

Efficiency of a Biological Filter System with Bioballs in the Removal of Pollutants from Municipal Wastewater

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The efficiency of a biological filter system using bioballs was evaluated for the removal of contaminants from municipal wastewater in the Punta de Doña sector of Moyobamba, Peru, where inadequate treatment systems lead to untreated discharges into local water bodies. The study aimed to reduce physical, chemical, and microbiological contaminants through a specially designed treatment system. Hydraulic calculations established a flow rate of 8.16 m³/s and system dimensions of 3.44 m by 1.60 m, divided into three compartments for sedimentation, biological treatment with bacteria immobilized on bioballs made from corrugated hoses, and filtration using sand, charcoal, and gravel. The highest removal efficiencies were observed in the seventh sampling, reaching 93.26% for total suspended solids, 91.36% for biochemical oxygen demand, 93.09% for chemical oxygen demand, 94.73% for turbidity, and 99.9% for thermotolerant coliforms. These results demonstrate the effectiveness of the system in improving wastewater quality and meeting the Maximum Permissible Limits established by Peruvian law.

1. Introduction

Water pollution represents one of the most critical environmental challenges of the 21st century, with profound implications for human health, ecosystems and sustainable development (Zamora-Ledezma et al., 2021). Increasing pressure on water resources has led to an alarming degradation of freshwater sources worldwide (Velmurugan et al., 2020). This pollution, resulting from various human activities, compromises the quality and availability of water, an essential resource for life. Wastewater generated by domestic, commercial and industrial activities can alter physical, chemical and biological conditions that significantly affect water quality (Liu et al., 2021). Wastewater management systems face the challenge of balancing social and economic sustainability. This underlines the need to develop and implement solutions that are not only technically effective, but also socially and economically viable (Silva, 2023).

In developing countries, limited wastewater treatment capacity often results in direct discharges that degrade receiving bodies and pose risks to public health and aquatic ecosystems. These structural and operational deficiencies underscore the need to evaluate more efficient treatment technologies, such as biological filtration systems employing bioballs, to enhance contaminant removal performance (Edokpayi et al., 2017; Ravindiran et al., 2023).

Several studies have demonstrated that biological and biofilm-based systems can effectively remove organic matter and suspended solids when appropriate support media and operating conditions are used. Deng et al. (2024) showed that intensified constructed wetlands incorporating biocarriers improved removal efficiencies compared with conventional systems, increasing COD removal from 6.9% in the control to 51.8% in enhanced

configurations. Although wetlands provide natural treatment, their performance for organic matter removal remains moderate. In contrast, aerobic biofilters packed with bioballs have achieved substantially higher removal efficiencies, reaching 83.33% COD, 83.56% TSS and 82.5% BOD at a 24-hour hydraulic retention time (Permatasari et al., 2018). These findings indicate that systems promoting active biofilm development on synthetic media tend to outperform passive, nature-based systems in organic matter and solids removal, as bioballs provide high surface area and favorable hydrodynamics that enhance microbial activity and pollutant degradation. This contrast supports the need to explore compact, engineered biofilm systems as effective alternatives for decentralized wastewater treatment.

The research gap lies in the absence of proven, low-cost biological filtration systems specifically adapted to the conditions of decentralized wastewater treatment. Although bioball-based filters have shown promising results in laboratory-scale and urban applications (Foysal et al., 2020; Somprasert et al., 2021), there is limited evidence of their performance where flow variability, sediment load and temperature fluctuations may affect system stability. The novelty of this study is the implementation and evaluation of an integrated design combining sedimentation, bioball-based biological treatment and granular filtration in a compact configuration. The objective of this article is to determine the effectiveness of this biological filter in removing pollutants from municipal wastewater and to analyze its technical feasibility as a scalable alternative for improving water quality in decentralized systems (Permatasari et al., 2018). The results of this study could support decision-making in wastewater management and facilitate the adoption of decentralized treatment solutions.

2. Materials and Methods

2.1 Materials

The materials and equipment used in the research included: rolls of corrugated polypropylene hose; 2" polyvinyl chloride (PVC) pipes and valves; charcoal; civil construction materials and tools (1/2" and 2" gravel; sand, cement, steel, water, concrete, shovels, mixers, personal protective equipment, among others); laboratory materials (test tubes, Winkler flasks, beakers, and test tubes); and laboratory equipment, such as the Hach DR 1900 spectrophotometer, the Bioevopeak ICB-B150E incubator, the Hach - 2100Q turbidimeter, and the Hach HQ40d pH meter.

2.2 Methods

The investigation was carried out in the Tumino ravine, Punta de Doña sector, city of Moyobamba, San Martín Department, Peru. The area comprised 40 houses, a car wash, and 2 restaurants, all connected to the sewer network that carries wastewater to a treatment system consisting of a septic tank and a trickling filter well. The biological filter was installed downstream of these units at 282668.41 E and 9332217.57 N. The filter was designed based on the NRC (National Research Council of the USA) sanitation method and using current regulations: R.M. No. 192-2018-VIVIENDA (Ministry of Housing, Construction and Sanitation). The AutoCAD 2020 program was used for the dimensioning and plans; calculating for this according to the formulas:

$$A = V/H \quad (1)$$

$$N = 1 \quad (2)$$

$$B = A/2 \quad (3)$$

$$L = 2 \cdot B \cdot N \quad (4)$$

The bio-balls were manufactured from 4 rolls of corrugated hose, with a total length of 400 m, cut to 2.5 cm and inserted into each other. The treatment system utilized three sequential compartments: one for particle sedimentation, one for biological treatment using bio-balls to remove the organic load, and a final filtration compartment that retains particles, residual organic matter, and microorganisms. The treated water was stored in a collection chamber before discharge, achieving progressive purification through physical, biological, and filtration processes. A 40-day operating period was established for conditioning to generate microorganism colonies in the second compartment and ensure their adhesion to the bio-ball surface. Sampling was conducted on the influent and effluent of the biological filter over three months. A total of 98 samples were collected, 49 from the influent and 49 from the effluent. The physicochemical and biological parameters evaluated were BOD₅, COD, TSS, turbidity, and thermotolerant coliforms. The percentage efficiency of the biological filter was determined for each parameter.

3. Results

3.1 Design of the biological filter with bioballs

Table 1 summarizes the main geometric parameters used for sizing the rectangular biological filter according to the NRC sanitation method.

Table 1: Sizing of the rectangular biological filter

Description	Symbol	Formula	Results	Units
Filter number	N	2	1	unity
Filter area	A	1	3.83	m ²
Filter width	W	3	1.30	m
Filter length	L	4	3.00	m

From the calculated values of the sizing of the biological filter, the internal dimensions of the three compartments were established as 1.31 × 0.95 × 1.20 m (L×W×D) for the first compartment, 1.31 × 0.51 × 1.20 m for the second, and 1.31 × 0.98 × 1.20 m for the third.

For the elaboration of the bioballs, 4 rolls of corrugated hose (each 100 m) were required, to be cut at 2.5 cm and embedded into each other. These materials were installed in the second compartment of the biological filter. Based on these values, the tank was partitioned into three compartments: a first sedimentation chamber (length ≈ 0.95 m), a second chamber filled with plastic bioballs (0.51 m) and a third filtration compartment (0.98 m), all with the same width (1.30 m) and water depth (1.20 m). The third compartment contained a stratified bed of 2" coarse gravel (0.20 m), ½" fine gravel (0.20 m), charcoal (0.15 m) and sand (0.35 m) arranged over a perforated pipe collection system to drain the treated effluent.

For the elaboration of the bioballs, 4 rolls of corrugated hose (each 100 m) were required, to be cut at 2.5 cm and embedded into each other. These materials were installed in the second compartment of the biological filter. Table 2 shows the details of the materials used in the compartments as well as their dimensions.

The volumes were calculated as the product of length, width, and height (L × W × H), and the reported values were rounded to two decimal places.

Table 2: Third compartment filter media data

Compartment	Filter material ID	Description	Length (m)	Width (m)	Height (m)	Volume (m ³)
Third compartment	1 (first layer)	2" coarse gravel	1.31	0.98	0.20	0.26
Third compartment	2 (second layer)	½" fine gravel	1.31	0.98	0.20	0.26
Third compartment	3 (third layer)	Charcoal	1.31	0.98	0.15	0.19
Third compartment	4 (fourth layer)	Sand	1.31	0.98	0.35	0.45

Figure 1 shows the Plan view of the biological filter and the Profile view of the biological filter.

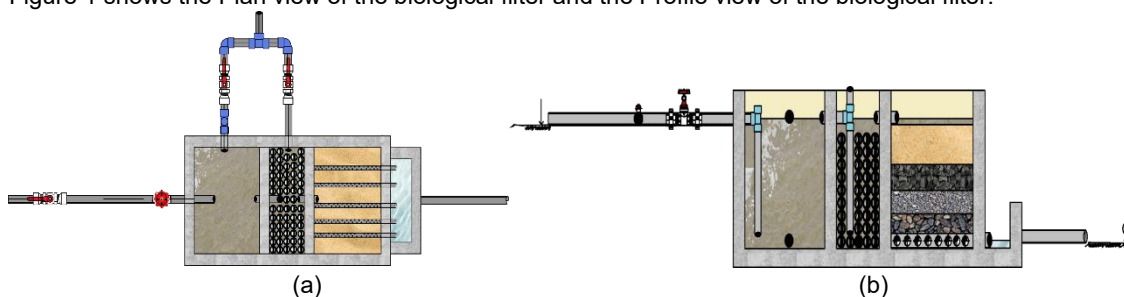


Figure 1: (a) Plan view of the biological filter and (b) Profile view of the biological filter.

3.2 Functioning of the biological filter with bioballs

3.2.1. Compartment system

The objective of the first compartment of the filter was to settle a portion of the suspended solids present in the wastewater, facilitating the initial conditioning of the water for subsequent processes. During the monitoring period, this compartment showed variable efficiencies in total suspended solids (TSS) and turbidity (TZ), with marked reductions during the second (TSS: 50.93%; TZ: 72.16%) and fourth/fifth samplings (TSS: 49.28%; TZ: 54.71%).

The second compartment provided biological treatment through microorganisms attached to the surface of the bioballs, which promoted the removal of organic matter and part of the suspended solids prior to final polishing in the granular filter.

The purpose of the second compartment was to carry out biological treatment by the action of microorganisms attached to the surface of the bioballs.

Figure 2 shows the horizontal and vertical sections of the second compartment.

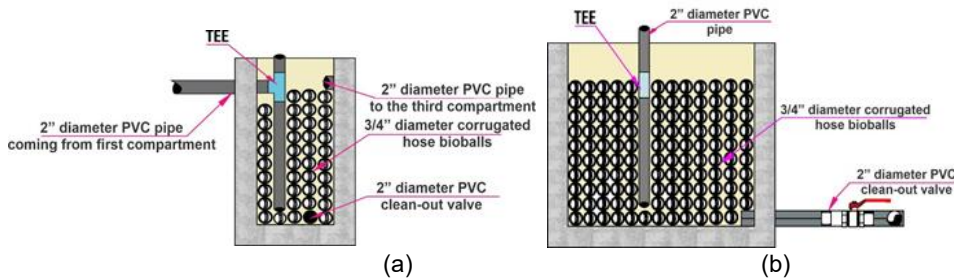


Figure 2: (a) Horizontal and (b) Vertical cuts of the second compartment.

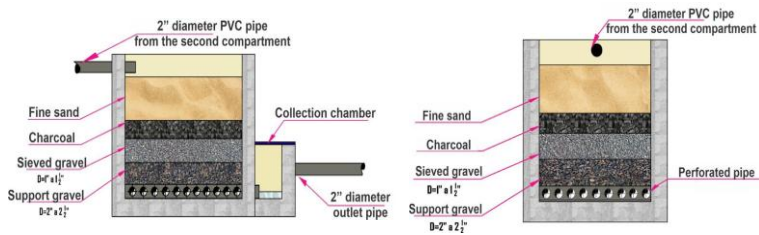


Figure 3: Horizontal and vertical cross-sections of the third compartment of the biological filter, showing the arrangement of the filter media (coarse gravel, fine gravel, charcoal, and sand) and the treated-water collection chamber.

3.2.2. Flow behaviour of the biological filter

The bio-ball biological filter, designed in three compartments, features a non-linear flow that optimizes wastewater treatment. Wastewater initially enters the first compartment and, upon reaching a controlled overflow level, flows into the second compartment through a 2" T-shaped pipe that directs the water to the bottom of the compartment, promoting mixing and contact with the bioballs. Subsequently, the water moves to the third compartment through another 2" pipe located at the top of the dividing wall, where the flow continues until it is collected by perforated pipes at the bottom of the third compartment. Figure 4 illustrates the overflow and flow behaviour through the compartments in the filter and the biofilter in operation.

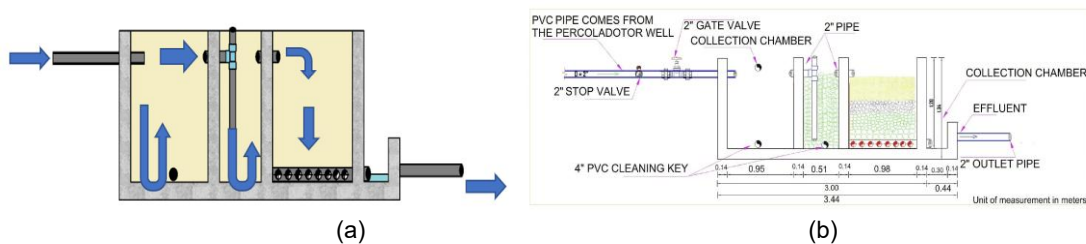


Figure 4: (a) Detail of vertical flow of the biological filter system (b) biofilter in operation.

3.3 Removal of pollutants

Figure 5 shows the variation in percentage removal efficiency for five parameters in municipal wastewater over seven consecutive tests. The Thermotolerant Coliforms (TTC) parameter exhibited the highest and most consistent removal efficiency, remaining unchanged at an average of over 92.14% (ranging from 84.28% to 99.99%). This performance shows that bioballs offer an extensive surface area that promotes the development of biofilms, facilitating the efficient capture, degradation, or inactivation of these microorganisms. Chemical Oxygen Demand (COD) also demonstrated a high level of efficiency with values ranging from 88.47% to 97.63%. This remarkable stability is evidence of highly effective chemical and biological oxidation of organic matter throughout the monitoring period. Biochemical Oxygen Demand (BOD) removal shows high performance, ranging from 85.58% to 97.04%. Although a temporary decrease is observed in measurement number 5 (87.35%), efficiency is quickly restored, reaching its peak in test 2 (97.04%). These data reaffirm the remarkable biological activity of the biofilm housed in the biospheres for the decomposition of biodegradable organic matter. The Total Suspended Solids (TSS) parameter is the least stable of the parameters evaluated. The analysis reveals significant drops in efficiency during measurements 2 (50.93%) and 4 (49.28%). These fluctuations could be a symptom of excessive biomass growth caused by changes in the system's loads or flows. This surplus can cause a temporary increase in the TSS concentration in the effluent, which reduces its removal efficiency. Turbidity (TZ) shows a similar efficiency pattern to TSS. This is predictable, as turbidity is closely correlated with the amount of suspended particles. Efficiency experiences notable reductions in analyses 2, 4, and 5, which directly coincides with the drops observed in TSS. However, the subsequent marked recovery in measurements 6 (81.15%) and 7 (94.73%) demonstrates the system's resilience to adjust and overcome unfavorable operating conditions.

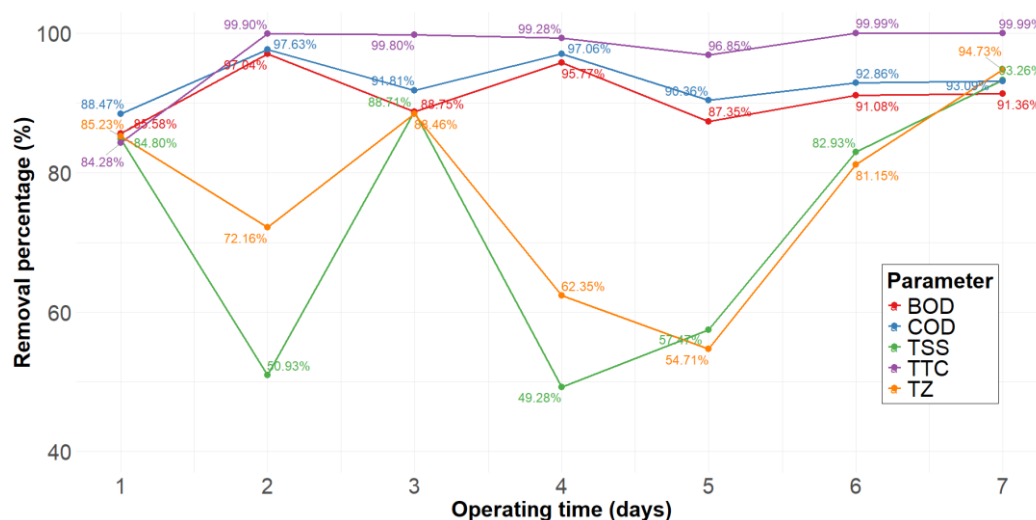


Figure 5: Percentages of removal of study parameters, post-treatment.

4. Conclusions

The study evaluated a three-compartment biological filtration system utilizing bioballs for municipal wastewater treatment. The system's design featured sequential chambers with internal dimensions of $1.31 \times 0.95 \times 1.20$ m (L×W×D), $1.31 \times 0.51 \times 1.20$ m, and $1.31 \times 0.98 \times 1.20$ m respectively, with the final compartment incorporating five perforated pipes for effluent distribution. Operational control was maintained through a gate valve, overflow pipe in the primary chamber, and dedicated cleaning pipes in the first two compartments. Performance monitoring over 98 days revealed peak removal efficiencies during the seventh sampling event, achieving 93.26% for total suspended solids (TSS), 93.26% for biochemical oxygen demand (BOD₅), 94.09% for chemical oxygen demand (COD), and 94.73% for turbidity. Notably, thermotolerant coliform removal consistently exceeded 99.9% in multiple sampling events (second, sixth, and seventh analyses), demonstrating superior pathogen reduction capabilities. Compliance with maximum permissible limits (MPL) was consistently achieved from the sixth sampling onward. The system demonstrated robust performance across physical, chemical, and microbiological parameters, presenting a viable decentralized treatment solution for municipalities like Moyobamba in the Amazon Region. Implementation in small urban centers requires careful hydraulic design and operational considerations, including periodic maintenance to address media saturation through

organic/inorganic matter removal and strategic replacement of adsorbent materials to sustain long-term treatment efficacy.

Nomenclature

TTC – total thermotolerant coliforms removal, %

BOD₅ – biological oxygen demand, %

COD – chemical oxygen demand, %

TSS – total suspended solids, %

TZ – turbidity, %

V – Filter volume, m³

H – Filter height, m

A – Filter area, m²

B – Filter width, m

L – Filter length, m

N – Number of filter units

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