RGSA – Revista de Gestão Social e Ambiental
ISSN: 1981-982X
Submission date: 10/1/2024
Acceptance date: 12/2/2024
DOI: https://doi.org/10.24857/rgsa.v19n1-031
Organization: Interinstitutional Scientific Committee
Chief Editor: Ana Carolina Messias de Souza Ferreira da Costa
Assessment: Double Blind Review pelo SEER/OJS

IMPACT OF HYDRAULIC RETENTION TIME ON THE QUALITY OF TREATED EFFLUENTS IN A HORIZONTAL SUBSURFACE FLOW WETLAND

Vladimir Antonio Rodríguez Núñez [1]
Atuey de Jesús Martínez Durán [2]
Rainier Vicente Sánchez Camacho [3]
José Ángel Vásquez Cuello [4]

ABSTRACT

Objective: This study aims to analyze the impact of hydraulic retention time (HRT) on the quality of treated effluents in a horizontal subsurface flow wetland. The research focuses on optimizing HRT to meet the standards established by Dominican Environmental Norms for wastewater discharges into surface waters, sanitary sewers, and coastal waters.

Theoretical Framework: The study is grounded in principles of artificial wetland design and operation, emphasizing sustainable treatment systems for wastewater. Concepts such as biological contaminant removal, oxygenation through vegetation, and sedimentation processes are central to understanding the mechanisms driving contaminant reduction.

Method: The horizontal subsurface flow wetland used in this study was colonized by Typha domingensis and monitored across seven HRTs (3, 5, 7, 9, 11, 13, and 15 days). Effluent quality was evaluated for parameters including coliforms, biochemical and chemical oxygen demand (BOD_5 and COD), nitrogen, phosphorus, turbidity, and suspended solids.

Results and Discussion: The findings showed that while most parameters reached normative levels at 3 days of HRT, total and fecal coliforms required 9 days to comply with limits. This indicates that with an additional disinfection system, a 3-day HRT could suffice, optimizing the system's efficiency while maintaining compliance. The discussion highlights the relationship between HRT and contaminant removal, with recommendations for system adjustments based on influent characteristics.

Research Implications: The study provides practical insights for the design and operation of artificial wetlands in resource-limited areas, promoting sustainable water treatment solutions. The results can inform policy and improve the efficiency of wastewater treatment practices in tropical and subtropical regions.

Originality/Value: This research contributes novel data from the Dominican Republic, showcasing the application of horizontal subsurface flow wetlands in achieving environmental compliance. It highlights the potential for tailored HRTs to optimize artificial wetlands, balancing operational costs and treatment efficiency.

Keywords: horizontal subsurface flow wetland, wastewater treatment, hydraulic retention time (HRT), contaminant removal, effluent quality.

[1] Universidad Tecnológica de Santiago (UTESA), Santiago de los Caballeros, Santiago, Dominican Republic. E-mail: sostenibilidad@utesa.edu Orcid: https://orcid.org/0000-0003-0828-7117
[2] Universidad Tecnológica de Santiago (UTESA), Santiago de los Caballeros, Santiago, Dominican Republic. E-mail: atueymartinez@utesa.edu Orcid: https://orcid.org/0000-0002-0224-2287
[3] Universidad Tecnológica de Santiago (UTESA), Santiago de los Caballeros, Santiago, Dominican Republic. E-mail: rainiersan76@gmail.com Orcid: https://orcid.org/0000-0002-6739-5102
[4] Universidad Tecnológica de Santiago (UTESA), Santiago de los Caballeros, Santiago, Dominican Republic. E-mail: josevasquez23@alumno.utesa.edu Orcid: https://orcid.org/0009-0004-6734-3398

IMPACTO DO TEMPO DE RETENÇÃO HIDRÁULICA NA QUALIDADE DOS EFLUENTES TRATADOS EM UM SISTEMA DE FLUXO SUBSUPERFICIAL HORIZONTAL

RESUMO

Objetivo: Este estudo tem como objetivo analisar o impacto do tempo de retenção hidráulica (TRH) na qualidade dos efluentes tratados em um sistema de fluxo subsuperficial horizontal. A pesquisa foca na otimização do TRH para atender aos padrões estabelecidos pelas Normas Ambientais da República Dominicana para descargas de águas residuais em corpos d'água superficiais, redes de esgoto sanitário e águas costeiras.

Referencial Teórico: O estudo está fundamentado em princípios de design e operação de sistemas artificiais de zonas úmidas, enfatizando soluções sustentáveis para o tratamento de águas residuais. Conceitos como remoção biológica de contaminantes, oxigenação através da vegetação e processos de sedimentação são essenciais para compreender os mecanismos que impulsionam a redução de contaminantes.

Método: O sistema de fluxo subsuperficial horizontal utilizado neste estudo foi colonizado por Typha domingensis e monitorado em sete TRHs (3, 5, 7, 9, 11, 13 e 15 dias). A qualidade do efluente foi avaliada em parâmetros como coliformes, demanda bioquímica e química de oxigênio (DBO_5 e DQO), nitrogênio, fósforo, turbidez e sólidos suspensos.

Resultados e Discussão: Os resultados mostraram que, enquanto a maioria dos parâmetros alcançou níveis normativos após 3 dias de TRH, os coliformes totais e fecais necessitaram de 9 dias para cumprir os limites estabelecidos. Isso indica que, com um sistema adicional de desinfecção, um TRH de 3 dias poderia ser suficiente, otimizando a eficiência do sistema enquanto mantém a conformidade. A discussão destaca a relação entre o TRH e a remoção de contaminantes, com recomendações para ajustes no sistema com base nas características do influente.

Implicações da Pesquisa: O estudo oferece insights práticos para o design e operação de zonas úmidas artificiais em áreas com recursos limitados, promovendo soluções sustentáveis para o tratamento de águas residuais. Os resultados podem informar políticas públicas e melhorar a eficiência das práticas de tratamento de águas residuais em regiões tropicais e subtropicais.

Originalidade/Valor: Esta pesquisa contribui com dados inéditos da República Dominicana, demonstrando a aplicação de sistemas de fluxo subsuperficial horizontal na obtenção de conformidade ambiental. Ela destaca o potencial de TRHs personalizados para otimizar zonas úmidas artificiais, equilibrando os custos operacionais e a eficiência do tratamento.

Palavras-chave: sistema de fluxo subsuperficial horizontal, tratamento de águas residuais, tempo de retenção hidráulica (TRH), remoção de contaminantes, qualidade do efluente.

IMPACTO DEL TIEMPO DE RETENCIÓN HIDRÁULICA EN LA CALIDAD DE EFLUENTES TRATADOS EN UN HUMEDAL SUBSUPERFICIAL DE FLUJO HORIZONTAL

RESUMEN

Objetivo: Este estudio tiene como objetivo analizar el impacto del tiempo de retención hidráulica (TRH) en la calidad de los efluentes tratados en un sistema de flujo subsuperficial horizontal. La investigación se centra en optimizar el TRH para cumplir con los estándares establecidos por las Normas Ambientales de la República Dominicana para descargas de aguas residuales en cuerpos de agua superficiales, redes de alcantarillado sanitario y aguas costeras.

Marco Teórico: El estudio se fundamenta en principios de diseño y operación de sistemas artificiales de humedales, enfatizando soluciones sostenibles para el tratamiento de aguas residuales. Conceptos como la eliminación biológica de contaminantes, la oxigenación a través de la vegetación y los procesos de sedimentación son esenciales para comprender los mecanismos que impulsan la reducción de contaminantes.

Método: El sistema de flujo subsuperficial horizontal utilizado en este estudio fue colonizado por Typha domingensis y monitorizado en siete TRH (3, 5, 7, 9, 11, 13 y 15 días). La calidad del efluente se evaluó considerando parámetros como coliformes, demanda bioquímica y química de oxígeno (DBO_5 y DQO), nitrógeno, fósforo, turbidez y sólidos suspendidos.

Resultados y Discusión: Los resultados mostraron que, si bien la mayoría de los parámetros alcanzaron niveles normativos a los 3 días de TRH, los coliformes totales y fecales requirieron hasta 9 días para cumplir con los límites establecidos. Esto indica que, con un sistema adicional de desinfección, un TRH de 3 días podría ser suficiente, optimizando la eficiencia del sistema mientras se mantiene el cumplimiento normativo. La discusión resalta la relación entre el TRH y la eliminación de contaminantes, con recomendaciones para ajustar el sistema en función de las características del influente.

Implicaciones de la Investigación: El estudio ofrece perspectivas prácticas para el diseño y operación de humedales artificiales en áreas con recursos limitados, promoviendo soluciones sostenibles para el tratamiento de aguas residuales. Los resultados pueden informar políticas públicas y mejorar la eficiencia de las prácticas de tratamiento de aguas residuales en regiones tropicales y subtropicales.

Originalidad/Valor: Esta investigación aporta datos inéditos de la República Dominicana, demostrando la aplicación de sistemas de flujo subsuperficial horizontal para cumplir con estándares ambientales. Destaca el potencial de TRH personalizados para optimizar humedales artificiales, equilibrando los costos operativos y la eficiencia del tratamiento.

Palabras clave: sistema de flujo subsuperficial horizontal, tratamiento de aguas residuales, tiempo de retención hidráulica (TRH), eliminación de contaminantes, calidad del efluente.

RGSA adota a Licença de Atribuição CC BY do Creative Commons (https://creativecommons.org/licenses/by/4.0/).

1 INTRODUCTION

Water pollution is one of the most severe environmental challenges affecting aquatic ecosystems worldwide, with wastewater being a significant source of contamination. This wastewater contains microplastics, pathogenic microorganisms, and various contaminants that not only degrade water quality but also threaten biodiversity and human health (Sáenz-Arias *et al.*, 2023). The impact is evident in regions such as Africa, Asia, and Latin America, where nearly all major rivers exhibit alarming pollution levels. Among the leading causes of this environmental degradation is the excessive nutrient load, which not only deteriorates water quality but is also often associated with the proliferation of pathogens. These combined factors significantly increase risks to both aquatic ecosystems and the communities that depend on them.

The challenge lies in the fact that untreated or inadequately treated discharges continue to affect aquatic ecosystems, exacerbating environmental and public health risks. Therefore, addressing wastewater treatment effectively is essential to mitigate the negative impact of these discharges and improve water quality in vulnerable areas, thus protecting ecosystems and the communities that rely on them.

Artificial wetlands have gained prominence as a cost-effective, sustainable, and efficient technology for removing contaminants from wastewater. Successfully used for over four decades, these systems have been primarily designed for municipal wastewater treatment.

However, in recent times, their use for treating agricultural, industrial, and landfill leachate wastewater has garnered increasing attention (Vymazal & Kröpfelová, 2009). Within wetlands, various processes such as aerobic/anoxic/anaerobic biodegradation, filtration, sorption, plant uptake, and photodegradation simultaneously facilitate the removal of organic substances, nutrients, micro-contaminants, and pathogens from wastewater. Their application is particularly advantageous in resource-limited regions and small to medium-sized communities, where low maintenance and simple operation are required.

This study focuses on a horizontal subsurface flow wetland where the hydrophytic plant Typha domingensis was used to colonize the system and enhance the treatment process. One of the most critical factors in the efficiency of these systems is hydraulic retention time (HRT), as longer contact time between wastewater, the substrate, and vegetation improves contaminant degradation. However, extending the HRT can entail operational and design limitations, making it essential to determine the optimal HRT to balance treatment efficiency with the operational feasibility of the wetland.

The primary objective of this study is to perform a preliminary analysis of the impact of HRT on the quality of treated effluents in a subsurface wetland, evaluating the behavior of the following water quality parameters: total coliforms, fecal coliforms, pH, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), color, turbidity, dissolved oxygen, suspended solids, temperature, ammonium nitrogen, total nitrogen, nitrate nitrogen, total phosphorus, and orthophosphates. The research aims to determine the most efficient HRT for the system, considering current environmental regulations and the feasibility of implementing such systems in rural or low-resource areas, where the adoption of more sophisticated technologies is limited.

This preliminary analysis provides valuable information for the design and operation of artificial wetlands for wastewater treatment, highlighting the importance of optimizing HRT to meet environmental normative limits and promote the system's sustainability and practicality in the long term. Additionally, this study is the first of its kind conducted using this methodology in the Caribbean and contributes to generating new knowledge from the Dominican Republic, a country that still faces limitations in scientific production (Domínguez-Valerio *et al.*, 2024).

2 METHODOLOGY

The methodology of an article outlines the procedures employed to conduct the research, including the type of study, sample selection, data collection and analysis methods, ethical considerations, and limitations of the study. Its detailed and transparent description is essential to guarantee the replicability and reliability of the results, in addition to providing a solid basis for the interpretation and generalization of the findings.

2.1 STUDY AREA

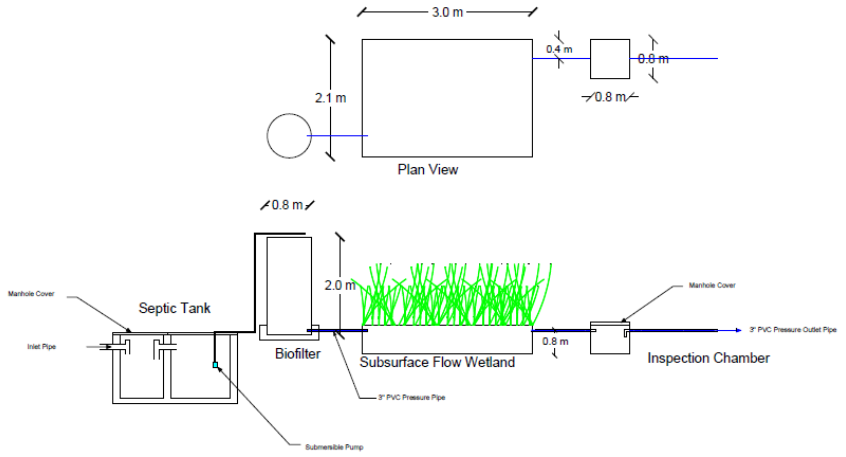
The experimentation was conducted in an area within the city of Moca, Espaillat Province, Dominican Republic, located at Zone 19 Q, East 340031.44 m and North 2145764.93 m, at an elevation of 186 meters above sea level. This region experiences long, warm, and cloudy summers, along with short and predominantly clear winters. Throughout the year, temperatures range from 19 °C to 32 °C, rarely falling below 17 °C or exceeding 34 °C. The warm season spans 4.5 months, from May 30 to October 15, with an average daily maximum temperature above 31 °C. The hottest month is July, with average maximum temperatures of 32 °C and minimums of 23 °C. The cool season lasts 2.9 months, from November 29 to February 26, with average daily maximum temperatures below 29 °C. January is the coldest month, with average minimum temperatures of 19 °C and maximums of 28 °C. The average annual precipitation is 1,170 millimeters.

2.2 EXPERIMENTAL AREA

A horizontal subsurface flow wetland was constructed for the study within a rectangular structure made of concrete blocks, with the side and bottom surfaces sealed with mortar. The wetland contains a filter medium 0.80 m in height from the bottom, composed of layers of gravel with sizes ranging between 1/2 and 1 inch, to ensure adequate hydraulic conductivity and reduce the risk of clogging. Additionally, the treatment system is equipped with hydrophytic vegetation (Typha domingensis), which colonizes the filter bed, aiding in oxygenating the substrate and water, removing nutrients from the wastewater, and promoting the development of the biofilm.

Figure 1

Scheme B for wastewater treatment.



The propagation of the Typha domingensis species was primarily carried out through stem-derived organs, by segmenting their rhizomes. Sixteen plants of this species were planted in the wetland, using a planting frame of 60 cm by 40 cm; the 60 cm separation between plants and 40 cm between rows. The roots were planted at a depth of 15 to 25 cm, ensuring they were completely covered by the substrate and protected from sunlight. A 16-week period was established for the colonization of the wetland area, resulting in the plants developing a strong root system and significant leaf coverage, reaching a total of 95 plants by the time wastewater monitoring began for the treatment process. The study area corresponds to an artificial wetland system with subsurface flow, featuring a rectangular geometry with dimensions of 2.10 m in width, 3.00 m in length, and 0.80 m in depth, covering a total area of 5.04 m³.

To verify the effectiveness of the constructed system, a 5.0 m³ volume of wastewater was used, adjusted according to the hydraulic retention time (HRT) under experimentation for each test dynamic. The wastewater utilized for treatment underwent various HRTs, allowing evaluation of how system efficiency in contaminant removal changed. The goal was to identify the most suitable retention time that optimizes purification without exceeding the system's capacity. Hydraulic Retention Time (HRT) refers to the average time wastewater remains in the treatment system before becoming effluent.

2.3 SAMPLING AND ANALYSIS

The HRT of the system was adjusted at intervals of three (3), five (5), seven (7), nine (9), eleven (11), thirteen (13), and fifteen (15) days. Monitoring was conducted on the influent and effluent corresponding to each HRT interval. This process was repeated three (3) times using influents with varying contaminant load concentrations, each representative of highly polluted water. The samples were collected by the company Laboratorio Ambiental y Energético (LAMENER), certified by the Ministry of Environment and Natural Resources of the Dominican Republic. Each sample was preserved and subsequently analyzed in the company's laboratory. The water quality parameters selected for this research are presented in Table 1, including the unit of measurement, symbol, and analytical method.

Table 1

Parameters, symbol, unit, and analytical method.

Parameter	Symbol	Unit	Analytical Method
Total Coliforms		MPN/100ml	SM-9221-B
Fecal Coliforms		MPN/100ml	SM-9221-E
Hydrogen Potential	pH	-	SM-4500-H+.B
Turbidity		NTU	SM-2130-B
Color		Pt-Co Units	SM-2120-C
Dissolved Oxygen	DO	% sat.	SM-4500-O-G
Suspend Solids	SS	mg/l	SM-2540-D
Temperature		° C	SM-2550-B
Chemical Oxygen Demand	COD	mg/l	SM-5220-D
Biochemical Oxygen Demand	BOD_5	mg/l	SM-5210-B
Ammonium Nitrogen	NH_4^+	mg/l	SM-4500-NH3
Total Nitrogen	N	mg/l	SM-4500-N-C
Nitrate Nitrogen	NO_3-	mg/l	SM-4500-$NO3^-$-E
Total Phosphorus	P	mg/l	SM-4500-P-C
Orthophosphates	$P\text{-}PO_4$	mg/l	SM-4500-P

3 RESULTS AND DISCUSSIONS

This study evaluated the removal efficiency of various contaminants in treated effluents using a horizontal subsurface flow wetland, varying the hydraulic retention time (HRT) from 3 to 15 days. The results obtained for each measured parameter are presented and analyzed below, comparing the influent values with the effluent values at the different HRTs mentioned. Table 2 shows the value of each parameter in the influent and effluent as a function of the hydraulic retention time, for experiment I.

Table 2

Physicochemical and microbiological characteristics of the wastewater treatment system, experimentation I.

Parameter	Unit	Effluent	Effluent Values According to Hydraulic Retention Time						
			3 days	5 days	7 days	9 days	11 days	13 days	15 days
Total Coliforms	MPN/100ml	16,000,000.0	49,000.0	24,000.0	14,000.0	330.0	240.0	240.0	240.0
Fecal Coliforms	MPN/100ml	16,000,000.0	49,000.0	13,000.0	14,000.0	330.0	240.0	240.0	240.0
Hydrogen Potential	-	7.7	7.7	7.1	7.5	7.7	7.3	7.2	7.3
Turbidity	NTU	168.5	4.0	2.0	5.0	6.0	15.0	6.0	10.0
Color	Pt-Co Units	730.5	10.0	7.0	10.0	4.0	13.0	4.0	8.0
Dissolved Oxygen	mg/l	0.4	1.1	2.2	9.0	17.6	12.0	8.0	13.3
Suspend Solids	mg/l	642.5	10.0	1.0	11.0	7.0	24.0	6.0	10.0
Temperature	° C	26.6	30.0	31.6	30.2	30.1	28.6	29.0	29.9
Chemical Oxygen Demand	mg/l	505.0	57.0	38.0	36.0	26.0	29.0	18.0	60.0
Biochemical Oxygen Demand	mg/l	151.5	15.3	13.0	10.6	5.3	5.6	5.3	16.8
Ammonium Nitrogen	mg/l	61.0	6.0	1.8	0.8	0.5	0.4	1.4	0.2
Total Nitrogen	mg/l	105.0	15.0	3.0	2.0	<1.0	<1.0	3.0	<1.0
Nitrate Nitrogen	mg/l	7.4	1.3	0.7	1.0	0.4	0.5	1.1	0.7
Total Phosphorus	mg/l	6.3	2.0	1.0	1.1	0.4	1.7	0.9	0.8
Orthophosphates	mg/l	2.5	0.7	0.4	0.4	0.2	0.6	0.3	0.3

3.1 EXPERIMENTATION I

Throughout the different HRTs, a gradually sustained reduction in total and fecal coliforms was observed, with almost identical behavior for both parameters. After 3 days, a significant reduction was achieved, decreasing from an initial influent concentration of 16,000,000 MPN/100 ml to 49,000 MPN/100 ml in the effluent, representing an initial reduction of 99.6937%. Subsequently, levels decreased to 330 MPN/100 ml at 9 days of HRT. Starting at 11 days, the highest reduction was observed, with total and fecal coliform levels of 240 MPN/100 ml, reaching a removal efficiency of over 99.9985%.

Turbidity and color, important indicators of water clarity and aesthetics, showed an irregular downward trend. Although the system reduced turbidity from 168.5 NTU to 4 NTU in just 3 days, values fluctuated slightly at longer HRTs, reaching up to 15 NTU at 11 days of HRT. A similar phenomenon was observed in color, which reached its lowest levels (4 U. Pt-Co) with a 9-day HRT but showed a slight rebound at longer HRTs (11 days). This behavior could be related to the mobilization of sedimented particles in the filter bed or variations in the

biodegradation of organic materials. Dissolved oxygen levels showed a continuous improvement as the HRT increased. While the influent exhibited very low values (0.4 mg/l), the effluent at 9 days of HRT reached optimal levels (17.6 mg/l), which slightly decreased at 11 and 15 days of HRT. This increase suggests greater oxygenation within the system as the water remains in contact with vegetation and the biofilm for longer periods, enhancing aerobic biodegradation processes.

Suspended solids displayed significant variability across different HRTs. After 3 days, a drastic reduction from 642.5 mg/l in the influent to 10 mg/l in the effluent was observed. However, suspended solids levels increased to 24 mg/l at 11 days of HRT, suggesting that longer retention times may slightly reintroduce particles into the system due to sediment resuspension or biofilm growth in the filter bed. The reduction in Chemical Oxygen Demand (COD) was significant, dropping from 505 mg/l to 57 mg/l at 3 days of HRT, representing an 88.71% reduction. However, the highest removal efficiency was observed at 9 days of HRT (94.85%), after which a slight increase in COD values was recorded at longer HRTs, suggesting possible system saturation or insufficient removal of more resistant organic compounds.

Biochemical Oxygen Demand (BOD_5), a key indicator of biodegradable organic load, also showed high removal efficiency. Within the first 5 days of HRT, BOD_5 decreased from 151.5 mg/l to 13.0 mg/l, corresponding to a 91.4% reduction. With 9 days of HRT, the system reached its best level of compliance, recording 5.3 mg/l. The concentration of ammonium nitrogen (NH_4^+) decreased from 61 mg/l in the influent to 0.5 mg/l with a 9-day HRT and to 0.2 mg/l at 15 days, demonstrating a high removal efficiency of over 99%. This reduction reflects the system's effectiveness in converting ammonium into other nitrogen forms through processes such as nitrification. Almost complete removal of total nitrogen was observed, with a reduction from 105 mg/l in the influent to less than 1 mg/l starting at 9 days of HRT. Total phosphorus decreased from 6.3 mg/l in the influent to 0.4 mg/l with a 9-day HRT, achieving an efficiency of 93.7%. For orthophosphates, values decreased from 2.5 mg/l to 0.2 mg/l with the same HRT, suggesting that biological processes and substrate adsorption play a crucial role in phosphorus removal.

Table 3

Physicochemical and microbiological characteristics of the wastewater treatment system, experiment II.

Parameter	Unit	Effluent	Effluent Values According to Hydraulic Retention Time						
			3 days	5 days	7 days	9 days	11 days	13 days	15 days

Total Coliforms	MPN/100ml	5,800,000.0	24,000.0	790.0	2,400.0	790.0	790.0	240.0	130.0
Fecal Coliforms	MPN/100ml	5,800,000.0	24,000.0	790.0	1,300.0	490.0	490.0	240.0	130.0
Hydrogen Potential	-	6.6	6.7	7.0	7.1	7.1	7.2	6.9	8.4
Turbidity	NTU	309.0	62.0	2.0	4.0	4.0	6.0	6.0	5.0
Color	Pt-Co U.	475.3	13.0	5.0	7.0	6.0	7.0	7.0	3.0
Dissolved Oxygen	mg/l	1.1	8.3	10.5	9.8	11.0	13.4	9.6	10.9
Suspend Solids	mg/l	729.3	10.9	2.0	1.0	6.0	3.0	2.0	6.0
Temperature	° C	27.0	29.0	28.7	29.5	28.4	27.0	26.7	29.3
Chemical Oxygen Demand	mg/l	448.5	137.0	32.0	26.0	23.0	17.0	24.0	27.0
Biochemical Oxygen Demand	mg/l	203.5	42.0	9.4	6.1	6.4	5.3	6.9	7.9
Ammonium Nitrogen	mg/l	58.5	3.2	0.6	0.3	0.1	0.1	0.1	1.2
Total Nitrogen	mg/l	127.5	7.0	<1.0	<1.0	2.0	<1.0	<1.0	2.0
Nitrate Nitrogen	mg/l	7.7	2.2	0.8	0.5	1.5	0.3	0.9	0.7
Total Phosphorus	mg/l	10.3	2.3	1.0	0.5	0.9	0.5	0.7	1.1
Orthophosphates	mg/l	3.4	0.8	0.3	0.2	0.3	0.2	0.2	0.4

3.2 EXPERIMENTATION II

When comparing the influent characteristics between Experimentation I and II, key differences are observed across several parameters. In Experimentation I, the influent had total and fecal coliform levels of 16,000,000 MPN/100 ml, significantly higher than the 5,800,000 MPN/100 ml observed in Experimentation II. Similarly, regarding biochemical oxygen demand (BOD), the influent in Experimentation I was 151.5 mg/l, whereas in Experimentation II, it was higher at 203.5 mg/l. This increase in Experimentation II suggests a greater organic load in the influent.

For other parameters, turbidity in Experimentation I was 168.5 NTU, whereas in Experimentation II it was considerably higher at 309 NTU, indicating a greater presence of suspended particles in the second influent sample. Regarding nutrients, the influent in Experimentation II had a higher nitrogen concentration, which could result in greater treatment demand to reduce levels to acceptable limits. Ammonium nitrogen also showed a relatively high load in both experiments. For phosphorus, it was higher in Experimentation II (10.3 mg/l) compared to Experimentation I (6.3 mg/l). These differences suggest that the influent in Experimentation II had a generally higher contaminant load, potentially requiring more intensive treatment to achieve the desired effluent levels.

The evaluation of treated water quality parameters in the horizontal subsurface flow wetland during Experimentation II, based on the HRT, reveals the following:

Total and fecal coliforms showed high reductions throughout the treatment process. Within the first 3 days, total coliforms decreased from 5,800,000 MPN/100 ml to 24,000 MPN/100 ml (99.586%). At 7 days, they decreased further to 2,400 MPN/100 ml (99.959%), and at 9 days, they dropped to 790 MPN/100 ml (99.986%), demonstrating remarkable bacterial removal efficiency. Similarly, fecal coliforms decreased significantly, reaching values of 130 MPN/100 ml at 15 days, representing a removal efficiency of over 99.997%. These results indicate that the system is very effective in reducing microbiological loads to safe levels with prolonged retention times.

Turbidity and color also showed considerable reductions. At 3 days, turbidity decreased from 309 NTU to 62 NTU (79.93%), and at 7 days, it reached levels as low as 4 NTU (98.71%), indicating that the wetland is effective at removing suspended particles. Color, which started at 475.3 U. Pt-Co, drastically reduced to 5 U. Pt-Co at 5 days (98.95%) and remained practically constant up to 15 days. Dissolved Oxygen (DO) levels increased significantly, rising from 1.1 mg/l in the influent to 8.3 mg/l at 3 days and reaching a maximum value of 13.4 mg/l at 11 days. This increase in oxygen concentration indicates that the wetland is well-oxygenated, favoring the processes of organic matter removal and other contaminants.

The reduction of suspended solids was also notable. From 729.3 mg/l in the influent, SS decreased to 109 mg/l at 3 days (85.06%) and further to 1 mg/l at 7 days (99.86%). At 11 days, the concentration remained low at 2 mg/l, indicating high efficiency of the wetland in removing suspended particles throughout the retention period. Chemical Oxygen Demand (COD) removal was significant, dropping from 448.5 mg/l in the influent to 137 mg/l at 3 days (69.45%). By 7 days, the value dropped further to 26 mg/l, demonstrating a 94.2% removal efficiency. Biochemical Oxygen Demand (BOD_5), on the other hand, decreased from an initial 203.5 mg/l to 9.4 mg/l at 7 days (95.38%) and remained at low values of 6.9 mg/l at 11 days, reflecting high efficiency in removing biodegradable organic matter.

Ammonium nitrogen decreased from 58.5 mg/l to 3.2 mg/l within the first 3 days (94.53%) and reached its lowest value of 0.1 mg/l at 9 days, representing a removal efficiency of 99.83%. Total nitrogen, which started at 127.5 mg/l, also showed a significant reduction, reaching concentrations below 1 mg/l at 5 days, reflecting the wetland's capacity to eliminate nitrogen forms from the water. Finally, total phosphorus decreased from 10.3 mg/l to 2.3 mg/l within the first 3 days (77.67%) and to 0.5 mg/l at 7 days (95.15%). Orthophosphates showed a similar removal trend, dropping from 3.4 mg/l to 0.3 mg/l at 7 days (91.18%).

Table 4

Physicochemical and microbiological characteristics of the wastewater treatment system, experiment III

Parameter	Unit	Effluent	Effluent Values According to Hydraulic Retention Time						
			3 days	5 days	7 days	9 days	11 days	13 days	15 days
Total Coliforms	MPN/100ml	790,000.0	240.0	2,400	330.0	170	230.0	240.0	240.0
Fecal Coliforms	MPN/100ml	790,000.0	240.0	2,400	330.0	170	230.0	240.0	240.0
Hydrogen Potential	-	7.6	7.2	7.6	8.1	6.9	7.9	7.7	8.2
Turbidity	NTU	116.0	6.0	4.0	11.0	11.0	11.0	10.0	10.0
Color	Pt-Co U.	257.0	4.0	2.0	9.0	7.0	9.0	7.0	7.0
Dissolved Oxygen	mg/l	1.6	12.0	15.0	27.9	7.8	20.0	15.0	20.0
Suspend Solids	mg/l	234.0	6.0	2.0	7.0	7.0	8.0	7.0	8.0
Temperature	° C	25.9	28.3	30.3	31.0	32.3	33.3	33.5	33.0
Chemical Oxygen Demand	mg/l	189.0	23.0	29.0	19.8	12.0	23.0	15.0	19.5
Biochemical Oxygen Demand	mg/l	78.0	6.7	7.8	5.0	3.8	5.0	4.8	6.5
Ammonium Nitrogen	mg/l	16.0	1.0	0.5	1.1	1.1	1.1	1.1	0.7
Total Nitrogen	mg/l	37.0	2.0	<1.0	2.0	2.0	<1.0	<1.1	<1.1
Nitrate Nitrogen	mg/l	6.8	0.6	0.4	0.6	0.8	0.3	1.0	0.8
Total Phosphorus	mg/l	4.9	0.9	0.9	1.2	1.6	1.3	0.9	1.0
Orthophosphates	mg/l	1.6	0.3	0.3	0.6	0.5	0.6	0.3	0.4

3.3 EXPERIMENTATION III

In Experimentation III, the influent entering the wastewater treatment system was characterized by generally lower concentrations of microbiological and chemical contaminants compared to the influents in Experimentations I and II.

The reduction in total and fecal coliforms showed a clear downward trend with increasing HRT. After 3 days, total coliform levels decreased from 790,000 MPN/100 ml to 240 MPN/100 ml, remaining relatively constant up to 15 days. A similar pattern was observed for fecal coliforms. As seen in Table 4, the initial coliform concentration in this experiment (790,000 MPN/100 ml) was much lower compared to Tables 2 and 3 (16,000,000 and 5,800,000 MPN/100 ml, respectively). This may facilitate faster bacterial removal due to the lower number of organisms to eliminate. Additionally, the influent in Experimentation III exhibited better initial conditions (lower BOD_5, COD, suspended solids, and nutrients). These conditions

promote better wastewater quality from the outset, potentially enabling more effective natural disinfection processes and microbial activity.

Regarding turbidity, a significant initial reduction was observed after 3 days (from 116 NTU to 6 NTU), remaining nearly constant up to 15 days. Similarly, color experienced a significant reduction, from 257 U. Pt-Co in the influent to 4 U. Pt-Co after 3 days, with slight increases between 7 and 11 days of HRT, but always remaining within acceptable limits. These results suggest that the wetland effectively removes suspended particles and compounds affecting water color, particularly at shorter retention times. Dissolved oxygen showed a considerable increase with longer HRT. After 3 days, DO rose by 650% (from 1.6 mg/l to 12 mg/l), reaching a maximum increase of 1,643.8% after 7 days (27.9 mg/l). Although levels decreased slightly in subsequent days, they remained significantly elevated compared to the influent.

Suspended solids experienced a significant reduction of 97.4% (from 234 mg/l to 6 mg/l) after 3 days. This trend remained stable across all evaluated retention times, with removal efficiency exceeding 96%. Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD_5) parameters exhibited significant reductions. After 3 days, COD decreased by 87.8% (from 189 mg/l to 23 mg/l). By 9 days, the reduction was even greater, reaching 93.6% (12 mg/l), indicating effective removal of organic matter. BOD_5 showed a 91.4% reduction after 3 days (from 78 mg/l to 6.7 mg/l) and achieved its maximum reduction of 95.1% at 9 days (3.8 mg/l).

Ammonium nitrogen showed a notable reduction of 93.75% after 3 days (from 16 mg/l to 1 mg/l), remaining below 1.1 mg/l across all evaluated HRTs. Total nitrogen also exhibited significant reductions, with a 94.6% decrease after 3 days (from 37 mg/l to 2 mg/l) and levels below 1 mg/l starting at 7 days. Total phosphorus showed an 81.63% reduction (from 4.9 mg/l in the influent to 0.9 mg/l) after 3 days, with slight increases in subsequent days but remaining under control. Orthophosphates showed a similar trend, with an 81.25% reduction after 3 days (from 1.6 mg/l to 0.3 mg/l), remaining at low levels throughout the 15-day period.

4 CONCLUSION

This research has shown that hydraulic retention time (HRT) is a critical and determining factor in the efficiency of the system for removing various contaminants present in wastewater. As HRT increases, significant improvements are observed in effluent quality. However, the optimal HRT varies depending on the type of contaminant, suggesting the need

for specific adjustments to the HRT based on the characteristics of the influent and treatment objectives. It is established that the 16-week colonization period for Typha domingensis was adequate for the wastewater treatment system, supporting biological processes that depend on the presence of oxygen and fostering an appropriate aerobic environment for the purification of certain contaminants. The monitored parameters reflect a good capacity for contaminant removal, largely attributed to the strong root development of the vegetation and its significant coverage over the wetland bed.

The analysis of the data obtained from the three sets of experiments has identified the minimum HRT required for each parameter to comply with the Dominican environmental standards:

Significant reductions in total and fecal coliforms, exceeding 99%, were achieved, which is crucial for ensuring the microbiological safety of treated water. Concentrations below the permissible limit of 1,000 MPN/100 ml, as established by Dominican environmental regulations, were achieved with an HRT of 9 days across all influent scenarios. The system was more efficient with influents containing lower bacterial loads. pH values remained within the regulatory range throughout the HRT, meeting the standard requirements. This indicates that the subsurface wetland system is capable of maintaining a neutral effluent condition suitable for aquatic life.

Turbidity was effectively reduced from the first few days, indicating good sedimentation of suspended particles. Color also showed a significant decrease. Starting with an influent of 487.6 U. Pt-Co, values dropped to 9.0 U. Pt-Co at 3 days and fluctuated between 4.7 and 9.7 U. Pt-Co until 15 days, when a final value of 6.0 U. Pt-Co was recorded. The reduction in color is associated with the degradation of organic matter and the retention of particles in the wetland substrate. Dissolved Oxygen (DO) levels showed a notable increase from an initial average value of 1.1 mg/l to 7.1 mg/l within the first 3 days. Subsequently, DO reached a maximum of 15.6 mg/l at 7 days, slightly decreasing but maintaining high levels at 14.7 mg/l at 15 days. This increase in DO is key to system efficiency, as it promotes the oxidation of organic matter and the removal of nutrients. The significant increase in dissolved oxygen in the treated water suggests that the Typha domingensis vegetation enhances oxygenation, improving water quality and the wetland's treatment capacity.

Suspended solids values remained below the regulatory limit of 35 mg/l starting at 3 days of HRT, indicating the wetland's efficiency in removing suspended solids from this point onward. Despite highly elevated influent values, the system achieved effective reduction, reaching its highest efficiency with retention times of 5 to 15 days, with removal rates exceeding

98% in all cases. This removal is likely associated with physical filtration through the granular medium and sedimentation processes within the wetland.

For Chemical Oxygen Demand (COD), an HRT of 3 days was determined to be sufficient to reduce concentrations below the regulatory limit of 130 mg/l. COD remained below this limit for all evaluated retention periods, indicating high efficiency in removing organic matter. The lowest values were observed after 9 days of retention. For BOD, an HRT of 3 days was also effective. Biochemical Oxygen Demand (BOD_5) levels were below the regulatory limit of 35 mg/l throughout the process, demonstrating an effective reduction in biodegradable organic matter. After day 7, values stabilized at low levels, with no significant further reductions, suggesting possible system saturation or insufficient removal of more resistant organic compounds. These results demonstrate the system's efficiency in removing biodegradable organic matter and oxidizable chemical compounds.

The results indicate that the system efficiently reduced nutrients, reaching very low levels that comply with the limits established by environmental regulations, contributing to the prevention of eutrophication in receiving bodies. Percentage reductions in contamination were significant across all analyzed parameters, especially for ammonium nitrogen, which achieved a 92.5% reduction at 3 days and over 98% from 7 days of HRT onward. Total nitrogen reductions exceeded 91% in the early days of treatment. Nitrate nitrogen removal was slightly slower, with an average reduction of just over 80% at 3 days. The removal of total phosphorus and orthophosphates was very effective from the first days, with a 76% reduction at 3 days and over 83% from 5 days of HRT onward. These reductions indicate high efficiency in nutrient removal, crucial for preventing eutrophication in receiving water bodies.

While total and fecal coliforms require a longer HRT (9 days) to reach the levels required by Dominican regulations, other parameters such as COD, BOD_5, various nitrogen forms, total phosphorus, orthophosphates, turbidity, color, suspended solids, pH, and DO achieved the permissible regulatory limits after just 3 days of HRT. This suggests that, with the implementation of an additional disinfection system, it would be possible to reduce the HRT to 3 days for efficient wastewater treatment at the contaminant concentrations observed in this study. This approach would not only optimize the treatment process but also maintain effectiveness in pollutant removal, comply with Dominican regulatory standards, and enhance the overall efficiency of the system.

ACKNOWLEDGEMENTS

The authors of this work would like to thank the Ministry of Higher Education, Science and Technology (MESCyT) of the Dominican Republic, who supported the research project "Biosistema Natural para el Tratamiento de las Aguas Residuales de Origen Doméstico en República Dominicana" through the National Fund for Innovation and Scientific and Technological Development (FONDOCyT) 2022 (Code 2022-2B2-157).

REFERENCES

Domínguez-Valerio, C.M., Altagracia Cuello Díaz, E.A., Orgaz-Agüera, F., & Campusano Polanco, M.E. (2024). Analysis of Dominican Scientific Production and its Relationship with the Country's Economic Sectors and the Objectives for Sustainable Development. *Revista de Gestão Social e Ambiental*, *18*(10), e8498-e8498. https://doi.org/10.24857/rgsa.v18n10-009

Sáenz-Arias, S. ., Garcés-Ordóñez, O. ., Córdoba-Meza, T., Blandon, L., Espinosa Díaz, L., Vivas-Aguas, L., & Canals, M. (2023). Contaminación por vertidos de aguas residuales: Una revisión de las interacciones microorganismos–microplásticos y sus posibles riesgos ambientales en aguas costeras colombianas: *Ecosistemas*, *32*(1), 2489. https://doi.org/10.7818/ECOS.2489

Vymazal, J., & Kröpfelová, L. (2009). Removal of organics in constructed wetlands with horizontal sub-surface flow: A review of the field experience. *Science of the Total Environment, 407*, 3911–3922. https://doi.org/10.1016/j.scitotenv.2008.08.032