

# Urban Wastewater Treatment with a Vertical Flow Wetland Constructed with Recycled Substrate

*Depuración de aguas residuales urbanas con humedal de flujo vertical construido con sustrato reciclado*

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**ABSTRACT:** This study had the **objective** of analysing the influence of implementing a vertical flow wetland constructed with recycled clay brick substrate on the treatment of urban wastewater. The **methodology** employed was based on an explanatory-level experimental research. An experimental wastewater treatment plant was constructed, and the study used a sample population consisting of urban wastewater from a rural community in the district of Buenos Aires, in northern Peru. The data collection instruments were adapted from Peruvian technical standards for particle size distribution, hydraulic conductivity, and porosity of the filter media, as well as from Peruvian standards for the evaluation of wastewater treatment plant effluents. The **results** determined that the particle size distribution used should have a uniformity coefficient between 3.8 and 5.0. In the treatment of urban wastewater, a removal percentage of 95.74% was obtained for biochemical oxygen demand, 88.47% for chemical oxygen demand, and 76.67% for turbidity. The **conclusion** of the research determined that the implementation of a vertical flow wetland constructed with a substrate made of recycled clay brick has a positive and statistically significant influence on the treatment of urban wastewater, demonstrating its potential as a sustainable and low-cost alternative, viable for application in rural communities.

**Keywords:** wastewater, recycled clay, constructed wetland, substrate.

**RESUMEN:** El presente trabajo tuvo como **objetivo** analizar la influencia de la implementación de un humedal de flujo vertical construido con sustrato proveniente de ladrillo de arcilla reciclado en la depuración de aguas residuales urbanas. La **metodología** empleada se basó en una investigación experimental de nivel explicativo. Se construyó una planta depuradora experimental y se trabajó con una población muestral constituida por el agua residual urbana de una comunidad rural del distrito de Buenos Aires en el norte del Perú. Los instrumentos para recolectar los datos fueron adaptados de las normas técnicas peruanas para granulometría, conductividad hidráulica y porosidad del medio filtrante y de las normas peruanas para evaluación de efluentes de plantas de tratamientos de aguas residuales. Los **resultados** determinaron que la granulometría a utilizar debe tener un coeficiente de uniformidad entre 3.8 y 5.0. En la depuración de las aguas residuales urbana se obtuvo un porcentaje de remoción de la demanda bioquímica de oxígeno de 95.74 %, de la demanda química de oxígeno de 88.47 % y de turbiedad del 76.67 %. La **conclusión** de la investigación determinó que la implementación de un humedal de flujo vertical construido con sustrato conformado por ladrillo de arcilla reciclado influye positiva y estadísticamente significativa en la depuración de aguas residuales urbanas evidenciando su potencial como una alternativa sostenible y de bajo costo, viable para su aplicación en comunidades rurales.

**Palabras clave:** Aguas residuales, arcilla reciclada, humedal construido, sustrato.

## 1. INTRODUCTION

Urban wastewater is the result of water use in human activities and, before being discharged into rivers or other bodies of water, must be treated using physical, chemical and biological processes. However, approximately 80% of this wastewater worldwide is discharged into surface water bodies without prior treatment, causing water pollution [1].

This pollution is exacerbated in rural or peri-urban areas that do not have adequate wastewater treatment systems [2]; in Latin America, one of the main sources of river pollution comes precisely from untreated wastewater discharged from communities [3]. 44% of all wastewater produced in countries with low levels of development is collected and disposed of in the natural environment without adequate treatment [4].

To address this problem, there are mechanisms for protecting the aquatic environment and recycling water resources, such as the efficient and effective treatment of urban wastewater [5]. This treatment is essential to eliminate the physical, chemical and biological contaminants present in wastewater and allow its reuse in non-potable activities [4], as only 28% of all contaminated water is treated in low-middle income countries, and in low-income countries only 8% receives treatment [6].

It should be noted that urban wastewater treatment has not kept pace with population growth, resulting in increased pollution in cities [7]. In this context, the implementation of constructed vertical flow wetlands is proposed as an ecological technology that provides a cost-effective and sustainable solution in dispersed communities and rural areas [8]. In order to maintain treatment efficiency in this type of wetland, due to the decrease in drainable porosity, they must be constructed with a substrate with optimal particle size distribution [9].

The filter medium selected for the construction of this model must have high efficiency in intercepting pollutants; it must also have a high anti-clogging capacity in order to preserve porosity and hydraulic conductivity [10].

In order to avoid the problem of clogging in this type of subsurface system, solutions have been proposed using alternative substrates such as concrete and recycled brick [11]. Similarly, the gradual use of blast furnace slag to replace conventional substrates is recommended; however, the problem of clogging remains in the long term when wastewater enters the system [9]. On the other hand, the use of lightweight expanded clay aggregate, known as LECA, is considered to produce better performance in the purification process, but monitoring is required to measure the level of efficiency in removing contaminants [12].

When selecting the substrate for this type of system, it is essential to consider hydraulic resistance, cost, availability and contaminant removal performance, as poor selection results in low levels of investment in management and environmental damage [14]. Inadequate substrate selection can cause obstructions in the treatment model, does not improve ecological efficiency, and does not reduce risks to public health or damage to the environment [13].

Previous studies have shown that the performance of a constructed vertical flow wetland system allows for the removal of 46% to 72% of biochemical oxygen demand, 40% to 68% of chemical oxygen demand, and 37% to 66% of oils and fats. These values suggest that contaminant removal is highly efficient [15].

The evaluation of treated urban wastewater using vertical flow constructed wetland technology in different design combinations yielded results of 88% removal of chemical oxygen demand, 94% removal of biochemical oxygen demand, and 91% removal of total suspended solids. This type of technology is viable in terms of construction, operation, and maintenance in population centres with fewer than 2,000 inhabitants [16].

## 2. MATERIALS AND METHODS

To evaluate the implementation of the vertical flow constructed wetland with recycled substrate, an experimental design with a control group and pre- and post-test analysis was established. A treatment plant was designed and built in the town of El Ala in the district of Buenos Aires, located in northern Peru. Samples were taken over a period of five months. The structural and hydraulic design calculations followed the model indicated in [17]. The screen chamber and distribution chambers for vertical flow constructed wetlands implemented in Denmark and with the components indicated in Figure 1.

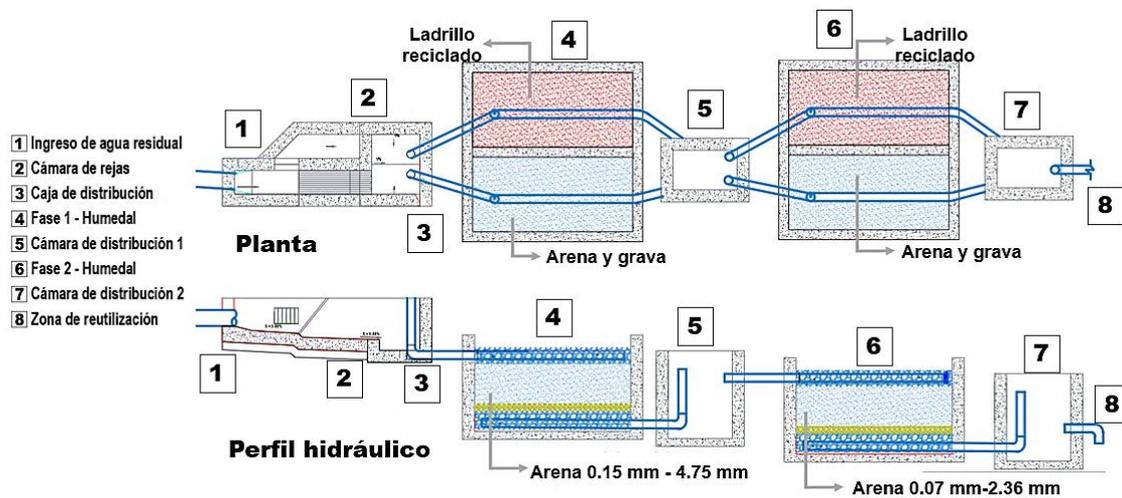


Figure 1. Components of the treatment plant. Source: own elaboration.

### 2.1 Phase 1. Design and construction of the vertical flow wetland

The treatment plant consisted of four vertical subsurface flow cells. In both phases indicated as components 4 and 6 in Figure 1, four cells were constructed; in two of them, gravel and sand were used (conventional substrate: SC) with a grain size selected according to infiltration capacity tests and a uniformity coefficient of less than 5.12; in the other two cells, two vertical flow wetlands were installed, consisting of recycled clay brick substrate (recycled substrate: SR) with selected grain size. The configuration of the cells in each phase followed the model shown in Figure 2.

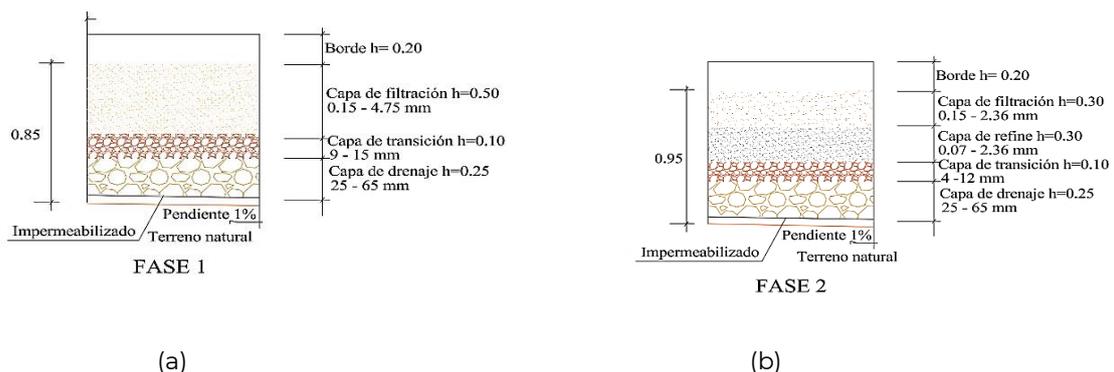


Figure 2. (a) and (b) Configuration of phases 1 and 2 of the vertical flow wetland cells. Source: own elaboration.

The methodological approach was based on an experimental design. The study population consisted of urban wastewater generated in a population group located in the district of Buenos Aires. The instruments used were certified by the municipal management unit of the local

commune. Three experimental groups and one control group were established, which followed the sequence shown in Figure 3.

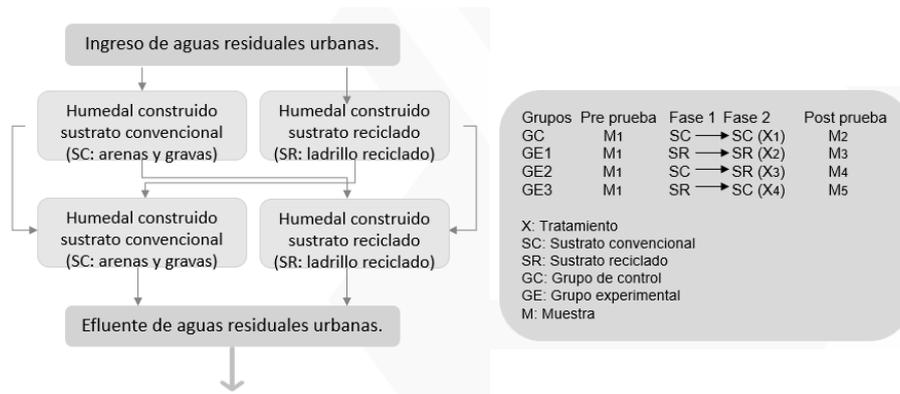


Figure 3. Composition of the experimental groups and control group. Source: own elaboration.

### 2.2 Phase 2. Testing of variables and data collection

Laboratory tests were carried out on the substrate used, such as particle size distribution analysis to determine the coefficient of uniformity, moisture content, water absorption percentage, specific weight and unit weight, porosity and water infiltration capacity of both the conventional substrate and the recycled substrate, in accordance with Peruvian technical standards. The data collection technique for the effluents obtained at the experimental treatment plant was observation during the research period. To determine the contaminant removal capacity, tests were carried out on treated urban wastewater as indicated in Table 1.

Table 1. Tests performed on treated urban wastewater.

N o.	Property	Test method
1	Temperature	SMEWW-APHA-AWWA-WEF Part 5550 B Temperature. Laboratory and field methods. 23rd Edition, 2017
2	pH	SMEWW-APHA-AWWA-WEF Part 4500-H+ BpH Valor con método electromecánico. 23rd Edition, 2017
3	Turbidity	SMEWW-APHA-AWWA-WEF Part 2130 BTurbidity. 23rd Edition, 2017.
4	BOD <sub>5</sub>	SMEWW-APHA-AWWA-WEF Part 5210 Biochemical Oxygen Demand (BOD). 5-Day BOD Test. 22nd Edition, 2012.
5	DQO	SMEWW-APHA-AWWA-WEF Part 5220 D. Chemical Oxygen Demand (COD). Closed Reflux, Colorimetric Method. 23rd Edition, 2017.
6	Thermotolerant coliforms	SMEWW-APHA-AWWA-WEF Part 9221 B. Multiple-Tube Fermentation Technique for Members of the Coliform Group. Standard Total Coliform Fermentation Technique. 23rd Edition, 2017

Source: own elaboration.

### 2.2 Phase 3. Data analysis

The tests were analysed at the local council's technical department office. Five samples were taken at the inlet and outlet of the system on a monthly basis over a period of five months. For data processing, the data obtained in the laboratory from the control and experimental groups of the system, both the physical, chemical and biological properties of the influent and effluent of the system, were taken and digitised in Excel format in a database, then processed using the software SPSS version 28.01.

Data collection was carried out on a monthly basis. HANNA HI 93703-11 equipment and HANNA waterproof multiparameter measuring equipment were used. The results were analysed by testing the hypotheses using Student's t-distribution. The data obtained in the effluent or input of the system (pre-test) were then analysed to see if they differed from the values of the influent or output (post-test) in both phases with respect to the mean values obtained. The t-statistic was calculated using (1).

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \quad s = \sqrt{\frac{\sum_{i=1}^n (d_i - \bar{d})^2}{n - 1}} \quad (1)$$

Where:

X<sub>1,2</sub>: Means of the observations obtained.

S<sub>1,2</sub><sup>2</sup>: Standard deviation of the differences.

n: Number of observation pairs.

d<sub>i</sub>: Difference between two measurements per subject.

$\bar{d}$ : Mean of the differences.

Assumption: Reject H<sub>0</sub> if sig < α (0.05) y accept H<sub>0</sub> if sig > α (0.05)

### 3. RESULTS

Table 2 shows the results of the construction characteristics of the experimental model and the physical and hydraulic properties of the filter medium in both phases of the system. It was determined that the infiltration capacity of the filter medium ranged from 3.53 to 4.00 mm/second. The porosity of the filter medium was between 38.07% and 39.41%.

**Table 2.**

(a) Construction characteristics of vertical flow wetlands.

(b) Physical and hydraulic properties of the filter medium in both phases of the system.

(a)

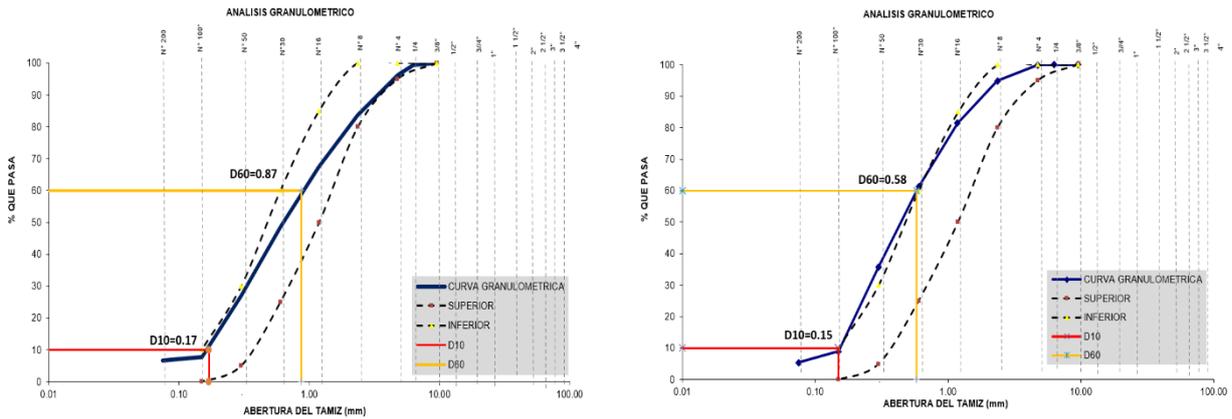
Phase	Type	m <sup>2</sup>	Substrate mm.	Height m.
Phase 1	Constructed wetland sand and gravel	1.87	0.15-4.75	0.50
	Constructed wetland recycled brick		9-15	0.10
			25-65	0.25
Phase 2	Constructed wetland sand and gravel	1.87	0.15-2.36	0.30
	Constructed wetland recycled brick		0.07-2.36	0.30
			4-12	0.10
			25-65	0.25

(b)

Test	Unit	Values	
		Phase 1	Phase 2
Moisture content	%	3.76	2.02
Uniformity coefficient	value	5.12	3.87
Specific weight	gr/cm <sup>3</sup>	2.58	2.58
Unit weight	gr/cm <sup>3</sup>	1.621	1.586
Percentage of absorption	%	0.70	0.70
Porosity	%	38.07	39.41
Infiltration capacity	mm/second	3.53	4.00

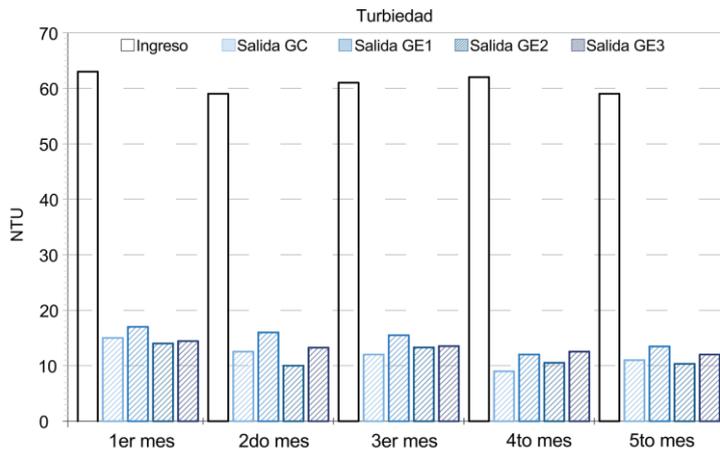
Source: own elaboration.

For optimal system performance, the substrate uniformity coefficient was between 3.87 and 5.12, according to the particle size distribution curves shown in Figure 3.



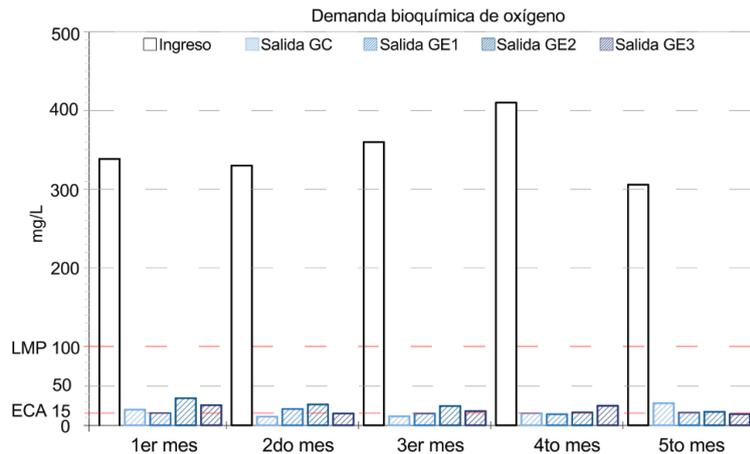
(a) (b)  
**Figure 3.** (a) and (b) Particle size distribution curves for phase 1 and phase 2 of the system.  
 Source: own elaboration.

Figure 4 shows the values obtained for the turbidity parameters measured in nephelometric turbidity units (NTU). The input value ranged from 59 NTU to 62 NTU during the 5 months of observation. In the first month of the experiment, values between 14 NTU and 17 NTU were obtained with an efficiency between 72% and 77%. In the fifth month of observation with the consolidated system, output values of 13.45 NTU were recorded in experimental group 1, 10.2 NTU in experimental group 2, and 12.0 NTU in experimental group 3. The highest efficiency was recorded in experimental group 2 with a value of 82.71%.



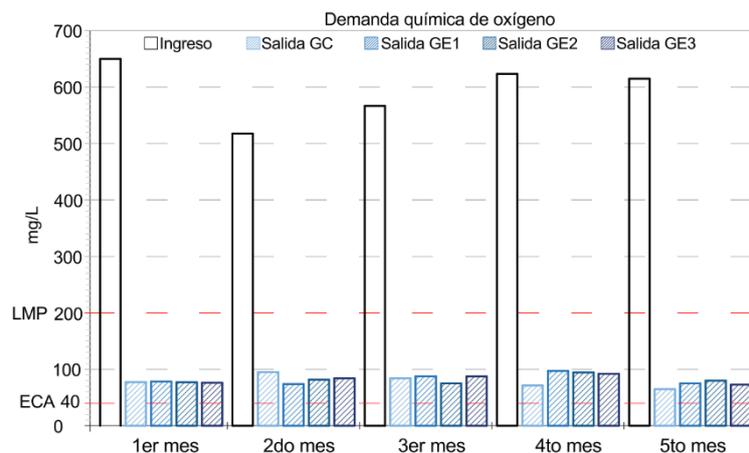
**Figure 4.** Turbidity removal values. Source: own elaboration.

The data shown in Figure 5 reflect the efficiency in removing biochemical oxygen demand contaminants after 5 days. The input value during the 5 months of observation was between 305 mg/L and 410 mg/L, with the highest input value recorded during the 4th month of observation. Experimental group 1 recorded output values between 12 mg/L and 28 mg/L. Experimental group 2 recorded an output value of 17 mg/L during the 5th month, and experimental group 3 recorded 18 mg/L during the last month of observation.



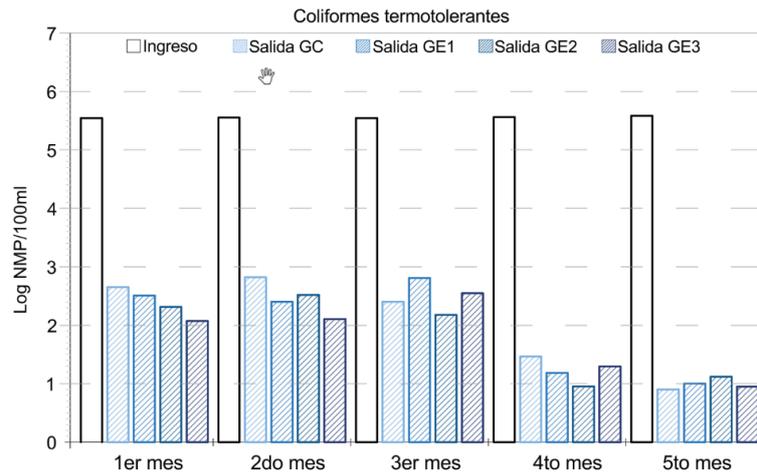
**Figure 5.** Removal values for the biochemical oxygen demand parameter. Source: own elaboration.

The data presented in Figure 6 correspond to the chemical oxygen demand parameter. Values between 520 mg/L and 658 mg/L were recorded at the inlet of the treatment plant. The highest inlet value was recorded during the first month. During the first month, experimental groups 1, 2, and 3 reported outlet values of 78 mg/L, 88 mg/L, and 81 mg/L, respectively. During the second month of observation, values between 75 mg/L and 95 mg/L were recorded. The efficiency of contaminant removal during the fifth month of observations was between 86.97% and 88.93%, with experimental group 1 obtaining the highest efficiency value.



**Figure 6.** Removal values for the chemical oxygen demand parameter. Source: own elaboration.

Figure 7 reports the values obtained in the removal of the biological parameter of thermotolerant or faecal coliforms. The values of the logarithms of the reports obtained are shown. At the entrance to the constructed treatment plant, values between  $3.5E+05$  and  $4.52E+05$  were recorded. In the third month of observation, outlet values between 150 NMP/100 ml and 650 NMP/100 ml were obtained, with experimental group 3 reporting the lowest value. During the fifth month, the highest efficiency records were obtained, with removal efficiency values of 99.9% recorded in the three experimental groups.



**Figure 7.** Removal values for the thermotolerant coliforms parameter. Source: own elaboration.

The values obtained for the physical, chemical and biological parameters of the urban wastewater treated at the treatment plant are detailed for each month and for each experimental group. Data was also collected from the control group in order to compare the efficiency of contaminant removal in the treated water. Similarly, the values of the contaminants at the point of entry into the system were recorded. All these values are shown in Table 3.

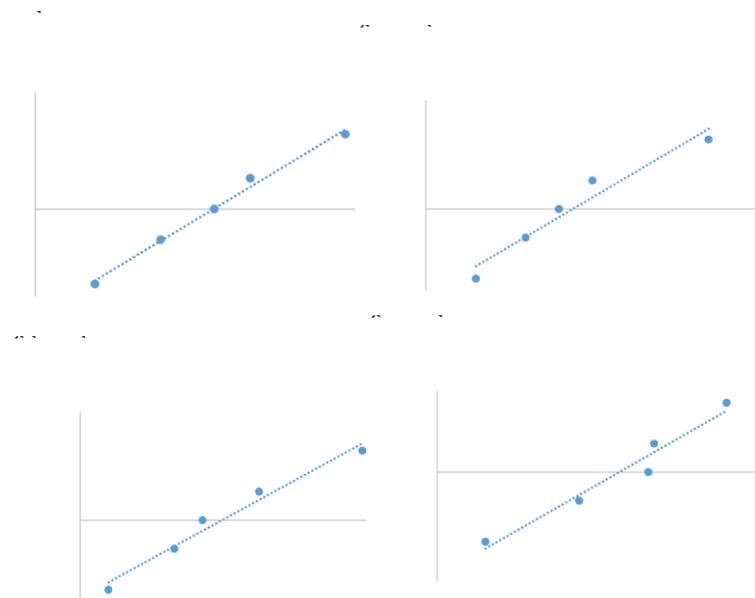
**Table 3.** Values obtained for the physical, chemical and biological parameters at the treatment plant.

Parameters	Turbidity	DBO <sub>5</sub>	DQO	CT	
	NTU	mg/L	mg/L	NMP/100ml	
1st month	Inlet	63.00	338.00	658.00	275000.00
	GC outlet	15.40	14.00	77.00	84.00
	GE1 outlet	16.20	27.00	75.00	114.00
	GE2 outlet	12.50	16.00	84.00	195.00
	GE3 outlet	14.35	23.50	81.00	245.00
2nd month	Inlet	58.00	330.00	520.00	473000.00
	GC outlet	12.10	22.00	84.00	120.00
	GE1 outlet	14.60	16.00	95.00	59.00
	GE2 outlet	8.00	21.00	58.00	95.00
	GE3 outlet	13.25	27.00	82.00	65.00
3rd month	Inlet	56.00	360.00	577.00	352000.00
	GC outlet	12.00	19.00	86.00	63.00
	GE1 outlet	12.00	18.00	84.00	62.00
	GE2 outlet	13.10	15.00	89.00	57.00
	GE3 outlet	13.50	19.00	75.00	93.00
4th month	Inlet	60.50	410.00	622.00	355000.00
	GC outlet	9.00	23.50	96.00	45.00
	GE1 outlet	13.10	20.00	78.00	33.00
	GE2 outlet	16.00	13.00	98.00	99.00
	GE3 outlet	12.50	22.00	95.00	63.00
5th month	Inlet	60.00	305.00	590.00	420000.00
	GC outlet	10.10	27.00	70.00	15.00
	GE1 outlet	14.00	13.00	68.00	15.00
	GE2 outlet	13.10	17.00	75.00	19.00
	GE3 outlet	11.00	14.00	80.00	13.00

Source: own elaboration.

As the sample size was less than 50 elements, the data collected were analysed using the Shapiro test – Wilk test to determine that they came from a normal distribution according to the graphical normality tests shown in Figure 8. After verifying the normality

assumption, the parametric Student's t-test was applied to check that the treatments performed were statistically significant in terms of the efficiency of removing contaminants from biochemical oxygen demand, chemical oxygen demand, turbidity, and thermotolerant coliforms.



**Figure 8.** Graphical normality tests on the data obtained through Q-Q analysis. Source: own elaboration.

In the analysis performed, there were “P” Sig. values less than 0.05 in all the parameters analysed, as shown in Table 4, and in all treatment combinations; Therefore, it was confirmed that the implementation of a vertical flow wetland made of recycled clay bricks in both phases, in a first phase, and sand and gravel in a second phase, and vice versa, has a positive influence on the treatment of urban wastewater in terms of turbidity, biochemical oxygen demand, chemical oxygen demand, and thermotolerant coliforms.

**Table 4.** Results of the Student's t-test. Source: own elaboration.

<b>Student's t-test</b>				
	<b>Values</b>	<b>Statistic</b>	<b>gl.</b>	<b>Sig.</b>
<i>Turbidity</i>	Experimental group 1	35.52	4	0.000002
	Experimental group 2	31.54	4	0.000003
	Experimental group 3	36.73	4	0.000002
	<b>Values</b>	<b>Statistic</b>	<b>gl,</b>	<b>Sig.</b>
<i>Biochemical oxygen demand</i>	Experimental group 1	19.35	4	0.000002
	Experimental group 2	17.81	4	0.000003
	Experimental group 3	18.99	4	0.000002
	<b>Values</b>	<b>Statistic</b>	<b>gl.</b>	<b>Sig.</b>
<i>Chemical oxygen demand</i>	Experimental group 1	19.34	4	0.000002
	Experimental group 2	27.26	4	0.000001
	Experimental group 3	22.81	4	0.000001
	<b>Values</b>	<b>Statistic</b>	<b>gl.</b>	<b>Sig.</b>
<i>Thermotolerant coliforms</i>	Experimental group 1	11.16	4	0.00018
	Experimental group 2	11.15	4	0.00018
	Experimental group 3	11.15	4	0.00018

Source: own elaboration.

The evaluation of the construction of the two-phase vertical flow wetland with substrate incorporating recycled clay brick allowed removal values of the physical parameter of turbidity between 72% and 82% to be obtained. In the removal of the biochemical oxygen demand chemical parameter, output values between 12 mg/L and 28 mg/L were obtained; in the chemical oxygen demand, output values between 75 mg/L and 95 mg/L were recorded. The removal efficiency of the biological parameter of thermotolerant coliforms was 99.9%.

## 4. DISCUSSION

The results were discussed by comparing the results obtained in this research with the values obtained and published in the scientific journals consulted. The values obtained for the physical, chemical, and biological parameters of urban wastewater treated by this system were taken into account. Likewise, the values obtained were taken into account and compared with the maximum permissible limits established in Peru for effluents set forth in [18].

For its part, in the event that the water obtained can be reused for irrigating long-stemmed trees, as well as for use in irrigating green areas, compliance with the environmental quality standards regulated for Peru, which are regulated in [19], was taken into account.

In terms of hydraulic design, Denmark's vertical wetland design guide was taken into account, adapting the use of local aggregates as a filter medium, as well as the use of recycled clay bricks obtained in the research location. Likewise, variables were introduced in the composition of the substrate in order to prevent clogging and saturation of the system, thereby extending its useful life.

Table 5 shows the efficiency percentages obtained in the removal of contaminants for each parameter and for each experimental group.

**Table 5.** Efficiency of removal of physical, chemical and biological parameters.

Parameter	Unit	GC (%)	GE1 (%)	GE2 (%)	GE3 (%)
Turbidity	UNT	83.17	76.67	78.17	81.67
Biochemical oxygen demand	mg/L	91.15	95.74	94.43	95.41
Chemical oxygen demand	mg/L	88.14	88.47	87.29	86.44
Thermotolerant coliforms	NMP/100ml	99.9	99.9	99.9	99.9

Source: own elaboration.

### 4.1 Experimental group 1

The results obtained from the implementation of recycled bricks in a vertical flow wetland in a two-phase system for urban wastewater treatment demonstrated that the model is efficient in removing physical, chemical, and biological contaminants.

In terms of chemical oxygen demand removal, the result was 88.47%, which exceeds that obtained in [13], which achieved an efficiency of 74.9% in chemical oxygen demand removal in its research. Based on this difference, it can be inferred that the concentration of pollutants is lower at the system inlet, since the system consisting of a screen chamber and sand trap receives discharges from rural dwellings, whereas the research consulted used an Imhoff tank to treat the organic load from dwellings located in urban areas.

The efficiency of biochemical oxygen demand removal with this combination of phases using recycled brick in both phases was 95.74%, similar to that obtained by [15], who achieved an efficiency of 72.00% in their research. This similarity allows the conclusion that these types of models, which use fired clay through the reuse of recycled clay bricks, show consolidation in the removal of this contaminant.

Regarding the particle size distribution used, phase 1 of the experimental model had a filtration layer with a height of 0.50 m and a particle size distribution of 0.075 mm to 4.75 mm. It also had a second transition layer with a height of 0.10 m and a recycled aggregate of 10 mm to 20 mm. Finally, the bottom layer was made up of stone measuring 20 mm to 60 mm. This grain size is similar to that used by [16], who conducted an experiment to determine the influence of grain size on the vertical flow wetland model, thus avoiding obstructions in the system. The optimal quantities of each fine material were manually selected for the filter medium in order to obtain effective removal, as shown in Figure 9a.

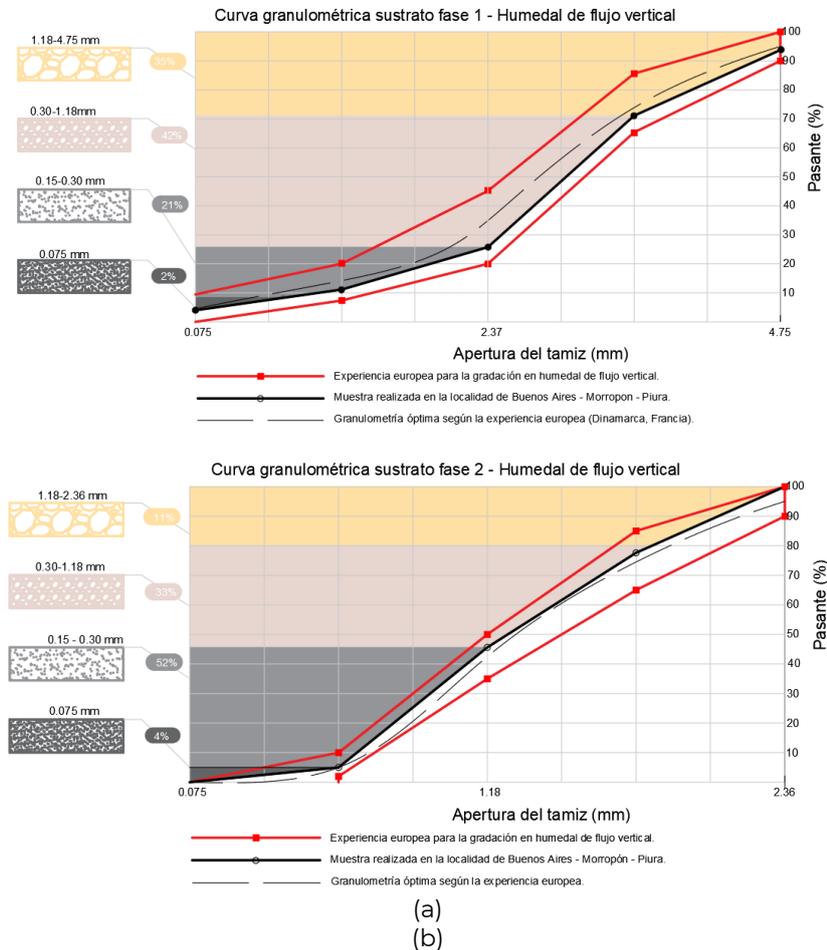


Figure 9. (a) Particle size distribution of the aggregate filter medium from phase 1 and (b) Particle size distribution of the aggregate filter medium from phase 2. Source: own elaboration.

## 4.2 Experimental group 2

In the experimental model, the results of using sand and gravel in the first phase and recycled clay bricks in the second phase in urban wastewater treatment demonstrated efficiency in removing physical, chemical, and biological contaminants.

The value obtained in the removal of biochemical demand was 94.43%, which was an acceptable value, similar to the value obtained by [20], who achieved 98.00% removal. Based on this difference, it can be inferred that the organic load that entered the experimental model varied over time, due, among other reasons, to the habits of family members and the increase in their number in December and January. It is also possible to deduce that, as indicated in the discussion of specific objective 1, the direct entry of the effluent without pre-treatment influences the difference in removal.

The research carried out by [16] showed that correct design and correct use of particle size prevents clogging of the model. Thus, the schemes used in Denmark were followed in

order to select the optimal quantities, with the use of sands from 0.075 mm to 2.36 mm in phase 2, where the wastewater treatment was refined, as shown in Figure 10b.

The results of this research were analysed and compared with the values established in Peruvian regulations, both for disposal into regulated water bodies in [18] and for reuse in the irrigation of tall-stemmed plants regulated for Peru in [19], concluding that the values obtained comply with the maximum limit for the final discharge of effluents. However, they do not comply with the values for reuse, because the biochemical oxygen demand indicates that the maximum value is 15 mg/L, and the research obtained a value of 17 mg/L, as verified in Table 6.

**Table 6.** Measurement parameters for treated urban wastewater.

Parameter	Unit	Maximum limit	Reuse	Results
		D.S. 03-2010	DS 04-2017	
Biochemical oxygen demand	BOD <sub>5</sub>	100 mg/l	15 mg/l	17 mg/l
Chemical oxygen demand	DQO	200 mg/l.	40 mg/l.	75 mg/l
Temperature	°C	< 35	Δ 3	25.1°C
Hydrogen potential	pH	6.5-8.5	6.5-8.5	7.25
Thermotolerant coliforms	NMP/100ml	10,000	1000	19

Source: own elaboration.

On the other hand, with regard to compliance with chemical oxygen demand, the removal of this contaminant obtained a value of 75 mg/L; however, for the reuse of treated water, a maximum value of 40 mg/L is required. Compliance with the parameters for temperature, hydrogen potential and thermotolerant coliforms was verified, as shown in Table 6.

### 4.3 Experimental group 3

In the experimental model built using recycled clay bricks in the first phase and sand and gravel in the second phase, with the particle size indicated in Figures 9a and 9b, a biochemical oxygen demand removal value of 14 mg/L was obtained in the fifth month of observation. L. According to the regulations indicated in Table 7, it was verified that the maximum limit for Peru indicated in [18], which specifies a maximum limit of 100 mg/L, was met. This means that water treated with this experimental model can be discharged into both surface and groundwater bodies.

Similarly, Table 7 shows the results of the research, which determined that the value obtained in the removal of chemical oxygen demand was 80 mg/L, which was higher than that specified in Peruvian national regulations for reuse in the irrigation of tall-stemmed plants or urban green areas. as the maximum value is 40 mg/L. Based on this result, it is concluded that wastewater treated with this experimental model cannot be reused, and the author considers that an additional phase is required in order to obtain the values established in the legal provisions.

**Table 7.** Measurement parameters for treated urban wastewater.

Parameter	Unit	Maximum limit	Reuse	Results
		D.S. 03-2010	DS 04-2017	
Biochemical oxygen demand	BOD <sub>5</sub>	100 mg/l	15 mg/l	14 mg/l
Chemical oxygen demand	DQO	200 mg/l.	40 mg/l.	80 mg/l
Temperature	°C	< 35	Δ 3	25.2°C
Hydrogen potential	pH	6.5-8.5	6.5-8.5	7.2
Thermotolerant coliforms	NMP/100ml	10,000	1000	13

Source: own elaboration.

The added value of this research lies in the fact that it has generated new knowledge on top of existing knowledge related to the proper treatment of urban wastewater in rural population centres with fewer than 2,000 inhabitants. The incorporation of recycled clay bricks and the adaptation of local aggregates in two-phase vertical flow constructed wetlands make it possible to solve the problem of improper urban wastewater disposal, improve the living conditions and public health of rural communities, reduce environmental pollution, and resolve the issue of water resource sustainability.

The practical implications of the research results are summarised in the feasibility of constructing a new theoretical framework that allows for the creation of a technical standard in Peru to regulate the guidelines and procedures for the implementation of treatment processes consisting of two-phase vertical flow constructed wetlands using different types of filter media and incorporating recycled clay bricks. The results obtained are presented as a concrete solution that resolves the poor disposal of urban wastewater, has low operating and maintenance costs, and can be replicated in communities with similar climatic characteristics and low-permeability soils.

## 5. CONCLUSIONS

The implementation of a vertical flow wetland constructed with a substrate made of recycled clay bricks in both phases resulted in the removal of 95.74% of biochemical oxygen demand contaminants with the stabilised system and 76.67% of turbidity with a hydraulic retention time of 2.5 days. This combination of phases did not experience any blockages during the observation period.

The implementation of a vertical flow wetland constructed with a substrate consisting of sand and gravel in the first phase and recycled clay bricks in the second phase resulted in 87.29% removal of chemical oxygen demand and 99.9% removal of thermotolerant coliforms. This combination of phases showed high efficiency in the removal of biological contaminants.

The implementation of a vertical flow wetland constructed with a substrate consisting of recycled clay bricks in the first phase and sand and gravel in the second phase resulted in a chemical oxygen demand removal rate of 95.41% and a turbidity removal rate of 81.67%. The combination performed well in removing chemical and biological contaminants. The aggregate to be used in the system phases must have a uniformity coefficient between 3.8 and 5.0 and a porosity between 38% and 40%.

The results obtained conclude that the implementation of a vertical flow wetland constructed with a substrate made of recycled clay bricks in both phases, combined with sand and gravel in the second phase and alternated, has a positive influence on urban wastewater treatment, as the removal values obtained comply with the maximum limits established in the current legal provisions in Peru. Likewise, it was verified that during the operation of the treatment plant, there were no obstructions to the system.

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**Principal researcher's declaration:** I declare that I assume full responsibility for the content, academic integrity, and results presented in this study, guaranteeing its scientific rigour and ethical compliance.

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