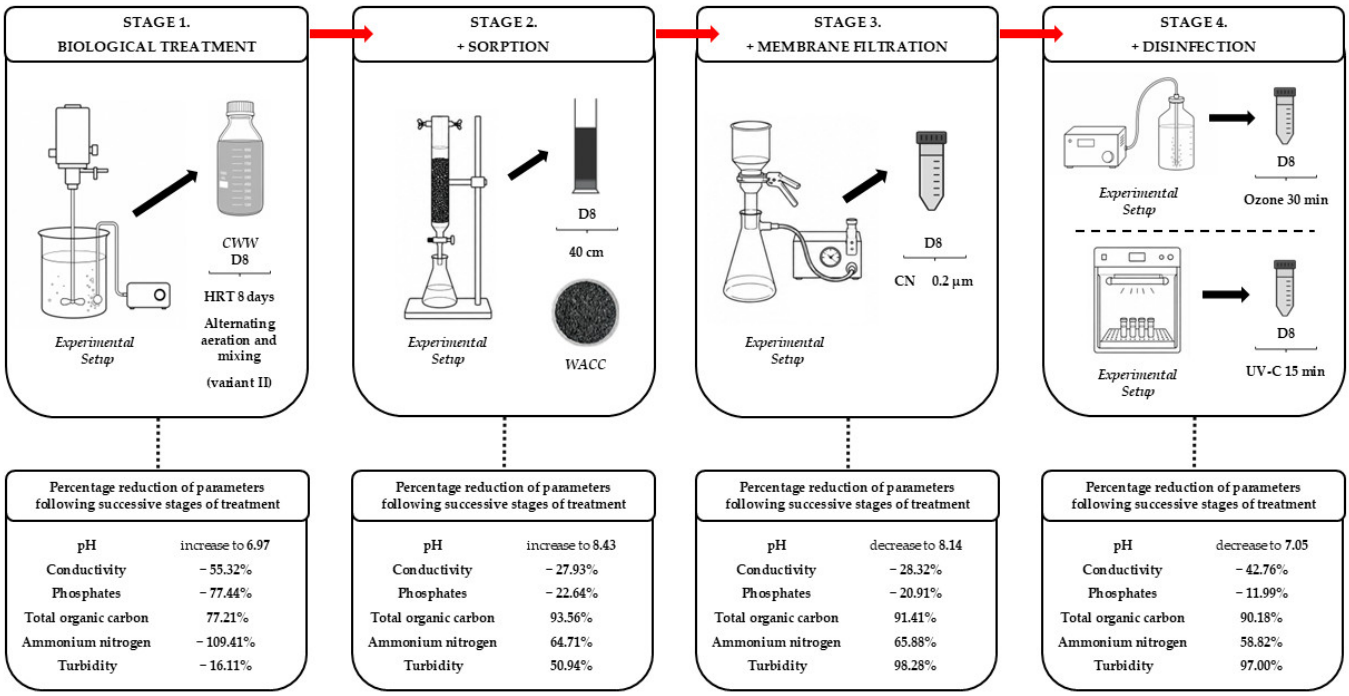


Figure 25. Percentage changes in physicochemical parameters at successive stages of the integrated wastewater treatment system in the best-performing variant—D8 (own elaboration).

An important aspect of the research was the evaluation of the effectiveness of the final disinfection. The use of a 15 min ozone treatment did not ensure complete elimination of microorganisms, as an increase in the total microbial count was still observed in some samples. Only by extending the ozonation time to 30 min, while maintaining a 15 min exposure to UV radiation, was it possible to achieve no detectable growth of bacteria, fungi, and yeasts on the applied microbiological media in all analyzed samples. Further extending

the ozonation time to 45 min did not improve the microbiological results but resulted in a deterioration of selected physicochemical parameters. For this reason, the treatment regimen involving 30 min of ozonation and 15 min of UV radiation should be considered the most favorable, ensuring high microbiological effectiveness under the tested conditions while preserving more favorable physicochemical properties of the treated wastewater.

4. Discussion

The results presented in this paper are a continuation of previous research on the development of an integrated, multi-stage wastewater treatment system for wastewater containing model pollutants in the form of an extract from Arabica and Robusta coffee beans (60:40) [8]. In the previous series of research, the effect of three concentrations of coffee extract (1, 10, and 20 g/L) on the efficiency of individual treatment stages was analyzed, whereas in the current research, the scope was narrowed to a concentration of 1 g/L, which in earlier experiments demonstrated the greatest potential for further modification of the entire treatment system. This approach enabled a detailed assessment of the impact of selected process parameters on the efficiency of pollutant removal without the additional influence of a variable organic pollutant load.

For a clearer overview, Table 5 compares the characteristics of the model wastewater, the treatment configurations, and the best results obtained in the previous and current research cycles.

Table 5. Comparison of treatment configurations and the best results obtained in the previous and current research cycles (own elaboration).

Treatment Stage Parameter	Previous Research [8]	Current Research
Type of wastewater	Model wastewater containing roasted Arabica and Robusta coffee bean extract (60:40)	Model wastewater containing roasted Arabica and Robusta coffee bean extract (60:40)
Coffee extract concentration	1, 10, and 20 g/L; 1 g/L selected for comparison of treatment configurations	1 g/L
Best biological treatment conditions	Alternating aeration and mixing; HRT 10 days	Alternating aeration and mixing; HRT 8 days for pH, turbidity and phosphate removal; HRT 15 days for ammonium nitrogen removal
Biological treatment results	pH: 4.92; turbidity: 25.5 NTU; phosphates: 25.03 mg/L; ammonium nitrogen: 15.6 mg/L; TOC: 21.88 mg/L	pH: 6.97 (HRT 8 days); turbidity: 6.18 NTU (HRT 15 days); phosphates: 23.67 mg/L (HRT 8 days); ammonium nitrogen: 7.5 mg/L (HRT 15 days); TOC: 22.39 mg/L (HRT 15 days)
Best adsorption conditions	WG-12 activated carbon; 20 cm bed	WACC activated carbon; 40 cm bed
Adsorption results	pH: 8.67; turbidity: 16.7 NTU; phosphates: 21.35 mg/L; ammonium nitrogen: 5.7 mg/L; TOC: 10.14 mg/L	pH: 8.43; turbidity: 8.83 NTU; phosphates: 16.36 mg/L; ammonium nitrogen: 3.0 mg/L; TOC: 11.34 mg/L
Best membrane filtration conditions	Cellulose nitrate (CN) membrane; pore diameter: 0.20 µm	Cellulose nitrate (CN) membrane; pore diameter: 0.20 µm
Membrane filtration results	pH: 8.14–8.20; turbidity: below 0.5 NTU; TOC: 13.33 mg/L	pH: 8.14; turbidity: below 0.5 NTU; TOC: 15.14 mg/L
Best final disinfection conditions	Ozonation: 20 min; UV-C radiation: 20 min	Ozonation: 30 min; UV-C radiation: 15 min

Table 5. *Cont.*

Treatment Stage Parameter	Previous Research [8]	Current Research
Final treatment results	pH: 4.02; turbidity: below 0.5 NTU; TOC: 9.72 mg/L; sanitary safety achieved	pH: 7.05; turbidity: 0.54 NTU; TOC: 17.30 mg/L; sanitary safety achieved
Overall outcome	Effective multi-stage treatment, with further improvement in organic matter removal during final disinfection	Improved final pH and nutrient removal, with favorable turbidity and microbiological quality

In both research cycles, identical variants of biological wastewater treatment were used: the first variant involved continuous aeration and mixing of the reactor contents for 22 h, and the second variant involved alternating aeration and mixing over the same period. Unlike previous research, which assumed an HRT of 10 days, this research analyzed two new HRT variants—8 and 15 days. This made it possible to determine the extent to which a change in retention time affects the efficiency of biological wastewater treatment and to identify more favorable conditions for conducting the process [8].

A comparison of the results obtained for the variant involving alternating aeration and mixing—which demonstrated the highest removal efficiency for key pollutants in both research cycles—showed a significant impact of HRT on the quality of the treated wastewater. The most favorable pH value was obtained at an HRT of 8 days (6.97), while for HRTs of 10 and 15 days, it was 4.92 and 5.67, respectively. Achieving a pH closer to neutral indicates more stable biological processes and a reduction in the excessive accumulation of acidic metabolic byproducts. In terms of turbidity, an improvement in wastewater quality was observed both for an HRT of 8 days (20.9 NTU) and, particularly, for an HRT of 15 days (6.18 NTU), compared to an HRT of 10 days (25.5 NTU). A similar trend was observed for phosphates, with the lowest concentration achieved at an 8-day HRT (23.67 mg/L), while for 10- and 15-day HRTs, the concentrations were 25.03 and 25.37 mg/L, respectively. A different trend was observed for ammonium nitrogen—its lowest concentration was achieved at an HRT of 15 days (7.5 mg/L), while for HRTs of 8 and 10 days, it was 17.8 and 15.6 mg/L, respectively. This result can be explained by the longer contact time between the wastewater and the biomass, which promotes the intensification of nitrification processes. In turn, the TOC analysis showed similar values for HRT of 10 days (21.88 mg/L) and 15 days (22.39 mg/L), while a higher value was recorded for an HRT of 8 days (40.15 mg/L), indicating that shortening the HRT limits the degree of biodegradation of some organic compounds [8].

The results obtained unequivocally confirm that HRT is one of the most important parameters determining the effectiveness of biological treatment of wastewater containing coffee bean extract. Appropriate selection of HRT allows for a compromise between the efficiency of removing specific groups of pollutants and the stability of the biological process.

Both research cycles also demonstrated that, following biological treatment, it is more appropriate to use an activated carbon sorption process prior to membrane filtration [8]. This is because sorption enables the removal of a significant portion of dissolved organic compounds, colored substances, and some of the compounds responsible for membrane fouling. As a result, the phenomenon of rapid membrane pore blockage was significantly reduced. Applying membrane filtration only after the sorption stage allowed its potential to be harnessed primarily for the removal of remaining suspended solids and fine particles, which translates into higher efficiency of the entire integrated system.

Previous research has also shown that sorption carried out under dynamic conditions—involving the passage of wastewater through a column filled with an activated carbon bed—is more effective than static sorption. For this reason, in the present research, in

addition to the previously analyzed bed height of 20 cm, beds with heights of 30 and 40 cm were also evaluated while maintaining the same filter column diameter [8].

A comparison of the results from both research cycles revealed a change in the most favorable conditions for the sorption process. In previous research, the highest efficiency was achieved with a 20 cm thick bed of WG-12 activated carbon, whereas in the current research, the best results were obtained with a 40 cm thick bed of WACC activated carbon. In both cases, similar pH values were obtained (8.67 and 8.43); however, the use of a thicker sorption bed and the WACC sorbent allowed for a further improvement in the quality of the treated wastewater. Turbidity decreased from 16.7 to 8.83 NTU, phosphate concentration from 21.35 to 16.36 mg/L, and ammonium nitrogen content from 5.7 to 3.0 mg/L. Only the TOC value was slightly higher than in previous research (11.34 mg/L versus 10.14 mg/L); however, this difference was negligible compared to the improvement in the other quality parameters [8]. The results indicate that increasing the bed height extended the contact time between the wastewater and the sorbent, allowing for fuller utilization of its sorption capacity and more effective removal of pollutants.

In both research cycles, the best results for the membrane filtration stage were obtained using a cellulose nitrate (CN) membrane with a pore diameter of 0.20 μm. After filtration, very similar pH values (8.14–8.20) and turbidity below 0.5 NTU were obtained, confirming the membrane's high efficiency in removing suspended solids and fine particles. At the same time, both previous and current research have shown that membrane filtration did not significantly affect the removal of phosphates and ammonium nitrogen, as these compounds occur primarily in dissolved form and freely pass through the membrane's micropores. In both sets of studies, however, a slight increase in TOC values was observed after membrane filtration (from 10.14 to 13.33 mg/L in the previous research and from 11.34 to 15.14 mg/L in the current research). This phenomenon may result from the partial leaching of small amounts of organic compounds from the membranes [8].

The final stage of the integrated system was a two-step disinfection process involving ozonation and UV irradiation. Previous research used 20 min of ozonation and 20 min of UV irradiation, whereas the current research focused on further identifying more favorable process parameters by analyzing three ozonation times (15, 30, and 45 min) with a constant UV exposure time of 15 min [8]. The reduction in UV exposure time was justified by the significant reduction in turbidity and organic matter content in the wastewater following earlier treatment stages. Under these conditions, UV radiation exhibits high disinfection efficiency even at shorter exposure times, while varying the ozonation duration allowed for an assessment of this process's impact on the additional oxidation of remaining organic compounds and the achievement of a synergistic effect between both disinfection methods.

The most favorable physicochemical parameters of the treated wastewater and full sanitary safety were achieved using 30 min of ozonation and 15 min of UV radiation. Compared to previous research, a significantly more favorable final pH value was achieved (7.05 versus 4.02), while in both cases turbidity was below 0.5 NTU. As in previous research, disinfection did not significantly affect the concentrations of phosphates and ammonium nitrogen. Differences were observed, however, for TOC—in the previous research cycle, this value decreased from 13.33 to 9.72 mg/L, whereas in the current research it remained virtually unchanged [8]. This indicates that the vast majority of organic compounds had already been removed during earlier stages of treatment, and that final disinfection served primarily to ensure the microbiological safety of the treated wastewater.

In summary, a comparison of both research cycles confirmed the effectiveness of the proposed integrated wastewater treatment system and demonstrated the possibility of further refining it through better selection of parameters for individual unit processes [8]. Of particular importance was the use of an appropriately selected HRT during biological

treatment, an increase in the height of the sorption bed, and the use of WACC activated carbon, which resulted in improved quality of the treated wastewater prior to the membrane filtration stage. Maintaining the sequence of processes—including biological treatment, sorption, membrane filtration, and final disinfection—allowed for high efficiency in contaminant removal while simultaneously reducing the load on subsequent process stages and ensuring high-quality treated wastewater.

The research conducted is supplemented by a review of existing literature on wastewater treatment technologies for the coffee industry, presented in Table 6.

Table 6. Overview of selected technologies for the treatment of coffee industry wastewater reported in the literature.

Wastewater/Substrate Characteristic	Treatment Method and Main Operating Conditions	Reported Treatment Efficiency	Reference
Industrial wastewater from a coffee processing plant	Anaerobic hybrid reactor combining an UASB reactor and an anaerobic filter (pilot-scale start-up research)	COD reduction of 77.2% at an organic loading rate of 1.89 kg COD/(m^3·d) and an HRT of 22 h. Higher loading rates (above 2.4 kg COD/(m^3·d)) resulted in process deterioration	[87]
Coffee processing wastewater characterized by high COD and low suspended-solids content	Chemical coagulation–flocculation using lime and coagulant T-1, followed by advanced oxidation processes (UV/H_2O_2 and $UV/H_2O_2/O_3$)	Chemical coagulation–flocculation using lime and coagulant T-1 achieved a 67% reduction in COD. Combining this treatment with UV/H_2O_2 further increased COD removal to 86%, although prolonged UV irradiation was required. Among the advanced oxidation processes investigated, $UV/H_2O_2/O_3$ was the most effective, achieving 87% removal of color, turbidity, and additional COD from the pre-flocculated coffee wastewater	[88]
Wastewater collected from a coffee processing plant, characterized by organic pollution expressed in terms of COD and BOD	Batch adsorption using activated carbon prepared from avocado peels (APC), compared with commercial activated carbon (CAC). The effects of operating parameters, including adsorbent dosage, contact time, pH, agitation speed, and particle size, were investigated	Under the reported optimum conditions, APC achieved COD and BOD reductions of 98.20% and 99.18%, respectively. Commercial activated carbon achieved reductions of 99.02% for COD and 99.35% for BOD	[89]
Coffee processing wastewater with influent COD concentrations of 978, 2401 and 4545 mg/L	Three up-flow anaerobic fixed-bed reactors (139.5 L each) packed with blast furnace cinders, polyurethane foam, or crushed stone, with porosities of 53%, 95%, and 48%, respectively. The HRT was maintained at 1.3 days	At the highest influent COD concentration (4545 mg/L), the polyurethane-foam reactor achieved COD removal efficiencies of 80% for unfiltered samples and 83% for filtered samples. Its higher performance was attributed to the greater porosity of the support medium, which promoted biomass retention	[90]

Table 6. *Cont.*

Wastewater/Substrate Characteristic	Treatment Method and Main Operating Conditions	Reported Treatment Efficiency	Reference
Effluent from the anaerobic biological treatment of coffee wet-processing wastewater, containing non-biodegradable organic compounds	Wet hydrogen peroxide catalytic oxidation (WHPCO) using Al–Ce–Fe-pillared interlayered clay (Al–Ce–Fe–PILC) as a catalyst. The process was conducted in a semi-batch reactor at 25 °C and atmospheric pressure for 5 h	The catalytic oxidation stage achieved a 66% reduction in COD and a 70% conversion of total phenolic compounds. Mineralization to CO_2 reached 50%. The combined biological and catalytic treatment achieved an overall COD reduction of 97%	[91]
Coffee pulping wastewater characterized by acidic pH (3.92–4.99) and high organic matter content. Initial COD ranged from 8320 to 10,400 mg/L, phosphorus from 60 to 94 mg/L, and nitrate nitrogen from 32 to 52 mg/L	SBR with anaerobic–aerobic operating phases. The study evaluated raw wastewater and wastewater diluted at a ratio of 1:4	For diluted wastewater, the effluent COD concentration decreased to 296 mg/L, phosphorus to 3 mg/L, and nitrate nitrogen to below 8 mg/L. Improved SBR performance after dilution, indicating the importance of influent characteristics for biological treatment efficiency	[92]
Industrial wastewater generated during soluble coffee production, containing complex mixtures of organic macromolecules	Sequential electrocoagulation–electrooxidation (EC–EO) using aluminium and graphite electrodes, respectively. Operational parameters were optimized to improve treatment efficiency	The integrated EC–EO process achieved complete decolorization, 74% COD removal, and 63.5% TOC removal. The treated effluent exhibited high oxidation state (AOS = 1.629) and improved biocompatibility (BOD_5/COD ≈ 0.6)	[93]
Coffee processing wastewater with an initial COD concentration of 45,955 mg/L, BOD_5 of 37,944 mg/L, TOC of 11,400 mg/L, pH of 3.95, and turbidity of 1481.7 NTU	A laboratory-scale EGSB anaerobic bioreactor operated under mesophilic conditions (26 ± 2 °C). HRT varied from 3 to 9 days, with an average pH of 7.5 ± 0.2	COD removal efficiency increased from 94% to 98% as the HRT increased from 3 to 9 days, with the highest removal achieved at an HRT of 9 days. Effluents treated at HRTs of 7–9 days met the COD discharge limits established by the WHO and Mexican environmental regulations. The α factor remained stable at 0.98 throughout reactor operation	[94]
Coffee processing wastewater, with an initial COD concentration of 1984 mg/L and an initial color intensity of 7000 PCU	Batch electrochemical coagulation (BECC) using stainless-steel (SS) and iron (Fe) electrodes in various configurations, including four-SS and four-Fe electrode arrangements and mixed SS–Fe configurations	The configuration comprising four stainless-steel electrodes, operated at 23 V and a current density of 120 A/m^2, achieved approximately 87% COD removal and 97.1% color removal. The use of polyaluminium chloride as a coagulant aid at 50 mg/L resulted in COD and color removal efficiencies of 80% and 92%, respectively	[95]

Table 6. *Cont.*

Wastewater/Substrate Characteristic	Treatment Method and Main Operating Conditions	Reported Treatment Efficiency	Reference
Acidic wastewater generated during wet coffee processing, particularly during the removal of pulp and mucilage from coffee cherries, containing recalcitrant organic matter	Anaerobic baffled bioreactor (ABR) coupled with a microfiltration (MF) membrane system. Two configurations (S1 and S2) were evaluated at HRT of 59 and 83 h, respectively, under mesophilic conditions and a transmembrane pressure (TMP) of 50 kPa. Both systems were operated for 1800 h	The S2 configuration achieved higher removal efficiencies than S1, with 81% COD removal, 98.7% turbidity removal, 72.6% total solids removal, 100% total suspended solids removal, and 61% total dissolved solids removal	[96]
Real coffee industrial effluent characterized by an initial COD concentration of 20,000 mg/L, turbidity of 1100 FAU, and total dissolved solids of 1520 mg/L	Integrated membrane bioreactor (IMBR) combining an aerobic biological treatment process with side-stream high-flux ultrafiltration (HF-UF; 5 kDa molecular weight cut-off), followed by thin-film-composite reverse osmosis (TFC-RO)	The integrated system reduced COD from 20,000 to 40 mg/L (approximately 99.8%), turbidity from 1100 FAU to 0 FAU, conductivity by 94%, and TDS by 76%. Complete removal of color and odor was also reported	[97]
Coffee processing wastewater generated during wet or dry coffee processing, characterized by dark color and high turbidity	Batch adsorption using activated carbon prepared from coffee husks. Adsorbent dosages of 5, 10, and 15 g were evaluated at contact times of 60, 90, and 120 min	The best results were obtained using 15 g of adsorbent and a contact time of 60 min, achieving turbidity and color reductions of 89.58% and 83.86%, respectively	[98]
Wastewater generated at a wet coffee processing plant	Aeration for 5, 10, 15, 20, or 25 days, followed by a 21-day constructed wetland treatment using *Cyperus ustulatus* or *Typha latifolia*, as well as an unplanted wetland configuration	The highest removal efficiencies were achieved after 25 days of aeration followed by treatment in a constructed wetland planted with *Typha latifolia*, reaching 97.4% COD removal, 98.1% BOD_5 removal, 87.8% total solids removal, 94.2% nitrate nitrogen removal, and 98.1% phosphate removal. The configuration with *Cyperus ustulatus* achieved 96.9% COD, 97.8% BOD_5, and 88.5% total solids removal under the same aeration period	[99]
Coffee processing industry wastewater generated from washing operations and a scrubber process, characterized by high organic pollution and low biodegradability, with an initial COD concentration exceeding 15,000 mg/L. Before the experiments, the wastewater was diluted to 10% (v/v) with distilled water	Dual-media biofilm reactor (DM-BR) containing sand and Hexafilter (HEX), compared with a control biofilm reactor (C-BR) containing sand only. Both reactors were operated at hydraulic retention times (HRTs) of 24, 48, and 72 h. The reactors were inoculated with recycled paper mill activated sludge and acclimatized for 97 days	The dual-media biofilm reactor achieved maximum average removal efficiencies of 47% for COD and 38% for ammonium nitrogen at an HRT of 48 h. The highest average removals of color (21%) and tannin–lignin compounds (29%) were obtained at an HRT of 24 h. The combination of sand and Hexafilter media improved COD and ammonium nitrogen removal compared with the sand-only reactor	[100]

Table 6. *Cont.*

Wastewater/Substrate Characteristic	Treatment Method and Main Operating Conditions	Reported Treatment Efficiency	Reference
Coffee processing industrial wastewater containing organic compounds	Hybrid electrochemical oxidation (ECO) combined with ultraviolet irradiation and hydrogen peroxide (UV/H_2O_2). The process parameters were investigated using response surface methodology (RSM) based on a central composite design (CCD), considering solution pH, electrolyte concentration (NaCl or $CaCl_2$), electric current, electrolysis time, and H_2O_2 dosage	The hybrid ECO–UV/H_2O_2 process achieved 99.61% COD removal under the optimal conditions (pH 7, current of 0.40 A, 1.5 g $CaCl_2$, and 40 min electrolysis time), with an energy consumption of 1.12 kWh/m^3	[101]
Wet coffee processing wastewater	Integrated treatment system comprising pretreatment by aeration and sedimentation, followed by horizontal subsurface-flow constructed wetlands (HSSFCW) planted with different macrophyte species (*Cyperus alternifolius*, *Vetiveria zizanioides*, and *Pennisetum purpureum*), with an unplanted gravel-filled bed serving as a control	The HSSFCW planted with *Vetiveria zizanioides* achieved removal efficiencies of 80.1% for COD, 78.5% for BOD_5, 79.6% for phosphate phosphorus, 70.2% for nitrate nitrogen, and 50.1% for ammonia nitrogen. These values represent the performance of the constructed wetland stage, following pretreatment by aeration and sedimentation	[102]
Wet coffee processing wastewater	Pulsed electrocoagulation process (PECP) conducted in a batch reactor. The optimal operating conditions determined using response surface methodology (CCD) were pH 7, NaCl concentration of 0.75 g/L, current of 0.45 A, and electrolysis time of 45 min	Under the optimal operating conditions, the PECP achieved removal efficiencies of 98.50% for COD, 99.50% for color, 99.00% for turbidity, 99.00% for phosphate, and 98.83% for nitrate, with a power consumption of 0.971 kWh/m^3	[103]
Industrial wastewater generated during instant coffee production (real industrial effluent; initial pH of 4.7)	Electrocoagulation (EC) using an iron anode and a stainless-steel cathode. The optimal operating conditions were: NaCl concentration of 1.78 g/L, current density of 150 A/m^2, electrode spacing of 3 mm, stirring velocity of 350 rpm, initial pH of 4.7, and electrolysis time of approximately 180 min	The EC process achieved approximately 97% color removal, 72% COD removal, and 65% TOC removal. The treated effluent exhibited an increased BOD_5/COD ratio of 0.437, indicating improved biodegradability, and was reported to be non-toxic and free of contaminants with molecular weights above 30 kDa. The total operating cost was 6.26 USD/m^3	[15]

Table 6. *Cont.*

Wastewater/Substrate Characteristic	Treatment Method and Main Operating Conditions	Reported Treatment Efficiency	Reference
Coffee processing wastewater generated during wet-processing operations, including pulping, mucilage removal, washing and soaking	Integrated treatment combining batch adsorption using coffee husk waste from the same coffee industry as an adsorbent, followed by ozonation. The optimal adsorption conditions were a contact time of 120 min and an adsorbent dosage of 5 g, followed by ozonation for 120 min at an ozone dosage of 15 g/h	Adsorption alone achieved 54.9% COD and 66.6% color removal. Subsequent ozonation increased the overall removal efficiencies to 82.3% for COD and 93.7% for color	[104]

The summary presented in Table 6 covers solutions developed between 1998 and 2026 and highlights the gradual evolution of the methods used—from conventional biological processes, such as UASB, EGSB, and SBR anaerobic reactors [87,90,92,94], through physico-chemical processes, including coagulation, electrocoagulation, adsorption, and advanced oxidation [88,89,93,95], all the way to integrated solutions combining biological, membrane, and oxidation processes [96,97,104].

The results cited confirm that individual technologies can provide high contaminant removal efficiency; however, their effectiveness depends on the composition of the wastewater, the initial contaminant load, and the process operating conditions. For this reason, multistage systems—in which individual methods complement one another—are becoming increasingly important. Our own research also aligns with this trend, involving a combination of biological treatment, activated carbon sorption, membrane filtration, and final disinfection using ozonation and UV-C radiation. The configuration used allows for the evaluation not only of the effectiveness of individual stages but, above all, of their interaction and impact on the final quality of the treated wastewater.

The results obtained should also be considered within the broader context of current trends in wastewater treatment technology, particularly regarding the requirements outlined in Directive (EU) 2024/3019 on the treatment of municipal wastewater. The new directive introduces significant changes in the approach to the design and operation of wastewater treatment plants, going beyond traditional requirements related to the removal of organic matter, suspended solids, and nutrients. Particular emphasis has been placed on the removal of micropollutants, improving the energy efficiency of treatment plants, advancing the circular economy, and reducing the environmental impact of the water and wastewater sector. One of the most important elements of the new regulations is the requirement to implement tertiary treatment at large wastewater treatment plants, enabling the removal of substances classified as "contaminants of emerging concern" (CEC), including residues of pharmaceuticals, plant protection products, and substances used in cosmetics [7].

In this context, the integrated treatment system developed in this research is a solution consistent with current trends in wastewater treatment technology. Although the research was conducted using a model contaminant—a coffee bean extract as a source of organic pollutants—the process sequence employed, which includes biological treatment, adsorption on activated carbon, membrane filtration, and final disinfection, corresponds to the concept of multi-barrier contaminant removal, which is currently recognized as one of the most promising approaches to meeting the requirements of Directive (EU) 2024/3019. The individual processes not only complement one another but also reduce the load on

subsequent technological stages by gradually removing specific groups of contaminants. This approach increases the operational stability of the entire system, improves the efficiency of final treatment, and can help reduce operating costs associated with advanced post-treatment processes.

In light of new legislative requirements, the sorption stage preceding membrane filtration may play a particularly important role. Biological and physicochemical processes commonly used in wastewater treatment plants contribute to the removal of many micropollutants; however, their effectiveness varies greatly and depends on both the physicochemical properties of individual compounds and the treatment technology employed [105–107]. In the present research, it was demonstrated that increasing the bed height and using WACC activated carbon significantly improved wastewater quality prior to membrane filtration by, among other things, reducing turbidity, phosphate concentrations, and ammonium nitrogen levels. The results indicate that a properly selected sorption stage effectively reduces the load on subsequent unit processes, creating more favorable operating conditions for the membranes. Although this research did not analyze the removal of priority micropollutants identified in Directive (EU) 2024/3019, numerous studies demonstrate that activated carbon is among the most effective materials used to eliminate many pharmaceutical compounds, pesticides, and other trace contaminants. Proper pre-treatment of wastewater before the membrane stage also significantly reduces fouling, which translates into longer membrane life, more stable system operation, and lower operating costs for the entire system [27,106].

Similarly, the membrane filtration stage used in the presented research is in line with current trends in wastewater treatment technology. Although the microfiltration used is not designed to effectively remove dissolved micropollutants, it plays a crucial role in further treating wastewater to remove remaining suspended solids and preparing it for potential use in more advanced membrane processes. It is worth noting that a certain degree of removal of the micropollutants listed in Directive (EU) 2024/3019 already occurs during conventional wastewater treatment. Therefore, this effect should be taken into account when calculating the total required removal rate of 80%. In practice, this means that the efficiency achieved through tertiary treatment should complement the effect obtained in earlier treatment stages, so that together they ensure the removal of at least 80% of the pollutant load entering the treatment plant. Domínguez et al. (2025) [106] demonstrated that only the use of nanofiltration and reverse osmosis makes it possible to achieve the microcontaminant removal efficiency exceeding 80% required by Directive (EU) 2024/3019 for most indicator compounds. It should be emphasized, however, that the performance of nanofiltration membranes is strongly dependent on the properties of individual contaminants, such as molecular weight, polarity, and degree of dissociation; therefore, removal efficiency can vary significantly among different groups of compounds. At the same time, nanofiltration membranes offer numerous operational benefits, including lower energy consumption compared to reverse osmosis [108–111]. The results obtained, as well as data from the literature, confirm the validity of using multi-stage treatment systems, in which the preliminary reduction in suspended solids, organic matter, and some biogenic compounds improves the operating conditions of membrane processes, increases their efficiency, and contributes to achieving high-quality treated wastewater.

It is also worth noting that the final treatment stages, involving ozonation followed by UV-C radiation, are consistent with current trends in wastewater treatment technology, where oxidation and disinfection processes play an increasingly important role in tertiary treatment. Ozonation enables the oxidation of organic compounds through direct reactions with molecular ozone and, depending on the operating conditions, may also involve indirect oxidation pathways associated with the formation of hydroxyl radicals (•OH). The contribution of these pathways depends, among other factors, on the pH of the treated

wastewater. Hydroxyl radicals are highly reactive and can contribute to the degradation of a broad spectrum of organic compounds, including persistent substances and contaminants of emerging concern (CECs) [107,112]. In the present research, UV-C radiation was applied as a subsequent disinfection step to improve the microbiological quality of the treated wastewater.

In the research presented in this work, the use of ozonation following the earlier stages of biological treatment, sorption, and membrane filtration made it possible to achieve high-quality treated wastewater while ensuring full sanitary safety. Importantly, the final disinfection was carried out after a significant reduction in suspended solids and organic matter, allowing the oxidation process to proceed under more favorable conditions. Reducing the concentration of organic compounds prior to ozonation decreases competition for reactive ozone and hydroxyl radicals, thereby increasing the efficiency of degradation of remaining pollutants while simultaneously reducing unnecessary oxidant consumption. This sequential process is currently recognized as one of the most effective technological solutions used in modern wastewater treatment systems [107].

Ferre et al. (2025) [107] further emphasize that the greatest efficiency in removing poorly biodegradable organic compounds is achieved not through the use of individual processes, but through their appropriate integration. The authors demonstrated that combining activated carbon adsorption with advanced oxidation processes leads to a synergistic effect. Adsorption is primarily responsible for removing a significant portion of dissolved organic compounds and reducing the pollutant load entering subsequent stages, while AOPs enable further degradation of compounds remaining in the wastewater, including intermediate products formed during earlier treatment stages. A similar approach was applied in this research, where adsorption on activated carbon preceded membrane filtration and final disinfection, which helped reduce membrane fouling and create more favorable conditions for the oxidation processes.

It is also worth noting that current trends in the development of wastewater treatment technologies—as outlined, among other things, by Directive (EU) 2024/3019—call for the implementation of solutions that simultaneously ensure high pollutant removal efficiency, rational energy consumption, and reduced operating costs. In this context, modifying the operating parameters of oxidation processes—rather than maximizing them—appears to be a particularly advantageous approach. The results obtained in this research showed that a 30 min ozonation and a 15 min UV radiation were sufficient to achieve high-quality treated wastewater and full microbiological safety. This means that extending the ozonation time did not lead to a proportional improvement in treatment efficiency, while it could increase the energy consumption of the entire process. This is consistent with the current approach presented both by Ferre et al. (2025) [107] and in European Commission documents regarding the implementation of Directive (EU) 2024/3019 [7,113], according to which future treatment technologies should be designed not only with a view to maximizing contaminant removal efficiency but also with a view to energy efficiency, sustainable use of resources, and minimizing the environmental footprint of the entire process.

In light of the requirements of Directive (EU) 2024/3019, Pasciucco et al. (2025) [114] emphasize that achieving the removal efficiency of at least 80% of indicator compounds required by the Directive will necessitate the implementation of advanced technologies that go beyond the capabilities of conventional biological treatment. Among the most promising solutions, the authors highlight advanced electrochemical oxidation processes (EAOPs), which demonstrate high degradation efficiency for poorly biodegradable organic compounds and great operational flexibility.

Although EAOP technology was not used in this research, the developed process system—which includes biological wastewater treatment, activated carbon sorption, mem-

brane filtration, and final disinfection using ozonation and UV radiation—is consistent with the concept of multi-stage treatment promoted by Pasciucco et al. (2025) [114]. The authors emphasize that advanced oxidation processes are most effective as the final stage of secondary wastewater treatment, when previous processes have removed a significant portion of the organic matter. This approach reduces energy consumption and increases the efficiency of oxidizing the remaining pollutants, which is of significant importance from the perspective of operating costs.

At the same time, Pasciucco et al. (2025) [114] point out that EAOP technologies are significantly more effective at removing micropollutants than nitrogen and phosphorus compounds; therefore, they should complement—rather than serve as an alternative to—biological wastewater treatment. These conclusions are consistent with the results obtained in this research, where the primary removal of ammonium nitrogen and phosphates occurred during biological treatment and sorption, while the final stage of ozonation and UV radiation primarily served to further treat the wastewater and ensure its sanitary safety. In light of the implementation of Directive (EU) 2024/3019, the use of electrochemical oxidation processes could complement the developed treatment system, increasing its effectiveness in removing micropollutants present in actual municipal and industrial wastewater.

In the context of implementing the requirements of EU Directive 2024/3019, hybrid technologies that combine biological processes with membrane separation are becoming increasingly important. Research by Mineo et al. (2025) [115], which compared IFAS–MBR and IFAS–UF systems, showed that both solutions enable very high removal efficiency of organic compounds (over 97% COD removal) and effective elimination of ammonium nitrogen; however, the use of a membrane bioreactor ensures significantly better total nitrogen removal efficiency. In the analyzed IFAS–MBR system, an average total nitrogen removal rate of approximately 85% was achieved, whereas in the configuration with a secondary clarifier and ultrafiltration, this value was approximately 75%. The authors point out that this difference stems primarily from a more favorable internal carbon-to-nitrogen ratio and better retention of slow-growing nitrifying bacteria due to the use of membranes. At the same time, the presence of biofilm on the carriers and on the membrane surfaces promotes the formation of anoxic microenvironments, enabling simultaneous nitrification and denitrification, which translates into greater process stability and more effective removal of nitrogen compounds.

Also noteworthy are the findings regarding the impact of the analyzed technologies on greenhouse gas emissions. Despite the widespread belief that membrane systems are characterized by high energy consumption, the research showed that the IFAS–MBR configuration generated a lower carbon footprint than the IFAS–UF system. This was primarily due to more efficient nitrogen removal, reduced nitrous oxide (N_2O) emissions, and lower energy consumption for the sludge recirculation process. N_2O emissions accounted for less than 0.1% of the incoming nitrogen, which is significantly lower than the values reported for many conventional wastewater treatment plants. In light of the growing importance of reducing greenhouse gas emissions and implementing the objectives of the European Green Deal, this aspect takes on particular significance when evaluating modern wastewater treatment technologies [115].

Mineo et al. (2025) [115] point out, however, that even the use of advanced biological membrane systems does not guarantee full compliance with all the requirements of the new European regulations. Neither of the two configurations analyzed achieved the required phosphorus concentrations (<1 mg P/L), which indicates the need for additional phosphorus removal methods, such as chemical precipitation or the intensification of biological phosphorus removal. These results confirm that future wastewater treatment plant

upgrades will require not only the implementation of tertiary treatment processes targeting micropollutants but also the modernization of conventional nutrient removal processes. At the same time, the results indicate that the integration of IFAS technology with membrane bioreactors is one of the most promising solutions for simultaneously achieving high-quality treated effluent, reducing the treatment plant's impact on the climate, and adapting the plants to increasingly stringent legal requirements.

In light of the increasingly stringent requirements outlined in EU Directive 2024/3019 and Regulation (EU) 2020/741 [7,116], integrated treatment systems that combine traditional mechanical processes with advanced oxidation methods are becoming increasingly important. Research by Castañeda Retavizca et al. (2026) [117] showed that the use of sand filtration as a pre-treatment step prior to ozonation improves the quality of secondary-treated wastewater and increases the efficiency of the entire process. Filtration alone resulted in a partial reduction in the concentration of micropollutants and a significant reduction in bacterial counts, thanks to which the subsequent ozonation required a lower ozone dose to achieve the disinfection effect. At the same time, despite a slight increase in the time required to achieve 80% removal of micropollutants, the entire filtration–ozonation system made it possible to meet the requirements of applicable European regulations regarding both the elimination of priority pollutants and the quality of water intended for reuse.

Castañedy Retavizcy et al. (2026) [117] indicate that the most favorable process conditions were achieved for a system comprising sand filtration and ozonation at a dose of 0.3 g $O_3 \cdot L^{-1} \cdot h^{-1}$ for 17.5 min, which ensured both effective disinfection and the required level of micropollutant removal. These results confirm that proper pre-treatment of wastewater prior to ozonation can reduce the demand for oxidant and, consequently, lower the process's operating costs. Another important aspect of the research was the analysis of disinfection byproducts. It was demonstrated that sand filtration did not affect the formation of bromates but reduced the concentration of chlorinated haloacetic acids. At the same time, an increase in the concentration of bromoform was observed, indicating the need to monitor byproducts when designing advanced wastewater treatment technologies. These results emphasize that the assessment of the effectiveness of advanced oxidation processes should include not only the degree of removal of micropollutants and pathogens, but also the potential risks associated with the formation of disinfection byproducts, which may pose an additional threat to the environment and human health.

Another important aspect of implementing the new requirements under Directive (EU) 2024/3019 is the energy efficiency of wastewater treatment plants. As Capodaglio points out (2025) [118], the amendment to the regulations shifts the assessment of treatment plant performance from focusing solely on pollutant removal efficiency to an approach that simultaneously considers energy consumption, greenhouse gas emissions, and the pursuit of energy neutrality. Consequently, conducting energy audits is becoming increasingly important, as they enable the identification of the most energy-intensive technological processes and the identification of opportunities for their modernization. Capodaglio (2025) [118] points out that aeration, membrane filtration, and advanced oxidation processes are characterized by particularly high energy demand; therefore, their selection should take into account not only maximum treatment efficiency but also an analysis of operating costs and environmental footprint.

The results obtained in this research are largely in line with the current trends in the development of modern wastewater treatment technologies, where high pollutant removal efficiency is increasingly considered alongside the need to improve energy efficiency. A sequential system comprising biological treatment, activated carbon sorption, membrane filtration, and final disinfection gradually reduced the pollutant load entering subsequent treatment stages. This pre-treatment created more favorable conditions for the final treat-

ment processes, allowing the UV exposure time to be limited to 15 min and demonstrating that extending the ozonation time beyond 30 min did not result in a significant improvement in the quality of the treated wastewater. Although this research did not assess energy consumption and operating costs, the results provide a basis for further investigations into how process parameters and treatment sequence affect the system's overall operational performance. This is consistent with the conclusions presented by Capodaglio (2025) [118], who emphasizes that meeting the requirements of Directive (EU) 2024/3019 requires not only the implementation of advanced pollutant removal technologies but also their design with energy efficiency in mind and the systematic modernization of wastewater treatment plant operations. In light of the new legislative requirements, future wastewater treatment systems should therefore be developed as integrated systems that simultaneously ensure high pollutant removal efficiency, rational energy management, and minimization of environmental impact.

The results obtained in this research should also be considered in the context of the potential for reusing treated wastewater, which is one of the key areas of development in modern water and wastewater management. The importance of this issue is emphasized in Directive (EU) 2024/3019, which, in art. 15, highlights the need to systematically promote the reuse of treated wastewater from municipal wastewater treatment plants wherever justified, taking into account environmental and health safety [7]. At the same time, Regulation (EU) 2020/741 establishes minimum quality requirements for reclaimed water intended for agricultural irrigation, with permissible parameters depending on the type of crops and the method of irrigation [116]. These documents serve as an important reference point for assessing water quality after treatment processes, although the scope of their direct application depends on the type of wastewater and the planned method of reuse.

For the best technological option, D8—which involves biological wastewater treatment with an HRT of 8 days and alternating aerobic and anaerobic phases, followed by sorption on activated carbon (WACC; 40 cm), membrane filtration (CN 0.20 μm), and final disinfection (ozone 30 min; UV radiation 15 min), the following final physicochemical parameters were obtained: pH 7.05, conductivity 363.90 μS/cm, turbidity 0.54 NTU, phosphate concentration 14.94 mg/L, ammonium nitrogen 3.50 mg/L, and total organic carbon 17.30 mg/L. Particularly favorable results were obtained for pH, conductivity, and turbidity, which are key indicators in assessing the potential suitability of water for selected non-municipal applications, including irrigation.

A comparison of the results with the Food and Agriculture Organization of the United Nations (FAO) guidelines on water quality for irrigation showed that the final pH value of 7.05 falls within the recommended range of 6.5–8.4. An equally favorable value was obtained for conductivity, which, after conversion, was approximately 0.364 dS/m. According to the FAO classification, a conductivity value below 0.7 dS/m indicates no restrictions related to salinity in water used for irrigation. These results indicate that, in terms of pH and conductivity, the treated wastewater exhibited favorable properties for potential agricultural use. It should be emphasized, however, that a full assessment of the water's suitability for irrigation also requires consideration of its ionic composition—in particular, the content of sodium, chlorides, and boron—as well as the sodium adsorption ratio (SAR), soil properties, and the requirements of the crops being grown [119].

Turbidity is also an important parameter from the perspective of reclaimed water quality. Regulation (EU) 2020/741 specifies a maximum turbidity value of 5 NTU for the highest quality class of reclaimed water (Class A), intended, among other things, for the irrigation of food crops consumed raw [116]. In the present study, a value of 0.54 NTU was obtained, which was more than nine times lower than the specified limit. Such a low turbidity level confirms the high efficiency of the multi-stage system used, particularly

in terms of removing suspended solids and fine particles, and indicates that the final effluent possesses favorable physical properties. It should be noted, however, that meeting the turbidity requirement is not sufficient to classify the treated water as Class A, since the regulation also specifies requirements for BOD concentration, total suspended solids, and microbiological indicators [116]. Therefore, the result obtained should be regarded as meeting a single quality criterion, rather than as confirmation that the entire effluent complies with the requirements of this class.

When assessing the potential for reusing treated wastewater, the content of biogenic compounds must also be taken into account. In the final effluent, the concentration of phosphates was 14.94 mg/L, while that of ammonium nitrogen was 3.50 mg/L. The presence of these compounds can have dual implications in the context of water reuse. On the one hand, excessive levels of these compounds can lead to adverse environmental changes, particularly eutrophication of surface waters and excessive nutrient enrichment of the soil. On the other hand, nitrogen and phosphorus can serve as an additional source of nutrients for plants, reducing the need for mineral fertilizers. For this reason, the suitability of water containing biogenic compounds should be assessed in relation to the nutrient requirements of specific crops, soil properties, and the anticipated irrigation rate. In this context, art. 15 of Directive (EU) 2024/3019 is also of significant importance, as it permits the nutrient content of reclaimed water to be taken into account when assessing its suitability for irrigation, provided that the amount of nutrients does not exceed the fertilizer requirements of the target crops [7].

The final TOC value of 17.30 mg/L, however, indicates the presence of residual organic matter in the treated wastewater. Although this parameter is not directly subject to the limits specified in Regulation (EU) 2020/741, its determination is an important supplement to the assessment of the physicochemical quality of water, particularly in the case of industrial wastewater containing complex mixtures of organic compounds [120]. The obtained value confirms that the integrated system used enabled a significant reduction in organic matter content, although complete removal was not achieved. It is worth noting, however, that the TOC value alone does not allow for an unambiguous assessment of the biodegradability or toxicity of the remaining organic compounds; therefore, in the event of planned water reuse in more demanding applications, it would be necessary to expand the scope of analysis to include additional quality indicators.

The analysis indicates that the final effluent obtained in variant D8 exhibited favorable physicochemical properties with respect to selected criteria for evaluating the quality of water intended for reuse, particularly in terms of pH, conductivity, and turbidity. At the same time, the measured concentrations of ammonium nitrogen and phosphates suggest that the reclaimed water could be considered a potential source of nutrients, although its use would require adjusting the application rates to the specific needs of the crops. It should be emphasized, however, that the research was conducted in a laboratory setting and utilized synthetic wastewater with the addition of a model contaminant in the form of an extract from roasted coffee beans, so the results do not directly confirm the possibility of safely reusing actual industrial wastewater. Confirming this possibility would require conducting research using actual wastewater, expanding the range of parameters analyzed to include microbiological indicators, metals, and potential micropollutants, as well as assessing the environmental and health risks associated with a specific method of water reuse. Nevertheless, the results obtained indicate significant potential for the developed system as a solution that supports the reduction in water consumption and the development of technologies enabling the reuse of properly treated wastewater.

5. Conclusions

The results obtained allowed us to draw the following conclusions:

1. The integrated treatment system, comprising biological treatment, activated carbon sorption, membrane filtration, and two-stage disinfection (ozonation and UV radiation), demonstrated its effectiveness in treating model wastewater containing organic compounds derived from coffee processing. The sequential application of these processes enabled progressive pollutant removal and improved the quality of wastewater at successive treatment stages.
2. The most favorable results for the system treating model wastewater were obtained for variant D8, which included alternating aeration and mixing phases and an HRT of 8 days. This system achieved 97.0% turbidity removal, 90.2% TOC removal, and 58.8% ammonium nitrogen removal, with a final pH of 7.05. Microbiological analyses performed after the integrated O_3/UV disinfection process showed no detectable growth of the investigated microorganisms under the applied culture conditions. The combination of 30 min ozonation and 15 min UV-C irradiation was identified as a favorable disinfection variant among the conditions tested. This treatment sequence provided an additional stage of wastewater disinfection and oxidation of residual organic compounds.
3. The results demonstrated that appropriate selection of process parameters, particularly HRT and ozonation time, can improve the overall treatment performance of the integrated system without requiring unnecessarily prolonged treatment in individual stages. The findings highlight the importance of considering the sequence of treatment processes and their operating conditions when designing integrated wastewater treatment systems. Further research, including energy consumption and operational cost assessments, is needed to determine the potential for improving the energy efficiency of the proposed system.
4. The main limitations of the developed system include limited phosphate removal efficiency and the dependence of nitrogen removal efficiency on the operating conditions of the biological process. Furthermore, intensive ozonation caused an increase in specific electrical conductivity, indicating the need to adjust process parameters according to the intended application of the treated wastewater.
5. The quality of the treated wastewater indicates its potential for discharge, subject to compliance with applicable regulatory requirements, and suggests the possibility of reuse after appropriate adjustment of its composition. However, applications requiring low concentrations of biogenic substances may necessitate an additional treatment stage for nitrogen and phosphorus removal.
6. Despite the use of a model contaminant in the form of coffee bean extract, the proposed sequence of processes—including biological treatment, activated carbon sorption, membrane filtration, and final disinfection—is consistent with the concept of multi-barrier wastewater treatment promoted in Directive (EU) 2024/3019. The developed system may provide a basis for further research into integrated treatment solutions aimed at improving pollutant removal efficiency and minimizing environmental impact. However, its potential contribution to energy efficiency and economic feasibility remains to be assessed through dedicated energy consumption and cost analyses. Furthermore, due to the lack of an assessment of the removal efficiency of micropollutants covered by Directive (EU) 2024/3019, further research is needed to verify the suitability of the proposed solution for meeting the requirements for quaternary treatment.
7. Further research should include an assessment of the developed system's performance in treating actual wastewater from the coffee industry, as well as an investigation of its effectiveness in removing micropollutants covered by Directive (EU) 2024/3019.

Another important research direction will be to determine the energy requirements of individual treatment stages and conduct a comprehensive economic and environmental assessment of the entire treatment train. This will provide a basis for evaluating the technical, economic, and environmental feasibility of its potential implementation.

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Abbreviations

The following abbreviations are used in this manuscript:

A15	Sample from a reactor into which synthetic wastewater was introduced—the hydraulic retention time is 15 days, and variant 1 of the reactor operating cycle was used
A8	Sample from a reactor into which synthetic wastewater was introduced—the hydraulic retention time is 8 days, and variant 1 of the reactor operating cycle was used
ABR	Anaerobic Baffled Bioreactor
Al–Ce–Fe–PILC	Al–Ce–Fe-Pillared Interlayered Clay
AOPs	Advanced Oxidation Processes
APC	Avocado Peel Carbon
B15	Sample from a reactor into which synthetic wastewater was introduced with the addition of a model pollutant, namely coffee bean extract—the hydraulic retention time is 15 days, and variant 1 of the reactor operating cycle was used
B8	Sample from a reactor into which synthetic wastewater was introduced with the addition of a model pollutant, namely coffee bean extract—the hydraulic retention time is 8 days, and variant 1 of the reactor operating cycle was used
BECC	Batch Electrochemical Coagulation
BOD	Biological Oxygen Demand
C15	Sample from a reactor into which synthetic wastewater was introduced—the hydraulic retention time is 15 days, and variant 2 of the reactor operating cycle was used
C8	Sample from a reactor into which synthetic wastewater was introduced—the hydraulic retention time is 8 days, and variant 2 of the reactor operating cycle was used
CA	Cellulose Acetate
CAC	Commercial Activated Carbon

C-BR	Control Biofilm Reactor
CCD	Central Composite Design
CE	Circular Economy
CEC	Contaminants of Emerging Concern
CN	Cellulose Nitrate
CN-CA	Mixed Cellulose Esters
COD	Chemical Oxygen Demand
CWW	Coffee Synthetic Wastewater
D15	Sample from a reactor into which synthetic wastewater was introduced with the addition of a model pollutant, namely coffee bean extract—the hydraulic retention time is 15 days, and variant 2 of the reactor operating cycle was used
D8	Sample from a reactor into which synthetic wastewater was introduced with the addition of a model pollutant, namely coffee bean extract—the hydraulic retention time is 8 days, and variant 2 of the reactor operating cycle was used
DM-BR	Dual-Media Biofilm Reactor
EAOPs	Electrochemical Advanced Oxidation Processes
EC–EO	Electrocoagulation–Electrooxidation
ECO	Electrochemical Oxidation
EGSB	Expanded Granular Sludge Bed
FAO	Food and Agriculture Organization of the United Nations
Fe	Iron
HEX	Hexafilter
HRT	Hydraulic Retention Time
HSSFCW	Horizontal Subsurface-Flow Con-Structed Wetlands
ICO	International Coffee Organization
IFAS	Integrated Fixed-film Activated Sludge
IFAS-MBR	Integrated Fixed-Film Activated Sludge—Membrane Bioreactor
IFAS-UF	Integrated Fixed-Film Activated Sludge—Ultrafiltration
IMBR	Integrated Membrane Bioreactor
MBR	Membrane Bioreactor
MF	Microfiltration
PCA	Plate Count Agar
PECP	Pulsed Electrocoagulation Process
RSM	Response Surface Methodology
SAR	Sodium Adsorption Ratio
SBR	Sequencing Batch Reactor
SS	Stainless-Steel
SWW	Synthetic Wastewater
TBX	Tryptone Bile X-Glucuronide Agar
TFC-RO	Thin-Film-Composite Reverse Osmosis
TMP	Transmembrane Pressure
TOC	Total Organic Carbon
UASB	Up-Flow Anaerobic Sludge Blanket
UF	Ultrafiltration
UV/H_2O	Ultraviolet Radiation Combined with Hydrogen Peroxide
UV/H_2O_2/O_3	Ultraviolet Radiation Combined with Hydrogen Peroxide and Ozone
WHPCO	Wet Hydrogen Peroxide Catalytic Oxidation

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