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Article

Potentiality of alginate-yeast biosorbent for biogas purification

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Abstract: The paper discussed the current research on the applicability of biosorbents for the purification of biogas, particularly the decrease of H_2S by using encapsulated or embedded biological biomass. This study investigated the potential of alginate-yeast biosorbent (AlgY) for biogas purification, focusing on hydrogen sulfide (H_2S) removal. A biogas column test was conducted to compare the biosorption efficiency of AlgY and pure alginate beads. Using Response Surface Methodology (RSM), the effects of column length, acquisition time, and biosorbent type were evaluated for CH_4, CO_2, and H_2S removal. Results depicted significant H_2S reduction, with AlgY achieving a p-value of < 0.0001 and a high correlation coefficient ($R^2 = 0.9518$). The relatively high correlation coefficient (R^2) of the tested quadratic model of all the responses were recorded (R^2; 0.5560, 0.5048, and 0.9518 for CH_4, CO_2, and H_2S respectively). According to the studies' preliminary findings, the type of biosorbent has a significant role in determining the biosorption effectiveness. The ANOVA of model terms depicted a significant p-value ($p < 0.05$) indicated a potential alginate-yeast (AlgY) biosorbent for H_2S purification or reduction.

Keywords: biosorbent; yeast-alginate bead; biogas

1. Introduction

The article reported the previous and ongoing research works on biobased materials that are biofiller and biosorbent adaptable for pollutant reduction through the encapsulated microbial biomass and embedded yeast biomass respectively. The findings broaden the green process technology approaches and help to minimize the secondary pollution problems in addressing environmental sustainability. The other part of the article presented the findings of the biosorbent preliminary study synthesized from dry yeast and maize silage biomass.

Various materials including microalgal biomass olive pomace [1], and banana fiber [2] have been previously examined for this purpose. Ciapponi [3] investigated how renewable fillers influence the mechanical properties of plasticized gluten. The findings revealed that incorporating microalgal biomass, which resulted in a modest enhancement of surface sensitivity to water. However, despite this increase in surface sensitivity, the biomass contributed to a reduction in water absorption kinetics and were assessed for materials in the presence of different flexibilities.

Consequently, biomass that derived from microalgae emerges as a compelling and sustainable resource for developing gluten-based materials, particularly for enhancing mechanical properties without compromising thermal stability or water resistance. Current research predominantly focuses on the progression of Polymer

Matrix Composites (PMCs), which are strengthened with various fibers (both natural and synthetic) and supplemented with fillers (both organic and inorganic). This emphasis is due to the inherent in these composites is a wide range of characteristics and attributes [4,5].

The possibility of yeast (Saccharomyces cerevisiae) biomass was encapsulated or immobilized in the calcium alginates beads. The findings of calcium alginatere beads encapsulated with yeast biomass for hydrogen sulphides (H_2S) and carbon dioxide concentration are presented. As mentioned in other sources, the majority of yeasts exhibit robust growth within the pH range of 4.5 to 6.5. However, virtually all species demonstrate the capability to thrive in media with either more acidic or alkaline conditions. Saccharomyces cerevisiae for instance, the primary species employed in industrial bioethanol production achieves optimal growth under pH conditions ranging from 4.0 to 6.0 [6]. Fungi growth is regulated by various factors, among them signalling molecules like hydrogen sulphide (H_2S), traditionally considered a toxic gas devoid of physiological function. Enzymatically and endogenously produced in numerous species, H_2S acts as a gaseous signalling molecule, playing a crucial role in various essential biological functions. A surface, intersurface, metabolism reaction could be a possible mechanism which occurs during the treatment process [7]. The experimental design incorporated the use of Response Surface Methodology (RSM). RSM offers a structured statistical design methodology for investigating the collective impact of two or more variables employed in an experiment [8].

Drawn from enzymatic reactions, particularly those originating from in vivo CO_2 metabolic processes, this approach could offer a more efficient and environmentally friendly method for CO_2 conversion. This is attributed to its elevated stereospecificity and enantioselectivity [9]. In principle, the biomineralization processes can employ carbon dioxide (CO_2) to produce $CaCO_3$ particles, and this preparation is recognized as an environmentally conscious and eco-friendly method for carbon dioxide sequestration [10]. The CO_2 catalytic conversion into $CaCO_3$ particles using calcium alginate (CA) occurs through three distinct stages.

$$CO_2 + H_2O \leftrightarrow \text{CA } HCO^{-3} + H^+ \tag{1}$$

$$HCO^{-3} \rightarrow H^+ + CO_2^{-3} \tag{2}$$

$$Ca^{2+} + CO_2^{-3} \rightarrow CaCO_3 \tag{3}$$

Of the mentioned reactions, step (1) is the least rapid, signifying that it serves as the rate-limiting step. Of the mentioned reactions, step (1) is the least rapid, signifying that it serves as the rate-limiting step [11]. The core concept is that CA catalyzes the swift conversion of H_2O and CO_2 into H^+ and HCO_3^- ions initially. Following this, the HCO_3^- undergoes an easy transformation into CO_3^{2-}, subsequently reacting with the introduced Ca^{2+} to yield $CaCO_3$ [12]. Bioassimilation refers to the mechanism through which organisms assimilate specific elements, compounds, or particles from their surroundings, incorporating them into their own physiological structures. It holds a crucial function in diverse living systems, manifesting both advantageous and adverse impacts on species and ecosystems

[13,14]. Adsorption is defined as the alteration in the density of a molecule at the surface layer of a solid material in comparison to the bulk phase per unit surface area. The term sorption is a comprehensive expression encompassing both absorption and adsorption processes [15]. These terms are often confused. Absorption is the incorporation of a substance in one state into another of a different state (e.g., liquids being absorbed by a solid or gases), i.e., into a three-dimensional matrix [16]. Biosorption or bio-adsorption may be simply defined as the removal of substances from pollution matrix of phases by biological materials [17].

The precise binding mechanisms may range from physical, i.e., electrostatic interactions, van der Waals forces, hydrogen bond, to chemical binding, i.e., ionic and covalent. Some of the reported mechanisms include absorption, (surface) adsorption, ion exchange, binding or surface complexation, (surface) precipitation or microprecipitation, and mineral nucleation. Biosorption is a property of both living and dead organisms, and their components. While most biosorption research concerns metals and related substances, the term is now applied to particulates and all manner of organic substances as well. Practically, all biological material has an affinity for metal species [18]. However, the term "biosorption" refers to the passive or physicochemical attachment of a sorbate to a biosorbent, essentially the binding of a chemical species to biopolymers. The definition, thus, specifically excludes metabolic or active uptake by living, metabolizing cells. In the literature, the term "biosorbent" includes the usage of dead biomass such as fibres, peat, rice hulls, forest by-products, chitosan and agro-food wastes as well as living plants, fungi, algae (unicellular microalgae, cyanobacteria, multicellular macroalgae) and bacteria. Biosorbents represent cheap filter materials often with high affinity, capacity and selectivity, and they are abundant and already available in most places [19–21].

2. Materials and method

2.1. Experimental setup and preparation of yeast-alginate bead

The experiments were conducted in a controlled laboratory setting. The experimental setup of the biosorbent preparation and the biogas purification column test are illustrated in **Figures 1** and **2** respectively.

A calcium alginate bead and yeast-alginate beads/biosorbent were prepared as described by [22] with minor modification. Alginate solution was firstly performed by stirring sodium alginate (Fisher Scientific) in warm distilled water. Yeast-alginate beads were prepared by mixing Saccharomyces cerevisiae with sodium alginate, followed by crosslinking with $CaCl_2$. Crosslinking agents were selected based on their ability to enhance bead stability and biosorption capacity. The 3.5 g dried yeast, Saccharomyces cerevisiae was mixed with 8 g of sodium alginate and added to 400 mL warm (50–60 ℃) distilled water and stir on the heater-magnetic stirrer for 5–10 min to obtain a yeast-alginate slurry. Later the heater was switch off and the calcium alginate (control) and yeast alginate slurry were kept under gentle stirring until the mixtures are mixed completely. The immobilization of Saccharomyces cerevisiae biomass was carried out in a 1 L beaker containing 0.1 M $CaCl_2$ solution with the agitation speed of 450 rpm. The prepared slurries were added drop-wise in a $CaCl_2$ solution using an appropriate dropper manually. The bead size (3 ± 0.3 mm of diameter) formed was stirred in the $CaCl_2$ solution for 20 min at room temperature to allow complete gelation. The spherical beads were washed several times to eliminate the remaining $CaCl_2$.

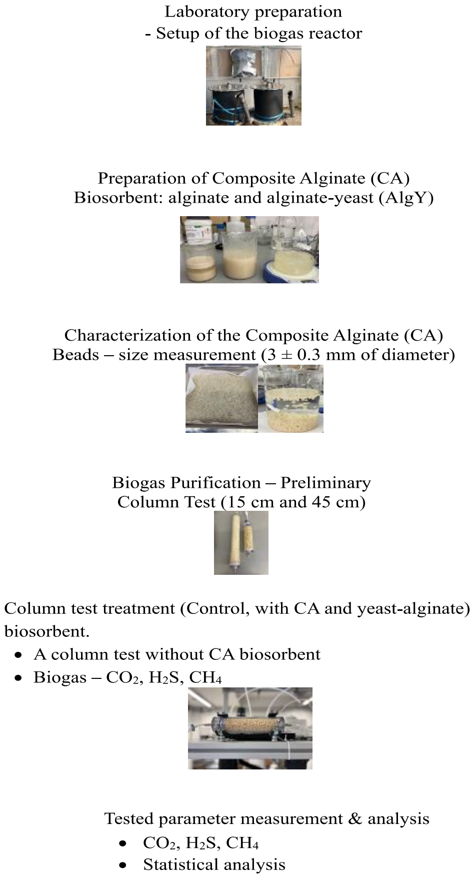


Figure 1. Illustrated the research flowchart of the study.

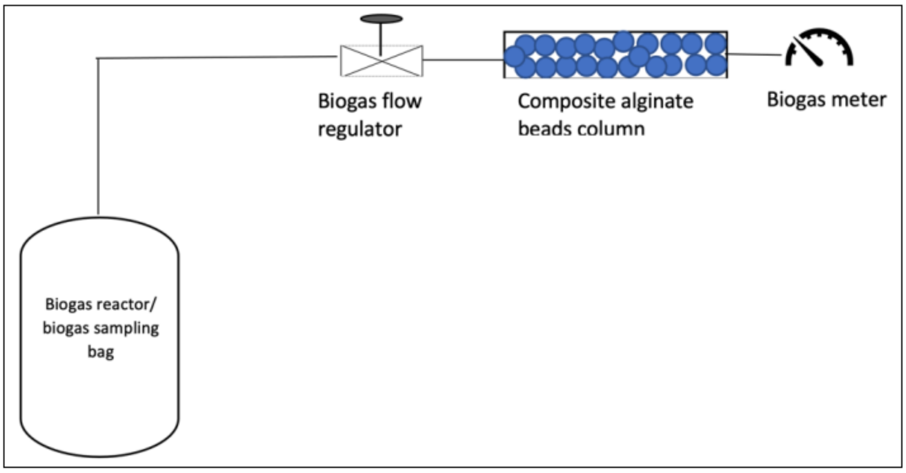


Figure 2. Schematic diagram of the biogas purification column test set up.

2.2. Design of experiment for biosorption test column

A Central Composite Design (CCD) was employed to investigate the effects of column length (15–45 cm), acquisition time (5–20 min), and biosorbent type (control and AlgY). **Table 1** summarized the CCD design of experiment depicted the three levels of the two numerical parameter variables, column length and acquisition time. Two different types of scrubbers/biosorbents that is sodium alginate and Alginate-yeast were selected as categorical variables. Statistical analyses using RSM were conducted with Design Expert software, evaluating model adequacy through *p*-values and R^2. The effects of these parameters on the ability of alginate-yeast encapsulation on the methane, carbon dioxide and hydrogen sulphide concentration of the maize silage anaerobic digester were discussed based on the response surface methodology (RSM) central composite design (CCD) and fitted model looking at the factor's interaction.

The experimental data were analyzed by RSM using the Design Expert 11.0 trial version (STAT-EASE Inc., Minneapolis, USA). The response surface was applied to describe the effects of different factors on yeast alginate biosorption. The 16 runs in a single block were designed to study the effects of three factors on three response variables. The Fisher's test (*F*-value) and *p*-value at 95% confident level was used to evaluate the statistically significant of the model equation and the model term. **Table 2** illustrated the summary of CCD experimental design selected for the experiment. The quality of the model fitted to the quadratic regression equation was determined via the coefficient of determination (R^2). The fitted equation was presented in contour and 3D plots to explain the relationship between the responses and the experimental levels. The results depicted the response variables of yeast alginate biosorbent with the control.

Table 1. Range of numerical and categorical variables used in the RSM central composite design.

Factors	**Unit**	**Type**	**Symbol codes**	**Coded levels**	
				−1	**1**
Length of column	cm	Numeric	X_1	15	45
Acquisition time	minute	Numeric	X_2	5	20
Type of biosorbent	-	Categoric	X_3	Control	AlgY

Table 2. Summary of RSM central composite design carried out in the study.

	Factor			**The experimental response data**		
Run	**Column length**	**Acquisition time**	**Type of biosorbent**	**CH_4**	**CO_2**	**H_2S**
	cm	**Minute**	**-**	**%**	**%**	**ppm**
1	30	5	Control			
2	45	5	AlgY			
3	15	12.5	AlgY			
4	30	5	AlgY			
5	45	20	AlgY			
6	45	12.5	AlgY			
7	15	12.5	Control			
8	30	20	Control			
9	45	12.5	Control			
10	15	20	Control			

Table 2. (*Continued*).

	Factor			**The experimental response data**		
Run	**Column length**	**Acquisition time**	**Type of biosorbent**	**CH_4**	**CO_2**	**H_2S**
	cm	**Minute**	**-**	**%**	**%**	**ppm**
11	15	20	AlgY			
12	45	5	Control			
13	15	5	Control			
14	45	20	Control			
15	30	20	AlgY			
16	15	5	AlgY			

3. Results

3.1. Performance of the preliminary study of the alginate biosorbent

The results of the preliminary study were depicted in **Tables 3** and **4** for the descriptive statistic of the biosorbent performance and the experimental response data (CH_4, CO_2, H_2S) towards the factors studied respectively. The results exhibited a promising reduction in H_2S concentrations for the alginate-yeast (AlgY) biosorbent. Alginate-yeast was observed to improve CH_4 purification compared to control of the overall experimental runs. Similar trend occurred in CO_2 concentrations reduction.

The Central Composite Design (CCD) of RSM was operated to analyse the three parameters; column length (X_1), acquisition time (X_2), and type of biosorbent (X_3) for biogas purification. The three independent factors were studied at two levels (−1, 1) as stated in **Table 1**. The CH_4, CO_2 and H_2S sorption efficiencies were noted as response values; Y_1, Y_2 and Y_3 respectively. Each experiment was the average of the triplicate. The 16 runs were randomly performed to analyse the process variable (**Table 2**). For Central Composite design, an appropriate fitted quadratic model was established to illustrate the effect of each factor and their quadratic interaction, which is determine in the following Equation (1).

$$Y = a_0 + \sum_{i=1}^{n} a_i + \sum_{i=1}^{n} a_{ii} X_i^2 + \sum_{i=1} \sum_{j=1}^{n} a_{ij} X_i X_j + Ɛ \qquad (1)$$

where Y is the predicted response, x_i and x_j are independent factors, a_0 is intercept, ai is linear coefficient, a_{ii} is quadratic coefficient, and a_{ij} is interaction coefficient, respectively whilst, Ɛ is the random error or uncertainties between predicted values. **Table 3** is the presented results (descriptive statistic) of the study outcomes/findings. It is not a data from any references.

Table 3. A descriptive statistic of the biosorption performance.

Response	**Unit**	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**
CH_4	%	51.3157	64.1025	55.9976	2.3037
CO_2	%	29.8682	40.9008	38.0869	3.0642
H_2S	ppm	0.0000	0.0045	0.0019	0.0014

Table 4. Experimental response data of the CCD.

	Factor			**The experimental response data**		
Run	**Column length**	**Acquisition time**	**Type of biosorbent**	**CH_4**	**CO_2**	**H_2S**
	cm	Minute	-	%	%	ppm
1	30	5	Control	54.0805	41.1018	0.0031
2	45	5	AlgY	55.7741	40.3798	0.0000
3	15	12.5	AlgY	55.6839	33.0012	0.0000
4	30	5	AlgY	61.5787	27.3164	0.0000
5	45	20	AlgY	57.7003	38.2491	0.0000
6	45	12.5	AlgY	56.1015	39.9914	0.0000
7	15	12.5	Control	51.5724	31.4814	0.0024
8	30	20	Control	55.3274	40.1459	0.0037
9	45	12.5	Control	55.3609	40.1261	0.0034
10	15	20	Control	55.7223	39.7518	0.0042
11	15	20	AlgY	55.9157	39.2705	0.0007
12	45	5	Control	55.5904	39.9123	0.0037
13	15	5	Control	55.9445	39.7251	0.0045
14	45	20	Control	55.1074	40.1981	0.0032
15	30	20	AlgY	57.3776	38.0508	0.0000
16	15	5	AlgY	56.0173	36.0266	0.0015

Response surface methodology (RSM) analysis of central composite design and model fitting were depicted in **Tables 5** and **6**. The experimental data, methane (CH_4), carbon dioxide (CO_2) and hydrogen sulphide (H_2S) in **Table 4** were utilized to develop the statistical model using multiple regression analysis fitting the quadratic model according to Equation (1). **Table 5** exhibited the fitted quadratic equation a significant model representing the relationships between H_2S and column length (X_1), acquisition time (X_2) and type of biosorbent (X_3). Among the tested model term H_2S depicted a significant response of the quadratic model with the *p*-value of 0.0006 suggesting a H_2S purification was significant at 95% (**Table 6**) in comparison to CH_4 and CO_2. Alginate-yeast (AlgY) recorded a *p*-value of < 0.0001 indicates the type of biosorbent is an importance factor which determine the biosorption efficiency. The relatively high correlation coefficient (R^2) of the tested quadratic model of all the responses were as follows; $R^2 = 0.5560$, 0.5048 and 0.9518 for CH_4, CO_2 and H_2S.

The Predicted R^2 of 0.7493 for H_2S is in reasonable agreement with the Adjusted R^2 of 0.8968 and the difference is less than 0.2. Whereby adequate precision measures the signal to noise ratio. A ratio greater than four (4) is desirable thus the ratio of 10.817 for H_2S indicates an adequate signal and suggested the model can be used to navigate the design space compared to CH_4 and CO_2 with recorded ratio of 3.6937 and 3.1679 respectively. Therefore, the H_2S results of the statistical analyses indicate the high adequacy of the tested quadratic model to represent the desired response of the parameter variables in this preliminary study of the biogas purification through biosorption with alginate-yeast biosorbent.

Table 5. The fitted model equations showing coefficients in terms of coded factors.

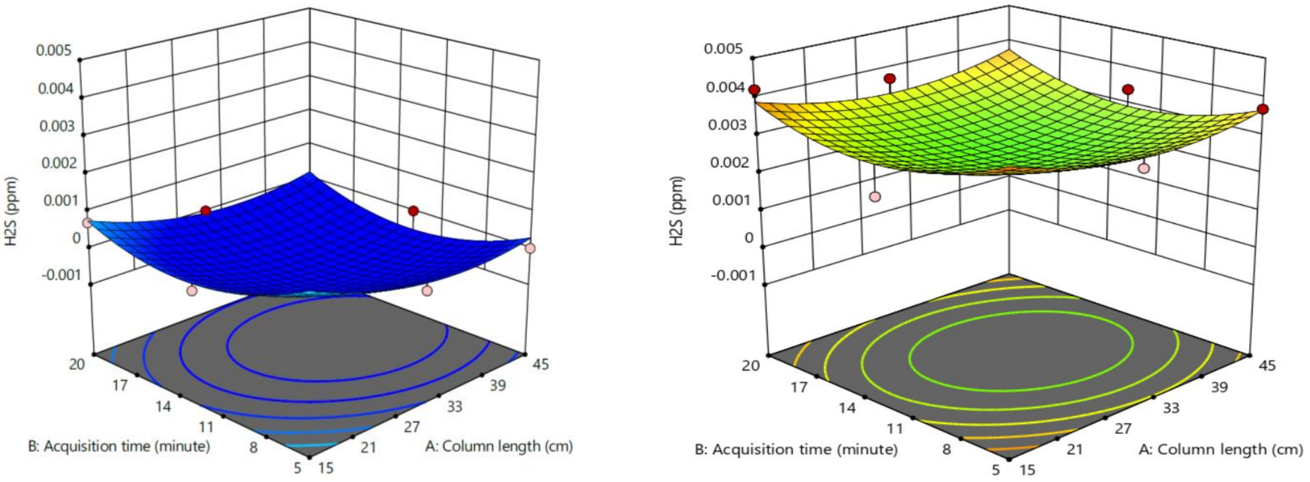
Response	**Fitted model equation**
H_2S	$0.0009 - 0.0002X_1 - 0.0001X_2 - 0.0016X_3 + 0.0001X_1X_2 - 0.0001X_1X_3 - 0.0001X_2X_3 + 0.0005X_1^2 + 0.0008X_2^2$

Table 6. Summary of analysis of variance (ANOVA) of fitted model.

Factors	**Responses fitted to the quadratic model.**					
	CH_4 (%)		**CO_2 (%)**		**H_2S (ppm)**	
	F-value	*p*-value	*F*-value	*p*-value	*F*-value	*p*-value
Model	1.10	0.4586	0.8919	0.5666	17.30	0.0006^{Sig}
X_1-Column length	0.4902	0.5064	1.97	0.2030	2.30	0.1732
X_2-Acquisition time	0.0723	0.7958	0.6445	0.4485	0.2555	0.6288
X_3-Type of biosorbent	4.90	0.0625	1.56	0.2512	129.53	$< 0.0001^{\text{Sig}}$
X_1X_2	0.1006	0.7604	0.2015	0.6671	0.1380	0.7213
X_1X_3	0.0159	0.9032	0.0056	0.9425	0.5007	0.5021
X_2X_3	0.1828	0.6818	0.8011	0.4005	0.0920	0.7705
X_1^2	0.8611	0.3843	1.06	0.3383	2.25	0.1770
X_2^2	1.15	0.3198	1.52	0.2578	4.91	0.0623
R^2	0.5560		0.5048		0.9518	
Adjusted R^2	0.0485		−0.0612		0.8968	
Predicted R^2	−1.3315		−1.3656		0.7493	
Adequate Precision	3.6937		3.1679		10.8167	

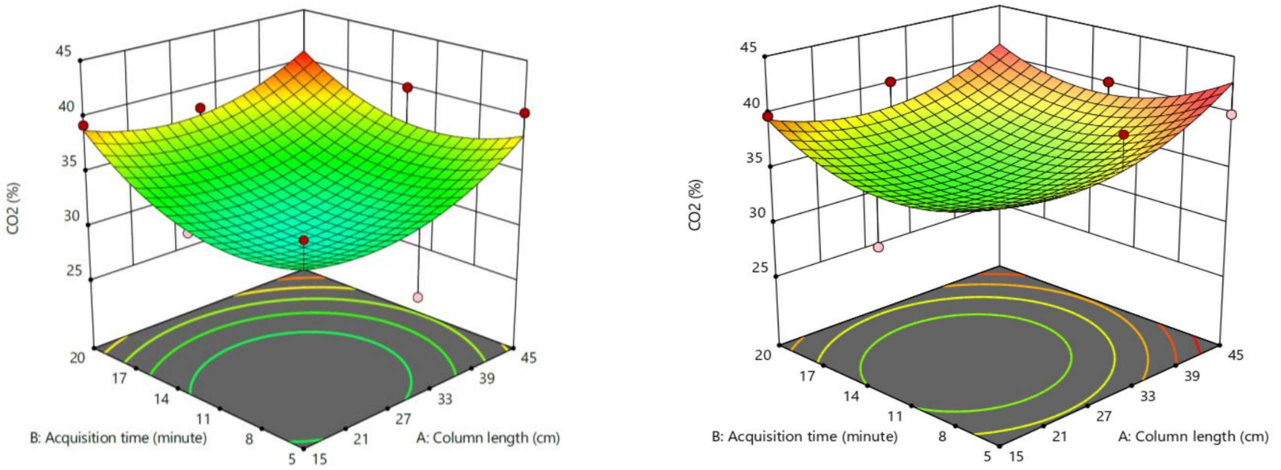
3.2. Effect of parameter variables on bead stability

The fitted quadratic equation of CH_4, CO_2 and H_2S were presented in response 3D surface plots as illustrated in **Figures 3a,b**, **Figures 4a,b** and **Figures 5a**,**b** to describe the relationship between the factors studied (column length, acquisition time, type of biosorbent). The interaction between sodium alginate and $CaCl_2$ solution, lead to a Ca^{2+} substitution with the Na^+ ions and later cross-interact with carboxylate groups (-COO-) and negatively polar groups (-OH) [23]. The process progressively integrates *Saccharomyces cerevisiae* into the gel formation. In addition, the yeast biomass was successfully encapsulated within the gel beads. The study applied the best reported conditions of sodium alginate and $CaCl_2$ concentrations, gelation time and mixing rpm from the published literature to obtain the beads stability. **Figures 3a,b** to **Figures 5a**,**b** illustrated the hydrogen sulphide, carbon dioxide and methane biosorption contour profile at different acquisition time and column length of alginate-yeast (AlgY) and Control respectively.



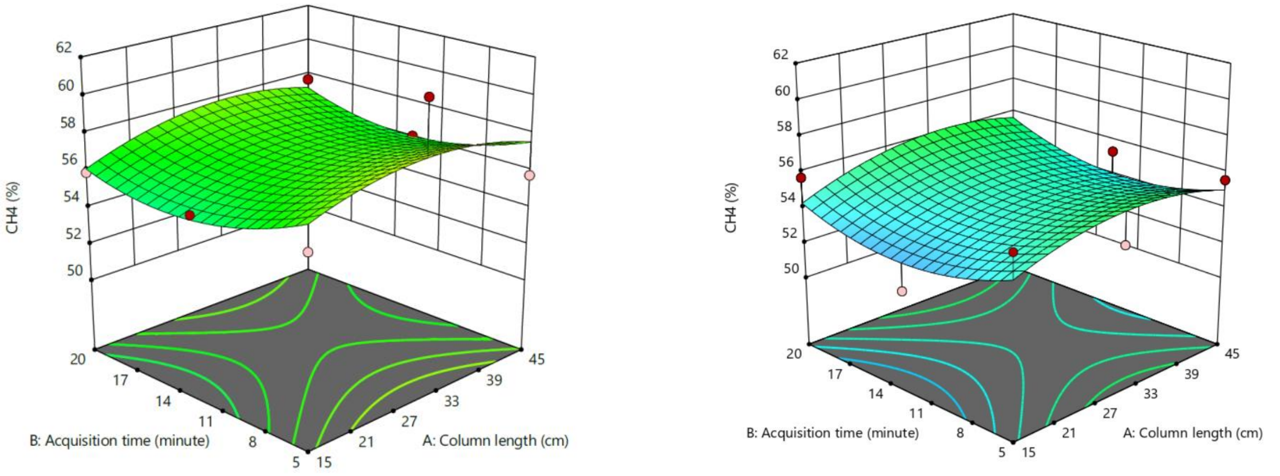
(a) (b)

Figure 3. Hydrogen sulphide biosorption contour profile at different acquisition time and column length. **(a)** AlgY; **(b)** control.



(a) (b)

Figure 4. Carbon dioxide biosorption contour profile at different acquisition time and column length. **(a)** AlgY; **(b)** control.



(a) (b)

Figure 5. Methane biosorption contour profile at different acquisition time and column length. **(a)** AlgY; **(b)** control.

The results exhibited the good absorption for H_2S compared to CO_2 and CH_4 with the encapsulated yeast beads as biosorbent. In addition, the effect of acquisition time and length of column insignificantly affected the biosorption and recommended further experiment should be incorporated the concentration of the encapsulated yeast biomass to correlate growth profile of the *Saccharomyces cerevisiae* during the biogas purification. The ANOVA of model terms in **Table 6** indicated only the factor of type of biosorbent represented a significant term ($p < 0.05$), suggesting the type of biosorbent variables of alginate bead could be considered to have a primary influence on gas biosorption. Varying a $CaCl_2$ and sodium alginate concentration will be added in the future work for cell encapsulation stability and efficiency.

4. Discussion

Alginate is presently employed across numerous industrial sectors, spanning biotechnology, bioengineering, biomedicine, clinical applications, pharmaceuticals, chemicals, textiles, packaging, construction, food and beverage production, aquaculture, dentistry, paper manufacturing, arts and crafts, as well as leisure activities [24]. Despite great potential in various applications, alginate exhibits some limitations especially when exposed to the physiological environment in sustaining the structure stability. As reported by [25] to address this issue, various materials have been introduced into the alginate structure, resulting in the formation of robust composite materials. For example, incorporating adhesive peptides, natural polymers, or synthetic polymers into alginate moieties yields an enhanced composite material. This material not only exhibits superior mechanical properties compared to native alginate but also offers additional healing capabilities and facilitates improved tissue regeneration for instance in medical applications and the food industry.

The reported findings additionally suggests that the carboxylic groups present on the surface of TEMPO-oxidized nanocellulose (TOCN) may contribute to the formation of the structure of alginate-based films. The enhanced insolubility and mechanical strength, coupled with the decreased water vapour permeability of the crosslinked films, could significantly broaden the utilization of polysaccharides in diverse applications, particularly in food packaging [26]. Cross-linking also significantly enhances mechanical properties, along with the use of suitable plasticizers, which enhance film flexibility and broaden their potential applications [27,28]. A notable feature of alginates is their ability to interact with multivalent metal cations, particularly calcium ions, which create linkages between MM and GG blocks of the polymer, resulting in a three-dimensional network [29–31].

The prevalent approach for removing hydrogen sulfide and carbon dioxide from gas entails subjecting natural gas to an alkaline solution. One widely recognized approach for hydrogen sulfide removal relies on the reaction between hydrogen sulfide and iron oxide, wherein the gas is directed through a bed of wood chips infused with iron oxide. Solid sorbents utilized in fixed bed reactors for H_2S capture can operate through two distinct mechanisms that is physisorption which weak bonds form between H_2S and the substrate. Chemisorption involves chemical bonds between the adsorbate and the substrate [32]. Biosorbents, originating from sustainable sources like plant-based materials, animal waste, and marine biomass, can be conveniently tailored to enhance their adsorption capacity. This adaptability makes them exceptionally effective in tackling a wide range of pollutants [33,34]. Several studies have reported the biosorption efficiency of colour chemicals in textile wastewater using bacterial biomass [35]. The ability of bacterial biomass to adhere to dye particles is due to the presence of hydroxyl, carboxyl, amino, and phosphate groups within the peptidoglycan layer of the cell wall. As biosorption is a metabolically self-sufficient process, microbial cell growth does not necessitate additional nutrients. Utilizing a straightforward entrapment technique, Saccharomyces pastorianus, a representative yeast strain, was immobilized and subsequently microencapsulated in alginate for the purpose of eliminating cationic dye [36].

Numerous research groups have focused on employing the most prevalent biopolymers to adsorb hazardous heavy metal ions and other noxious pollutants. In recent studies, it has been found that the most effective polymers for adsorption are not cellulose or starch, but rather chitin, algae, and their primary derivatives, chitosan and alginate [37]. Among these polymers, alginate has garnered interest for its environmentally friendly nature and cost-effectiveness. Derived from brown algae, alginate can be readily shaped into beads or biofilm through uncomplicated immersion in a crosslinking agent, such as multi-valent cations. Typically, the process of alginate encapsulation includes forming spherical beads by introducing an alginate solution into a solution containing a crosslinking agent [38]. While alginate encapsulation offers numerous advantages, it has not been applied as an encapsulation polymer for dry yeast clay, specifically Saccharomyces cerevisiae, in the context of atmospheric pollutant adsorption.

Encapsulated cells experience restrained replication, enhancing their ability to convert substrate into product more efficiently compared to planktonic cells. This limited replication also contributes to their increased stress resistance [39]. Typically, encapsulated cells demonstrate higher product yields than planktonic cells, as they direct less substrate toward the generation of new biomass [40]. This efficiency enables them to process feedstock more effectively. Additionally, alginate beads exhibit good reusability, maintaining their performance even after undergoing five rounds of simple sorption–desorption procedures.

Biosorption of alginate derived from brown algae widely employed for heavy metals removal in polluted water. The sodium alginate biosorbent possess high affinity through gelation [41] and rich in functional groups like carboxyl and hydroxyl, can effectively crosslink with cations [42]. The carboxyl group’s negative nature allows for electrostatic adsorption with heavy metal ions, leading to chelation simultaneously [43]. In other reported study Ca-alginate beads was addressed to portray a biodegradable property. They exhibit significant efficacy in removing uranium and thorium ions with high capacity, presenting a promising alternative for the biosorption of radionuclides from waste streams [44]. Thus, the efficacy of the biopolymers has yet to be explored to achieve sufficient selectivity for toxic gases abatement and gas purification.

The limitation on using calcium alginate matrices for encapsulating cells in wastewater pollution abatement may stem from the existence of elevated concentrations of dissolved monovalent cations (mainly Na^+, K^+, and Mg^{2+}) in high-salt effluents. These cations have the potential to displace divalent cations, ultimately causing the degradation of the polymer matrix structure [45]. Typically, the formation of a three-dimensional polymer network is facilitated by the ionic interaction between alginate chains and calcium ions [46]. Strategies such as modification, immobilization, or encapsulation using various organic or inorganic materials could enhance the selectivity and stability of Ca-alginate beads. These microorganisms exhibit remarkable pollutant uptake capabilities, can self-regenerate, and incur minimal operational costs. Moreover, Versatility in utilizing a diverse range of carbon or nitrogen sources is evident in both pure and mixed bacterial cultures [47]. Finally, this study demonstrated the potential application of the dual function of biological biomass (i) biofilter and (ii) biosorbent incorporated with natural polymers suggestting a viable green material for pollution abatement that is able to minimize the carbon footprint. The possible mechanism of the AlgY absorbent in reducing the H_2S concentration is through the alteration of H_2S biogas to act as a signaling molecule. The signalling molecule promotes the growth of yeast. Gu et al. [48] reported the effect of the phenotypic or transcriptomic alternations on the fungal growth enhancement by H_2S is exhibited in the intracellular association of H_2S in their findings.

5. Conclusion

This research employs RSM to assess alginate-yeast (AlgY) performance under varying experimental conditions, bridging existing gaps in biosorption efficiency studies. The overall preliminary findings of AlgY as a biosorbent for biogas reduction especially for H_2S, reveal a positive potential application and can be explored further. The significance of the screening model of AlgY biosorbent depicted the type of biosorbent variables of alginate bead influence the biogas sorption. The results exhibited the potential of AlgY for biogas purification, achieving significant H_2S removal ($R^2 = 0.9518$, $p < 0.0001$). Hydrogen sulfide (H_2S) is a common contaminant in biogas that poses environmental and operational challenges. Biosorbents such as alginate-yeast (AlgY) have gained attention due to their biodegradability, cost-effectiveness, and potential for gas purification however this preliminary work can be further explored to determine the compositions of the spent AlgY biosorbent. The spent AlgY biosorbent composition analyses will lead to the understanding of the H_2S reduction mechanism as well as CO_2 and CH_4 responses. AlgY offers a potentially sustainable alternative to traditional chemical-based methods and, open path for the physico-chemical and biological-based reaction mechanisms. The preliminary findings of the study are unable to explain the reduction mechanism of the tested gaseous which reflected the high removal efficiencies reported for H_2S. It is best to run the Langmuir and Freundlich isotherms study to estimate the adsorption capacity of the AlgY biosorbent. Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) can be used to further visualize any changes in the internal and surface structure of the AlgY biosorbent.

6. Recommendation

Varying a $CaCl_2$ and sodium alginate concentration can be considered in future work for cell encapsulation stability and efficiency. This can be entailed and explored in (i) optimizing $CaCl_2$ and sodium alginate concentrations to improve biosorption, (ii) exploring alternative crosslinking agents like iron and (iii) evaluating the economic feasibility of scaling up AlgY biosorbents.

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References

1. Boudria A, Hammoui Y, Adjeroud N, et al. Effect of filler load and high-energy ball milling process on properties of plasticized wheat gluten/olive pomace biocomposite. Advanced Powder Technology. 2018; 29(5): 1230-1238. doi: 10.1016/j.apt.2018.02.015
2. Nataraj D, Sakkara S, HN M, et al. Properties and applications of citric acid crosslinked banana fibre-wheat gluten films. Industrial Crops and Products. 2018; 124: 265-272. doi: 10.1016/j.indcrop.2018.07.076
3. Ciapponi R, Turri S, Levi M. Mechanical Reinforcement by Microalgal Biofiller in Novel Thermoplastic Biocompounds from Plasticized Gluten. Materials. 2019; 12(9): 1476. doi: 10.3390/ma12091476
4. Madhu P, Sanjay MR, Senthamaraikannan P, et al. A review on synthesis and characterization of commercially available natural fibers: Part-I. Journal of Natural Fibers. 2018; 16(8): 1132-1144. doi: 10.1080/15440478.2018.1453433
5. Rohan T, Tushar B, G T M. Review of natural fiber composites. IOP Conference Series: Materials Science and Engineering. 2018; 314: 012020. doi: 10.1088/1757-899x/314/1/012020
6. Wu Y, Li B, Miao B, et al. Saccharomyces cerevisiae employs complex regulation strategies to tolerate low pH stress during ethanol production. Microbial Cell Factories. 2022; 21(1). doi: 10.1186/s12934-022-01974-3
7. Gu Z, Sun Y, Wu F, et al. Mechanism of Growth Regulation of Yeast Involving Hydrogen Sulfide From S-Propargyl-Cysteine Catalyzed by Cystathionine-γ-Lyase. Frontiers in Microbiology. 2021; 12. doi: 10.3389/fmicb.2021.679563
8. Baş D, Boyacı İH. Modeling and optimization I: Usability of response surface methodology. Journal of Food Engineering. 2007; 78(3): 836-845. doi: 10.1016/j.jfoodeng.2005.11.024
9. Bierbaumer S, Nattermann M, Schulz L, et al. Enzymatic Conversion of CO2: From Natural to Artificial Utilization. Chemical Reviews. 2023; 123(9): 5702-5754. doi: 10.1021/acs.chemrev.2c00581
10. Zhang H, Zhang T, Zang J, et al. Construction of alginate beads for efficient conversion of CO2 into vaterite CaCO3 particles. Food Hydrocolloids. 2022; 130: 107693. doi: 10.1016/j.foodhyd.2022.107693
11. Wu S, Chen J, Ma L, et al. Design of carbonic anhydrase with improved thermostability for CO2 capture via molecular simulations. Journal of CO2 Utilization. 2020; 38: 141-147. doi: 10.1016/j.jcou.2020.01.017
12. Qian C, Ren X, Rui Y, et al. Characteristics of bio-CaCO3 from microbial bio-mineralization with different bacteria species. Biochemical Engineering Journal. 2021; 176: 108180. doi: 10.1016/j.bej.2021.108180
13. Nikolaivits E, Pantelic B, Azeem M, et al. Progressing Plastics Circularity: A Review of Mechano-Biocatalytic Approaches for Waste Plastic (Re)valorization. Frontiers in Bioengineering and Biotechnology. 2021; 9. doi: 10.3389/fbioe.2021.696040
14. El-Sherif DM, Eloffy MG, Elmesery A, et al. Environmental risk, toxicity, and biodegradation of polyethylene: a review. Environmental Science and Pollution Research. 2022; 29(54): 81166-81182. doi: 10.1007/s11356-022-23382-1

15. Crini G, Lichtfouse E, Wilson LD, et al. Conventional and non-conventional adsorbents for wastewater treatment. Environmental Chemistry Letters. 2018; 17(1): 195-213. doi: 10.1007/s10311-018-0786-8
16. Gadd GM. Biosorption: critical review of scientific rationale, environmental importance and significance for pollution treatment. Journal of Chemical Technology & Biotechnology. 2008; 84(1): 13-28. doi: 10.1002/jctb.1999
17. Vijayaraghavan K, Balasubramanian R. Is biosorption suitable for decontamination of metal-bearing wastewaters? A critical review on the state-of-the-art of biosorption processes and future directions. Journal of Environmental Management. 2015; 160: 283-296. doi: 10.1016/j.jenvman.2015.06.030
18. Aksu Z. Application of biosorption for the removal of organic pollutants: a review. Process Biochemistry. 2005; 40(3-4): 997-1026. doi: 10.1016/j.procbio.2004.04.008
19. Lim AP, Aris AZ. A review on economically adsorbents on heavy metals removal in water and wastewater. Reviews in Environmental Science and Bio/Technology. 2013; 13(2): 163-181. doi: 10.1007/s11157-013-9330-2
20. Ong ST, Keng PS, Lee SL, et al. Low Cost Adsorbents for Sustainable Dye Containing-Wastewater Treatment. Asian Journal of Chemistry. 2014; 26(7): 1873-1881. doi: 10.14233/ajchem.2014.15653
21. Gupta VK, Nayak A, Agarwal S. Bioadsorbents for remediation of heavy metals: Current status and their future prospects. Environmental Engineering Research. 2015; 20(1): 1-18. doi: 10.4491/eer.2015.018
22. Soo CL, Chen CA, Bojo O, et al. Feasibility of Marine Microalgae Immobilization in Alginate Bead for Marine Water Treatment: Bead Stability, Cell Growth, and Ammonia Removal. International Journal of Polymer Science. 2017; 2017: 1-7. doi: 10.1155/2017/6951212
23. Touloupakis E, Rontogiannis G, Silva Benavides AM, et al. Hydrogen production by immobilized Synechocystis sp. PCC 6803. International Journal of Hydrogen Energy. 2016; 41(34): 15181-15186. doi: 10.1016/j.ijhydene.2016.07.075
24. Hurtado A, Aljabali AAA, Mishra V, et al. Alginate: Enhancement Strategies for Advanced Applications. International Journal of Molecular Sciences. 2022; 23(9): 4486. doi: 10.3390/ijms23094486
25. Ahmad Raus R, Wan Nawawi WMF, Nasaruddin RR. Alginate and alginate composites for biomedical applications. Asian Journal of Pharmaceutical Sciences. 2021; 16(3): 280-306. doi: 10.1016/j.ajps.2020.10.001
26. Xiao J, Zhao K, Tian X, et al. Impact of calcium-carboxylate interactions in cellulose nanofiber reinforced alginate based film with triple-decker-like structure. LWT. 2021; 151: 112197. doi: 10.1016/j.lwt.2021.112197
27. Russo R, Malinconico M, Santagata G. Effect of Cross-Linking with Calcium Ions on the Physical Properties of Alginate Films. Biomacromolecules. 2007; 8(10): 3193-3197. doi: 10.1021/bm700565h
28. Zhao Y, Qiu J, Xu J, et al. Effects of crosslinking modes on the film forming properties of kelp mulching films. Algal Research. 2017; 26: 74-83. doi: 10.1016/j.algal.2017.07.006
29. Li D, Wei Z, Xue C. Alginate-based delivery systems for food bioactive ingredients: An overview of recent advances and future trends. Comprehensive Reviews in Food Science and Food Safety. 2021; 20(6): 5345-5369. doi: 10.1111/1541-4337.12840
30. Girón-Hernández J, Gentile P, Benlloch-Tinoco M. Impact of heterogeneously crosslinked calcium alginate networks on the encapsulation of β-carotene-loaded beads. Carbohydrate Polymers. 2021; 271: 118429. doi: 10.1016/j.carbpol.2021.118429
31. Senturk Parreidt T, Müller K, Schmid M. Alginate-Based Edible Films and Coatings for Food Packaging Applications. Foods. 2018; 7(10): 170. doi: 10.3390/foods7100170
32. Georgiadis A, Charisiou N, Goula M. Removal of Hydrogen Sulfide From Various Industrial Gases: A Review of The Most Promising Adsorbing Materials. Catalysts. 2020; 10(5): 521. doi: 10.3390/catal10050521
33. Crini G, Torri G, Lichtfouse E, et al. Dye removal by biosorption using cross-linked chitosan-based hydrogels. Environmental Chemistry Letters. 2019; 17(4): 1645-1666. doi: 10.1007/s10311-019-00903-y
34. Osman AI, Farrell C, Al-Muhtaseb AH, et al. The production and application of carbon nanomaterials from high alkali silicate herbaceous biomass. Scientific Reports. 2020; 10(1). doi: 10.1038/s41598-020-59481-7
35. Ellafi A, Dali A, Mnif S, et al. Microbial Enzymatic Degradation, Spectral Analysis and Phytotoxicity Assessment of Congo Red Removal By Bacillus spp. Catalysis Letters. 2023; 153(12): 3620-3633. doi: 10.1007/s10562-023-04272-8
36. Blaga AC, Zaharia C, Suteu D. Polysaccharides as Support for Microbial Biomass-Based Adsorbents with Applications in Removal of Heavy Metals and Dyes. Polymers. 2021; 13(17): 2893. doi: 10.3390/polym13172893
37. Benettayeb A, Ghosh S, Usman M, et al. Some Well-Known Alginate and Chitosan Modifications Used in Adsorption: A Review. Water. 2022; 14(9): 1353. doi: 10.3390/w14091353
38. He Y, Zhang N, Gong Q, et al. Alginate/graphene oxide fibers with enhanced mechanical strength prepared by wet spinning.

Carbohydrate Polymers. 2012; 88(3): 1100-1108. doi: 10.1016/j.carbpol.2012.01.071

39. Gulli J, Yunker P, Rosenzweig F. Matrices (re)loaded: Durability, viability, and fermentative capacity of yeast encapsulated in beads of different composition during long-term fed-batch culture. Biotechnology Progress. 2019; 36(1). doi: 10.1002/btpr.2925
40. Moreno-García J, García-Martínez T, Mauricio JC, et al. Yeast Immobilization Systems for Alcoholic Wine Fermentations: Actual Trends and Future Perspectives. Frontiers in Microbiology. 2018; 9. doi: 10.3389/fmicb.2018.00241
41. Gao X, Guo C, Hao J, et al. Adsorption of heavy metal ions by sodium alginate based adsorbent-a review and new perspectives. International Journal of Biological Macromolecules. 2020; 164: 4423-4434. doi: 10.1016/j.ijbiomac.2020.09.046
42. Feng Y, Wang Y, Wang Y, et al. In-situ gelation of sodium alginate supported on melamine sponge for efficient removal of copper ions. Journal of Colloid and Interface Science. 2018; 512: 7-13. doi: 10.1016/j.jcis.2017.10.036
43. Rusu L, Suceveanu EM, Blaga AC, et al. Insights into Recent Advances of Biomaterials Based on Microbial Biomass and Natural Polymers for Sustainable Removal of Pharmaceuticals Residues. Polymers. 2023; 15(13): 2923. doi: 10.3390/polym15132923
44. Kumar M, Seth A, Singh AK, et al. Remediation strategies for heavy metals contaminated ecosystem: A review. Environmental and Sustainability Indicators. 2021; 12: 100155. doi: 10.1016/j.indic.2021.100155
45. Voo WP, Ravindra P, Tey BT, et al. Comparison of alginate and pectin based beads for production of poultry probiotic cells. Journal of Bioscience and Bioengineering. 2011; 111(3): 294-299. doi: 10.1016/j.jbiosc.2010.11.010
46. Klokk TI, Melvik JE. Controlling the size of alginate gel beads by use of a high electrostatic potential. Journal of Microencapsulation. 2002; 19(4): 415-424. doi: 10.1080/02652040210144234
47. Shabir M, Yasin M, Hussain M, et al. A review on recent advances in the treatment of dye-polluted wastewater. Journal of Industrial and Engineering Chemistry. 2022; 112: 1-19. doi: 10.1016/j.jiec.2022.05.013
48. Gu Z, Sun Y, Wu F, et al. Corrigendum: Mechanism of Growth Regulation of Yeast Involving Hydrogen Sulfide From S-Propargyl-Cysteine Catalyzed by Cystathionine-γ-Lyase. Frontiers in Microbiology. 2021; 12. doi: 10.3389/fmicb.2021.761240