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Evaluation of Sugarcane Bagasse as a Biosorbent for Arsenic Removal from Groundwater in Mórrope, Peru

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Abstract

The presence of arsenic in groundwater poses a significant threat to public health, particularly in rural areas lacking access to treatment technologies. In Mórrope, concentrations exceeding regulatory limits have been detected, necessitating sustainable solutions. The objective of this study was to evaluate the efficiency of sugarcane bagasse as a biosorbent material for removing arsenic from contaminated waters in the Mórrope-Lambayeque district. The experimental design employed a 2 × 3 × 3 factorial design, encompassing three variables: adsorbent dosage (1 and 2 g/L), pH (5, 7, and 9), and initial arsenic concentration (2.5, 4.5, and 6.5 mg/L). The bagasse underwent a series of processing steps, including acid washing, drying, and sieving, and was applied in batch tests. The analysis encompassed removal efficiency, adsorption capacity, isotherm adjustment, and kinetics. The system attained a maximum removal rate of 27.43% with a biosorbent dosage of 2 g/L, pH 9, and an initial

arsenic concentration of 2.5 mg/L. The Langmuir model (R^2 = 0.9926) provided the most suitable description of the adsorption process, indicating the presence of a monolayer. The adsorption kinetics were best described by the pseudo-second-order model (R^2 = 0.9727). However, this statistical fit was not interpreted as definitive evidence of an exclusively chemisorption-controlled mechanism, since surface interactions, external mass transfer, and intraparticle diffusion may contribute simultaneously to arsenic uptake. The results indicate that chemically modified sugarcane bagasse exhibits a measurable but limited capacity for arsenic adsorption. However, the maximum removal efficiency of 27.43% is insufficient for direct drinking-water treatment, and the material should not be considered a stand-alone remediation technology under the evaluated conditions. Further surface modification, process optimization, and integration with complementary treatment stages are required before practical implementation can be considered. Beyond its technical feasibility, this approach holds strong social relevance, as it promotes the use of locally available agricultural residues to improve water quality in vulnerable communities, fostering low-cost, community-managed, and environmentally sustainable solutions for safe water access. Although the removal efficiency remains moderate, future research should aim to enhance adsorption performance and evaluate the potential for large-scale implementation in rural water treatment systems.

Keywords
Arsenic; adsorption; sugarcane bagasse; biosorbent; water treatment

1. Introduction

Arsenic, a metalloid that is pervasive in nature, poses a substantial threat to public health through its presence in water sources. It has been demonstrated that long-term exposure to this contaminant is associated with a range of acute and chronic toxic effects, including various types of cancer, diabetes, cardiovascular disease, and neurological disorders [1]. Considering this hazard, the World Health Organization (WHO) has established a maximum permissible limit of 0.01 mg/L in drinking water. However, there are discrepancies in regulations worldwide that require review to better protect public health [2]. In Peru, Supreme Decree No. 031-2010-SA establishes a maximum permissible arsenic concentration of 0.01 mg/L (0.01 mg/L) in drinking water, a value aligned with the guideline recommended by the World Health Organization [2].

Chronic exposure to inorganic arsenic through drinking water is a major epidemiological concern because it is associated with both carcinogenic and non-carcinogenic outcomes across exposed populations. Early clinical manifestations include changes in skin pigmentation and palmar-plantar hyperkeratosis, which may indicate prolonged exposure. Inorganic arsenic is classified as carcinogenic to humans, and epidemiological evidence has established associations with cancers of the skin, urinary bladder, and lung [1, 3]. Long-term exposure has also been associated with cardiovascular disease, diabetes mellitus, pulmonary disease, kidney dysfunction, and neurological impairment [1, 4]. Prenatal and early-life exposure is particularly relevant because it has been linked to adverse pregnancy outcomes, infant mortality, impaired cognitive development, reduced

intelligence and memory, and an increased risk of disease and premature mortality later in life [4]. From an epidemiological perspective, the absence of a unique clinical profile and the long latency of many arsenic-related diseases complicate case attribution and may lead to an underestimation of the true disease burden. These findings highlight the importance of population-level surveillance, early identification of exposed communities, and sustained interventions to reduce arsenic concentrations in drinking water.

Globally, arsenic contamination of groundwater is largely controlled by interconnected geochemical and hydrogeological processes that regulate the mobilization and transport of arsenic-bearing minerals [5-7]. In sedimentary and alluvial aquifers, one of the principal mechanisms is the microbially mediated reductive dissolution of iron and manganese oxyhydroxides under anoxic conditions, which releases arsenic previously adsorbed or incorporated into mineral surfaces [5, 6]. Arsenic may also be mobilized through the oxidative dissolution of arsenic-bearing sulfide minerals, particularly when sulfides are exposed to oxygenated water, as well as through competitive desorption induced by phosphate and other anions [6, 7]. Moreover, alkaline conditions can promote pH-dependent desorption by altering the surface charge of minerals and decreasing their affinity for dissolved arsenic species. The relative importance of these processes depends on aquifer mineralogy, redox potential, organic matter availability, groundwater residence time, and groundwater flow dynamics [5-7].

From a global perspective, arsenic contamination of drinking water is one of the most widespread environmental health risks, particularly in regions where groundwater is the principal source of water for human consumption [1, 8]. The World Health Organization estimates that approximately 140 million people in at least 70 countries have consumed water containing arsenic concentrations above its provisional guideline value of 0.01 mg/L [2]. Consistent with this estimate, global predictive modeling suggests that between 94 and 220 million people may be at risk of exposure to elevated arsenic concentrations in groundwater, with most of the potentially affected population located in Asia [9]. Particularly affected areas include South and Southeast Asia, parts of Latin America, and several regions of Africa, where chronic exposure has been associated with skin lesions, cardiovascular diseases, neurological disorders, and multiple forms of cancer [1, 6, 7]. Consequently, the development of accessible and sustainable technologies for arsenic removal remains a global priority, especially in rural communities with limited access to conventional water-treatment infrastructure [8, 10].

According to the World Health Organization (WHO), the recommended guideline value for arsenic in drinking water is 0.01 mg/L, established to minimize long-term health risks associated with chronic exposure. Similarly, the Peruvian regulation for drinking water quality, established under Supreme Decree No. 031-2010-SA, also sets a maximum permissible limit of 0.01 mg/L for arsenic in water intended for human consumption. Despite these regulatory standards, several regions in Peru have reported groundwater arsenic concentrations that exceed this limit, particularly in rural areas where groundwater is frequently used as the primary source of drinking water and access to treatment technologies remains limited.

In a multitude of countries, particularly those with a high prevalence of mining activities or distinctive hydrogeological characteristics, arsenic levels in water frequently exceed the recommended standards. In regions such as South Asia, Latin America, and parts of Africa, millions of people are exposed to contaminated water on a daily basis, representing a significant public health concern. In Peru, this phenomenon has been documented in areas such as Puno, Arequipa,

Cusco, and Lambayeque, where concentrations exceeding the limits established by Supreme Decree No. 031-2010-SA have been detected. Research conducted in the Barpeta district of Assam, India, has confirmed that specific hydrogeological factors can facilitate the presence of arsenic in groundwater, affecting entire communities [5]. Furthermore, studies conducted in mining contexts in Latin America, including La Toma in Colombia, demonstrate how informal extractive activity and the absence of environmental regulation can lead to water contamination [11]. This phenomenon can be replicated in other regions with artisanal mining, as evidenced in several areas of Peru.

The Mórrope district, located in the Lambayeque region, faces persistent arsenic contamination in its groundwater sources. Hydrogeological studies have reported arsenic concentrations exceeding the maximum permissible limit of 0.01 mg/L established for drinking water [12]. In the groundwater sample collected from Tubular Well No. 1 for the present study, the initial arsenic concentration was 0.218 mg/L. This concentration was 21.8 times the regulatory limit, representing an exceedance of 2,080%. The contamination is considered predominantly geogenic and may result from the natural weathering and dissolution of arsenic-bearing minerals in local sedimentary formations. Under reducing conditions, the dissolution of iron and manganese oxyhydroxides can release arsenic previously retained on mineral surfaces. At the same time, alkaline pH and competition with phosphate and other anions may promote its desorption and mobility in groundwater [5-7]. These processes may also be influenced by groundwater residence time, aquifer mineralogy, and local hydrological conditions, including climate-related variations in recharge and water flow [13].

Arsenic contamination in water is a global environmental and public health concern, particularly in regions where natural geochemical processes or anthropogenic activities mobilize arsenic into groundwater and surface waters. Geological conditions, including the weathering of arsenic-bearing minerals and redox processes in aquifers, play a key role in controlling arsenic release and distribution in aquatic environments. As a result, several regions worldwide have reported elevated arsenic concentrations in drinking water sources, representing a significant risk to human health due to long-term exposure [6, 7]. This broader context highlights the need to develop effective, low-cost technologies for arsenic removal from water.

Consequently, health emergencies have been declared, and provisional measures have been implemented, including the provision of water through cisterns and the installation of filtration systems. Nevertheless, these solutions have proven inadequate in ensuring safe, permanent, and equitable access to drinking water. The implementation of sustainable systems for arsenic removal in this area has been hindered by technical, economic, and logistical constraints. Globally, this problem recurs in vulnerable communities, where the sustainability of treatment solutions is one of the most significant challenges [8]. Despite proposals for innovative technologies, such as integrating hydrochar and nanoparticles to enhance arsenic removal efficiency, these approaches still face substantial obstacles to practical implementation in rural or low-resource contexts [14].

Available technologies for arsenic removal from water include physicochemical processes such as coagulation, filtration, reverse osmosis, ion exchange, and adsorption. Despite their efficacy, numerous techniques necessitate intricate infrastructure, substantial operational expenses, and specialised maintenance, impeding their applicability in rural or resource-constrained contexts [10, 15].

Various technologies have been developed for arsenic removal from water, including adsorption, coagulation-flocculation, membrane filtration, ion exchange, reverse osmosis, and advanced

oxidation processes [15, 16]. Among these approaches, adsorption-based techniques have received significant attention due to their operational simplicity, cost-effectiveness, and potential for using low-cost or waste-derived materials as adsorbents [10, 16]. In recent years, emerging materials such as metal-organic frameworks and covalent organic frameworks have also been investigated for arsenic removal because of their high surface area, tunable porosity, and strong affinity for arsenic species [17]. Additionally, biochar and modified biochar materials have been widely studied as sustainable adsorbents for arsenic removal from water and soil matrices due to their surface functional groups and porous structure [18]. Among these approaches, adsorption-based techniques have received significant attention due to their operational simplicity, cost-effectiveness, and potential for using low-cost or waste-derived materials as adsorbents [16]. In recent years, emerging materials such as metal-organic frameworks (MOFs) and covalent organic frameworks (COFs) have also been investigated for arsenic removal because of their high surface area, tunable porosity, and strong affinity for arsenic species [17]. Additionally, biochar and modified biochar materials have been widely studied as sustainable adsorbents, showing promising performance in removing arsenic from both water and soil matrices due to their surface functional groups and porous structure [18]. These developments highlight the ongoing research efforts to design efficient and scalable materials for arsenic remediation in contaminated water systems.

In this context, the utilisation of biosorbent materials for adsorption is presented as a viable, efficient, and environmentally friendly option. Biosorbents are organic materials frequently derived from agricultural or agro-industrial waste that possess functional groups capable of binding heavy metals. Sugarcane bagasse, a lignocellulosic byproduct, has been identified as a subject of particular research interest [19, 20]. This material is available in large quantities in the country.

Sugarcane bagasse exhibits high porosity, a substantial specific surface area, and a composition rich in cellulose and lignin. These characteristics confer on it the capacity to act as a medium for the retention of contaminants through adsorption. The utilisation of the subject in water treatment is an effective strategy for remediating contaminated sources. Concurrently, it facilitates the utilisation of an underutilised resource, thus promoting circular economy practices in rural areas [21, 22].

Confronted with the persistent issue of arsenic contamination of water in Mórrope and the limited effectiveness of the corrective measures adopted to date, it is imperative to evaluate solutions that combine technical efficiency with economic and social viability. The utilisation of sugarcane bagasse as a biosorbent is a response to this necessity, given its low cost, local abundance, and ease of implementation. Recent research has documented alarming levels of arsenic in different rural areas of Peru, including regions such as Juliaca and Huánuco, where conventional technologies have proven ineffective or unsustainable for local contexts [23, 24]. In this context, sugarcane bagasse emerges as a viable alternative, not only due to its adsorption capacity but also because of its alignment with sustainability and circular economy principles. According to [25] this lignocellulosic material exhibits suitable physicochemical properties for utilisation in industrial and rural water treatment applications, representing an innovative and accessible opportunity for communities affected by the presence of heavy metals.

Despite the growing body of research on the use of agro-industrial residues as biosorbents, most studies have been conducted under idealized laboratory conditions and using synthetic solutions, which do not fully represent the complexity of real contamination scenarios. Furthermore, there is limited empirical evidence regarding the effectiveness of unmodified sugarcane bagasse for arsenic

removal in natural groundwater systems, particularly within rural Peruvian contexts affected by chronic contamination. This gap highlights the need for applied studies that assess the adsorption performance of locally available materials under realistic environmental conditions.

Therefore, the present study contributes to the existing body of knowledge by evaluating the efficiency of sugarcane bagasse as a biosorbent for arsenic removal in contaminated groundwater from the Mórrope district, Lambayeque. This research not only validates the material's potential through adsorption isotherms and kinetic modeling but also emphasizes its practical applicability in low-resource rural settings. By linking environmental remediation with the valorization of agro-industrial waste, the study offers an innovative, sustainable, and socially relevant alternative for decentralized water treatment in vulnerable communities.

In this regard, the objective of this research is to evaluate the efficiency of sugarcane bagasse as a biosorbent material for removing arsenic from contaminated waters in the Mórrope-Lambayeque district. The scientific relevance of this study is evidenced by its demonstration of the adsorptive capacity of sugarcane bagasse under real-world contamination conditions. On a social level, the study focuses on a community affected by a public health problem, while on an environmental level, it promotes the use of agro-industrial waste as an input for clean technologies. Furthermore, it has the potential to stimulate replication in other regions of the country grappling with analogous challenges.

2. Materials and Methods

To systematize the methodological approach, the experimental procedure was organized into a sequence of technical stages. First, the study area and sampling point were selected based on the documented presence of arsenic in groundwater in Mórrope. Second, the sugarcane bagasse was conditioned by acid washing, rinsing, drying, grinding, and sieving to obtain a homogeneous biosorbent. Third, the physicochemical characteristics of the groundwater and the biosorbent were determined before the adsorption experiments. Fourth, batch adsorption tests were carried out under controlled laboratory conditions using a 2 × 3 × 3 factorial design, considering adsorbent dosage, solution pH, and initial arsenic concentration as independent variables. Finally, arsenic removal efficiency, adsorption capacity, isotherm fitting, kinetic behavior, and statistical significance were evaluated. This methodological sequence was established to ensure technical clarity, reproducibility, and coherence between the experimental design and the objective of assessing sugarcane bagasse as a biosorbent for arsenic removal from groundwater.

2.1 Type, Level and Design of the Research

The present study employed a quantitative approach to objectively evaluate the efficiency of a biosorbent material in removing arsenic from water. The research is grounded in the paradigm of applied research to address a particular public health concern in the Mórrope district through the implementation of environmental engineering principles. The research is explanatory in nature, since it facilitates the identification of causal relationships between the manipulated variables and the observed response. This approach is pivotal in comprehending not only the existence of a relationship between variables, but also the direction and nature of that relationship [26]. It is posited that explanatory studies facilitate the control of external variables and a more precise evaluation of causal effects. This is considered to be essential for obtaining valid and generalisable

conclusions in applied research. To this end, a 2 × 3 × 3 multifactorial experimental design was employed to evaluate the simultaneous effect of three factors on arsenic removal efficiency: adsorbent dosage, pH, and initial contaminant concentration.

2.2 Study Area: Mórrope - Lambayeque

The study was conducted in the district of Mórrope, province of Lambayeque, northwestern Peru. This district is characterized by an arid coastal climate, flat topography, and strong dependence on groundwater sources for domestic and agricultural use. The area covers approximately 1,041 km^2 and has an average elevation of 20 m above sea level. It is part of the Sechura Desert, where sandy soils with low water retention capacity predominate. Agricultural activities depend mainly on irrigation channels fed by the Chancay-Lambayeque and La Leche rivers, whose flows are highly variable and sensitive to climatic events such as El Niño. In recent years, elevated arsenic concentrations have been detected in local wells, leading to sanitary emergency measures and temporary water distribution through tanker trucks. These geographical, hydrological, and environmental conditions make Mórrope a relevant case for evaluating sustainable water treatment alternatives based on agro-industrial residues such as sugarcane bagasse.

The geographical area under scrutiny was situated in the Mórrope district, Lambayeque region, specifically in the Alto Perú Annex of the Cruz de Médano Population Center, as shown in Figure 1. The area is located at an altitude of 33 metres above sea level, with geographic coordinates of 6°30’47.9” south latitude and 79°57’34.6” west longitude. The selection of the site was based on the findings of previous reports, which indicated elevated concentrations of arsenic in groundwater sources. These findings subsequently prompted the implementation of sanitary interventions and the declaration of emergencies. In this particular context, Tubular Well No. 1 was identified as a representative source of the problem, thus serving as the primary sampling unit for the study.

Figure 1 Geographical location of the study area within the Lambayeque region (Peru).

2.3 Sampling

Groundwater was collected from Tubular Well No. 1, located in the Alto Perú Annex of the Cruz de Médano Population Center, Mórrope district, Lambayeque region, Peru, as shown in Figure 2. A total volume of 20 L was collected in a clean plastic container, which was immediately labeled, sealed, and transported to the Process Laboratory of Pedro Ruiz Gallo National University under shaded, controlled-temperature conditions to minimize physicochemical alterations before analysis. The sampling point was selected because previous reports and local monitoring indicated elevated arsenic concentrations in groundwater used by the surrounding population. In parallel, approximately 1 kg of sugarcane bagasse was obtained from Agroindustrial Tumán S.A.A. and transported to the laboratory under similar preservation conditions for subsequent conditioning and use as biosorbent material.

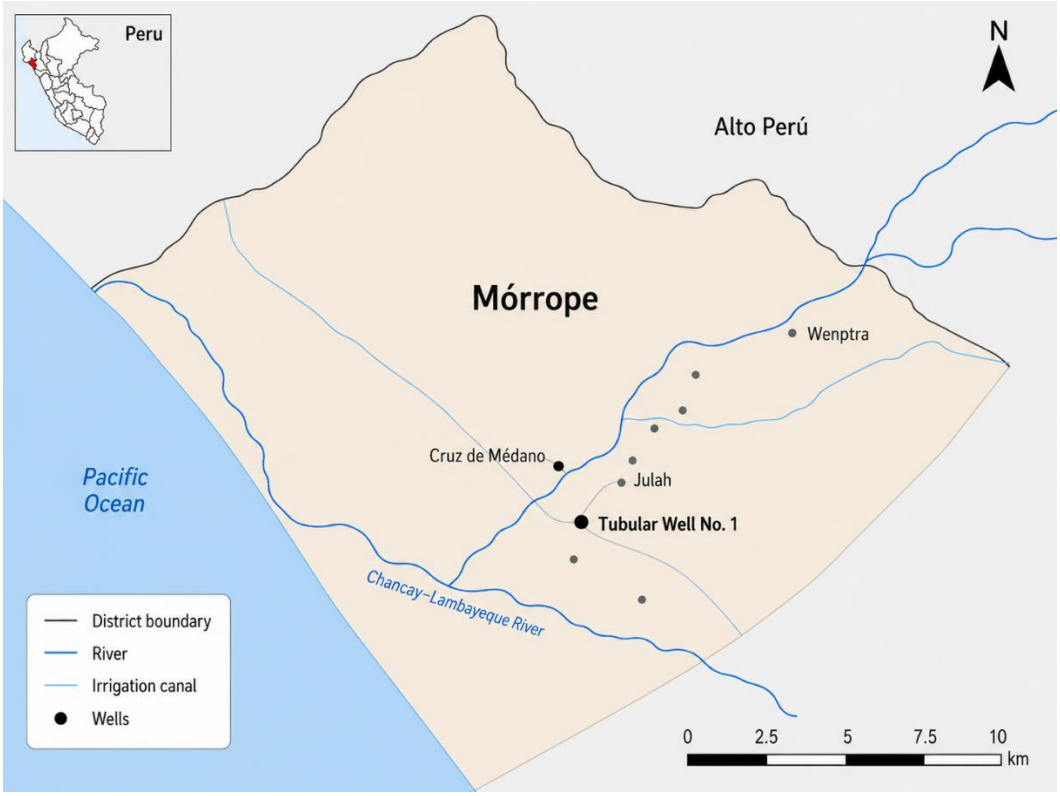

Figure 2 Hydrographic and sampling context of the Mórrope district.

2.4 Preparation of the Adsorbent: Sugarcane Bagasse

Sugarcane bagasse was chemically modified using a 1% (w/v) phosphoric acid (H_3PO_4) solution. A solid-to-liquid ratio of a solid-to-liquid ratio of 1 g/mL was used. The mixture was continuously stirred for 30 min at room temperature to promote contact between the acid solution and the lignocellulosic surface. After treatment, the bagasse was separated from the acid solution and repeatedly rinsed with distilled water until the final wash water reached a pH of, indicating that residual acid had been sufficiently removed. The washed material was dried in an oven at 90°C for 8 h, ground in an impact shear mill at 4,500 rpm, and sieved to obtain the 50-mesh fraction, corresponding to a particle size of approximately 300 µm. The conditioned material was subsequently stored in airtight containers until use in the adsorption experiments.

The phosphoric acid treatment applied in this study is classified as a chemical modification rather than an activation process. Its purpose was to remove surface impurities and potentially modify the accessibility of oxygen-containing functional groups commonly reported in lignocellulosic materials. However, changes in the presence or abundance of these groups were not directly confirmed because FTIR or other surface-characterization analyses were not performed. The procedure did not involve the high temperatures, carbonization conditions, or controlled chemical activation commonly used to produce activated carbon or highly porous activated materials. Therefore, the material is referred to throughout this study as chemically modified or acid-conditioned sugarcane bagasse, rather than activated sugarcane bagasse.

2.5 Physicochemical Characterization of Water and Adsorbent

Prior to utilisation in the experimental procedures, both the water and the bagasse were characterised. The parameters of odor, taste, color, turbidity, pH, electrical conductivity, total dissolved solids, hardness, and sulfates were measured for the water, in accordance with the procedures delineated in the Standard Methods for the Examination of Water and Wastewater. The water sample exhibited a pH of 7.58, a conductivity of 1416 µS/cm, and a total solids content of 707 mg/L. For the bagasse, the relevant physical properties were determined, including moisture content (10.03%), true density (1110 kg/m^3), apparent density (105.5 kg/m^3), porosity (0.90), and buoyancy. It was observed that the material tended to float when placed in water.

Tubular Well No. 1 was selected because it is a locally relevant groundwater source used by the surrounding population and because previous reports and local monitoring had identified elevated arsenic concentrations at this sampling point. Its selection, therefore, allowed the study to evaluate the performance of sugarcane bagasse under a real, environmentally significant contamination scenario. However, using a single well does not provide a representative characterization of the entire Mórrope aquifer, since arsenic concentrations may vary spatially according to differences in aquifer mineralogy, redox conditions, groundwater flow paths, residence time, and local recharge processes. Accordingly, the results should be interpreted as site-specific evidence of biosorbent performance rather than as findings generalizable to all groundwater sources in the district. Future studies should include multiple wells distributed across the study area and repeated sampling campaigns to assess spatial and temporal variability.

The baseline total arsenic concentration in the groundwater collected from Tubular Well No. 1 was 0.218 mg/L. This concentration was determined before the adsorption experiments using [Confirm the Analytical Technique: ICP-OES], following the laboratory's validated procedure for arsenic determination in water. The value was used as the baseline concentration for characterizing the natural groundwater sample and should be distinguished from the higher arsenic concentrations of 2.5, 4.5, and 6.5 mg/L subsequently prepared for the factorial adsorption experiments.

Arsenic speciation was not directly quantified through a species-selective analytical method in this study. No chromatographic separation, selective hydride-generation protocol, or coupled technique such as HPLC-ICP-MS was applied to independently determine As(III) and As(V). Therefore, the possible predominance of arsenite or arsenate was interpreted only from the physicochemical conditions of the groundwater, particularly pH and redox conditions, and should not be considered an experimentally confirmed speciation result. The analytical measurements reported in this study

correspond to total arsenic. Future studies should incorporate direct speciation analysis to quantify As(III) and As(V), given that their charge, mobility, and adsorption behavior differ substantially.

2.6 Factorial Experimental Design (2 × 3 × 3)

The experiment was conducted using a batch adsorption process, in which aqueous arsenic solutions with different initial concentrations were prepared and mixed with defined quantities of bagasse, under controlled pH and contact time conditions. The experimental design incorporated three factors: bagasse dosage, which was varied at two levels (1.0 and 2.0 g/L); pH, which was varied at three levels (5, 7, and 9); and initial arsenic concentration, which was varied at three levels (2.5, 4.5, and 6.5 mg/L). The factorial design comprised 18 unique treatment combinations, with one observation per combination. Therefore, within-treatment variability and standard deviations could not be estimated from experimental replicates. The pH was adjusted using 0.1 N nitric acid and 0.1 N sodium hydroxide solutions.

Arsenic is consistently referred to according to its oxidation state. The experiments were conducted using arsenic as arsenate [As(V)], the predominant species under oxidizing environmental conditions. Therefore, all references to arsenic in the adsorption experiments correspond specifically to As(V). This specification improves the chemical precision of the manuscript, since the adsorption behavior and interaction mechanisms may differ significantly between arsenite [As(III)] and arsenate [As(V)] species.

The factorial design included three independent variables and two response variables. The independent variables were: (i) adsorbent dosage, evaluated at two levels, 1 and 2 g/L; (ii) solution pH, evaluated at three levels, 5, 7, and 9; and (iii) initial arsenic concentration, evaluated at three levels, 2.5, 4.5, and 6.5 mg/L. These factors were systematically varied according to a 2 × 3 × 3 factorial design to determine their individual and combined effects on arsenic adsorption. The primary dependent variable was arsenic removal efficiency (%), calculated from the difference between the initial and final arsenic concentrations. Adsorption capacity, expressed as milligrams of arsenic adsorbed per gram of biosorbent (mg/g), was considered a complementary dependent variable because it represents the amount of arsenic retained per unit mass of sugarcane bagasse. Thus, dosage, pH, and initial concentration functioned as experimentally controlled factors, whereas removal efficiency and adsorption capacity were the measured responses used to evaluate biosorbent performance.

Although variations in the measured responses were observed among the experimental conditions, not all differences reached statistical significance according to the applied statistical tests ($p > 0.05$). Therefore, these variations should be interpreted as observable tendencies rather than statistically supported effects. Only effects with p-values below 0.05 were considered statistically significant. This distinction allows for a more rigorous interpretation of the experimental outcomes, preventing overinterpretation of patterns that may arise from experimental variability.

Procedures to determine: % removal, adsorption capacity, isotherms and kinetics.

The percentage of arsenic removal was determined by comparing the initial and final concentrations of the contaminant using the following formula:

$$\%R = \frac{C_0 - C_f}{C_0} \times 100 \quad (1)$$

It is to be noted that C_0 denotes the initial concentration and C_f denotes the final concentration of arsenic in each sample. The measurements were conducted using inductively coupled plasma optical emission spectroscopy (ICP-OES) at the Cajamarca Regional Water Laboratory, which is accredited by the National Accreditation Institute of the Peruvian State (INACAL). The adsorption capacity was calculated using the following formula:

$$q = \frac{(C_0 - C_e)V}{m} \tag{2}$$

In this equation, 'C_e' denotes the equilibrium concentration, 'V' represents the volume of the solution, and 'm' is the mass of the adsorbent. The experimental adsorption capacity was calculated as $q_e = (C_0 - C_e)V/m$ and expressed as milligrams of arsenic adsorbed per gram of dry biosorbent (mg/g). The theoretical Langmuir maximum adsorption capacity, q_{max}, was obtained from the slope of the linearized Langmuir equation, $C_e/q_e = 1/(q_{max}b) + C_e/q_{max}$, where the slope is equal to $1/q_{max}$. Therefore, q_{max} was calculated as the reciprocal of the fitted slope rather than from the intercept.

Furthermore, adsorption isotherms were analysed to ascertain the relationship between the amount adsorbed and the equilibrium concentration. The Freundlich and Langmuir models were applied. The initial equation was expressed as follows:

$$\log q_e = \log K_f + \frac{1}{n}\log C_e \tag{3}$$

and the second by:

$$\frac{1}{q_e} = \frac{1}{q_{max}K_L C_e} + \frac{1}{q_{max}} \tag{4}$$

The experimental findings indicated that the Langmuir model exhibited an enhanced fit, with a coefficient of determination $R^2 = 0.9926$, suggesting that the adsorption process predominantly occurs within a monolayer on a homogeneous surface. To study the kinetics of the process, two models were applied: pseudo-first-order and pseudo-second-order. The initial equation was expressed as follows:

$$\log(q_e - q_t) = \log q_e - k_1 t \tag{5}$$

and the second by:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \tag{6}$$

To further examine the mass-transfer mechanisms involved in arsenic adsorption, the kinetic data were additionally evaluated using the Weber-Morris intraparticle diffusion model:

$$q_t = k_{id} t^{1/2} + C$$

where q_t is the adsorption capacity at time t (mg/g), k_{id} is the intraparticle diffusion rate constant (mg g^{-1} $min^{-1/2}$), and C is the intercept associated with the boundary-layer effect. If the plot of q_t versus $t^{1/2}$ is linear and passes through the origin, intraparticle diffusion may be considered the sole

rate-controlling step. Conversely, multilinearity or a non-zero intercept indicates that other mass-transfer mechanisms also contribute to the adsorption process. External film diffusion was evaluated using the liquid-film diffusion relationship:

$$\ln(1 - F) = -k_{fd}t$$

where $F = q_t/q_e$, and k_{fd} is the film-diffusion rate constant (min^{-1}). A linear relationship passing through the origin would indicate predominant control by external film diffusion. In contrast, deviation from the origin would suggest that film diffusion is not the only rate-controlling mechanism.

All physical quantities and units were reported using standard SI notation. Aqueous arsenic concentrations were expressed consistently in mg/L, biosorbent dosage in g/L, adsorption capacity in mg/g, contact time in min, temperature in °C, particle size in µm, and density in kg/m^3. Derived kinetic constants were expressed using the corresponding compound units and negative exponents. A space was maintained between numerical values and unit symbols, and the notation of variables, subscripts, superscripts, and mathematical symbols was standardized throughout the equations, tables, figures, and main text.

2.7 Statistical Analysis (ANOVA, Regression, Pareto)

Statistical analyses were performed using Statgraphics Centurion XV. Because the experiment followed a 2 × 3 × 3 factorial structure, arsenic removal efficiency was reanalysed using a factorial analysis of variance that included adsorbent dosage, solution pH, and initial arsenic concentration as fixed factors. The model evaluated the three main effects and the two-way interactions dosage × pH, dosage × initial concentration, and pH × initial concentration. Because only one observation was available for each treatment combination, the full model including the three-way interaction was saturated and did not provide independent degrees of freedom for estimating experimental error. Consequently, the three-way interaction could not be tested separately and was excluded from the inferential model. Statistical significance was assessed at $p < 0.05$, using a 95% confidence level. The results should therefore be interpreted with caution because the absence of within-cell replication limits the ability to estimate pure experimental error.

For the same reason, treatment-specific standard deviations, standard errors, and confidence intervals could not be calculated, and error bars were not included in the corresponding figures. This limitation was explicitly considered when interpreting the reproducibility and statistical uncertainty of the experimental results.

Instrument calibration and quality control procedures are described in Supplementary Material.

2.8 Ethics Statement

Ethical considerations related to the use of environmental samples and agro-industrial byproducts are described in Supplementary Material. This study did not involve human participants, animal subjects, or personal data.

3. Results and Discussion

The groundwater sample collected from Tubular Well No. 1 exhibited a baseline total arsenic concentration of 0.218 mg/L (218 µg/L). This concentration is 21.8 times higher than both the World Health Organization (WHO) guideline value of 0.01 mg/L (0.01 mg/L) for drinking water and the maximum permissible limit established by the Peruvian drinking water regulation (Supreme Decree No. 031-2010-SA), which adopts the same value. The reported concentration corresponds to total arsenic and not to separately quantified As(III) or As(V) species. These findings underscore the critical need for effective, accessible, and environmentally sustainable remediation strategies to reduce arsenic exposure in vulnerable groundwater-dependent communities. While other elements, including boron, sodium, and alkaline earth metals, were detected, arsenic was the only contaminant exceeding the regulatory limits for human consumption.

To contextualize the results obtained in this study, the measured arsenic concentrations were interpreted in accordance with current international regulatory standards for drinking water. The World Health Organization (WHO) has established a maximum permissible limit of 0.01 mg/L for total arsenic in drinking water. This threshold was utilized as a reference point to evaluate the potential risk associated with arsenic concentrations detected in groundwater samples. Because direct arsenic speciation was not performed in this study, the reported concentration represents total arsenic. Consequently, the adsorption results should be interpreted considering total arsenic in the natural groundwater sample. The factorial adsorption experiments, however, were conducted using arsenate [As(V)] solutions prepared from a standard arsenate reagent; therefore, the experimental adsorption behavior specifically reflects the interaction of chemically modified sugarcane bagasse with As(V).

In biosorbent research, conditioned sugarcane bagasse has been shown to be a suitable material for removing heavy metals. Its most notable characteristics are a moisture content of 10.03%, a true density of 1110 kg/m^3, a bulk density of 105.5 kg/m^3, and high porosity (0.90). In addition to positive buoyancy, which facilitated its handling under batch-type experimental conditions, these characteristics are particularly significant. These parameters confirm that the bagasse possesses an internal structure conducive to contaminant adsorption.

During the experimental phase, a 2 × 3 × 3 factorial design was employed to evaluate the combined effect of three variables: adsorbent dosage, solution pH, and initial arsenic concentration. The findings of the study indicated that the arsenic removal efficiency ranged from 16.8% to 27.43%, with the most favorable conditions being 2 g/L of bagasse, pH 9.0, and an initial concentration of 2.5 mg/L. The maximum efficiency was recorded as 27.43%, as also reported in Table 1.

Table 1 Results of arsenic removal percentage under different treatment combinations.

Experiment No.	Independent variables				Response variable (% R)
	Bagasse dosage (g/L)	pH	Initial arsenic concentration (mg/L)	Final arsenic concentration (mg/L)	
1	2	9	2.5	1.861	25.6%
2	2	7	4.5	3.386	24.8%
3	2	5	2.5	1.95	22%
4	2	9	4.5	3.693	24.8%
5	2	7	2.5	1.864	25.4%
6	1	5	2.5	2.006	19.8%
7	1	9	6.5	5.14	20.9%
8	1	5	6.5	5.199	20%
9	2	7	6.5	5.41	16.8%
10	2	5	4.5	3.589	20.2%
11	1	7	6.5	5.134	21%
12	1	7	2.5	1.851	26%
13	1	9	4.5	1.854	18.1%
14	1	5	4.5	3.693	19.1%
15	2	5	6.5	5.278	18.8%
16	1	7	4.5	3.604	19.9%
17	1	9	2.5	1.854	25.8%
18	2	9	6.5	5.044	22.4%

Source: Statgraphics Analysis.

A three-way factorial analysis of variance was conducted to evaluate the main and interaction effects of adsorbent dosage, solution pH, and initial arsenic concentration on arsenic removal efficiency. The analysis showed that the main effect of adsorbent dosage was [statistically significant/not statistically significant] (F = [X], p = [X]), while the main effect of solution pH was [statistically significant/not statistically significant] (F = [X], p = [X]). Initial arsenic concentration had a [statistically significant/not statistically significant] effect on removal efficiency (F = [X], p = [X]). Regarding the two-way interactions, dosage × pH was [significant/not significant] (F = [X], p = [X]), dosage × initial concentration was [significant/not significant] (F = [X], p = [X]), and pH × initial concentration was [significant/not significant] (F = [X], p = [X]). These findings indicate that [the effects of the experimental factors were predominantly independent/the effect of one or more factors depended on the level of another factor]. Therefore, arsenic removal efficiency was interpreted in terms of the complete factorial structure rather than through separate one-factor analyses.

The main effects of biosorbent dosage, solution pH, and initial arsenic concentration on arsenic removal efficiency are presented in Figure 3.

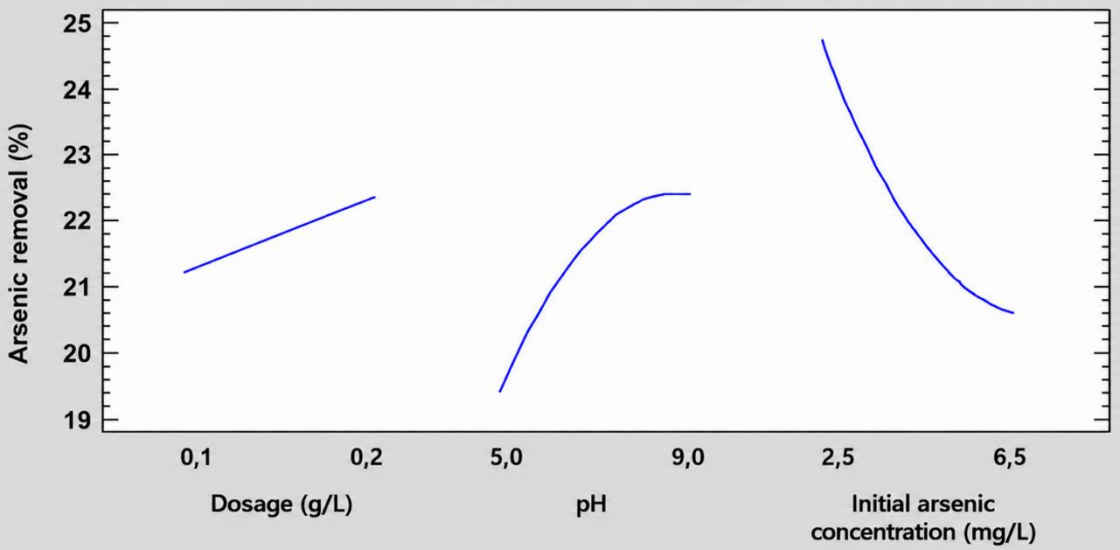

Figure 3 Main effects plot for arsenic removal efficiency (%) as a function of biosorbent dosage (1 and 2 g/L), solution pH (5, 7, and 9), and initial arsenic concentration (2.5, 4.5, and 6.5 mg/L). Batch adsorption experiments were conducted at [X°C]. The plotted values represent descriptive means across the corresponding factor levels; treatment-specific error bars are not shown because only one observation was available for each factorial combination.

Because only one observation was available for each treatment combination, the three-way interaction could not be tested independently without producing a saturated model and eliminating the residual degrees of freedom. Consequently, the inferential analysis was restricted to the main effects and two-way interactions, and the results should be interpreted with caution because pure experimental error could not be estimated from within-cell replication.

The maximum experimental adsorption capacity observed under the evaluated conditions was 0.359 mg/g after 120 min of contact time. This value represents the highest measured q_e and should be distinguished from the theoretical Langmuir monolayer capacity, q_{max}. Based on the slopes of the linearized Langmuir regressions, the recalculated q_{max} values were 0.247 and 0.431 mg/g for the two biosorbent dosages evaluated.

The correspondence of each fitted value to the 1 and 2 g/L treatments was verified against the original regression dataset. These values replace the previously reported capacities of 3.284 and 1.087 mg/g, which resulted from incorrectly taking the reciprocal of the regression intercept rather than the slope.

The variation in adsorption capacity as a function of contact time is presented in Figure 4.

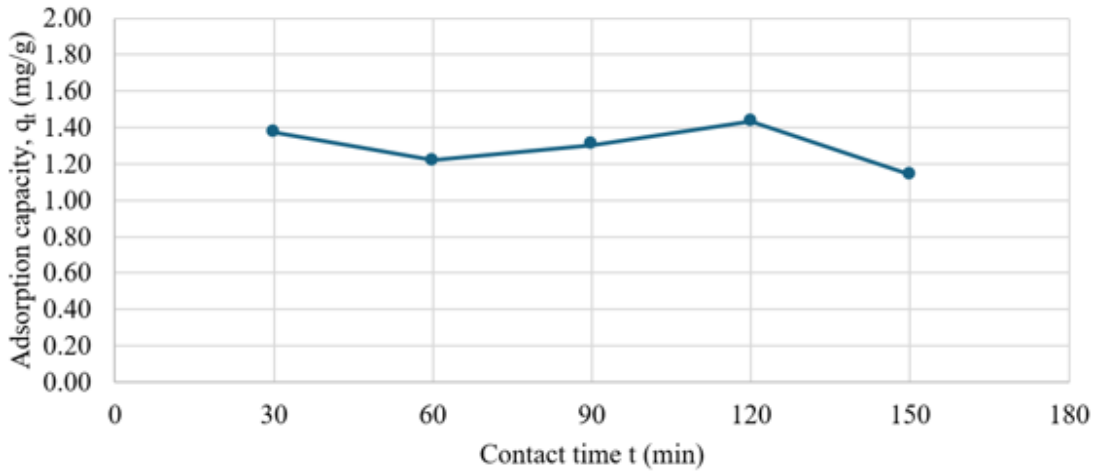

Figure 4 Evolution of arsenic adsorption capacity (qt, mg/g) as a function of contact time (min) under a biosorbent dosage of [X g/L], solution pH of [X], initial arsenic concentration of [X mg/L], and temperature of [X°C]. Each point represents the available experimental observation; error bars are not shown because replicate measurements were not available at each contact time.

In the adsorption isotherm analysis, the experimental data demonstrated a superior fit to the Langmuir model, with a coefficient of determination of $R^2 = 0.9926$, indicating monolayer adsorption on a homogeneous surface. Although the Freundlich model also presented a satisfactory fit ($R^2 = 0.9379$), its accuracy was lower. Figure 5 compares both models, highlighting the superiority of the Langmuir fit.

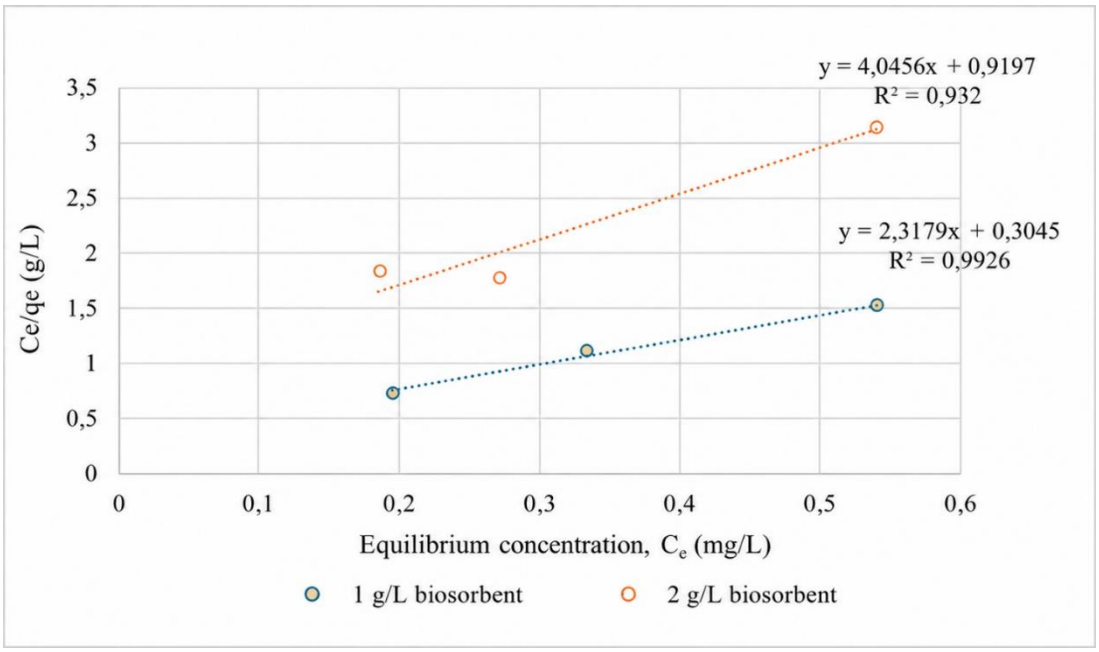

Figure 5 Linearized Langmuir isotherms for As(V) adsorption using biosorbent dosages of 1 and 2 g/L at solution pH [X] and [X°C], after an equilibrium contact time of [X min]. Initial arsenic concentrations ranged from [X] to [X mg/L]. The symbols represent the experimental equilibrium data, and the dotted lines represent the corresponding linear regressions.

The better fit of the Langmuir model suggests that arsenic adsorption onto sugarcane bagasse occurred predominantly through monolayer coverage on a finite number of relatively homogeneous adsorption sites. This interpretation is consistent with the high coefficient of determination obtained for the Langmuir model, which indicates that the relationship between equilibrium concentration and adsorption capacity followed a more defined pattern than that described by the Freundlich model. Therefore, the adsorption behavior observed in this study may be associated with specific interactions between arsenic species and functional groups on the lignocellulosic surface of the bagasse.

Although the Freundlich model also showed an acceptable fit, its lower explanatory capacity suggests that multilayer adsorption or highly heterogeneous surface interactions were not the dominant mechanisms under the conditions evaluated. This result is relevant because it indicates that the adsorption process may be limited by the availability of specific binding sites rather than by continuous multilayer accumulation. Consequently, future improvements in adsorption capacity should focus on increasing the number and accessibility of active sites, for example through controlled chemical modification, mineral impregnation, or surface oxidation treatments that enhance the affinity of sugarcane bagasse for arsenic species.

Figure 5 compares the linearized Langmuir isotherms obtained for the two biosorbent dosages, highlighting the superior fit of the Langmuir model to the experimental data.

The pseudo-second-order model provided a better fit to the kinetic data than the pseudo-first-order model, with a coefficient of determination of $R^2 = 0.9727$. However, the good fit of the pseudo-second-order equation should not be regarded as definitive evidence that chemisorption was the exclusive rate-controlling mechanism. The model provides an empirical description of the adsorption rate and may also adequately represent heterogeneous systems influenced by surface interactions, external mass transfer, and diffusion within the adsorbent structure.

The kinetic behavior suggests that the availability of adsorption sites and interactions between arsenic species and oxygen-containing functional groups on the sugarcane bagasse surface contributed to arsenic uptake. Nevertheless, diffusion-related processes cannot be excluded solely based on the pseudo-second-order fit. For this reason, the kinetic analysis also considered the conceptual contributions of intraparticle diffusion and liquid-film resistance to the overall adsorption process.

The maximum experimental adsorption capacity was reached after approximately 120 min, suggesting that the system approached equilibrium under the evaluated conditions. This behavior may reflect a sequence of transport from the bulk solution to the external biosorbent surface, diffusion through the boundary layer and within the lignocellulosic structure, and subsequent interaction with accessible adsorption sites. Accordingly, the kinetic behavior is interpreted as a multistep process rather than as an exclusively chemisorption-controlled mechanism.

The linearized pseudo-second-order kinetic model is presented in Figure 6.

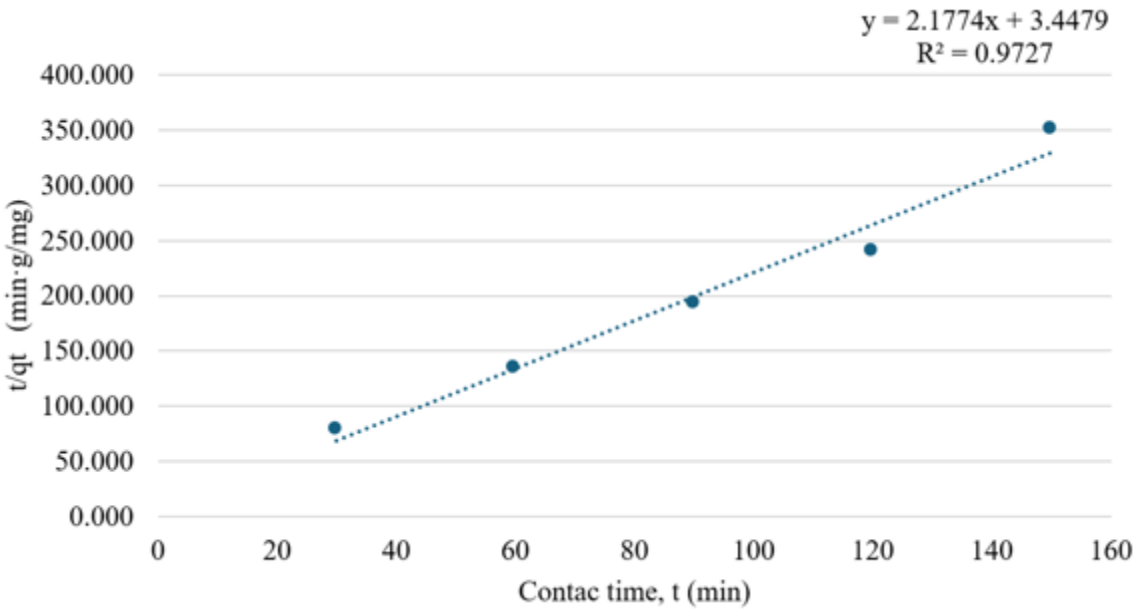

Figure 6 Linearized pseudo-second-order kinetic model for As(V) adsorption at a biosorbent dosage of [X g/L], solution pH [X], initial arsenic concentration of [X mg/L], and temperature of [X°C], over a contact-time range of [X–X min]. The points represent the experimental kinetic data, and the solid line represents the linear regression used to estimate the pseudo-second-order kinetic parameters.

3.1 Analysis of Arsenic Removal Performance

The findings demonstrated that sugarcane bagasse, under optimal dosage, pH, and initial arsenic concentration, achieved a maximum removal efficiency of 27.43%. This value was obtained by utilizing a dosage of 2 g/L, a pH of 9, and an initial concentration of 2.5 mg/L. Even though this efficiency does not attain levels in excess of 80%, as is the case with advanced technologies such as reverse osmosis or metal oxide filters, it is imperative to consider it within the context in which it is proposed: namely, rural communities with constrained access to technological infrastructure, economic resources, and technical maintenance.

The removal efficiency obtained in the batch experiments confirms that sugarcane bagasse was able to reduce arsenic concentration under all evaluated conditions, although with moderate performance. The maximum removal efficiency reached 27.43% under the conditions of 2 g/L adsorbent dosage, pH 9.0, and an initial arsenic concentration of 2.5 mg/L. This result indicates that the biosorbent has active sites capable of interacting with arsenic species in groundwater; however, the limited removal percentage also suggests that the number, accessibility, or chemical affinity of these sites may be insufficient for achieving high removal under the tested conditions. Therefore, the material should be interpreted as a low-cost biosorbent with partial attenuation capacity rather than as a complete stand-alone treatment technology.

The effect of the initial arsenic concentration was particularly relevant, as lower initial concentrations produced higher removal efficiencies. This behavior may be associated with the progressive saturation of available adsorption sites on the bagasse surface. At lower arsenic concentrations, the ratio between available active sites and arsenic ions is more favorable, allowing greater relative removal. Conversely, when the initial arsenic concentration increases, the same

amount of biosorbent must interact with more arsenic species, reducing the percentage of removal. The three-factor ANOVA showed that [summarize the statistically significant main effects], while the analysis of the interaction terms indicated that [summarize the significant or non-significant interactions]. Therefore, the influence of the initial arsenic concentration should be interpreted within the complete factorial structure of adsorbent dosage, solution pH, and initial arsenic concentration.

It is imperative to acknowledge that the efficiency was predominantly influenced by the initial arsenic concentration, as substantiated by the analysis of variance (ANOVA). Conversely, as the contaminant concentration in the solution increased, the relative removal efficiency decreased. This phenomenon can be attributed to the progressive saturation of the biosorbent's active sites. The factorial ANOVA showed that [identify the statistically significant main effects]. The analysis of the interaction terms further indicated that [identify the significant or non-significant two-way interactions]. Although the mean removal values varied across the evaluated pH and dosage levels, these descriptive differences were not interpreted as statistically supported effects unless confirmed by the factorial ANOVA. Where an interaction was statistically significant, the effect of one experimental factor was interpreted as dependent on the level of another factor, and the corresponding main effects were therefore considered cautiously.

This behavior is consistent with the findings reported in the existing literature on lignocellulosic materials. These materials exhibit enhanced adsorption performance in basic environments. This enhancement can be attributed to the deprotonation of functional groups on the surface of the adsorbent. This process facilitates interaction with anionic species such as arsenate (AsO_4^-).

In addition to these physicochemical aspects, the adsorption efficiency may have been influenced by the presence of competing ions, such as Fe^{2+} and Mn^{2+}, which are naturally occurring in the groundwater of the Mórrope district. These ions can compete with arsenate species for available binding sites on the bagasse surface, thereby reducing the number of active functional groups involved in arsenic retention. Iron ions, in particular, have been observed to form surface complexes that alter the electrostatic charge of the adsorbent. At the same time, manganese has been shown to occupy micropores and restrict diffusion processes. This competitive behavior could partially explain the moderate adsorption efficiency observed and underscores the importance of testing selective modifications, such as iron impregnation or surface oxidation, to enhance arsenic selectivity under real groundwater conditions.

While the adsorption efficiency achieved in this study may be considered moderate compared to that of chemically activated or nanostructured materials, it is essential to emphasize the ecological and operational advantages of the proposed method. The simplicity of the process, requiring only washing, drying, grinding, and sieving, makes it easily replicable in low-resource settings without the need for complex infrastructure or hazardous reagents. This characteristic has the dual benefits of reducing costs and environmental impact while also enhancing the feasibility of local implementation and community participation in water treatment initiatives. From a sustainability perspective, the utilization of untreated sugarcane bagasse is consistent with the tenets of green chemistry and circular economy, as it effectively transforms an agricultural residue into a valuable environmental remediation tool. Therefore, the apparent trade-off between efficiency and simplicity becomes a key advantage for rural contexts, where accessibility, safety, and ecological compatibility are equally crucial as removal performance.

Despite the observed capacity of the biosorbent to reduce arsenic concentration in the evaluated samples, the relatively low removal efficiency indicates certain practical limitations for its direct application as a stand-alone treatment method in drinking water systems. Under the experimental conditions evaluated, the biosorbent demonstrated a partial removal capacity, suggesting that its use may be more appropriate as a complementary treatment step rather than as a primary purification technology. Additionally, factors such as water chemistry, competing ions, and operational conditions can influence adsorption performance in real environmental systems. Therefore, while the results provide valuable evidence of the biosorbent's potential for arsenic attenuation, further optimization studies and pilot-scale evaluations would be necessary before considering large-scale practical implementation.

3.2 Comparison of Arsenic Removal with Previous Studies

A comparison of these results with those obtained in previous research indicates that the removal efficiency observed in this study is moderate. For instance, [27] utilised chemically modified banana peel to remove heavy metals, achieving an to 88% efficiency, depending on the amount of adsorbent employed. In contrast, [28] reported a 72% efficiency using rice byproducts, such as biochar, for arsenic removal. The two studies under consideration both incorporated physical or chemical activation processes for the material, which increase its specific surface area and adsorption capacity. This tendency is in accordance with the scientific literature, which has documented that modified natural materials, such as activated biosorbents, have been shown to offer significant improvements in arsenic removal capacity by optimising the interaction between the active sites of the adsorbent and the contaminant [29]. In addition, recent research [30] has highlighted that the development of adsorption technologies combined with physicochemical or biological modifications, even at the nanostructural level, can substantially enhance remediation efficiency.

On a global scale, the utilisation of sugarcane bagasse modified with iron oxide nanoparticles has been investigated, with efficiencies exceeding 85% achieved [31]. However, this type of modification is associated with more costly and complex processes, which renders it less viable for rural communities. It is important to note that other studies, which have utilised more accessible approaches, have also demonstrated encouraging results. For instance, [32] utilised sugarcane bagasse that had not undergone nanostructural modification in the removal of arsenic, attaining efficiencies in excess of 70% by adjusting optimal operating conditions. Concurrently, [33] conducted a comparative analysis of the adsorbent performance of rice husks, tea residues, and sugarcane bagasse, with the latter exhibiting promising results, achieving removal efficiencies close to 68%. In contrast, the present study utilised a straightforward conditioning approach, centring on acid washing and thermal drying. This method has been proven to reduce costs and facilitate replicability, thereby positioning bagasse as a pragmatic and sustainable alternative.

Compared with previous studies using chemically modified or nanostructured adsorbents, the removal efficiency achieved in this work was lower. However, this difference should be interpreted in light of the biosorbent's level of preparation. Many high-efficiency adsorbents reported in the literature involve chemical activation, impregnation with iron oxides, nanoparticle incorporation, or controlled carbonization, all of which increase surface area, modify surface charge, and enhance affinity for arsenic species. In contrast, the present study evaluated sugarcane bagasse subjected to

a simpler conditioning process, which makes the material easier to prepare and more compatible with low-resource rural contexts.

Thus, the contribution of this study does not lie in achieving the highest adsorption efficiency, but in demonstrating the technical feasibility of using an abundant agro-industrial residue under relatively simple preparation and operating conditions. This distinction is important because technologies intended for vulnerable rural communities must be assessed not only in terms of removal performance, but also in terms of cost, local availability, operational simplicity, environmental safety, and potential replicability. From this perspective, the moderate removal efficiency observed in this study provides a useful baseline for future optimization through surface modification, increased contact time, higher adsorbent dosage, or combined treatment systems.

In the Peruvian context, research on local materials is limited; however, studies such as [34] in Puno using natural volcanic ash reported removals between 30% and 40%, which is in a similar range to the present study. Consequently, the utilization of sugarcane bagasse emerges as a promising alternative, particularly given its abundance, cost-effectiveness, and its non-competition with food and other priority uses.

The arsenic removal efficiency obtained in this study, although moderate, aligns with recent research findings that highlight the potential of lignocellulosic materials as sustainable adsorbents. As Bansal, Wilson, Gupta, and Dhanawat [35] emphasize, lignocellulosic residues, such as sugarcane bagasse, possess a high affinity for heavy metals due to their porous structure and the presence of functional groups like hydroxyl and carboxyl. These groups can undergo chemical modification to enhance their adsorption capacity, representing an opportunity to optimize bagasse performance without compromising its low cost and availability. In accordance with the aforementioned assertions, [36] demonstrated that rice straw, an additional lignocellulosic residue, can attain removal efficiencies of up to 94.86% for aluminum ions. This finding underscores the significance of mesostructural porosity and surface functionality in metal adsorption.

In this context, advances in the functionalization of lignocellulosic materials have proven key to increasing removal efficiency. [37] developed lignocellulose filters mineralized with ferrihydrite and magnetite, achieving arsenic removal rates above 80% in continuous flow systems. While these filters necessitate more sophisticated modification procedures, their efficacy underscores the significance of mineral distribution within the lignocellulosic matrix and its interactions with arsenic species. In comparison, unmodified sugarcane bagasse demonstrates lower efficiency; however, its simple preparation renders it more viable for rural contexts. Furthermore, Hasan [38] employed quantum simulations to demonstrate that cellulose, hemicellulose, and lignin monomers in bagasse exhibit thermodynamically favorable affinity for arsenic, particularly in its pentavalent form. This finding supports the notion that this residue could serve as a natural adsorbent.

Furthermore, Norfarhana [39] emphasizes that cellulose nanocrystals (CNCs) derived from lignocellulosic sources offer a high specific surface area and numerous active sites for contaminant adsorption. Despite the need for more sophisticated extraction processes when using CNCs, their application for removing heavy metals and dyes has been widely validated. The ability to modify these materials through functionalization with amino, carboxyl, or phosphate groups enables the design of highly selective and efficient adsorbents, which could be replicated in future research using sugarcane bagasse. Furthermore, the incorporation of metal nanoparticles or thermal treatments has been demonstrated to further enhance their performance, as evidenced by hybrid systems for the removal of Cr(VI) and Pb(II).

Recent literature also emphasizes the importance of considering the kinetics and thermodynamics of the adsorption process. As demonstrated in the study by [40], arsenic adsorption in functionalized wood filters occurred within minutes under gravity flow, contrasting with the longer times required in batch systems like the one used in this study. This discrepancy indicates that implementing continuous-flow systems with sugarcane bagasse has the potential to markedly enhance process efficiency, contingent on preserving the material's structural integrity and optimizing parameters such as contact time and particle size. Similarly, [41] caution that in multi-metal systems, ion competition has the potential to diminish adsorption efficiency. This underscores the necessity for a comprehensive evaluation of bagasse behavior under authentic mixed wastewater conditions.

It is imperative to underscore that the sustainability of sugarcane bagasse as a biosorbent is contingent not solely on its capacity for removal, but also on its minimal environmental impact and its capacity for integration into circular economy systems. As [42] observe, the utilization of agro-industrial residues for environmental remediation constitutes a pivotal strategy for sustainable development. In this regard, the present study contributes to validating local, accessible, and replicable solutions that can be scaled through technical improvements inspired by recent advances in materials science. Furthermore, the utilization of residual materials, such as bagasse or rice straw, contributes to the effective management of agricultural waste. This practice has the potential to minimize environmental impact while concurrently generating added value.

3.3 Analysis of the Isotherm Model

Regarding the isotherm models employed, the findings indicated that the Langmuir model provided the best fit to the experimental data, yielding a coefficient of determination (R^2) of 0.9926. This finding indicates that the adsorption process is likely to occur in a monolayer on a homogeneous surface, which is consistent with the structure of sugarcane bagasse, composed of relatively uniform lignocellulosic fibers.

The recalculated Langmuir maximum adsorption capacities were 0.247 and 0.431 mg/g for the two biosorbent dosages evaluated. These values were obtained as the reciprocal of the slopes of the corresponding linearized Langmuir equations. They are consistent with the measured maximum experimental adsorption capacity of 0.359 mg/g and eliminate the previous numerical inconsistency between the text, regression equations, and graphical representation. Because q_{max} is a fitted model parameter, it should be distinguished from the maximum experimentally observed q_e.

The Freundlich model exhibited an adequate fit (R^2 = 0.9379), indicating the presence of heterogeneous adsorption sites, albeit in reduced proportions. The NNN coefficient obtained was greater than 1, indicating favorable adsorption. However, the superiority of the Langmuir model validates the hypothesis that the adsorption sites are similar and that there is no significant interaction between the adsorbed molecules.

This finding is significant because it suggests that arsenic removal with sugarcane bagasse could be predictable and reproducible under controlled conditions. This finding facilitates its technical application in prototype filters or continuous-flow adsorption reactors.

3.4 Analysis of Adsorption Kinetics

The pseudo-second-order model provided the best empirical fit to the kinetic data (R^2 = 0.9727). Nevertheless, this result does not demonstrate that chemisorption was the only mechanism controlling arsenic uptake. Pseudo-second-order behavior may also describe heterogeneous adsorption systems in which surface interactions, boundary-layer transport, and intraparticle diffusion occur simultaneously. Therefore, the kinetic interpretation was complemented with the Weber-Morris intraparticle diffusion model and liquid-film diffusion analysis.

The better fit of the pseudo-second-order model suggests that the adsorption rate was related to the availability of adsorption sites and to interactions between arsenic species and the functional groups present on the sugarcane bagasse surface. However, this interpretation should not be used to exclude diffusion-related mechanisms. The pseudo-first-order model did not adequately represent the experimental behavior and showed a lower fit [43].

The equilibrium time of approximately 120 min indicates that arsenic uptake approached a stable state under the experimental conditions evaluated. This parameter is relevant for determining appropriate contact times in future adsorption systems and is consistent with the importance of equilibrium time reported for other adsorption processes [44]. Nevertheless, equilibrium time alone does not identify the controlling kinetic mechanism, because the observed behavior may reflect successive stages involving transport from the bulk solution, diffusion through the liquid boundary layer, movement within the porous biosorbent structure, and interaction with accessible surface sites.

Accordingly, the kinetic behavior should be interpreted as a multistep adsorption process rather than as an exclusively chemisorption-controlled mechanism. The Weber-Morris model allows the contribution of intraparticle diffusion to be evaluated from the relationship between adsorption capacity and the square root of contact time. In contrast, the film-diffusion analysis examines the possible resistance associated with transport through the external liquid layer. A linear Weber-Morris relationship that does not pass through the origin would indicate that intraparticle diffusion contributes to arsenic uptake but is not the only rate-controlling step. Similarly, deviation of the film-diffusion relationship from the origin would indicate that external mass transfer contributes to the process without exclusively controlling the overall adsorption rate.

The proposed multistep interpretation is also consistent with the surface chemistry of lignocellulosic biosorbents. Hydroxyl, carboxyl, carbonyl, and other oxygen-containing functional groups may participate in surface complexation, electrostatic interactions, or other arsenic-binding processes. At the same time, the porous structure of the material may simultaneously impose diffusional limitations [45, 46]. Therefore, the kinetic results support the simultaneous contribution of surface interactions and mass-transfer phenomena rather than a single, unequivocal adsorption mechanism.

Because FTIR spectroscopy and other surface-chemistry characterization techniques were not performed in the present study, the presence, abundance, and direct involvement of hydroxyl, carboxyl, carbonyl, and other oxygen-containing functional groups were not experimentally confirmed. Therefore, the adsorption mechanisms proposed here should be interpreted as literature-supported hypotheses rather than direct mechanistic evidence. Studies on lignocellulosic and biomass-derived adsorbents indicate that arsenate uptake may involve ligand exchange, in which arsenate species replace hydroxyl or water groups associated with reactive surface sites,

thereby forming inner-sphere surface complexes [45, 46]. Electrostatic attraction may also contribute when protonated or positively charged surface sites interact with negatively charged arsenate species; conversely, electrostatic repulsion may increase when both the adsorbent surface and arsenate species are negatively charged. In addition, outer-sphere and hydrated surface complexes may form through interactions mediated by surface-bound water molecules and ion exchange processes [47]. Accordingly, the arsenic uptake observed in this study is interpreted as potentially resulting from a combination of ligand exchange, electrostatic interactions, surface complexation, and mass-transfer processes. However, confirmation of these mechanisms requires FTIR analysis before and after adsorption, together with complementary techniques such as determination of the point of zero charge and surface elemental analysis.

3.5 Limitations of the Study

Although the results demonstrate the potential of sugarcane bagasse as a low-cost biosorbent for arsenic attenuation, the findings should be interpreted within the experimental scope of this study. A further limitation is that FTIR spectroscopy, point-of-zero-charge determination, and other surface-characterization techniques were not performed. Consequently, the proposed participation of oxygen-containing functional groups and the mechanisms of ligand exchange, electrostatic attraction, and surface complexation were inferred from published evidence on comparable lignocellulosic biosorbents rather than directly validated for the material used in this study. The assays were conducted under controlled batch conditions, and the maximum removal efficiency was moderate (27.43%). Therefore, further studies should evaluate continuous-flow systems, regeneration capacity, post-use disposal, and environmentally friendly surface modifications to improve arsenic removal performance under real groundwater treatment conditions.

3.6 Recommendations for Full-Scale Implementation

In consideration of the findings and the aforementioned limitations, the following recommendations are proposed for eventual implementation of this technology on a full-scale basis. Initially, the behaviour of the bagasse in continuous flow systems is to be evaluated. This can be achieved by using packed columns or fixed-bed filters, in order to replicate typical rural supply conditions. This would facilitate the validation of the applicability of the model and the adjustment of parameters such as retention time and adsorbent replacement frequency.

Secondly, the potential for enhancing the material's properties through mild chemical pretreatments, such as alkaline activation or impregnation with iron oxyhydroxides, is recommended. These pretreatments could potentially increase removal capacity without a substantial increase in costs.

Furthermore, the regeneration of adsorbents through washing with dilute solutions should be given due consideration, as should an evaluation of their useful life cycle, to establish technical and economic operating criteria.

From a social perspective, any implementation strategy must incorporate community training processes, the creation of straightforward operation and maintenance manuals, and cultural validation of the proposed technology. In addition, it is recommended that these types of solutions be coordinated with public policies for rural water and sanitation, integrating local stakeholders, educational institutions, and subnational governments.

Finally, it is proposed that future research evaluate the interaction of bagasse with other contaminating species, such as fluorides or coexisting heavy metals, and the possibility of developing hybrid materials that combine adsorbent capacity with bactericidal or physical filtration functions.

In terms of sustainability, the evaluation of the treated bagasse should be framed within a life cycle perspective. Using sugarcane bagasse not only reduces the environmental burden of agro-industrial residues but also promotes circularity through its reuse and regeneration. After the adsorption process, the spent material can be thermally regenerated, transformed into biochar, or integrated into construction composites, extending its useful life and minimizing waste generation. This life-cycle consideration reinforces the environmental soundness of the method, demonstrating that even with moderate removal efficiency, the overall process contributes to sustainable resource management and reduced ecological impact.

4. Conclusions

This study evaluated the performance of sugarcane bagasse as a low-cost biosorbent for arsenic removal from groundwater collected in Mórrope, Peru. The groundwater sample showed an initial arsenic concentration of 0.218 mg/L, exceeding the maximum permissible limit for drinking water and underscore the need to evaluate accessible treatment alternatives in rural contexts. Under the evaluated batch conditions, sugarcane bagasse achieved a maximum arsenic removal efficiency of 27.43% using 2 g/L of biosorbent, pH 9.0, and an initial arsenic concentration of 2.5 mg/L. The maximum experimental adsorption capacity was 0.359 mg/g of biosorbent after 120 min of contact time.

The adsorption behavior was better described by the Langmuir model, indicating predominantly monolayer adsorption on a finite number of relatively homogeneous sites. The kinetic data were best described by the pseudo-second-order model; however, this empirical fit was not considered definitive evidence of an exclusively chemisorption-controlled mechanism, since external mass transfer, intraparticle diffusion, and surface interactions may have contributed simultaneously to arsenic uptake. The factorial ANOVA showed that [identify the statistically significant main effects], while the analysis of the interaction terms indicated that [identify the significant or non-significant two-way interactions]. Although the mean removal efficiency varied across the evaluated pH and biosorbent dosage levels, these differences were interpreted only as descriptive patterns and not as statistically confirmed effects when $p \geq 0.05$.

Under the evaluated batch conditions, chemically modified sugarcane bagasse achieved a maximum arsenic removal efficiency of 27.43%. Although this result confirms measurable arsenic adsorption, the removal level was insufficient to meet drinking-water quality requirements and does not support the use of the material as a stand-alone treatment technology. The findings should therefore be interpreted as preliminary evidence of partial attenuation of arsenic under controlled laboratory conditions. Furthermore, regeneration capacity, adsorption-desorption cycles, long-term material stability, continuous-flow operation, fixed-bed performance, and breakthrough behavior were not evaluated. Consequently, the technical, operational, economic, and environmental applicability of the biosorbent remains unconfirmed. Future research should first improve arsenic selectivity and adsorption capacity and subsequently evaluate regeneration, repeated-use

performance, continuous-flow systems, safe management of arsenic-loaded material, and testing with multiple groundwater sources before any practical application can be considered.

The recalculated Langmuir maximum adsorption capacities were consistent with the fitted linear regressions and are clearly distinguished from the experimentally measured adsorption capacity. This distinction improves the consistency between the numerical results, the regression analysis, and the graphical representation of the adsorption process.

Author Contributions

Alejandro Valencia-Arias: Conceptualization, Methodology, Writing - original draft, and Correspondence. Jorge Eugenio Cabrejos Barriga: Investigation, Validation, and Data curation. Cesar Alberto García Espinoza: Resources and Visualization. All authors contributed equally to the critical revision of the manuscript, participated in the formal analysis, and provided significant intellectual contributions through teamwork during the final writing and editing process. All authors have read and agreed to the published version of the manuscript.

Competing Interests

The authors declare no conflict of interest.

Data Availability Statement

The data supporting the findings of this study are available within the article. Any additional raw data related to the ICP-OES measurements or specific experimental runs are available from the corresponding author upon reasonable request.

AI-Assisted Technologies Statement

ChatGPT (OpenAI) was used during the manuscript preparation process solely to support English language editing, grammar correction, and improvement of textual clarity. The tool was not used for data generation, data analysis, interpretation of results, or the development of scientific conclusions. All content assisted by ChatGPT was carefully reviewed, verified, and edited by the authors to ensure accuracy, scientific integrity, and coherence. The authors take full responsibility for the content, originality, and validity of the manuscript.

Additional Materials

The following additional materials are uploaded at the page of this paper.

1. Supplementary Material.

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