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Sustainable reduction of sulfate contained in gypsum waste: perspectives and applications for agroforestry waste and sanitary sewage

Redução sustentável de sulfato contido em resíduos de gesso: perspectivas e aplicações para resíduos agroflorestais e esgoto sanitário

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ABSTRACT

This review article explores sustainable biotechnological strategies for converting sulfate compounds and lignocellulosic waste, focusing on using sulfate-reducing bacteria (SRB) and the valorization of agroforestry residues and sanitary sewage. SRB show potential in effluent treatment, mine drainage, and the removal of sulfate and heavy metals from wastewater, with their metabolic activity being influenced by factors such as pH, temperature, and chemical oxygen demand/sulfate ($COD/SO_4^{=}$) ratio. In the context of a sustainable bioeconomy, the challenge of converting lignocellulosic waste into value-added products is addressed through physical pretreatment techniques such as milling, extrusion, microwave irradiation, and ultrasound, which are efficient in valorizing waste from urban tree pruning. The article highlights the importance of bioreactors in transforming raw materials into desirable biochemical products, discussing different types of bioreactors, such as batch, continuous stirred tank, airlift, fluidized bed, upflow anaerobic sludge blanket (UASB), and bubble column, and their specific advantages and disadvantages. Sustainable sulfate reduction is the central focus, integrating the application of SRB and the conversion of lignocellulosic waste in a way that complements the objectives of the work and promotes a more cohesive flow in the summary. Thus, the interrelationship between effluent treatment strategies and waste valorization is emphasized from an environmental sustainability perspective, highlighting the relevance of this study in the broader context of a sustainable bioeconomy.

Keywords: sulfate reduction; SRB; effluent treatment; valorization of lignocellulosic waste; sustainable bioeconomy; waste pretreatment

RESUMO

Este artigo de revisão aborda estratégias biotecnológicas sustentáveis para a conversão de compostos de sulfato e resíduos lignocelulósicos, com foco na utilização de bactérias redutoras de sulfato (BRS) e na valorização de resíduos agroflorestais e esgoto sanitário. As BRS demonstram potencial no tratamento de efluentes, drenagem de minas e remoção de sulfato e metais pesados de águas residuais, sendo sua atividade metabólica influenciada por fatores como pH, temperatura e relação demanda química de oxigênio/sulfato — $DQO/SO_4^{=}$. No contexto de uma bioeconomia sustentável, o desafio de converter resíduos lignocelulósicos em produtos de valor agregado é abordado por meio de técnicas de pré-tratamento físico, como moagem, extrusão, irradiação por micro-ondas e ultrassom, eficientes na valorização de resíduos de poda de árvores urbanas. O artigo destaca a importância dos biorreatores na transformação de matérias-primas em produtos bioquímicos, discutindo diferentes tipos de biorreatores, como batelada, tanque agitado contínuo, *airlift*, leito fluidizado, reator anaeróbio de fluxo ascendente (UASB) e coluna de bolhas, e suas vantagens e desvantagens específicas. A redução sustentável do sulfato é o foco central, integrando a aplicação de BRS e a conversão de resíduos lignocelulósicos de maneira a complementar os objetivos do trabalho e promover um fluxo mais coeso no resumo. Assim, enfatiza-se a inter-relação entre as estratégias de tratamento de efluentes e a valorização de resíduos em uma perspectiva de sustentabilidade ambiental, destacando-se a relevância deste estudo no contexto mais amplo de uma bioeconomia sustentável.

Palavras-chave: redução de sulfato; BRS; tratamento de efluentes; valorização de resíduos lignocelulósicos; bioeconomia sustentável; pré-tratamento de resíduos.

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Introduction

Plaster gypsum, a semi-hydrated calcium sulfate obtained through dehydration of the gypsum mineral ($CaSO_4.2H_2O$), plays a vital role in the construction industry. Employed in various products such as ceiling tiles, partition blocks, and *drywall*, gypsum is integral to numerous construction applications (Guedri et al., 2023). However, construction, renovation, and demolition activities result in significant amounts of waste, known as construction and demolition waste (CDW), which includes, in addition to plaster, materials such as wood, concrete, and heavy metals.

The presence of gypsum in CDW brings environmental challenges due to its high content of sulfate and heavy metals, limiting its reuse and posing risks when discarded in landfills, such as the formation of biogenic sulfide (Camarini and Pinheiro, 2014; Kijjanapanich et al., 2014; Cordon et al., 2019). At the same time, the construction industry has been seeking technological solutions that align efficiency, economy, and sustainability, emphasizing recycling and reuse of CDW (Ghaffar et al., 2020).

Another relevant challenge is agroforestry waste, especially from tree pruning, which constitutes a significant by-product of agricultural and urban activities. These wastes, if not managed correctly, can contribute to environmental problems. Still, on the other hand, they offer opportunities for sustainable use, such as in producing renewable energy and improving soil quality (Picchio et al., 2023).

Sanitary sewage, a mixture of domestic and industrial wastewater, emerges as a crucial source of organic matter and nutrients and is another available waste. Proper sewage treatment is vital to public health and environmental sustainability, and the use of innovative technologies, such as sulfate-reducing bacteria (SRB), can transform this challenge into a valuable resource for a sustainable bioeconomy (Li et al., 2023).

Therefore, this study focuses on the sustainable treatment of gypsum waste, particularly those from SRB, and its interaction with agroforestry waste and sanitary sewage treatment. The research aims to contribute to knowledge about biological sulfate reduction. It highlights the importance of this topic in the broader context of waste management, as discussed by Zang et al. (2022) and other scholars in the field.

Development

Sulfate's environmental and industrial importance

Sulfate, the basic radical of sulfuric acid, is one of the most prevalent anions found in nature. It originates from groundwater from carbonate rocks composed of calcite, dolomite, and aragonite. The list should also include secondary minerals such as gypsum, pyrite, and, through the oxidation of ionic sulfides, metal compounds from acid mine drainage (AMD), as well as effluents from various industries, such as mining, livestock, processed foods, paper and cellulose, dyes, and detergents, among others (Kijjanapanich et al., 2014; Zhang et al., 2020a).

The largest consumer share of sulfur is in the agricultural fertilizer industry, which requires around 60% of global production (Alexander et al., 2023). Used as an essential nutrient for plants, most sulfates are used in the form of sulfuric acid to produce phosphoric acid; from this, phosphorus is another crucial nutritional element in the fertilization of crops. With the drop in sulfur emissions due to environmental restrictions, soils are depleted of this element and, therefore, need to be replaced (Wagenfeld et al., 2019). In the polymer industry, sulfates can also be applied as raw materials and as catalysts for synthesis reactions, such as vulcanization in manufacturing harder and more heat-resistant tires, according to Wagenfeld et al. (2019). Furthermore, producing batteries containing sulfur metals can increase their storage power at a lower cost, which is, for example, an essential factor for renewable energy storage.

Sulfate can cause pollution of surface and underground waters, acidification of soils, and corrosion and scale in pipes, structures, and equipment, resulting in delays in irrigation and water drainage systems (Brahmacharimayum et al., 2019). When in contact with animals, including humans, large intakes of sulfate alter methemoglobin and sulfhemoglobin levels, causing symptoms such as dehydration and diarrhea (Runtti et al., 2018). In animals living in fresh waters, sulfates can be lethal due to the breakdown of the osmotic balance, as the high concentration leads to water salinization.

Sulfate-reducing bacteria

General characteristics

SRB are prokaryotic microorganisms that play a crucial role in anaerobic environments (Kushkevych et al., 2021). These bacteria are characterized by their ability to use sulfate ($SO_4^{=}$) as an electron acceptor in their metabolism, converting it into hydrogen sulfide (H_2S). This process is at the heart of the carbon cycle and the production of sulfur, an essential element for various biological and industrial processes. In addition to their ecological function, SRB have significant applicability in biotechnology, especially in sulfate bioreduction in effluent treatments, mine drainage, and calcium sulfate compounds. Due to their metabolic versatility, SRB can utilize a diverse range of organic and inorganic substances for energy generation, making them valuable biological tools for the remediation of contaminated environments and sustainable industrial processes (Ayangbenro et al., 2018). The importance of SRB extends beyond their role in natural environments, contributing significantly to the development of clean and efficient technologies. This diverse group of obligate anaerobes, including both proteobacteria and Gram-positive bacteria, can adapt to extreme conditions, including the presence of oxygen and varying temperatures, from psychrophilic to thermophilic conditions.

Diversity and ecology of sulfate-reducing bacteria

SRB thrive in anoxic environments where organic materials and sulfates are abundant, playing an essential role in the biodegradation of organic matter. This group of bacteria exhibits remarkable metabolic diversity, allowing them to adapt to a wide range of environments and conditions (Michas et al., 2020). Some SRB species can survive even in the presence of oxygen, which significantly expands their ecological range. They are classified into different categories, including proteobacteria and Gram-positive bacteria. Furthermore, SRB include psychrophilic species, which reproduce at low temperatures, and extremophile species, adapted to extreme environments.

Mesophilic SRB, growing optimally at temperatures between 20 and 45°C, are found in a variety of environments, while thermophilic SRB, capable of surviving at temperatures above 70°C, are particularly notable in environments such as hydrothermal vents (Tang et al., 2009). This ecological diversity of SRB makes them essential components in many natural ecosystems, from freshwater and marine ecosystems to anaerobic soil areas and wetlands. The ability to utilize hydrogen and other sources of organic matter to obtain energy through oxidation is a key aspect of their ecological function, contributing significantly to global biogeochemical cycles, including the sulfur cycle.

Role of sulfate-reducing bacteria in reducing sulfates and producing H_2S

SRB, specialized microorganisms that use sulfate ($SO_4^=$) as an electron acceptor in their metabolism, play a vital role in reducing sulfates and producing H_2S. This action results in the generation of H_2S, a critical byproduct of various biological and industrial processes (Tian et al., 2017). This biochemical mechanism has significant implications, especially in environments where reduction of sulfur compounds is required. SRB are particularly important in environments such as freshwater and marine ecosystems, hydrothermal vents, anaerobic soil areas, and wetlands. They play a prominent role in using hydrogen from organic matter to obtain energy through oxidation, a process that is directly linked to sulfate reduction. Furthermore, these bacteria are essential in environmental applications such as wastewater treatment and heavy metal removal (Kijjanapanich et al., 2014).

As found by Liu et al. (2018), SRB activity is strongest at temperatures around 30°C, while it is weak at temperatures of 50°C. Low temperatures and low pH values can reduce the efficiency of sulfate reduction by SRB. $S^=$ has an inhibitory effect on the growth of SRB, and the inhibition increases with a higher $S^=$ concentration. Different chemical oxygen demand/sulfate ($COD/SO_4^=$) values affect the symbiotic environment between SRB and metagenes, leading to the growth of different dominant strains and indirectly affecting the efficiency of sulfate reduction. The most suitable $COD/SO_4^=$ ratio for desulfurization by SRB is theoretically from 0.5 to 1.5. Still, $SO_4^=$ cannot be effectively reduced to H_2S by SRB when the $COD/SO_4^=$ value is between 0.5 and 1.5 due to the lack of electron donors. The most appropriate $COD/SO_4^=$ value for good desulfurization efficiency is from 1.5 to 2.5.

In effluent treatment, SRB can be used to effectively remove sulfate and heavy metals, transforming them into less harmful and more manageable forms. This process contributes not only to water purification but also to mitigating the negative environmental impacts of industrial and urban effluents. The role of SRB in reducing sulfates and producing H_2S is also essential in industrial processes, such as in the production of fertilizers, rubber, and pigments, where the presence of sulfates can be problematic (Karnachuk et al., 2021).

Sulfate-reducing bacteria in Sulfidogenic Processes

SRB play a vital role in sulfidogenic processes, which are fundamental to the biogeochemical sulfur cycle. In these processes, SRB reduce sulfur compounds, particularly sulfate ($SO_4^=$), using it as an electron acceptor in their metabolism. This process produces H_2S, a key component in several environmental and industrial contexts. The ability of SRB to metabolize sulfur compounds and oxidize organic and inorganic carbon sources is crucial for the balance and maintenance of diverse ecosystems (Ranadev et al., 2023). They are found in a variety of environments, including freshwater and marine ecosystems, hydrothermal vents, anaerobic soil areas, and wetlands. In these locations, SRB use hydrogen from organic matter to obtain energy through oxidation, a process closely linked to sulfate reduction. In addition to their environmental role, SRB are also of great interest for biotechnological applications, especially in wastewater remediation and heavy metal removal. By reducing sulfate, they contribute to water purification, transforming potentially harmful compounds into more stable forms that are less harmful to the environment.

Another critical aspect of SRB metabolism is the utilization of electron donors such as short-chain fatty acids (e.g., lactate and acetate), long-chain acids, and aromatic compounds (Finke et al., 2007; Zhang et al., 2016; Dordević et al., 2020). This broad spectrum of usable substrates highlights the versatility and adaptability of SRB to different environmental conditions.

Use of sulfate-reducing bacteria in industrial effluent treatment

SRB play a fundamental role in treating industrial effluents, significantly mitigating sulfate emissions from activities such as the production of fertilizers, rubber, pigments, mining, and domestic sewage. These industrial processes often release large amounts of sulfate, which can cause water and soil contamination through leaching. In these contexts, SRB are a viable and environmentally sustainable alternative for treating effluents (Reis et al., 2022). They begin the transformation process by reducing sulfates, using cheap carbon sources as electron donors. This process not only helps to reduce the concentration of sulfate in effluents but also contributes to the generation of H_2S, which can be recovered and used in other applications.

The primary mechanism used by SRB in sulfate reduction involves the dissimilatory reduction of sulfate and the use of carbon sources as electron donors. This process is essential for the production of H_2S. It is exemplified by species such as *Desulfobacter* and *Desulfovibrio*, which are classified as sulfidogenic due to their ability to use sulfate as an energy source in reactions to produce new biomass (Zhang et al., 2016). In addition to their role in reducing sulfates and heavy metals, SRB are also employed as environmental markers for corrosion analysis, highlighting their versatility and broad spectrum of applications in industrial contexts (Asif et al., 2021).

Metabolism and diversity of sulfate-reducing bacteria

SRB have a unique and diverse metabolism, allowing them to play a significant role in the biogeochemical sulfur cycle and microbial desulfurization processes. These bacteria are capable of reducing the sulfate ion under anaerobic (or anoxic) conditions, producing sulfide and precipitating heavy metals, while also producing alkaline substances to improve pH. The diversity of SRB is remarkable, encompassing different species that can utilize a variety of electron donors, including sodium lactate, ethanol, and hydrogen. This metabolic diversity allows SRB to operate efficiently in a wide range of environments, contributing to the removal of sulfate ions and heavy metals in different contexts and industrial wastewater. Studies carried out by several researchers have shown the effectiveness of SRB in the synchronous removal of sulfate ions and heavy metals, achieving fixation rates of iron, copper, lead, and other heavy metals of up to 87–100%. Furthermore, SRB have been shown to be effective in removing Mn^{2+} and Pb^{2+} by up to 93 and 90%, respectively (Yuya et al., 2019).

The role of SRB in sulfidogenic processes is of particular ecological and biotechnological interest, given their ability to interact with other bacteria, including methanogenic bacteria. These interactions are influenced by environmental variables such as sulfate concentrations, carbon substrates, and COD to sulfate ratios. Furthermore, the operating mode of bioreactors significantly impacts microbial enrichment, based on the r/K selection theory. This theory describes strategists adapted to resource-rich environments (r) and those adapted to resource-limited environments (K), each with distinct growth characteristics and ecological niches (Guo et al., 2022).

Acid mine drainage treatment

SRB are crucial in treating AMD, one of the mining industry's most severe environmental challenges. AMD is characterized by wastewater with a generally acidic pH and rich in sulfate ions, iron, and toxic metal ions, such as Cu^{2+}, Zn^{2+}, and Pb^{2+}. The use of SRB in treating AMD is a promising biotechnological approach, offering advantages such as high efficiency, low energy consumption, and being environmentally friendly (Bayrakdar et al., 2009). SRB reduce the sulfate present in these waters, helping precipitate heavy metals and improving overall water quality. This treatment process involves adapting the environment to promote the growth and metabolic activity of SRB. This adaptation is essential, as treatment efficiency depends on specific environmental conditions, including the water's chemical composition and the microbial ecosystem's characteristics. In the uncontrolled release of AMD, sulfidogenic processes carried out by SRB are considered more effective due to advantages such as better thickening of the metallic sludge and lower solubility. To optimize treatment, it is often necessary to add a suitable carbon source to promote biological sulfate reduction (Nguyen et al., 2020).

Sulfate-reducing bacteria and operating conditions in bioreactors

The Erlenmeyer flask offers several advantages for microbial cultivation when used as a batch-scale bioreactor (Schirmer et al., 2022), as they are also easy to handle and allow adequate agitation of the culture medium. Although used on a small scale in laboratories, the cultivation principles and conditions can often be scaled up to larger bioreactors, allowing for a smooth transition from laboratory research to larger-scale processes. These bottles allow for easy monitoring of cultures, which is essential for microbial growth follow-up, metabolite production, and other relevant parameters. The process can occur with or without agitation and aeration through diffusion (shaker incubator with orbital shaking and heating). Dong et al. (2023) used Erlenmeyer flasks to monitor the growth of SRB. These bacteria exhibited an "S-"type growth curve, and their logarithmic growth phase was quantified throughout 14–86 h, demonstrating high activity and robust growth metabolism. For this, the ideal temperature range was 32–35°C, where their activity was the highest. As the concentration of $S^{=}$ in the culture system gradually increased, SRB activity was inhibited, possibly leading to cell death. SRB were shown to be most active in an environmental pH range of 7–8, although they could tolerate pH values in the range of 5–8. The relationship between COD and sulfate ($SO_4^{=}$) that most favored the growth of SRB was 2.

Upflow anaerobic sludge blanket (UASB) reactors can be used for laboratory-scale wastewater treatment as they are essential in treating sulfate-rich effluents. Bertolino et al. (2013) worked with biological sulfate reduction in a UASB under poor mixing conditions, obtaining results well below expectations. However, by improving the mixing conditions with biomass recirculation and increasing the upward flow velocity, the sulfate removal rate increased significantly, reaching 89% removal. This highlighted the importance of mixing conditions in the performance of this bioreactor for substrate degradation and sulfate reduction. Thus, the absence of defined guidelines for geometry design, material selection, construction, operating rules, and especially starting conditions significantly hampers researchers who wish to conduct treatability tests using laboratory-scale UASB reactors (Najib et al., 2017; Pererva et al., 2020). However, most studies in the literature do not provide details about these reactors' construction and operational conditions, making it difficult to replicate the experiments.

Kijjanapanich et al. (2014) investigated the biological removal of sulfate from leachate generated from CDW and evaluated the effect of bioreactor configuration on this process. These researchers used different bioreactor configurations, including an upflow bioreactor (UASB), an anaerobic gaslift membrane bioreactor (GLAM), and a downflow bioreactor (inverted fluidized bed-LFI). They monitored important parameters such as sulfate removal, sulfide production, alkalinity consumption, and H_2S formation. The study results showed that the three bioreactor configurations can be used to treat CDW leachate, achieving sulfate removal efficiency in the 75–85% range. In these systems, SRB used the sulfate present in the leachate. A high calcium concentration had a negative impact on the UASB granules, resulting in the precipitation of $CaCO_3$ on the surface of the granules. On the other hand, a calcium concentration of up to 1000 mg/L did not adversely affect the sulfate removal efficiency of the LFI and GLAM systems. The effluents from these bioprocesses still showed high concentrations of sulfide (except GLAM) and calcium, which need to be removed before reusing the water in the leaching process or before disposing it into the environment.

Sustainable sources of carbon and nutrients

The primary critical connections between sustainable carbon and nutrient sources and SRB include (Zhang et al., 2022): 1. SRB's need for sustainable carbon sources for nutrition and growth; 2. The importance of these sources in the sulfate reduction process, essential for SRB metabolism; 3.The role of SRB in the nutrient cycle, especially in the sulfur cycle; 4. The use of SRB in bioremediation, where sustainable carbon sources are fundamental; and 5. The contribution to environmental sustainability when using renewable resources. Based on these premises, these techniques suggest using agroforestry waste and gypsum as sources of carbon and nutrients for SRB. This not only efficiently treats waste but also contributes to the circular economy.

Challenges and opportunities in using sulfate-reducing bacteria

The use of SRB in biotechnological and environmental processes offers several opportunities but also faces significant challenges. These bacteria, essential for sulfate reduction and effluent treatment, play an important role in ecological balance and a sustainable bioeconomy (van den Brand, 2015). SRB are fundamental in treating effluents, especially in industrial contexts such as mining, where they help mitigate sulfate emissions and remove heavy metals. Its use aligns with global efforts to transition to a bioeconomy based on sustainable resources, reducing dependence on fossil resources and carbon dioxide emissions. SRB can convert waste, such as urban tree pruning, into valuable resources, optimizing the use of underutilized bioresources. Among the challenges, effective management of SRB requires specific conditions, such as maintaining an anaerobic environment and adjusting carbon and nutrient sources. Another challenge is that competition between SRB and other bacteria, such as methanogenic bacteria, in treatment systems can affect the efficiency of sulfate reduction and anaerobic digestion processes (Oliveira et al., 2021). Furthermore, factors such as temperature, pH, and the COD/$SO_4^{=}$ ratio can significantly influence SRB metabolic activity, requiring careful control to optimize the effectiveness of the treatment.

Studies have aimed to apply environmental technologies to obtain nutrients and energy sources from industrial waste, biological objects, and organic pollutants (Kanda et al., 2019). In recent years, there has been a tendency toward reducing the use of phosphate, potash, and nitrogen fertilizers, associated with decreased natural resources required to produce such fertilizers. The solution to this problem may be the use of organic waste that contains phosphorus (P), nitrogen (N), and potassium (K) (Xie et al., 2023). One of these wastes is sewage sludge. Sewage sludge contains, on average, 1–3% nitrogen, 1–5% phosphorus, and 0.2–0.7% potassium, therefore being an excellent source for the isolation or recovery of biogenic elements (Tao, 2019).

Pretreatment of lignocellulosic biomass

Several factors contribute to the resistance of lignocellulosic biomass (LB) to conversion into value-added products such as biofuels, chemicals, and materials. This recalcitrance is due to the presence of a crystalline structure of cellulose, the degree of lignification, and the structural heterogeneity and complexity of cell wall constituents (Baruah et al., 2018). The choice of a more suitable pretreatment technique depends on the type of LB used, as the composition of cellulose, hemicellulose, and lignin can vary between different lignocellulosic sources (Matheri et al., 2018; Siddique et al., 2023). In this work, preference was given to reviewing physical pretreatment methods due to such procedures' strong, environmentally friendly nature.

The physical pretreatment of LB, characteristic of agroforestry waste, comprises an essential preliminary step before other pretreatment methods (Galić et al., 2021). One of the objectives of this pretreatment is to reduce particle size, which results in increased surface area and a decrease in the degree of polymerization and crystallinity of the biomass. For example, milling reduces the crystallinity and particle size of LB. It can reduce particle size down to 0.2 mm. A study by Chang et al. (1997) revealed that biomass particles smaller than 0.4 mm do not have a notable effect on the hydrolysis yield. Extrusion is considered one of the most commonly used physical pretreatment techniques. This technique is based on the action of one or two screws that rotate in a tight cylinder, which is equipped with temperature control (Zhang et al., 2020b). The use of microwave irradiation as an unconventional heating method for the pretreatment of LB under an applied electromagnetic field. Ooshima et al. (1984) carried out the first microwave irradiation pretreatment study. Since then, this method has been considered convenient due to several advantages, including easy operation, energy efficiency, minimal formation of inhibitors, and high heating capacity in a short period of time (Camani et al., 2020).

The pretreatment of LB by ultrasound (US) is based on the principle of cavitation through ultrasonic radiation. Cavitation, or the formation of acoustic micro- and nanobubbles within the liquid, generates shear forces that break the complex network structure of the LB and promote the extraction of desired compounds, such as cellulose, hemicellulose, and lignin (Muthuvelu et al., 2019). The choice of solvents (water, dilute aqueous solutions of inorganic or alkaline acids, organic solvents, or ionic liquids) is crucial to determining the ideal conditions for US pretreatments (Suresh et al., 2020). Several factors influence US treatment, including US frequency, sonication duration, ultrasonic generator power, and temperature.

The LB pretreatment proposed in this review addresses physical methods due to its environmentally friendly nature. This pretreatment is essential before other methods, aiming to reduce the size of the biomass particles, increase the surface area, and reduce the degree of polymerization and crystallinity, as in the case of grinding. This is innovative because it addresses the resistance of LBs to conversion into value-added products due to their crystalline structure, degree of lignification, and complexity of cell wall constituents.

Conclusions

Understanding sulfate properties, exploring biological conversion strategies, and using agroforestry waste and sewage can play a fundamental role in promoting sustainable management practices for this compound, with positive impacts on the environment and human health.

SRB can utilize a wide variety of carbon sources in the form of organic or inorganic substances to generate energy. These bacteria play a significant role in several biotechnologies, including wastewater treatment, mine drainage, and sulfate and heavy metal removal from wastewater. However, SRB metabolic activity is sensitive to a series of environmental factors, such as pH, temperature, $COD/SO_4^{=}$ ratio, electron donors, oxidation-reduction potential, hydraulic retention time, and the presence of concomitant ions.

To promote SRB efficiency, optimizing environmental conditions, such as temperature and pH, for each species is vital. Furthermore, controlling the concentration of sulfide ions and maintaining the appropriate COD-to-sulfate ratio is crucial to ensure the effectiveness of sulfate reduction. Competition for substrates between SRB and methanogenic bacteria must also be considered in anaerobic digestion processes.

Another important point addressed in this study is the use of lignocellulosic waste in the transition to a sustainable bioeconomy. Pretreatment of these biomasses using physical techniques, such as grinding, extrusion, microwave irradiation, and US, can facilitate their conversion into value-added products. The choice of pretreatment technique must be guided by the biomass's characteristics and the process's economic objectives.

Understanding the properties of sulfate, the strategic use of SRB, and the valorization of agroforestry residues play a vital role in the search for more sustainable practices in managing this compound. Optimizing environmental conditions and pretreatment of LB are essential steps toward a more sustainable bioeconomy. Therefore, bioreactors play a fundamental role as essential tools for advances in biotechnology, enabling efficient and controlled biological and biochemical processes.

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Authors' contributions:

ARAÚJO, G.P.: conceptualization; methodology; investigation; writing – original draft. PAIVA, G.M.S.: conceptualization; methodology; investigation; writing – original draft. LINS, I.V.: conceptualization; methodology; investigation; writing – original draft. SANTOS, V.A.: conceptualization; methodology; investigation; writing – review and editing; project administration; funding acquisition. SANTOS, L.B.: validation; supervision. BENACHOUR, M.: validation; writing – review and editing; funding acquisition. CAVALCANTI, D.L.: validation; supervision.

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