



EVALUATION OF THE USE OF FILTER BEDS WITH BIOCLASTIC GRANULATE AT PILOT SCALE FOR PHOSPHORUS REMOVAL IN SEWAGE POST-TREATMENT

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ABSTRACT

Objective: To evaluate the use of filter beds with bioclastic granulate at pilot scale for phosphorus removal in sewage post-treatment.

Theoretical Framework: Demand for sustainability highlights the use of the bioclastic granulate *Lithothamnium calcareum* in the removal of phosphorus and metal ions from wastewater, with low cost and diffuse pollution control.

Method: The pilot-scale system for phosphorus removal was implemented at the outlet of an activated sludge wastewater treatment plant. Cylindrical filters were installed in parallel, with a diameter of 110 mm and bed heights of 30, 40, and 50 cm (F1, F2, and F3). The bioclastic granulate bed was fractionated using 4.75 and 1.0 mm sieves. Filters operated for four days under an average flow of 1.90 L·min⁻¹. Bed density and porosity of the media were determined. Total phosphorus concentrations were monitored at the inlet and outlet of each filter during the operation period.

Results and Discussion: Maximum phosphorus removal efficiencies were 51.38% in F1, 54.72% in F2, and 62.50% in F3. Filter F3 maintained its adsorption efficiency throughout the operation. The pilot-scale evaluation demonstrated the feasibility of using bioclastic granulate for phosphorus removal in sewage post-treatment systems based on the activated sludge process.

Research Implications: Enables commercial filter development and evaluates agricultural reuse of phosphorus-saturated media.

Originality/Value: Proposes a simple, scalable, and low-cost alternative for phosphorus removal in urban effluents.

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Keywords: *Lithothamnium Calcareum*, Phosphorus, Wastewater, Fixed-Bed.

AVALIAÇÃO DO USO DE LEITOS FILTRANTES COM GRANULADO BIOCLÁSTICO EM ESCALA PILOTO PARA REMOÇÃO DE FÓSFORO NO PÓS-TRATAMENTO DE ESGOTO

RESUMO

Objetivo: Avaliar o uso de leitos filtrantes com granulado bioclástico em escala piloto para remoção de fósforo no pós-tratamento de esgoto.

Referencial Teórico: Demanda por sustentabilidade destaca o uso do granulado bioclástico *Lithothamnium calcareum* na remoção de fósforo e íons metálicos em esgoto, com baixo custo e controle da poluição difusa.

Método: A escala piloto para remoção de fósforo no pós-tratamento de esgoto foi implantada em uma estação do tipo lodo ativado. Foram instalados filtros cilíndricos em paralelo, com diâmetro de 110 mm e alturas de 30, 40 e 50 cm (F1, F2 e F3). O leito do granulado bioclástico foi fracionado em peneiras de 4,75 e 1,0 mm. Os filtros operaram por quatro dias, com vazão média de 1,90 L.min⁻¹. Foram determinados no leito densidade aparente e porosidade. Foram monitoradas as concentrações de fósforo total na entrada e saída dos filtros no período de operação.

Resultados e Discussão: As concentrações de fósforo apresentaram eficiência máxima de 51.38% em F1, 54.72% em F2 e 62.50% em F3. Filtro F3 manteve a eficiência da adsorção após o período de operação. A avaliação em escala piloto torna viável o uso do granulado bioclástico para remoção de fósforo no pós-tratamento de esgoto em estações do tipo lodo ativado.

Implicações da Pesquisa: Viabiliza filtros comerciais e avalia reaproveitamento agrícola do meio filtrante saturado com fósforo.

Originalidade/Valor: Apresenta alternativa simples, escalável e de baixo custo para remoção de fósforo em efluentes urbanos.

Palavras-chave: *Lithothamnium Calcareum*, Fósforo, Águas Residuárias, Leito Fixo.

EVALUACIÓN DEL USO DE LECHOS FILTRANTES CON GRANULADO BIOCLÁSTICO A ESCALA PILOTO PARA LA REMOCIÓN DE FÓSFORO EN EL POS-TRATAMIENTO DE AGUAS RESIDUALES

RESUMEN

Objetivo: Evaluar el uso de lechos filtrantes con granulado bioclástico a escala piloto para remoción de fósforo en pos-tratamiento de aguas residuales.

Marco Teórico: Demanda por sostenibilidad destaca uso del granulado bioclástico *Lithothamnium calcareum* en la eliminación de fósforo e iones metálicos en aguas residuales, con bajo costo y control de la contaminación difusa.

Método: Se implementó un sistema piloto para la remoción de fósforo en la salida de una estación de tratamiento de aguas residuales con lodos activados. Se instalaron filtros cilíndricos en paralelo, con 110 mm de diámetro y alturas de lecho de 30, 40 y 50 cm (F1, F2, F3). El granulado bioclástico fue fraccionado con tamices de 4,75 y 1,0 mm. Los filtros operaron durante cuatro días con un caudal medio de 1,90 L·min⁻¹. Se determinaron la densidad aparente, porosidad del lecho y se monitorearon las concentraciones de fósforo total en la entrada y salida.

Resultados y Discusión: Las eficiencias máximas de remoción de fósforo fueron 51,38% en F1, 54,72% en F2 y 62,50% en F3. El filtro F3 mantuvo su eficiencia de adsorción tras el período operativo. La evaluación piloto demuestra la viabilidad del granulado bioclástico en el pos-tratamiento de aguas residuales con lodos activados.



Implicaciones de la investigación: Viabiliza el desarrollo de filtros comerciales y evalúa el uso agrícola del medio saturado con fósforo.

Originalidad/Valor: Presenta una alternativa simple, escalable y de bajo costo para la remoción de fósforo en efluentes urbanos.

Palabras clave: *Lithothamnium Calcareum*, Fósforo, Aguas Residuales, Lecho Fijo.

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1 INTRODUCTION

The insufficient coverage of sewage collection and treatment in Brazil reveals critical structural limitations for the management of water resources and the promotion of public health (Pereira & Souza, 2020; Santos, 2018). In 2017, the average service with sewage network among the hundred largest Brazilian municipalities reached 72.77% of the population, contrasting with the national average of only 52.4% (Instituto Trata Brasil, 2019). This scenario highlights the need for affordable, efficient and sustainability-aligned technological solutions to expand the reach of sanitation services (ANA, 2017; Mota & Von Sperling, 2009). In this sense, the collection and treatment of domestic effluents can be directed to the discussion for the development of accessible post-treatment solutions. In addition, effluents released into water bodies do not meet the removal of nutrients, such as phosphorus and nitrogen present in high concentrations, even after treatment in consecrated secondary systems (Pereira & Souza, 2020; Santos, 2018).

The phosphorus present in domestic sewage occurs both in the form of inorganic and organic phosphate, and its concentration is essential for microbial and algal growth (ANA, 2017; Mota & Von Sperling, 2009). However, excess of this nutrient in water bodies can result in eutrophication processes (ANA, 2017). Conventional sewage treatment systems prioritise the removal of organic matter, while maintaining phosphorus concentrations close to those of raw sewage (Mota & Von Sperling, 2009). To mitigate eutrophication, strategies for nutrient removal through physical-chemical or biological processes are studied (Silva *et al.*, 2021a; Veneu *et al.*, 2023). Thus, methodologies have been developed to recover and reuse these nutrients in the form of slow-release fertilisers, promoting their efficient capture and reuse in the context of the circular economy (Barboza *et al.*, 2025; Portella *et al.*, 2025).

Biogenic bioclastic granules have emerged as versatile alternatives in different environmental and industrial applications (Silva *et al.*, 2021a; Veneu *et al.*, 2023). Red algae



of the genus *Lithothamnium calcareum*, in the form of bioclastic granules, have potential as raw material for processes such as water purification, nutrient control in aquatic ecosystems, substrate in *wetland* systems, as well as consolidated uses in agriculture, cosmetic industry, animal nutrition and biomaterials (Veneu *et al.*, 2023; Veneu *et al.*, 2017). The *bioclastic granulate has a specific surface, in addition to other characteristics that point it as a possible sorbent of substances contained in leachates such as ammonia nitrogen, phosphorus and some organic compounds* (Caletti, 2017; Silva *et al.*, 2021a).

The validation of technologies based on bioclastic granules requires pilot-scale studies, fundamental to reproduce the real conditions of sewage treatment systems in the country (Barboza *et al.*, 2025; Portella *et al.*, 2025). The pilot operation allows to measure the efficiency of contaminant removal against variations in organic load and other factors inherent to decentralised or small systems. In addition, the data obtained help in the technical dimensioning, economic viability and integration of the processes to the circular economy strategies. Thus, research focused on the capture and reuse of phosphorus in effluents represents a technical-scientific advance with direct implications for sustainable nutrient management (ANA, 2017; Silva *et al.*, 2021a; Veneu *et al.*, 2023). Resource use and nutrient recovery can integrate bio-based solutions and contribute to the strengthening of sustainable practices and the expansion of environmental sanitation in Brazil. Finally, the present work had as objective the hydraulic dimensioning, the construction of prototypes of filters with bioclastic granulate filter bed and the accomplishment of tests on a pilot scale, seeking an efficient and low cost solution for the removal of nutrients in the post-treatment.

2 THEORETICAL FRAMEWORK

2.1 STRATEGIC PHOSPHORUS RECOVERY IN SEWAGE TREATMENT

The treatment of sanitary sewage from urban centres has as main objective the reduction of organic matter, pathogenic microorganisms, suspended solids and, in certain circumstances, also of nutrients present in sanitary sewage, provided that the absence of toxic waste is presumed (ANA, 2017). In evaluating the efficiency of domestic effluent treatment systems, factors such as the reduction in the concentration of undesirable compounds, the final quality desired for the effluent and / or the receiving body, in addition to its legal framework (ANA, 2017; Mota & Von Sperling, 2009) should be considered. These criteria should be referenced in the Resolutions of the National Council



of the Environment - CONAMA nº 357/2005 and nº 430/2011, as well as in the specific legislation of each State (BRAZIL, 2005; BRAZIL, 2011).

Resolution No. 430, of May 13, 2011, of the National Council of the Environment - CONAMA (BRAZIL, 2011), establishes a minimum efficiency of removal of 60% of the biochemical oxygen demand (BOD), with the possibility of removing nutrients such as phosphorus and / or nitrogen. These regulations require comprehensive quality standards, so that effluents can be discharged without posing a risk to public health or causing significant impacts to the environment (ANA, 2017; Mota & Von Sperling, 2009). The choice of the treatment process in a Sewage Treatment Plant (STP) is not restricted to environmental, legal or sanitary requirements, but is also influenced by economic, social, operational aspects, by the availability of area (ANA, 2017). In this context, the growing demand for technologies that reconcile environmental efficiency, economic viability and resource reuse emphasises the importance of interdisciplinary scientific approaches that prioritise the use of nutrients, such as phosphorus, in sewage treatment systems.

Phosphorus appears in natural waters due to sewage discharges, where faecal organic matter and powder detergents used on a large scale domestically constitute the main source (ANA, 2017). Drained waters in agricultural and urban areas can also cause excessive presence of phosphorus in natural waters (ANA, 2017; Mota & Von Sperling, 2009). Thus, phosphorus can be present in water in three forms: organic phosphates, in which form phosphorus composes organic molecules; orthophosphates, represented by radicals, which combine with cations forming inorganic salts in water; and polyphosphates, or condensed phosphates, polymers of orthophosphates (Mota & Von Sperling, 2009). The removal and reuse of this element in sewage treatment systems are relevant strategies for the control of diffuse pollution and for the promotion of a circular economy, since the agricultural use of this material represents an alternative for its valorisation, allowing the controlled return of the nutrient to the soil (ANA, 2017; Mota & Von Sperling, 2009).

2.2 TECHNOLOGICAL POTENTIAL OF BIOCLASTIC GRANULES

The bioclastic granulate consists of *Lithothamnium calcareum* and is one of the main constituents of marine reefs and corals, a calcareous algae of the *Coralline* family, being formed by a stone branch and crystallises calcium carbonate in its cell walls (Silva *et al.*, 2021a; Silva *et al.*, 2021b). The reserves are located on the coast of the state of Espírito Santo approximately 24 km from the coast of Itapemirim at a depth of 13 to 20 metres, where the bioclastic granulate



finds in the marine depth all the elements in their organic, vegetal and marine state (Nogueira, 2019). The main constituent of the bioclastic granulate is CaCO_3 , which presents itself in the form of calcite, providing greater stability in solution and providing the necessary elements for the removal of phosphorus present in landfill leachate (Veneu *et al.*, 2023; Veneu *et al.*, 2017).

The commercialisation of seaweed on the Brazilian coast was regulated aiming at the exploitation of live limestone deposits in Brazil (IBAMA, 2006). Among these algae, *Lithothamnium calcareum* stands out and is recognised for its porosity and composition rich in calcium and magnesium carbonate, which provides large surface area and binding capacity with phosphate ions, favouring mechanisms such as adsorption and surface precipitation (Barboza *et al.*, 2025; Portella *et al.*, 2025). In addition, the use of calcium and magnesium as phosphorus precipitating agents arouses interest **due to the potential for reuse of precipitates in agriculture** (Veneu *et al.*, 2023; Veneu *et al.*, 2017). The porous structure of bioclastic granules favours its application in the removal of metal ions from industrial effluents, and this biomass is valued for attributes such as wide availability, low cost and possibility of reuse (Silva *et al.*, 2021a; Silva *et al.*, 2021b).

3 METHODOLOGY

3.1 PREPARATION OF BIOCLASTIC GRANULES

The bioclastic granulate was purchased by PrimaSea, Brazil. The raw material was dried in a conventional oven (CienLab, Brazil) at 60 °C for 48 h and ground in a Willey mill (Marconi M. A. 680, Brazil). The dry material prevented agglutination of the particles in the mill body and blades. The material was fractionated and classified into sieves (Bertel, Brazil) with meshes of 4.75 mm and 1 mm.

3.2 FILTER BED TESTING AND PILOT SCALE INSTALLATION

The test of the filter beds demanded the use of new materials, as well as the reuse of components from previously deactivated filtration systems. Three filter units were constructed, consisting of brown PVC tubes with a nominal diameter of 110 mm and useful heights of 30 cm, 40 cm and 50 cm, identified respectively as F1, F2 and F3. Inside the tubes, retention structures of the filter bed were fixed based on the bioclastic granulate and white plates of high density polythene (HDPE) adapted as stoppers were used. Associated with these plates, a



polyester filter element was inserted with the function of containing the migration of particulate solids in suspension (Figure 1).

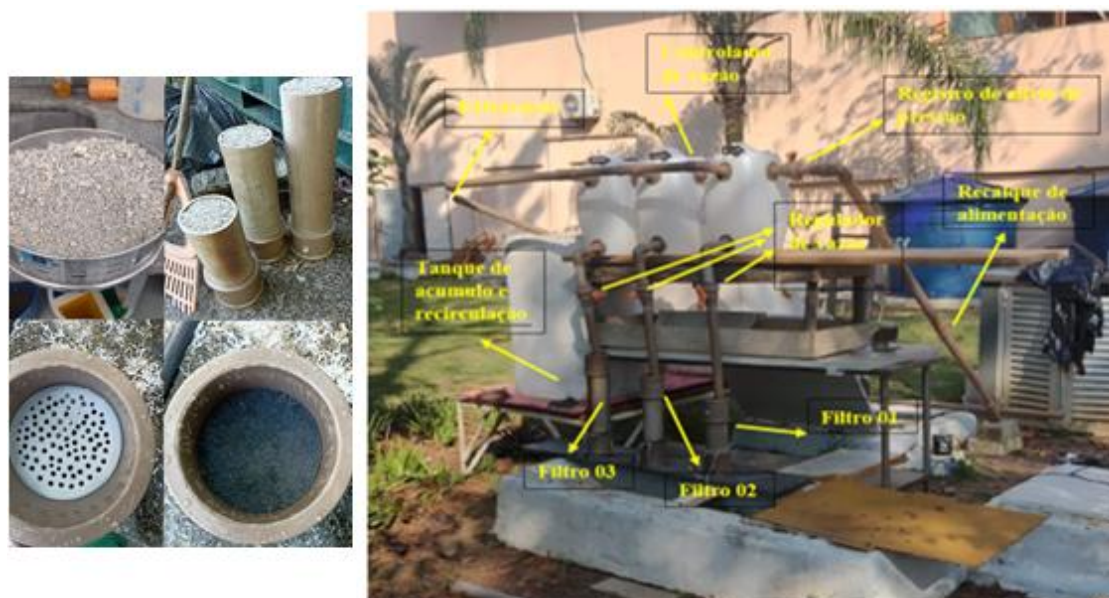
The pilot scale was installed in the Sewage Treatment Plant (STP) of the commercial enterprise BAYSIDE, located in the hydrographic region of Guanabara Bay, in the state of Rio de Janeiro, Brazil. The WWTP adopts the biological process of activated sludge operated in sequencing batch reactors (SBR) and was designed for a daily average flow rate of 63.0 m³/day, with an influent organic load of 25.20 kg BOD/day. Considering the particularities of the intermittent disposal regime inherent to the RBS system, it was necessary to adapt the power line of the experimental filters. To enable the continuous operation of the filters, filter beds containing bioclastic granulate were incorporated, which were integrated at the outlet of the treated effluent, allowing the continuous supply of affluent to the filter system (Figure 1).

The WWTP operates with the disposal of the treated effluent by means of a repression system, since the outlet quota of the valve is drowned in relation to the point of release. This hydraulic condition, combined with the RBS system, required the implementation of a flow control to ensure the continuous operation of the filters. For this, pumps with records as flow regulators were used, allowing precise adjustment of the feed. The excess is diverted to accumulation tanks connected in closed circuit with the lift, ensuring recirculation and avoiding losses. This arrangement ensures continuous and controlled flow, minimising the effects of the oscillations caused by the pumps and the batch regime (Figure 1).



Figure 1

Assembly of filter beds containing bioclastic granulate and installation on a pilot scale at the Sewage Treatment Plant (STP) of the commercial enterprise BAYSIDE, located in the hydrographic region of Guanabara Bay, in the state of Rio de Janeiro, Brazil.



3.3 DETERMINATION OF THE STARTING FLOW

The initial premises were defined and the operating conditions were adjusted to the reality of the system in the field. Based on bench scale tests performed in the laboratory, the initial flow rate for system operation was calculated. For the tests with three filters in bench scale and pilot scale, a relationship was established between the mass of the intermediate column of each system and its respective work flow. Thus, the starting flow of the filters was determined based on the mass of F2 (Qp), adopting 1/4 of the bench flow for application in the prototype, in order to prolong the column depletion time in the field. Considering the variability inherent to the real environment, the instantaneous flow measurement procedure was adopted for each sample collection. These measurements were performed for four days under time interval in hours, generating the measurements in sequence from T1 to T24. A container with a known volume of 4.9 litres was used for measurement at each moment T_i .

3.4 DETERMINATION OF FILTER BED DENSITY AND POROSITY

The masses of the three fixed beds composed of bioclastic granulate were determined. With the useful volume (filter bed) known for each filter, it was possible to calculate the



apparent density of the bed at different heights. For the determination of porosity, the masses of the dry fixed beds were initially obtained. Then, the same beds were weighed after being saturated with effluent, allowing to estimate the mass of retained liquid and the volume occupied by the fluid. From these data, the porosity of each of the three filters used was calculated.

3.5 DETERMINATION OF THE TOTAL PHOSPHORUS CONCENTRATION OF THE FILTER BED

Considering the premises of item 3.3 and 3.4, a sampling routine was established at the output of the filters in order to evaluate the efficiency in the removal of phosphorus from the effluent treated by the sequential batch activated sludge (SBR) system. The collection was carried out at 24 different times throughout the experimental time, with input and output samples. The experiment was conducted over four consecutive days, in which, at each previously established time, one sample was collected from the entrance and three from the exit, one for each filter.

The total phosphorus concentration (P_{total}) was determined in order to monitor the performance of the filters and evaluate the effectiveness of the beds filtered with bioclastic granulate. Colourimetric methodologies were adapted according to the recommendations of the *Standard Methods for the Examination of Water and Wastewater* (APHA, 2018). It was verified the removal efficiency of the treatment process in the filters aiming at the reduction of the P_{total} parameter, considering η the efficiency as the P removal efficiency in the filtration system, **P_{total} inlet** the total concentration of phosphorus at the filter inlet and **P_{total} outlet** the total concentration of phosphorus at the filter outlet. The removal efficiency was calculated by the relative reduction of phosphorus concentration according to Equation 1:

$$\eta (\%) = \frac{P_{total\text{entrada}} - P_{total\text{saída}}}{P_{total\text{entrada}}} \times 100 \quad (1)$$

4 RESULTS AND DISCUSSION

4.1 FILTER BED TEST AND STARTING FLOW RATE



From the test of the filter beds, the dimensions of height, volume and cross-sectional area of the simulated filters F1, F2 and F3 were determined (Table 1). In addition, the **bench-scale tests allowed the calculation of the starting flow rate for the system operation**. For the determination of the flow rate in the pilot filters, **a relationship** was established **between** the mass of the intermediate bench column and that of the intermediate pilot column, **being considered** the respective work flow of each system. For the definition of the starting flow (Q_p) of the filters, the intermediate height F2 filter was selected and 1/4 of the bench flow was adopted for application in the prototype, **with the objective of increasing** the column depletion time in the field. For the Q_p adjustment, the mass of the intermediate bench column (24 g) and that of the pilot intermediate column (3942 g) were considered, in **addition to the bench flow of the intermediate height filter (46.3 mL / min), with column depletion in 120 minutes (Table 1)**. From the data generated, the instantaneous flow measurement procedure was adopted at each time of sample collection, represented in the time intervals between T_1 to T_{24} , following the hydraulic variation over the time of operation of the filters (Table 2).

Table 1

Dimensions of height, volume and cross-sectional area of the filters adopted for the test of filter beds with bioclastic granules.

	Height (m)	Volume (m ³)	Area (m ²)
F1	0.30	2.25×10^{-3}	7.51×10^{-3}
F2	0.40	3.00×10^{-3}	7.51×10^{-3}
F3	0.50	3.76×10^{-3}	7.51×10^{-3}



Table 2

Record of the real-time flow measurement, represented in the time intervals between T_1 to T_{24} , of the filters adopted for the test of filter beds with bioclastic granules.

Date	Measurement	Time (h)	F1 time(s)	F2 time (sec)	F3 Time (s)	F1 flow rate (L/min)	F2 flow rate (L/min)	F3 flow rate (L/min)
DAY 1	T1	09:15	158	159	156	1.86	1.85	1.88
	T2	10:15 AM	154	160	151	1.91	1.84	1.95
	T3	11:15	151	158	148	1.95	1.86	1.99
	T4	12:15 PM	159	153	157	1.85	1.92	1.87
	T5	13:15	150	156	150	1.96	1.88	1.96
	T6	2:15 PM	144	159	151	2.04	1.85	1.95
	T7	3:15 PM	156	155	162	1.88	1.90	1.81
	T8	4:15 PM	151	157	151	1.95	1.87	1.95
DAY 2	T9	09:00	156	155	153	1.88	1.90	1.92
	T10	10:00	155	152	154	1.90	1.93	1.91
	T11	11:00	152	158	153	1.93	1.86	1.92
	T12	12:00	149	158	158	1.97	1.86	1.86
	T13	13:00	144	159	154	2.04	1.85	1.91
	T14	2:00 PM	159	158	149	1.85	1.86	1.97
DAY 3	T15	09:00	155	150	165	1.90	1.96	1.78
	T16	10:00	161	143	151	1.83	2.06	1.95
	T17	11:00	163	146	156	1.80	2.01	1.88
	T18	12:00	157	151	152	1.87	1.95	1.93
	T19	13:00	159	155	151	1.85	1.90	1.95
	T20	2:00 PM	154	157	155	1.91	1.87	1.90
DAY 4	T21	09:00	148	152	152	1.99	1.93	1.93
	T22	10:30	149	163	153	1.97	1.80	1.92
	T23	12:00	160	155	158	1.84	1.90	1.86
	T24	13:30	158	157	151	1.86	1.87	1.95
Average flow rate						1.91	1.90	1.91

4.2 APPARENT DENSITY AND POROSITY OF THE FILTER BED

The bulk density was determined by inserting the granules into the useful body of the filter (packed bed column) with a known volume, so that the amount of sample exceeding the limits of the container could be removed with a ruler. From this, the mass of the packed material was determined by weighing, allowing the calculation of the apparent density according to the relationship between mass (kg) and occupied volume (m^3), expressed in kg / m^3 (Table 3). The porosity was calculated by the ratio between the volume of voids (or pores) present in the material and the total volume occupied by the filter column, being expressed as a dimensionless



fraction (Table 3). A reduction in the apparent density of the filter bed was observed as the volume increased, from 1047.35 kg / m³ in F1 to 1017.26 kg / m³ in F3, accompanied by an increase in porosity, which ranged from 50% to 57%. The porosity values vary according to the apparent density of the material and the way of packing the bed, influencing the performance of the filter system. This property is fundamental to evaluate the capacity of the material to allow the passage of fluids through its bed, being related to the processes of absorption, adsorption and percolation.

Table 3

Determination of the apparent density and porosity from the bed masses and the bed volume in the filter.

	Dry Bed Mass (kg)	Volume (m3)	Apparent Density (kg/m ³)	Weight Wet Bed (kg)	Porosity (€)
F1	2.98	2.85x10 ⁻³	1047.35	4.48	0.50
F2	3.94	3.80x10 ⁻³	1037.10	6.04	0.53
F3	4.83	4.75x10 ⁻³	1017.26	7.61	0.57

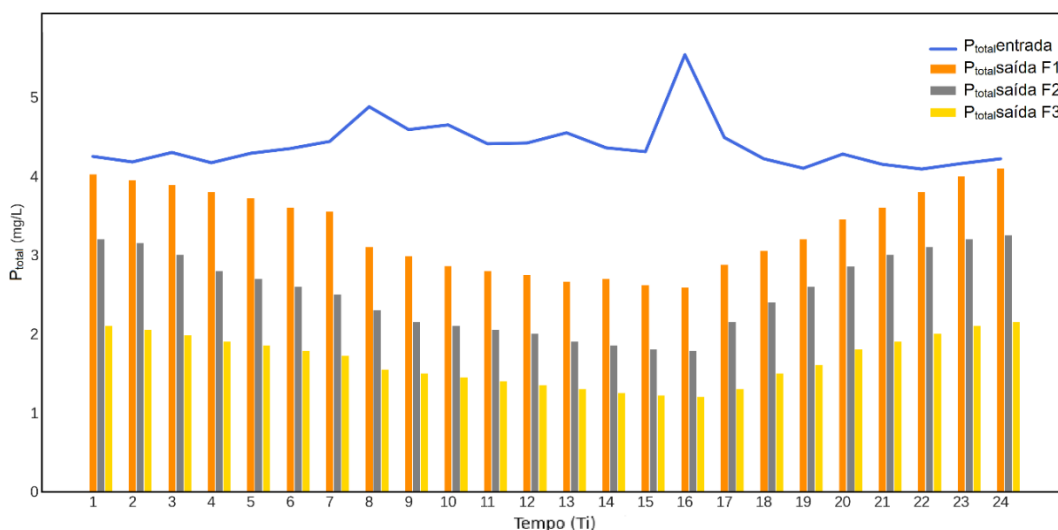
4.3 TOTAL PHOSPHORUS CONCENTRATION OF THE FILTER BED

Figure 2 illustrates the variation of the concentration of P_{total} at the system input and the concentrations observed at the output of three different filters (F1, F2 and F3) over 24 consecutive measurements (Time T1 to T24). The concentration of the influent ($P_{totalentrada}$) was kept relatively constant, varying between 4.2 and 5.6 mg/L, providing a stable baseline for comparative evaluation of filter efficiency.



Figure 2

Comparative performance of the filters F1, F2 and F3 in the removal of total phosphorus (P_{total}) over the experimental time (T_i) between T_1 and T_{24} .



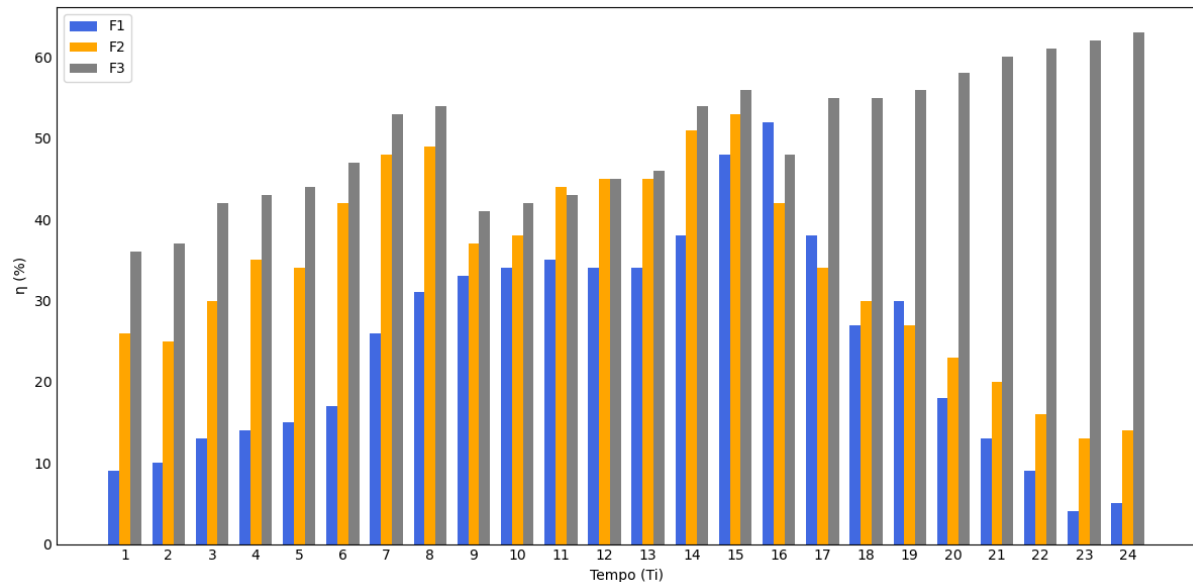
The F3 filter showed P_{total} concentrations consistently below 2.0 mg/L at the outlet and this performance may be associated with the efficiency of the surface adsorption process. This performance may be related to factors such as particle size, contact time, filtration rate and bed disposition, which directly influence the exposure and accessibility of the active sites present in the material. The trend of increase in the concentration of P_{total} at the output of the F1 and F2 filters from T_{16} suggests possible exhaustion of the adsorptive capacity or saturation of the filter materials in these systems. The F2 filter presented intermediate performance, with removal up to about half of the experiment, followed by a gradual increase in the output concentrations, suggesting the beginning of saturation of the adsorptive sites. The F1 filter presented the lowest removal efficiency, with values closer to the inlet concentration, which indicates a limitation in the adsorptive capacity of the material used.

Figure 3 illustrates the efficiency variation of the three different filters (F1, F2 and F3) over 24 consecutive measurements (Time T_1 to T_{24}). The performances and efficiencies observed in F3 show the potential of the bed under optimised conditions to maximise its adsorptive capacity.



Figure 3

Comparative efficiency (η) of Filters F1, F2 and F3 in the removal of total phosphorus (p_{total}) over experimental time (T_i) between T_1 and T_{24} .



The F3 filter presented stability and efficiencies superior to the F1 and F2 filters over the operation time, reaching maximum efficiency in time T_{24} of 51.38% in F1, 54.72% in F2 and 62.50% in F3. The results suggest that, although the bed is the same in the three filters, the operating conditions adopted in F3 favoured a greater efficiency of the adsorption process, possibly due to the greater specific area of the bed, which favoured the contact between the phosphorus of the effluent and the active surface of the material. The results indicate that the operational model of the F3 filter has potential for applications in treatment systems focused on the removal of phosphorus.

The structure of the filter bed plays a fundamental role in the efficiency of the system, since its specific surface area, porosity and physical arrangement determined the degree of interaction between the effluent and the bed. In the F3 filter, the bed configuration may have potentiated the use of the properties of the bioclastic granulate, favouring both the adsorption and the formation of precipitates on the surface of the material (Barboza *et al.*, 2025). The adequate distribution and compaction of the bed contribute to the increase of the available active sites, intensifying the phosphorus removal and, consequently, the overall performance of the system (Portella *et al.*, 2025).



5 CONCLUSION

The present study affirmed the feasibility of using bioclastic granules in filter beds for phosphorus removal on a pilot scale, with emphasis on the F3 filter. The results reinforce the potential application of this material in the post-treatment of sewage from activated sludge systems, offering a low-cost, simple and scalable solution. The agricultural reuse of the saturated filter medium points to promising strategies for waste recovery and circular economy. Future research can explore the agronomic application of saturated material, the behaviour of phosphorus in the soil and the adaptation of technology to decentralised systems, increasing its environmental and social impact.

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