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Effect of Pumice Particle Size on Organic Matter Removal (BOD_5 and COD) from Slaughterhouse Wastewater

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This study evaluates the effect of pumice stone particle size on organic matter removal, expressed as Biochemical Oxygen Demand (BOD_5) and Chemical Oxygen Demand (COD) from highly polluted municipal slaughterhouse wastewater. A pilot-scale continuous flow filtration system was implemented using three different pumice stone diameters (5 mm, 10 mm, and 15 mm) under a constant hydraulic retention time of 1 h 03´ 39”. Raw wastewater exhibited extremely high average organic loads of 1,467.0 mg/L for BOD_5 and 2,935.1 mg/L for COD. Statistical analysis (ANOVA and Tukey’s test) demonstrated that the removal efficiency is influenced by the filter media's granulometry (p-value < 0.0001). The 5 mm diameter pumice stone recorded the highest removal rates, achieving average efficiencies of 49.3 % for BOD_5 and 44.1 % for COD, compared to 33.2 % and 32.0 % for the 15 mm media, respectively. The findings indicate that reducing the pumice particle size substantially increases the available surface area and pore multiplication, thereby maximizing organic matter retention. Although smaller granulometry optimizes the physical-chemical adsorption capacity of the volcanic rock, complementary treatments are required to fully meet environmental discharge standards for high-strength agro-industrial effluents.

1. Introduction

The conservation of water resources is a critical global challenge, as rapid industrialization and inadequate sanitation continue to threaten aquatic ecosystems (Breida et al., 2020; Yang et al., 2021). Among industrial discharges, municipal slaughterhouses pose environmental challenges, generating highly complex liquid effluents that include blood, washing waters, intestinal content, and manure. Consequently, these effluents carry extraordinary loads of suspended solids, Biochemical Oxygen Demand (BOD_5), and Chemical Oxygen Demand (COD). In fact, the average levels of BOD_5 and COD in slaughterhouse wastewater can be 6.3 and 9.8 times higher, respectively, than those found in typical municipal wastewater (Bustillo-Lecompte and Mehrvar, 2015; Metcalf et al., 1991). High concentrations of organic matter severely deplete dissolved oxygen, negatively impacting aquatic flora and fauna while altering the physical-chemical properties of receiving water bodies (Raffo and Ruiz, 2014). To mitigate this environmental impact and comply with discharge regulations, implementing economical and feasible treatment technologies is essential (Aleksić et al., 2020; Musa and Idrus, 2021). While biological treatments are widely used, physical-chemical processes like adsorption and filtration are considered highly effective due to their operational simplicity and cost-efficiency (Vanani and Ostad-Ali-Askari, 2023).
Particularly in the Peruvian Amazon region of Moyobamba, recent studies have emphasized the urgent need to implement compact and decentralized filtration systems to mitigate the impact of municipal and agro-industrial effluents on local water bodies (Casique Guevara et al., 2026). In this context, pumice stone a highly porous volcanic rock composed primarily of felsic volcanic glass (predominantly SiO_2 and Al_2O_3) emerges as a highly suitable filter medium. Its unique physical characteristics, including low apparent density (0.4 to 0.9 g/cm3),

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extensive pore volume, and large surface area, enhance the adsorption and ion exchange processes while providing an excellent support matrix for microbial growth (Ali et al., 2023; Çifçi and Meriç, 2017). Although several studies have demonstrated the general potential of pumice as an adsorbent for wastewater treatment (Vásconez, 2018; Vargas, 2019), a recent comprehensive review on rock-based adsorbents highlights that most existing research is limited to batch-mode experiments, and scalability to continuous-flow industrial systems has not been sufficiently scrutinized (Srinivasulu and Sreenivasulu, 2025).
Furthermore, while theoretical capacity increases in finer particles (< 100 µm) due to higher reactive surface areas (Alraddadi and Assaedi, 2021; Srinivasulu and Sreenivasulu, 2025), implementing such micro-fractions in real, highly concentrated slaughterhouse effluents inevitably leads to rapid filter clogging. Therefore, the main scientific contribution of this work lies in systematically evaluating the specific effect of different macroscopic pumice particle sizes (5 mm, 10 mm, and 15 mm) under continuous flow conditions. This approach bridges the gap between laboratory batch studies and pilot-scale industrial applications, seeking the optimal granulometry that maximizes organic matter retention without compromising the operational viability of the filter.

2. Materials and methods

2.1 Study area

The research was conducted at the municipal slaughterhouse of Moyobamba (coordinates: Latitude 6° 01' 37" S, Longitude 76° 59' 12" W), located in the San Martín region, Peru. The pilot-scale pumice stone filtration system was installed within the facility's premises to directly treat the generated wastewater under real operating and environmental conditions.

2.2 Experimental design

To evaluate the strict effect of pumice particle size on organic matter removal, the experimental setup was structured as shown in Figure 1, following a sequential logical order:
Description of the treatment system: The raw wastewater supply point was established at the primary sedimentation well of the slaughterhouse's existing treatment plant. Due to the high presence of coarse solids (such as rumen and hair), a ¼-inch nylon mesh was installed at the intake to act as a primary screen.
The wastewater was transported via 1-inch PVC pipes using a 0.5 HP centrifugal pump to a 1,100 L main storage tank, elevated on a metal platform 1.5 m above ground level.
Operation and hydraulic description: The system operated under a continuous flow regime to simulate real industrial discharge conditions. The 1,100 L storage tank compensated for the irregular generation of effluents during slaughtering hours. To ensure a highly controlled distribution, the effluent from the main tank was directed into a secondary 50 L polyethylene container equipped with a float valve, functioning as a constant hydraulic head pressure regulator. Using ½-inch PVC pipes and independent flow control valves, a total distribution flow of 0.763 L/min was assigned.

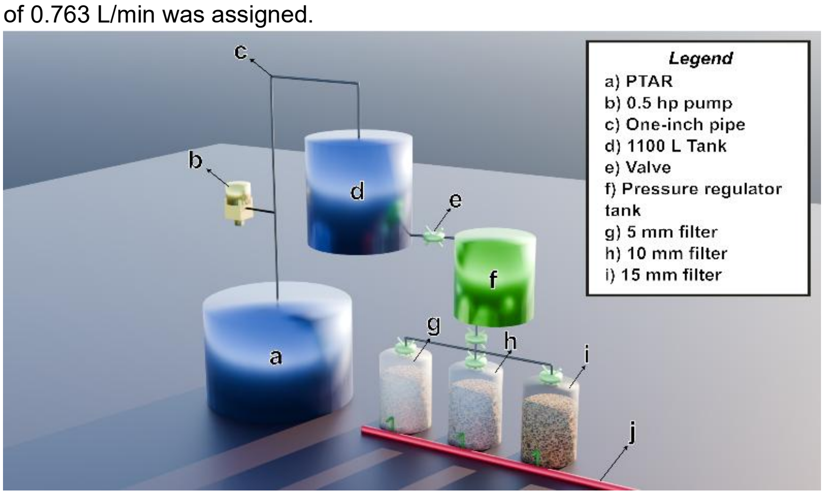

Figure 1: 3D schematic representation of the pilot-scale filtration system implemented at the Moyobamba municipal slaughterhouse. (a) Primary sedimentation tank for raw wastewater intake; (b) 0.5 hp centrifugal pump for effluent transfer; (c) one-inch PVC distribution network; (d) 1,100 L storage tank; (e) flow control valves; (f) 50 L pressure regulator tank equipped with a float valve to ensure a constant hydraulic head; (g-i) 20 L filtration units containing pumice stone media with 5 mm, 10 mm, and 15 mm diameters respectively; (j) four-inch effluent discharge pipe.

Evaluated factors: The primary independent variable was the diameter of the pumice stone media. Three specific granulometric fractions (5 mm, 10 mm, and 15 mm) were selected after a strict sieving process. The filtration units consisted of three transparent plastic buckets (38.5 cm in height and 34.1 cm in diameter) with a total capacity of 20 L each. These buckets were packed at 80 % of their capacity with the previously classified pumice media, yielding an effective filter volume of 16 L per unit. This resulted in a specific, constant inflow of 0.254 L/min for each individual filter. By dividing the 16 L effective volume by the specific inflow rate, the hydraulic retention time (HRT) for each system was established at exactly 1 h 03´ 39”. The dependent variables were the BOD_5 and COD removal efficiencies. The treated effluents were safely discharged into an absorption well via a 4-inch PVC pipe.

2.3 Sampling and analytical methods

Prior to data collection, the system was operated during an acclimatization period to ensure the stabilization of microbial activity within the porous structure of the pumice stone. Data collection was then conducted through eight sampling events with a weekly frequency over a two-month period. Raw wastewater samples (influent) were collected directly from storage tank well before entering the distribution system. Treated wastewater samples (effluents) were collected exactly at the discharge points of each of the three independent pumice filters. Sampling followed protocols for water quality monitoring, using completely airtight plastic bottles (1,000 mL for BOD_5 and 100 mL for COD). For BOD_5, the bottles were completely filled to prevent bubble formation, while for COD, the samples were chemically preserved by adding H2SO4. All samples were properly labeled, stored in a thermal box, and immediately transported to the laboratory.
Laboratory analyses were performed according to the Standard Methods for the Examination of Water and Wastewater (APHA, 2015). Due to the extremely high initial concentrations, samples were diluted to ensure precise measurements. BOD_5 was measured using a HANNA H198193 multiparameter device after 5 days of incubation. COD was analyzed spectrophotometrically on the sampling day using a HACH DR-900 multiparameter device.
To estimate the efficiency of the pumice filters in retaining organic matter, the following equation*,* Eq(1)*,* was applied (Mejía-Lopez et al., 2017):

$$\% \ efficiency = \frac{(C_a - C_e)}{C_a} \times 100 \tag{1}$$

Where C_a represents the concentration in the influent (raw wastewater) and C_e represents the concentration in the effluent (treated wastewater).

2.4 Data analysis

To evaluate the statistical significance of the pumice particle size on pollutant removal, descriptive and inferential analyses were performed. Normality (Shapiro-Wilk) and homogeneity of variances (Levene) tests were applied to confirm parametric conditions. Student's paired t-test was utilized to compare influent and effluent concentrations. Subsequently, an analysis of variance (ANOVA) was executed to determine significant differences among the three granulometric treatments. Finally, Tukey’s HSD post hoc test was utilized to identify the optimal pumice stone diameter. All statistical analyses and graphical representations (including boxplots and temporal evolution charts) were generated using RStudio software with R version 4.5.1.

3. Results and discussion

3.1 Influent and effluent characterization

Figure 2 presents the temporal evolution of these organic loads, illustrating the concentrations and removal efficiencies throughout the entire 8-week monitoring period.
Regarding municipal industrial wastewater from slaughterhouses, it is known that BOD_5 and COD concentrations can be 6.3 and 9.8 times higher, respectively, than typical municipal wastewater (Bustillo-Lecompte and Mehrvar, 2015; Metcalf et al., 1991). The raw wastewater presented in this study showed extreme concentrations of 1,467.0 mg/L for BOD_5 and 2,935.1 mg/L for COD on average, vastly exceeding the Maximum Admissible Values (VMA) for agro-industrial effluents.
After the continuous flow filtration process, the effluent treated with the 5 mm pumice filter presented the lowest concentrations: an average of 741.5 mg/L of BOD_5 and 1,628.3 mg/L of COD. An analysis of variance (ANOVA) confirmed that these differences were significant compared to the 10 mm and 15 mm filters showed higher BOD_5 ($F = 5.59$, $p = 0.0039$) averages of 874.9 mg/L and 975.5 mg/L, and COD ($F = 4.46$, $p = 0.0111$) averages of 1,837.5 mg/L and 1,989.9 mg/L, respectively (Figure 2). This suggests that smaller particle size enhances filtration performance due to increased surface area and contact time.

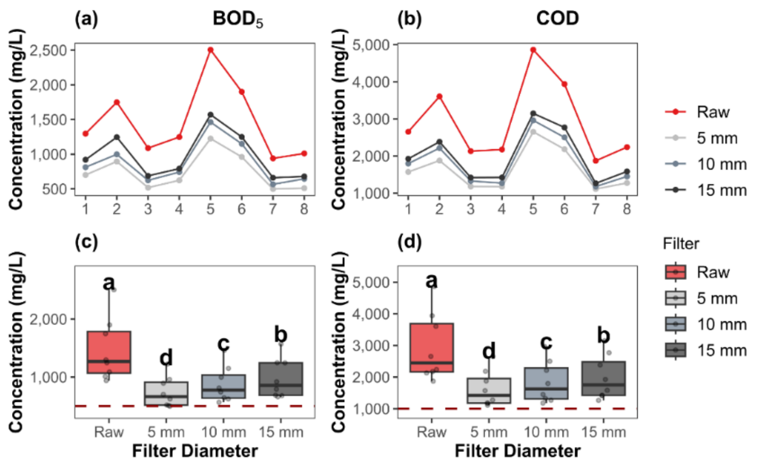

Figure 2: Temporal and statistical organic load removal for different pumice particle sizes. (a) Temporal BOD_5 and (b) COD concentrations over the 8-week monitoring period; statistical distribution of (c) BOD_5 and (d) COD concentrations in raw wastewater and filtered effluents. Lowercase letters indicate significant differences among groups based on Tukey's HSD test ($p < 0.05$).

3.2 Effect of particle size on removal efficiency

Pumice diameter had a significant effect on removal efficiency, with clear differences observed among treatments for both BOD_5 ($F = 68.28$, $p < 0.0001$) and COD ($F = 39.87$, $p < 0.0001$). Furthermore, Tukey's HSD post hoc test (Figure 3c and 3d) revealed that the 5 mm treatment differed significantly from the 10 mm and 15 mm treatments, while the difference between 10 mm and 15 mm was less pronounced. The 5 mm consistently achieved the highest removal rates, with average efficiencies of 49.3 % for BOD_5 and 44.1 % for COD. This result highlights the sensitivity of the system to media size, indicating that even moderate increases in particle diameter can significantly reduce treatment efficiency.

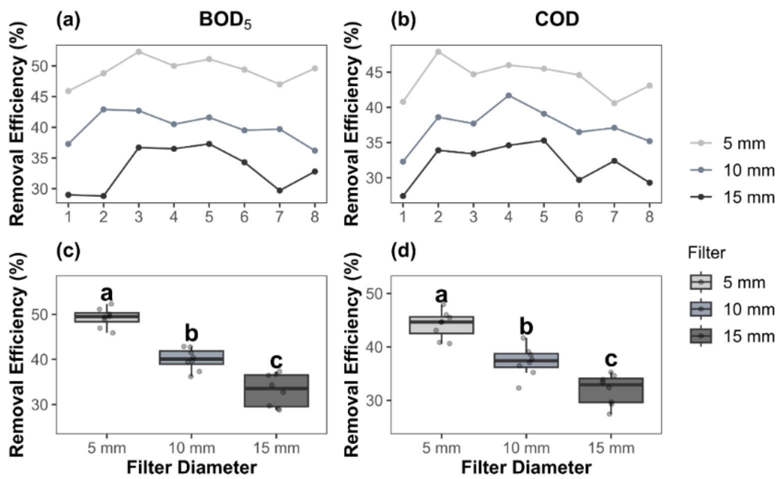

Figure 3: Efficiency of pumice particle size on organic load removal. (a) Temporal BOD_5 and (b) COD removal efficiency (%) over the 8-week monitoring period; statistical distribution of (c) BOD_5 and (d) COD removal efficiency (%) for 5 mm, 10 mm, and 15 mm pumice diameters. Lowercase letters indicate significant differences among groups based on Tukey's HSD test ($p < 0.05$).

This behavior is fundamentally associated to the physical properties of the mesoporous volcanic rock. As stated by Alraddadi and Assaedi (2021), reducing the macroscopic size of pumice particles inherently generates a substantially larger reactive surface area and multiplies the accessible porous spaces per unit of volume. Consequently, the 5 mm media has the physical-chemical adsorption capacity and provides a denser matrix for the retention of suspended solids and organic matter, emerging as a promising and low-cost alternative for specific agro-industrial treatments. These findings align with those reported by Fetene and Addis (2020) and Mocha and Moreira (2021), who also observed enhanced removal capacities when utilizing smaller pumice fractions (below 5 mm) for phosphate and swine wastewater treatments. However, it was observed that the overall efficiency (averaging near 50 %) remained lower than other pilot studies treating slaughterhouse effluents. For instance, Vásconez (2018) and Vargas (2019) achieved efficiencies exceeding 65 % using larger pumice diameters (9.5 to 12.7 mm). This indicates that particle size alone does not determine performance, but rather its interaction with operational conditions such as HRT. While previous studies operated with an HRT of over 5 hours, the present continuous flow system operated with an HRT of merely 1 h 03´ 39”. A shorter contact time limits the interaction between the organic load and the mesoporous structure of the pumice, preventing the system from reaching maximum adsorptive saturation. Furthermore, towards the final weeks of monitoring, a slight decrease in efficiency was observed across all filters, indicating a progressive saturation of the porous media and a potential overpopulation of retained microbial biomass (Vásconez, 2018). This behavior suggests the need for periodic media replacement or regeneration to maintain stable long-term performance. The critical importance of optimizing the physical structure and pore availability of filtration media to maximize organic matter retention has also been recently demonstrated in similar advanced porous filtration systems (Mohamad Said et al., 2025).

4. Conclusions

The evaluation of pumice stone as a filtration medium for high-strength municipal slaughterhouse wastewater demonstrated that particle size is a critical determinant of treatment efficiency. Reducing the granulometry to 5 mm optimized the physical-chemical adsorption process, achieving average removal rates of 49.3 % for BOD_5 and 44.1 % for COD. This performance is directly attributed to the multiplication of accessible porous spaces and the expanded reactive surface area characteristic of smaller mesoporous volcanic rocks. However, benchmarking these results against current Peruvian environmental regulations reveals that a single-stage pumice filtration system operating under a short continuous-flow hydraulic retention time (1 h 03´ 39”) is insufficient to independently meet the Maximum Permissible Limits (MPL) and Maximum Admissible Values (VMA). The extreme initial organic loads averaging 1,467.0 mg/L for BOD_5 and 2,935.1 mg/L for COD coupled with early signs of progressive filter saturation, restricted the maximum removal capacity compared to extended-contact systems. Consequently, while 5 mm pumice stone represent an excellent, low-cost support matrix that maximizes initial organic retention, its practical application at an industrial scale necessitates integration into hybrid treatment configurations. Incorporating longer retention times or coupling the pumice filtration phase with anaerobic biological processes is highly recommended to achieve full regulatory compliance and ensure sustainable agro-industrial wastewater management. This study provides novel experimental evidence under continuous flow conditions, contributing to bridging the gap between laboratory-scale adsorption studies and practical pilot-scale applications.

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