

## Investigating the Biosorption Potential of *Ulva intestinalis* Linnaeus for Efficient Removal of Phenol from Aqueous Solutions

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### ABSTRACT

Phenol and its substitutes are among the hazardous organic pollutants that are frequently released by different industries. The maximum amount of total phenols that can be released into aquatic habitats is 15ppm, as determined by environmental standards. For this reason, it is crucial to develop effective methods for removing phenolic chemicals from wastewater. This work explores the possibility of using the green macroalga *Ulva intestinalis* Linnaeus 1753 as a biosorbent to extract phenol from aqueous solutions. The study investigated the biosorption ability of macroalgal biomass concerning multiple parameters, such as the starting pH of the solution, the concentration of phenol, the duration of contact, and the biosorption dose. The Langmuir adsorption isotherm was determined to be the most appropriate model among the others to describe how green macroalga biosorbs phenol. Regarding phenol biosorption kinetics, a pseudo-second-order model characterized the process on green macroalgal biomass. The maximum capacity for phenol uptake per gram of green macroalga was determined to be 211mg, highlighting the significant potential of this biosorbent for phenol removal. This study emphasizes the promising role of *Ulva intestinalis* Linnaeus as an effective biosorbent for the elimination of phenol from aqueous solutions, contributing to the development of sustainable and efficient wastewater treatment strategies.

### INTRODUCTION

The escalating importance of preserving and enhancing water quality is steadily gaining recognition due to its essential role in sustaining life. Water resources face contamination from a myriad of sources (Hanafy *et al.*, 2021; Younis *et al.*, 2023). The rapid advancements in technology on a global scale in recent times have resulted in significant adverse effects on the natural environment, particularly the contamination resulting from intensified industrialization, agricultural practices, global environmental transformations, and various human activities. A crucial aspect of this pollution involves the transportation of toxic organic pollutants and heavy metals between soil and water,

resulting in high levels of these pollutants. This phenomenon has been extensively studied and documented by several scholars, such as **Younis (2020)**, **Soliman *et al.* (2020)**, **El-Naggar *et al.* (2021)** and **Taher *et al.* (2023)**, highlighting the severity of the issue and its implications for the environmental sustainability.

The existence of organic contaminants, particularly phenolic compounds, in wastewater poses significant challenges due to their exceptionally high toxicity, limited biodegradability, and potential for environmental persistence (**Elkady & Younis, 2023**).

The hydrocarbon and plastic industries serve as the main sources of phenol and its derivatives. Phenolic compounds are classified as priority pollutants by both the Environmental Protection Agency (EPA) and the World Health Organization (WHO) due to their inherent toxicity. In pursuit of safeguarding public health, these organizations have collaborated to establish a maximum allowable concentration of 1mg/ L for phenol in drinking water (**USEPA, 2004**). Upon entering water bodies, a portion of phenolic compounds can be retained and may undergo reactions, leading to the formation of additional toxic compounds. These compounds pose a threat to organisms since they enter the food chain, thereby amplifying the potential risks associated with phenol contamination (**Keith & Telliard, 1979**).

Various treatment methods, including electrocoagulation (**Olya & Pirkarami, 2013**), extraction (**Yang *et al.*, 2014**), biological treatment (**Nakhli *et al.*, 2014**), electrofenton process (**Asgari *et al.*, 2016**), ozonation (**Cheng *et al.*, 2018**), photocatalytic (**Vaiano *et al.*, 2018**), and adsorption (**Saleh *et al.*, 2019; Younis *et al.*, 2020; Alminderej *et al.*, 2022**) have been employed to remove phenol and its derivatives from aqueous solutions. Among these methods, adsorption has emerged as the most widely adopted approach due to its cost-effectiveness, environmental compatibility, reversibility, and rapidity. Furthermore, adsorption can be applied in diverse settings to mitigate environmental pollution (**Alalwan *et al.*, 2018**).

Many studies have been conducted to identify economical and eco-friendly biomass adsorbents viz. algae, suitable for phenolic waste treatment. Numerous studies on Algae, in particular, exhibit exceptional biosorption properties compared to other biomass materials. They boast advantages such as low cost, high adsorption coefficients, resistance to environmental factors and impurities, and, in some cases, comparable retention capacities to synthetic resins (**Lodeiro *et al.*, 2006; Chen *et al.*, 2011**).

While the biosorption capabilities of red, green, and brown seaweeds have been extensively investigated for other pollutants and metals in recent years (**Davis *et al.*, 2000; Hashim & Chu, 2004; Murphy *et al.*, 2008; Lee & Park, 2012; Bibak *et al.*, 2023**), information regarding their potential for phenol adsorption remains scarce or non-existent.

Previous research by **Aravindhana et al. (2007)** has employed green macroalgae as adsorbents for dye removal. Moreover, **Deng et al. (2007)** has shown the efficacy of algae in the elimination of heavy metals. Chelation and ion exchange mechanisms play crucial roles in the adsorption process of heavy metals. The binding between phenol and algae is believed to be driven by hydrophobic interactions. In the case of phenolic compound biosorption, hydrophobic and donor-acceptor interactions are considered significant contributing factors.

*Chlorophyceae* seaweeds, commonly known as green algae, inhabit a wide range of environments, including intertidal zones and deeper waters. The genus *Ulva* (*U.*) was initially identified by Linnaeus in 1753, as cited in **Kong et al. (2011)**. Algae exhibit remarkable potential for exponential and diverse growth, with species occupying a vast array of habitats and environments (**Messyasz et al., 2010; Wolf et al., 2012**). They demonstrate adaptability in both brackish and saline freshwater environments (**Madalena et al., 2013**), showcasing their ability to thrive in various ecological conditions.

The objective of this study was to explore the potential of the widely available green macroalga *Ulva intestinalis* Linnaeus 1753 for extracting phenol from aqueous solutions. The investigation examined the influence of initial pH, initial concentration, contact time and adsorbent dosage on phenol biosorption by green macroalgae. The research also encompassed the isothermal and kinetics of biosorption. The Langmuir and Freundlich isotherms were applied to characterize the equilibrium biosorption behavior. The mathematical formulation of phenol biosorption by marine green algae incorporated the pseudo-first order and pseudo-second order kinetic models. These models were employed to accurately depict and understand the process of phenol biosorption by the algae.

## MATERIALS AND METHODS

### 2. Sample preparation

The specimens of green macroalga *Ulva intestinalis* (Linnaeus, 1753) were collected from the littoral zone of the Red Sea along the coastline of Ras Ghareb during the year 2022 (Latitude: 28° 22' 34" N and Longitude: 33° 05' 17" E). Subsequently, the freshly collected *Ulva intestinalis* Linnaeus samples were thoroughly rinsed with clean water to eliminate debris or contaminants. Following the cleaning process, the *Ulva intestinalis* Linnaeus samples were dried at room temperature.

The collected samples were then placed in an agate mortar positioned on a stable surface to maintain cleanliness and dryness. Agate mortars and pestles, composed of non-reactive agate stone, were used for their suitability for grinding and crushing biological

samples. The mortar employed possessed a deep and wide bowl-shaped cavity to accommodate the samples.

The *Ulva intestinalis* Linnaeus samples were ground in the agate mortar until they reached the desired level of fineness, subsequently passing through analytical sieves for further refinement. Once adequately crushed, the resulting material was collected from the agate mortar using a clean spatula. The crushed *Ulva intestinalis* Linnaeus was then transferred to a clean and dry container for subsequent analysis and experimentation. Throughout the study, only analytical-grade chemicals and reagents were utilized.

### **2.1. Preparation of stock solution of phenol**

The phenol used in this investigation was obtained from Sigma-Aldrich Co., Germany, without any additional purification steps. To prepare a stock solution with a concentration of 1mg/ L, 1.0g of phenol was dissolved in one liter of double-distilled water.

For laboratory experiments, the stock solution was diluted to various desired concentrations ranging from 10 to 250mg/ L of phenol. The concentration of phenol was determined using a UV/VIS spectrophotometer.

### **2.3. Biosorption experiments**

Biosorption experiments were conducted to investigate the relationship between phenol adsorption and other factors, such as initial solution, adsorption dose, pH and contact time of adsorption. Protonated macroalgae, weighing 150mg, were agitated in flasks containing 50mL of phenol solution with an initial concentration of 10mg/ L. The initial solution pH varied from 3.0 to 10.0. The optical density of the phenol solution remained unaffected by changes in pH. Agitation was continued for 24 hours, surpassing the equilibration time determined through preliminary tests.

To examine the impact of macroalgae quantity on equilibrium uptake, a similar agitation method was employed using protonated macroalgae weighing between 50 and 250mg mixed with a phenol solution with an initial concentration of 50mg/ L. The effect of initial concentration on equilibrium uptake was determined by introducing 50mg of macroalgae to 50mL of phenol solution with various initial concentrations ranging from 10 to 250mg/ L. Experiments on phenol adsorption by *Ulva intestinalis* Linnaeus, identified in 1753, were conducted at different time intervals, with samples collected at 3, 6, 12, 18, and 24 hours. The sorbent constant dosage, initial phenol concentration, and pH were maintained throughout.

To investigate the impact of adsorbent dosage, known quantities of *Ulva intestinalis* Linnaeus ranging from 10 to 250mg were agitated for 24 hours in an aqueous

solution containing 50mg/ L of phenol. For studying biosorption kinetics and equilibrium, 50mL of phenol solution with known initial concentrations was agitated with 150mg of macroalgae. All experiments were conducted using a shaker at a constant agitation speed of 200 revolutions per minute and at room temperature.

Subsequently, samples taken at different intervals were filtered using a cellulose acetate membrane filter with a pore size of 0.45mm. The phenol concentration in the supernatant was measured using a UV-vis spectrophotometer. The equilibrium quantity of phenol adsorbed onto the macroalgae was determined using the mass balance equation as follows:

$$Q_e = \frac{V}{W} (C_i - C_e) \quad (1)$$

Where  $C_i$  and  $C_e$  represent the initial and equilibrium concentrations of phenol solution in milligrams per liter, respectively;  $Q_e$  is the equilibrium phenol concentration on macroalgae in grams per gram;  $V$  is the volume of phenol solution in liters, and  $W$  is the mass of macroalgae utilized in grams.

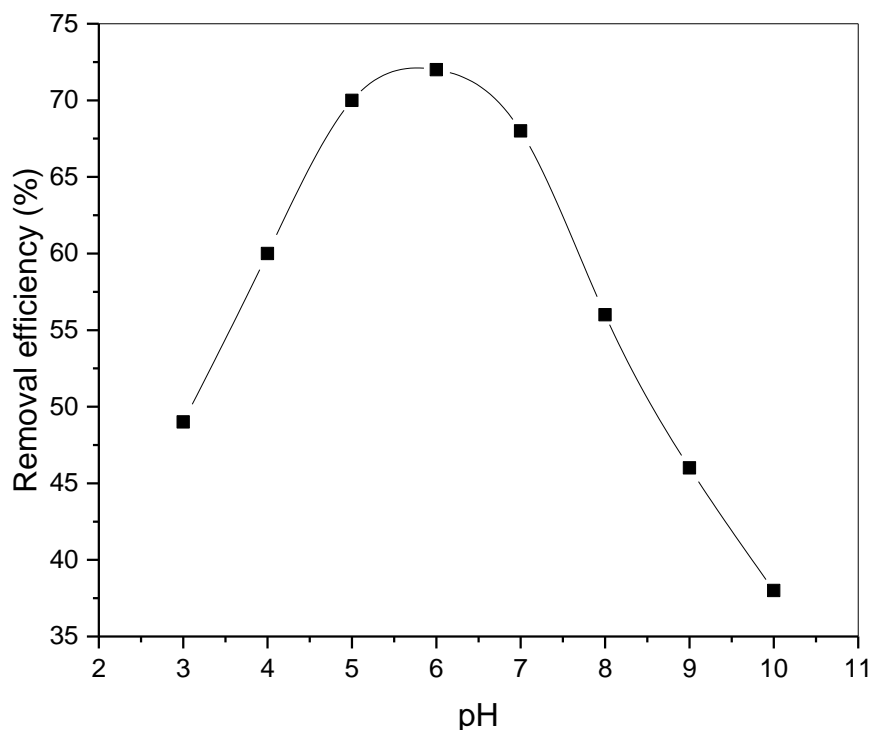
## RESULTS AND DISCUSSION

### 3. Effect of initial pH

The biosorption capacity is primarily determined by the pH of the solution. The effect of initial pH on biosorption provides insights into the physicochemical interaction between the solute in the solution and the adsorptive sites of the adsorbent.

Fig. (1) illustrates the impact of initial pH on phenol biosorption by macroalgae under the specified experimental conditions. Biosorption increases as the initial pH rises, reaching a maximum at pH 6.0, beyond which it decreases significantly. This observed effect can be attributed to the relationship between the initial pH and the degree of ionization of the biosorbent and sorbate. At low pH levels, the algal surface becomes neutral with a pKa of 3.85 (Rubin *et al.*, 2006). Beyond this threshold, the aggregate surface charge becomes negative. Similarly, phenol exhibits anionic behavior at higher pH levels, with a pKa of 9.90 (Younis *et al.*, 2020).

Based on these observations, acidic phenols are present at pH values below 6.0, while neutral/undissociated phenolic compounds preferentially adsorb in their molecular form onto the macroalgal surface.



**Fig. 1.** pH-Dependent adsorption of phenol by *Ulva intestinalis* Linnaeus, 1753

The decrease in phenol biosorption within the pH range of 6 to 10 can be attributed to increased electrostatic repulsion between the negatively charged sorbent and sorbate. **Mattson *et al.* (1969)** reported that phenol and its derivatives adsorb onto activated carbon through a "donor–acceptor complex" mechanism, where the solute's aromatic ring acts as an electron acceptor, and the carbonyl surface-oxygen groups function as electron donors.

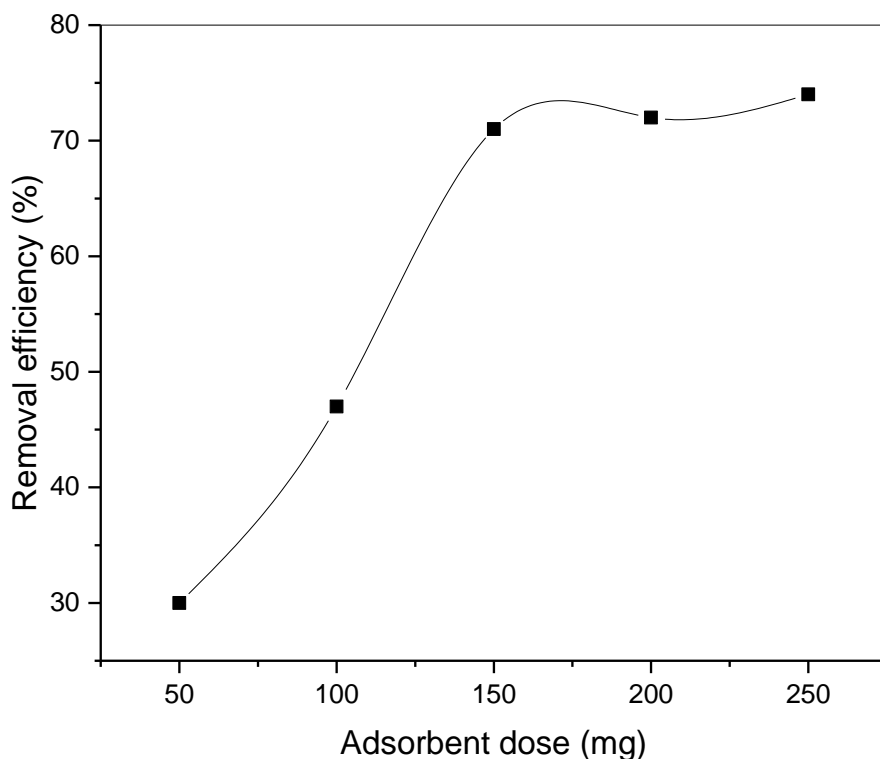
### **3.1. The influence of adsorbent dosage**

The influence of adsorbent material dosage on the efficiency of the phenol adsorption process was investigated. Practical experiments were conducted using varying doses of *Ulva intestinalis* Linnaeus powder, ranging from 50 to 250mg, while keeping all other variables constant at optimal parameters.

Fig. (2) presents the results obtained from this investigation, indicating a direct correlation between the percentage of phenol removal and the dose of the adsorbent material. Specifically, a decrease in the quantity of *Ulva intestinalis* Linnaeus powder used in the adsorption unit resulted in a corresponding decrease in the efficiency of

phenol adsorption. The highest percentage of phenol removal was achieved at a dosage of 250mg.

This outcome can be ascribed to the presence of active sites within the adsorbent material. When the biomass content is minimal, both the surface area and the number of active sites are relatively small. Hence, a lower quantity of phenol molecules is absorbed from the pollutant solution onto the surface of the adsorbent material, compared to the case when the adsorbent concentration is increased. By increasing the dosage of the adsorbent material (*Ulva intestinalis* granules) in the adsorption unit, the percentage of phenol molecules extracted from contaminated water solutions is enhanced. The diminished quantity of available adsorption sites can be traced back to the partial aggregation of marine seaweed in solution, as documented in other research of **Rubin et al. (2006)**, **Saleh et al. (2019)**, **Younis et al. (2020)** and **Alminderej et al. (2022)**.



**Fig. 2.** Biosorbent dose-dependent adsorption of phenol by *Ulva intestinalis* Linnaeus, 1753

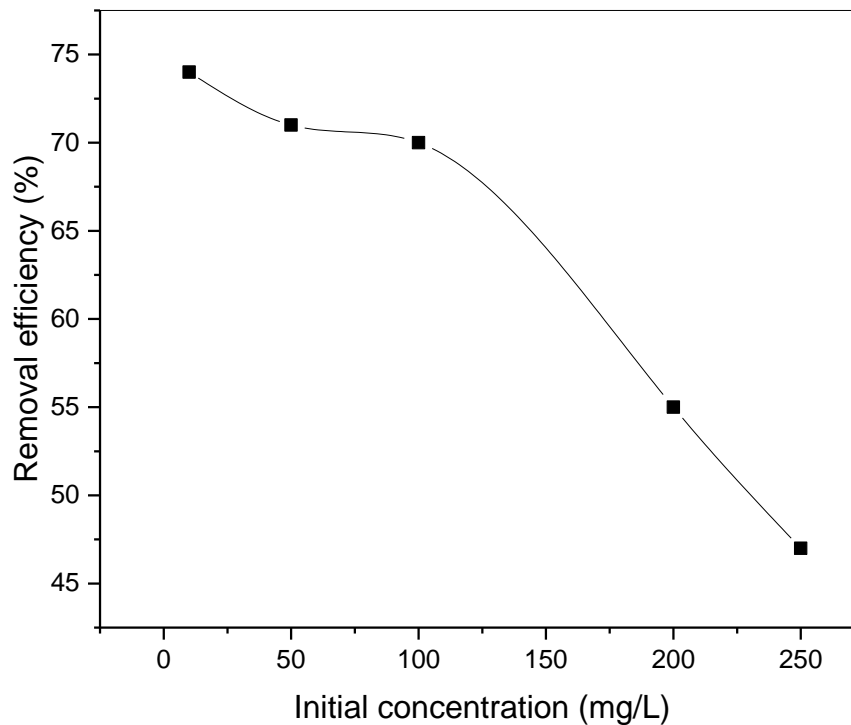
### **3.2. The influence of the initial phenol concentration**

The influence of the initial concentration of phenol on the adsorption process was investigated using *Ulva intestinalis* Linnaeus powder as the adsorbent medium. Fig. (3)

illustrates the results, indicating a decrease in the percentage of phenol removal from the polluted solution since the initial concentration of phenol increased while keeping all other variables at their optimal values.

This phenomenon can be attributed to the removal capacity of the adsorbent medium being only marginally affected by the initial concentration of phenol. Additionally, the adsorbent medium possesses a finite number of active sites, which become saturated at a certain concentration of phenol.

Consequently, an increased quantity of phenol molecules competed for the available active sites on the surface of the adsorbent medium. Since the quantity of phenol molecules in the polluted solution at lower concentrations is relatively smaller compared to higher concentrations, the percentage of phenol removal exhibited a decline as the initial concentration of phenol increased. Phenol was removed at the highest percentage rates of 74% and 47% at initial phenol concentrations of 10 and 250mg/ L, respectively.



**Fig. 3.** Initial concentration-dependent adsorption of phenol by *Ulva intestinalis* Linnaeus, 1753



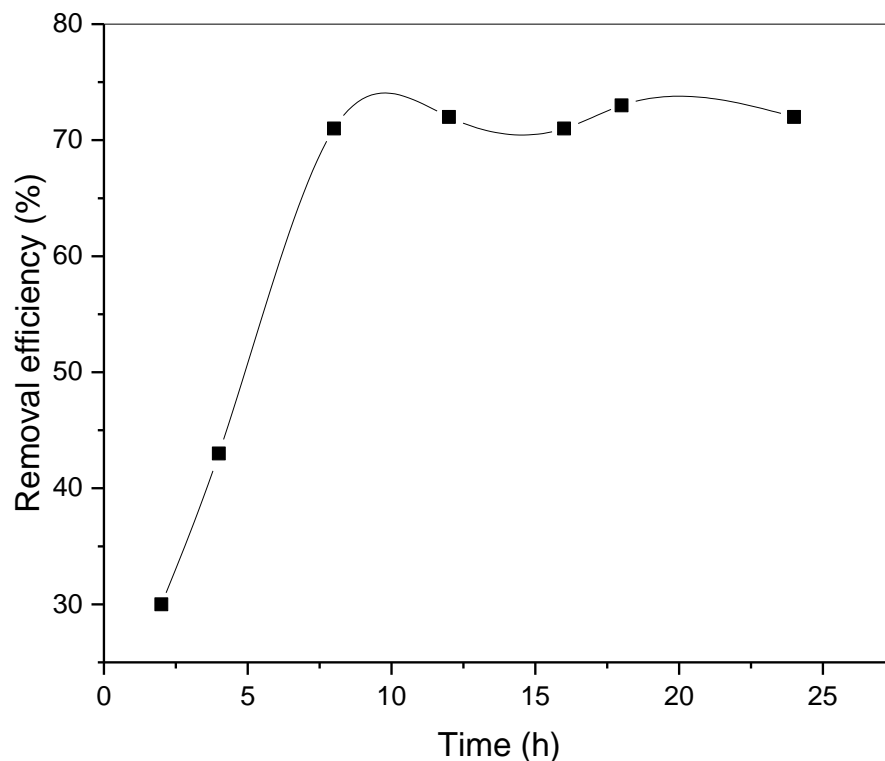
Based on these findings, it is determined that *Ulva intestinalis* Linnaeus powder effectively eliminates phenol contamination from aqueous solutions, as evidenced by its high percentage of phenol removal.

### ***3.3. The influence of contact time***

The influence of contact time on phenol removal efficacy from aqueous solutions was examined, as depicted in Fig. (4). Assuming all other variables were held constant at their optimal values, the results showed that an extended contact duration during the adsorption process led to an improvement in the phenol remediation. The contact time was fixed at 24 hours for this investigation.

This improvement can be attributed to the prolonged interaction between phenol and the biosorbent media when the contact time of the polluted solution was increased, while the agitation velocity of the aqueous solution with the adsorbent biomaterial remained constant. Hence, *Ulva intestinalis* Linnaeus powder captured a greater quantity of phenolate ions, leading to a higher percentage of phenol removal from the polluted solution.

Furthermore, Fig. (4) demonstrates a progressive increase in the adsorption rate until it reaches equilibrium after an initial rapid and substantial increase in adsorption efficiency within the first eight hours. This observation can be explained by the abundance of active sites initially present on the surface of the biosorbent material.



**Fig. 4.** Contact time-dependent adsorption of phenol by *Ulva intestinalis* Linnaeus, 1753

During the progression of the adsorption process, the rate gradually diminished due to the formation of attachments with phenol molecules or phenolate ions. Saturation is achieved when the number of absorbent particles detaching from the surface equals the number of molecules attaching to the surface. This equilibrium is reached as the number of active sites continues to decrease. This finding aligns with the findings reported in prior studies of **Saleh *et al.* (2019)**, **Younis *et al.* (2020)** and **Alminderej *et al.* (2022)**.

Algae employ diverse mechanisms to mitigate the impact of harmful phenol pollutants. These mechanisms encompass hydrolysis, photodegradation, adsorption, accumulation, and biodegradation. The cell wall of macroalgae, comprising polymer components like protein and cellulose, possesses various functional groups. These functional groups include carboxylate, amine, imidazole, phosphate, sulfhydryl, sulfate, and hydroxyl groups, which actively participate in the process of biosorption.

### 3.4. Adsorption isotherms

Adsorption, a fundamental process in chemistry, exhibits intriguing oscillations as described by mathematical models such as the Freundlich and Langmuir equations. The Freundlich equation, the oldest known mathematical model, is widely employed despite its empirical nature.

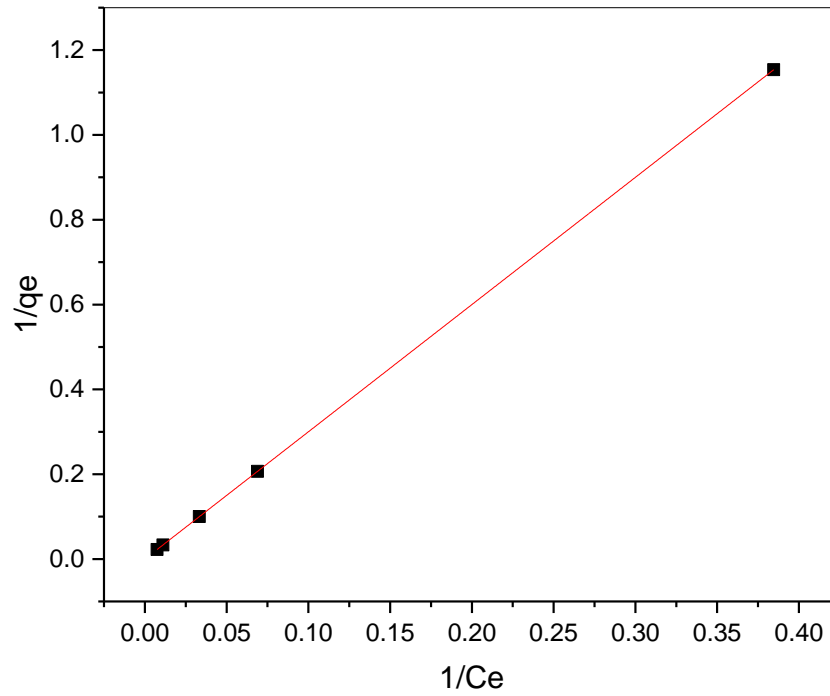
According to the Freundlich theory, adsorbent-active sites possess a range of binding energies, creating an energetically heterogeneous surface. This isotherm suggests the absence of adsorbate saturation, implying an infinite surface area and the possibility of multilayer sorption. The model establishes a relationship between the equilibrium concentration of solute in the solution ( $C_e$ ) and the quantity of solute adsorbed ( $q_e$ ) as follows:

$$q_e = \frac{q_{max} K_L C_e}{1 + K_L C_e} \quad (2)$$

The Langmuir sorption isotherm effectively characterizes the absorption of pollutants from liquid solutions. It assumes that sorption occurs at specific, homogeneous locations on the adsorbent's surface. Once a site is occupied, subsequent sorption is prohibited. The driving force for sorption is the solution concentration, while the available surface area determines the rate of sorption.

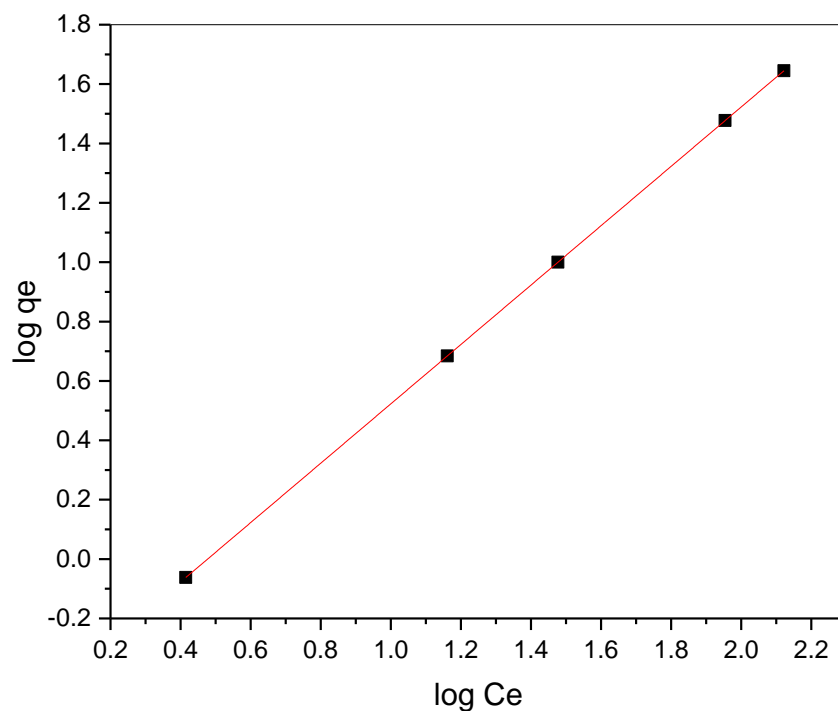
$$q_e = \ln(kf) + \frac{1}{n} * \ln C_e \quad (3)$$

The Freundlich constants,  $kf$  and  $n$ , correspond to the adsorption capacity and intensity. A gentle slope (high  $n$  value) indicates adsorption throughout the concentration range, while a steep slope (low  $n$  value) suggests effective adsorption at high concentrations but less effectiveness at low concentrations.



**Fig. 5.** Model fit of Langmuir adsorption isotherms of phenol by *Ulva intestinalis* Linnaeus, 1753

The linearized forms of both isotherm equations allow for the determination of Langmuir and Freundlich constants. The Langmuir constants,  $q_{max}$  (mg/ g) and  $K_L$  (L  $\text{mg}^{-1}$ ), represent the maximum adsorption capacity and adsorption energy or net enthalpy, respectively.



**Fig. 6.** Model fit of Freundlich adsorption isotherms of phenol by *Ulva intestinalis* Linnaeus, 1753

The linear isotherms exhibited by *Ulva intestinalis* Linnaeus powder confirms its competitive adsorption. Similar to the influence of initial pH on adsorption, the adsorption of algae is primarily driven by polar interactions such as the formation of hydrogen bonds. Each hydroxyl group on the surface competes for the ability to interact with the pollutant, resulting in energy release. Saturation of the adsorption capacity occurs when the adsorbent mass is completely loaded with phenol. Table (1) presents the isotherm constants and kinetic parameters for phenol adsorption by *Ulva intestinalis* Linnaeus powder.

The Langmuir and Freundlich isotherms exhibited a linear relationship between the depicted parameters (Figs. 6, 7). The Langmuir constants were calculated as 0.98g/ L, with an  $R^2$  value of 0.99. The Freundlich isotherm yielded  $K_f$  and  $1/n$  values of 0.33g/ L and 1, respectively, along with an  $R^2$  value of 0.99. The  $R^2$  values indicate that green macroalgae's phenol biosorption aligns with Langmuir and Freundlich model isotherm (Table 1).

**Table 1.** Modeling adsorption isotherm and kinetic parameters for phenol adsorption by *Ulva intestinalis* Linnaeus powder

Adsorption model	Parameters	Phenol
Langmuir	$Q_{\max}$	211
	$K_L$	0.0015
	$R_L$	0.98
	$R^2$	0.99
Freundlich	$1/n$	1
	$K_F$	0.33
	$R^2$	0.99
First- order	$K_1$	0.033
	$q_e$	2.186
	$R^2$	0.525
Second-order	$K_2$	-11.92
	$q_e$	0.862
	$R^2$	0.995

Table (2) provides the adsorption capacity values for various cost-effective materials used as adsorbents for phenol removal. This study reveals that the sorption capacity of green macroalgae surpasses that of previously reported non-conventional low-cost adsorbents for phenol absorption from aqueous solutions.

### 3.5. Phenol biosorption kinetics

In evaluating the biosorption process as a unit operation, biosorption kinetics and equilibrium are two crucial physicochemical factors to consider. Biosorption kinetics determine the rate at which the solute is absorbed, and the time required for the biosorption reaction to complete. Various kinetic models can be employed to understand the behavior of the adsorbent and investigate the underlying mechanism of the biosorption process.

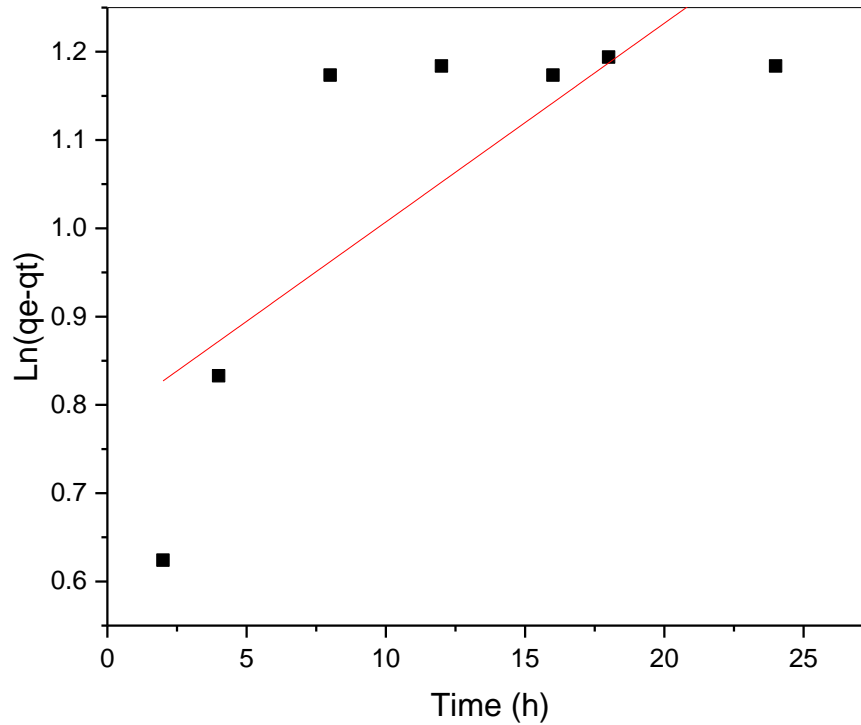
**Table 2.** Comparative analysis of phenol adsorption capacities utilizing various adsorbents

Raw material	Initial concentration	$Q_{\max}$ (mg/ g)	Reference
Olive pomace	50	4- 5	Stasinakis <i>et al.</i> (2008)
Macrocystis integrifolia Bory	50	97.37	Navarro <i>et al.</i> (2009)
Lessonia nigrescens Bory	50	18.64	Navarro <i>et al.</i> (2009)
Baggase fly ash	75	23	Srivastava <i>et al.</i> (2006)
Sawdust based Activated carbon	10	2.82	Mohanty <i>et al.</i> (2005)
Dried date palm fibers (DPF)	100	19.57	Alminderej <i>et al.</i> (2022)
Si-DPF nanomaterials (Si-DPF)	100	31.35	Alminderej <i>et al.</i> (2022)
Magnetic palm kernel biochar	10	10.84	Hairuddin <i>et al.</i> (2019)
Silica-coated caulerpa proliferata nanoparticles	50	137.55	Younis <i>et al.</i> (2020)
Amino modified SiNPs	50	35.20	Saleh <i>et al.</i> (2019)
Non-amino modified SiNPs	50	16.4	Saleh <i>et al.</i> (2019)

The **Lagergren** rate equation (1898), one of the earliest rate equations for biosorption in liquid/solid systems, offers insights into the biosorption rate considering solid capacity. The rate constant associated with biosorption can be determined using the pseudo-first order rate expression as follows:

$$\frac{dq_t}{dt} = k_1 (q_e - q_t)^2 \quad (4)$$

Where,  $q$  represents the amount of phenol adsorbed (mg/ g) at time  $t$  (min), and  $q_e$  denotes the amount of phenol adsorbed (mg/ g) at equilibrium. The pseudo-first order rate constant is denoted as  $k_1$ .



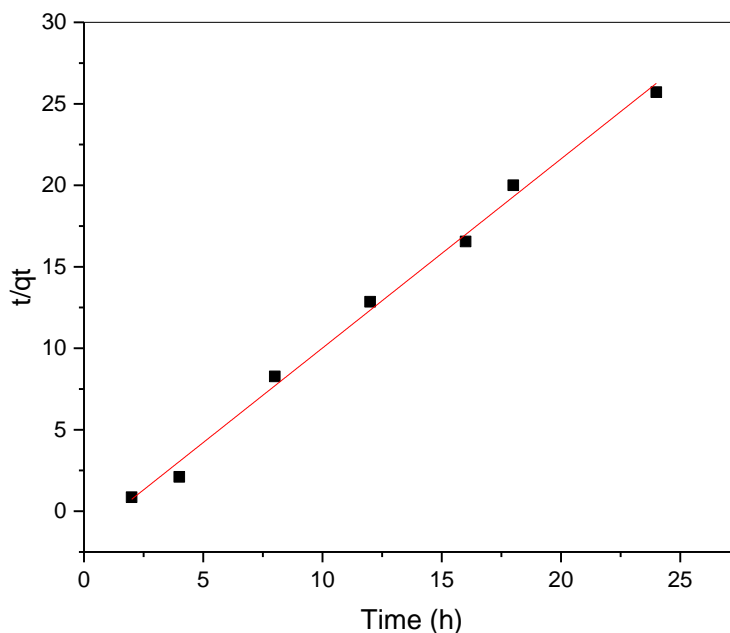
**Fig. 7.** Pseudo- first -order kinetic plots for phenol adsorption on *Ulva intestinalis* Linnaeus, 1753 at phenol concentration of 10mg/ L, pH of 6, and biomass concentration of 0.15g/ 50mL

Alternatively, biosorption kinetics can be described by a pseudo-second order equation, as proposed by **Ho and McKay (1999)** as follows:

$$\frac{t}{qt} = \frac{1}{k_2 q^2} + \frac{1}{q} t \quad (5)$$

The rate constant ( $k_2$ ) and  $q_e$  of the second order can be calculated from the intercepts and slopes of the graphs generated by plotting  $t/qt$  versus time  $t$ .





**Fig. 7.** Pseudo-second-order kinetic plots for phenol adsorption on *Ulva intestinalis* Linnaeus, 1753 at phenol concentration of 10mg/ L, pH of 6, and biomass concentration of 0.15g/ 50mL

The correlation coefficients between the second-order and first-order kinetic models were calculated and compared. The second-order kinetic model's correlation coefficient was higher than that of the first-order kinetic model (Figs. 7, 8). This indicates that the pseudo-second-order kinetic model provides a more accurate description of phenol biosorption kinetics by the modified green macroalgae compared to the pseudo-first-order kinetic model. The non-illustrated Figs. in the plot exhibited linearity, further supporting the validity of the pseudo-second-order kinetic model, which yielded an average regression coefficient of  $R^2$ .

## CONCLUSION

It was observed that the adsorption of phenol onto *Ulva intestinalis* Linnaeus is influenced by the pH of the solution. An initial pH of 6.0 achieved a maximum uptake of approximately 72%. The excellent fit of the equilibrium data to the Langmuir isotherm model confirmed the formation of a monolayer of phenol on the biosorbent. The effect of adsorbent dosage was also investigated, revealing a lower mass requirement for achieving saturation compared to previous studies utilizing similar or different adsorbents. This indicates the enhanced efficiency of *Ulva intestinalis* Linnaeus as a phenol adsorbent.

The results revealed that the most favorable conditions were observed at a pH of 6; a contact time of 8 hours; an adsorption dose of 150mg, and an initial phenol concentration of 50mg/ L. These conditions were found to maximize the efficiency of phenol extraction using *Ulva intestinalis* as a biosorbent. Both the Freundlich and Langmuir models were employed to analyze the sorption isotherm data, revealing a mixed adsorption mechanism. The Langmuir and Freundlich constants suggest that exchanged *Ulva intestinalis* Linnaeus has a higher affinity for phenol.

The optimized parameters obtained from this study were applied in the phenol removal process, demonstrating the efficacy of *Ulva intestinalis* Linnaeus, a green macroalgal species, as an adsorbent for eliminating phenol from aqueous solutions. These findings contribute to a deeper understanding of the adsorption mechanism of phenol and its analogues, as well as their potential application as efficient and cost-effective adsorbents in the treatment of phenol-containing effluent.

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