Bioremediation potential of *Caulerpa racemosa* for lead (Pb) and cadmium (Cd) removal from seawater: growth performance and metal uptake mechanisms

[1]Ratna I. Sari, [1]Ardhani D. Wahyuningtyas, [1]Indrian R. Amalia, [2]Dian Permana, [2]Endah Soetanti, [2,3]Rahma Aulia, [4]Zaenal A. Siregar, [4]Dasep Habullah, [4]Gagan Garnawansah

[1] Directorate for Laboratory Management, Research Facilities, and Science and Technology Park, National Research and Innovation Agency, Jakarta, Indonesia; [2] Research Center for Fishery, National Research and Innovation Agency, Bogor, Indonesia; [3] Fisheries Department, Faculty of Agriculture, Universitas Gadjah Mada, Yogyakarta, Indonesia; [4] Research Center for Marine and Land Bioindustry, National Research and Innovation Agency, Serpong, Indonesia. Corresponding author: G. Garnawansah, gagan.garnawansah@gmail.com, gaga005@brin.go.id

Abstract. *Caulerpa racemosa* was evaluated for its capacity to eliminate cadmium (Cd) and lead (Pb) from seawater and its growth response under sub-lethal metal stress. This study investigates the potential of *C. racemosa* as a bioremediation agent for reducing Pb and Cd concentrations in seawater. Experiments were conducted at the Jepara Brackish Water Aquaculture Fisheries Center (BBPBAP) Indonesia, where *C. racemosa* was exposed to Pb and Cd, each at concentrations of 0.1, 1, and 10 ppm respectively, for 15 days. Heavy metal concentrations were measured using Graphite Furnace - Atomic Absorption Spectrophotometry (GF-AAS), while biomass growth and specific growth rate (SGR) were monitored periodically. The results demonstrated maximum removal efficiencies of 96.17% for Pb and 99.91% for Cd at 10 ppm. Initial biomass reduction suggested physiological stress, but recovery in growth was observed between days 10-15, particularly in the 10 ppm Pb and 1 ppm Cd treatments. Statistical analysis, including ANOVA and Tukey HSD test, confirmed significant differences in metal reduction efficiency across different treatments, indicating a concentration-dependent response. The biosorptive capacity of *C. racemosa* is attributed to the functional groups on its cell walls, which facilitate the binding of heavy metal ions. Additionally, the study highlighted the physiological adaptation of *C. racemosa* under metal stress. These findings position *C. racemosa* as a promising and sustainable candidate for remediating heavy metal-polluted aquatic ecosystems.
Key Words: bioaccumulation, growth response, heay metal removal, marine algae, seawater remediation.

Introduction. Heavy metals, such as cadmium (Cd) and lead (Pb), are widespread in aquatic ecosystems, originating from both natural processes and anthropogenic activities like industrial discharges, agricultural runoff, and urban wastewater. Industrial activities, particularly in coastal zones, have increasingly burdened aquatic ecosystems with these contaminants (Tamilselvan et al 2012; Adriansyah et al 2018. These metals are very persistent, resist biodegradation, and bioaccumulative, disrupting physiological processes and trophic dynamics in marine systems (Idrees et al 2018; Simou et al 2024). They accumulate in marine organisms and magnify through the food chain, posing significant risks to aquatic ecosystems and human health. The bioaccumulation of these contaminants can lead to higher concentrations in top predators and adverse health effects in humans through the consumption of contaminated seafood (Said et al 2025). Additionally, heavy metal pollution disrupts coastal seaweed communities by altering diversity and composition, which impacts the stability of the entire food web (Bashir et al 2025).

Bioremediation using seaweed presents a sustainable and eco-friendly solution for resolving heavy metal pollution issues in water habitats. Seaweeds, including macroalgae such as *Gracilaria* spp. and *Sargassum* spp., effectively accumulate heavy metals through physical adsorption and ion exchange processes, which involve association between metal ions and functional groups on the seaweed cell walls, thereby enhancing removal efficiency (Varabih & Nofirman 2023). *Caulerpa racemosa*, a species abundant in Indonesian waters (Kepel et al 2024), stands out for its high surface area and potential for metal binding through its cell wall components (Amanda et al 2021). Commonly known as sea grapes, this species demonstrates high efficiency in removing hazardous metal like Pb and Cd from contaminated water. The use of seaweed offers significant advantages as it is affordable, widely available, and provides a cost-effective alternative to traditional remediation methods (Foday Jr. et al 2021). Unlike conventional approaches, *C. racemosa*-based bioremediation utilizes natural biological processes to remove or detoxify pollutants, reducing reliance on expensive and potentially harmful chemical treatments (Freitas et al 2008; Yulianto et al 2018). Additionally, seaweed cultivation can yield valuable biomass for commercial use, creating economic incentives for bioremediation efforts (Neveux et al 2018). Studies have shown the successful application of seaweeds in reducing heavy metal concentrations in soil and water, improving plant growth and soil quality (Ahmed et al 2021), and effectively treating industrial wastewater (Znad et al 2022).

Previous research has demonstrated the ability of *Caulerpa lentillifera* to serve as a biofilter in vannamei shrimp (*Litopenaeus vannamei*) polyculture, where it significantly reduced water turbidity, total organic matter, and ammonia levels while improving shrimp survival and production performance compared to monoculture systems (Margono et al 2021). The goal of this study is to appraise the capacity of *C. racemosa* to reduce Pb and Cd concentrations in seawater and assess its growth under pollutant exposure. By examining the biosorption efficiency of *C. racemosa* for these metals and its physiological responses to pollution, this research seeks to provide insights into the potential of an eco-friendly solution for rehabilitating aquatic environments polluted with heavy metals.

Material and Method

***Study location and experimental design**.* The experiment was conducted at the Jepara Brackish Water Aquaculture Fisheries Center (BBPBAP), Indonesia, during July-August 2020. This facility was selected due to its advanced Integrated Multi-Trophic Aquaculture (IMTA) systems, which optimize water quality and nutrient balance for marine biota cultivation. The center maintains nutrient levels (nitrates and phosphates) ideal for *Caulerpa*, and its IMTA systems enhance water quality and stabilize the environment for cultivation (Sachoemar et al 2014; Darmawan et al 2022). *C. racemosa* was collected from local cultivation ponds and acclimatized before use. Treatments included exposure to Pb and Cd at concentrations of 0.1 ppm (A), 1 ppm (B), and 10 ppm (C), respectively, alongside a control (ambient seawater). The selected concentration range (0.1-10 ppm) reflects both environmentally relevant levels and supra-environmental conditions commonly used in biosorption studies (Tamilselvan et al 2012; Ihsan et al 2015; Yulianto et al 2018). Each treatment was replicated thrice using 100 L tanks filled with 80 L seawater.

***Preparation of pollutants and experimental setup**.* Pb and Cd were administered as $Pb(NO_3)_2$ and $Cd(NO_3)_2$ solutions, respectively. Stock solutions of 100 ppm were diluted to achieve desired concentrations. A total of 300 g of *C. racemosa* (with 100 g sampled for growth measurements) was introduced into each tank, while aeration and temperature were maintained uniformly.

***Analytical procedures**.* Heavy metal concentrations were measured on days 0 and 15 using Graphite Furnace - Atomic Absorption Spectrophotometry (GF-AAS). Growth performance was tracked by measuring biomass weight on days 0, 5, and 15. Specific growth rate (SGR) was calculated using the formula (Abdel-Tawwab et al 2010):

$$SGR = \frac{\ln(W_t) - \ln(W_0)}{t} x\ 100$$

where: W_t = final biomass weight (g);
W_0 = initial biomass weight (g);
T = the duration of the experiment (days).

***Statistical analysis*.** R software version 4.5.0 was employed to analyze the complete data (R Core Team 2021). Biomass growth and percentage reduction of Pb and Cd were assessed via one-way ANOVA to identify significant differences between treatments. Upon finding significant differences through ANOVA ($p < 0.05$), Pairwise differences between treatment means were assessed using Tukey's Honest Significant Difference (HSD) post hoc test. All results are expressed as mean±standard deviation, and statistical significance is reported at the 95% confidence level.

Results. *C. racemosa* demonstrated significant reductions in Pb and Cd concentrations across all treatments after 15 days of cultivation (Figure 1). The highest removal efficiencies were observed at 10 ppm for both metals, with Pb and Cd reductions reaching 96.17% and 99.91%, respectively. At 1 ppm, Pb and Cd concentrations decreased by 62.14% and 99.90%, while at 0.1 ppm, reductions of 50.00% for Pb and 99.86% for Cd were recorded. The control treatment also showed moderate decreases in Pb (57.69%) and Cd (52.70%), which may be attributed to low initial dissolved metal concentrations and equilibrium dynamics between metal uptake and release processes (Yulianto et al 2018; Amanda et al 2021). These results highlight the strong biosorptive and bioaccumulative capacity of C. racemosa, particularly under higher contamination levels.

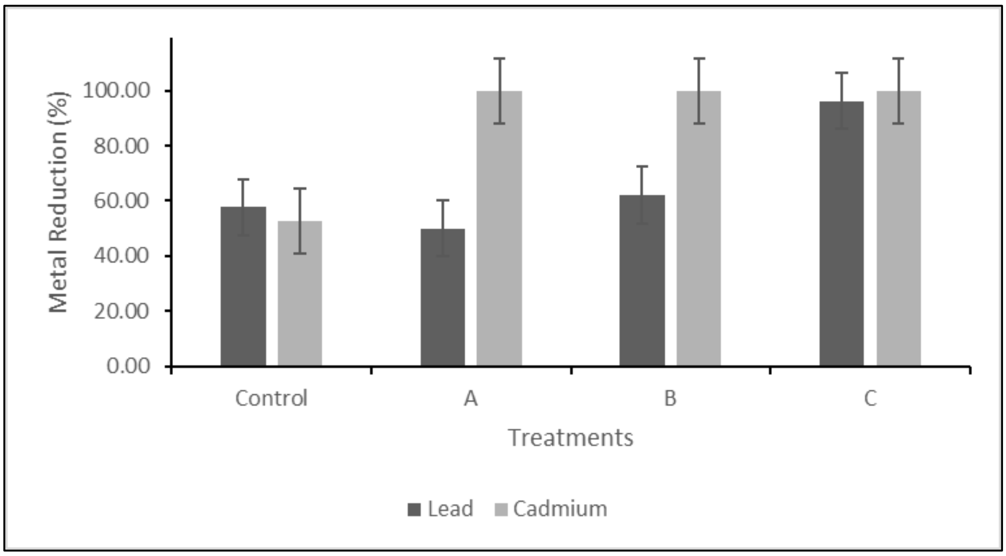

Figure 1. Pb and Cd concentration reductions in seawater after 15 days of *Caulerpa racemosa* cultivation.

***Growth response of Caulerpa racemosa*.** Exposure to Pb and Cd induced distinct growth patterns (Figure 2).

Biomass initially increased in all treatments by day 5 but declined sharply between days 5-10, indicating physiological stress. Recovery was observed by day 15 in Pb-B (1 ppm), Pb-C (10 ppm), and Cd-B (1 ppm) treatments, as evidenced by increased specific growth rates (Table 1). The control group exhibited consistent growth, achieving the highest absolute biomass gain (23.00±1.41 g) (Table 2).

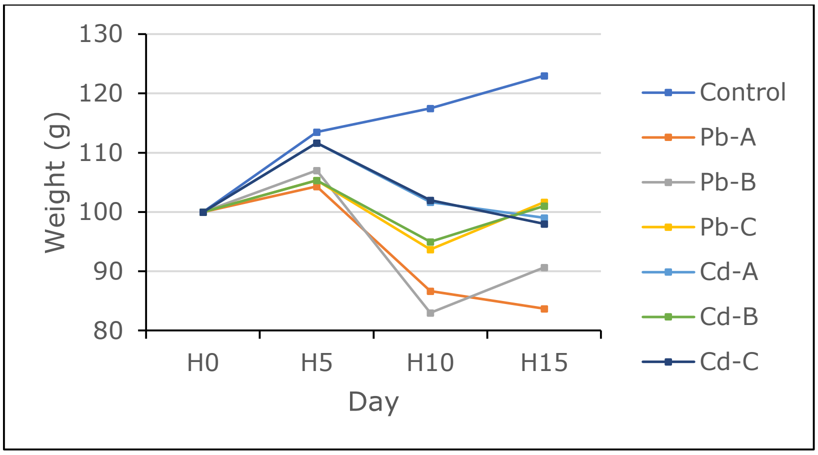

Figure 2. Biomass weight changes of *Caulerpa racemosa* across treatments.

Table 1

SGR of *Caulerpa racemosa* under different Pb and Cd concentrations

Treatment	*lnW₀*	*lnWₜ*	*SGR (% day⁻¹)*
Control	4.61±0.00	4.81±0.34	1.38±0.34
Pb-A	4.61±0.00	4.43±3.75	-1.19±3.75
Pb-B	4.61±0.00	4.51±2.89	-0.65±2.89
Pb-C	4.61±0.00	4.62±3.51	0.11±3.51
Cd-A	4.61±0.00	4.60±3.06	-0.07±3.06
Cd-B	4.61±0.00	4.62±2.95	0.07±2.95
Cd-C	4.61±0.00	4.58±2.32	-0.13±2.32

Table 2

Absolute growth and final weight of *Caulerpa racemosa* after 15 days of metal exposure

Treatment	*Initial weight (W_0) (g)*	*Final weight (W_t) (g)*	*Absolute growth (g)*
Control	100±0.00	123.00±1.41	23.00±1.41
Pb-A	100±0.00	83.67±42.58	-16.33±42.58
Pb-B	100±0.00	90.67±18.03	-9.33±18.03
Pb-C	100±0.00	101.67±33.60	1.67±33.60
Cd-A	100±0.00	99.00±21.39	-1.00±21.39
Cd-B	100±0.00	101.00±19.04	1.00±19.04
Cd-C	100±0.00	98.00±10.21	-2.00±10.21

Statistical analysis of biomass. One-way ANOVA revealed no significant treatment effect on final biomass ($F = 0.753$, $p > 0.05$; Table 3). One-way ANOVA for percentage reduction of heavy metals by *C. racemosa* revealed a highly significant effect of treatment on metal removal efficiency ($F = 713.3$, $p < 0.001$), indicating strong statistical differences between groups (Table 4). The post hoc analysis (Tukey HSD) indicated statistically significant differences in outcomes across various concentration treatments of Cd and Pb. For Cd treatments, Cd-B (1 ppm) and Cd-C (10 ppm) both significantly outperformed Cd-A (0.1 ppm), suggesting a concentration-dependent effect ($p < 0.001$). However, no significant difference was found between Cd-B and Cd-C ($p = 0.906$) (Table 5). In Pb treatments, Pb-B (1 ppm) and Pb-C (10 ppm) both significantly outperformed Pb-A (0.1 ppm), and Pb-C also significantly surpassed Pb-B, further emphasizing the dose-dependent response (Table 5).

Table 3

One-way ANOVA of *Caulerpa racemosa* biomass at day 15 under different Pb and Cd treatments

Source of variation	*df*	*SS*	*MS*	*F*	*P-value*
Treatment	6	4405.32	734.22	0.753	0.617
Residual (error)	14	13644.13	974.58		
Total	20	18049.45			

Note: df = degrees of freedom; SS = sum of squares; MS = mean square; F = F-statistic; P-value = probability value.

Table 4

One-way ANOVA for heavy metal reduction (%) across treatments

Source of variation	*df*	*SS*	*MS*	*F*	*P-value*
Treatment	5	8638	1727.6	713.3	2.08e-14
Residual (error)	12	29	2.4		
Total	17	8667			

Note: df = degrees of freedom; SS = sum of squares; MS = mean square; F = F-statistic; P-value = probability value.

Table 5

Tukey HSD pairwise comparisons for heavy metal reduction (%) among treatments

Comparison	*Mean difference (%)*	*95% CI (lower-upper)*	*P-value*	*Significant*
Cd-A – Cd-B	-45.2	-49.95 to -40.46	< 0.001	Yes
Cd-A – Cd-C	-46.63	-51.37 to -41.88	< 0.001	Yes
Cd-B – Cd-C	1.42	-3.32 to 6.17	0.906	No
Pb-A – Pb-B	-12.03	-16.78 to -7.29	< 0.001	Yes
Pb-A – Pb-C	-46.75	-51.49 to -42.01	< 0.001	Yes
Pb-B – Pb-C	-34.72	-39.46 to -29.98	< 0.001	Yes

Discussion. The present study confirms the dual function of *C. racemosa* as both a biosorbent and a tolerant macroalga under Pb and Cd contamination in seawater. The high removal efficiency observed, particularly at elevated concentrations (up to 96.17% for Pb and 99.91% for Cd), suggests that the biosorption capacity of *C. racemosa* remained effective even under high metal loads. The seaweed's ability to absorb heavy metals like Pb and Cd is likely due to the many chemically active groups on its cell surface, such as carboxyl, sulfate, and amine groups, which attract and bind these metals from the surrounding seawater (Nessim et al 2011; Raya & Ramlah 2012; Amanda et al 2021). These findings are consistent with recent studies showing that the functional groups present on algal cell walls play a central role in the passive uptake and binding of heavy metal ions, thereby enhancing biosorption and bioremediation efficiency in algae (e.g., phosphate, hydroxyl, carboxyl, and amino groups facilitating strong electrostatic attraction and complexation with metal ions) in both macro- and microalgal systems (Ordóñez et al 2023).

Initial biomass reductions in several treatments, particularly at lower concentrations (e.g., Pb-A and Cd-A), suggest a physiological stress response typical of early exposure phases to toxic metals. However, the observed recovery in SGR during days 10 to 15 in Pb-B, Pb-C, and Cd-B treatments reflects a degree of physiological adaptation. This adaptive response may involve multiple mechanisms, including vacuolar sequestration, phytochelatin synthesis, and intracellular compartmentalization, as also reported in *C. racemosa* and other seaweeds under metal stress (Purnamawat et al 2014; Ihsan et al 2015).

The relatively lower SGR observed in the 0.1 ppm treatments may suggest that metal concentrations at this level, although sublethal, were sufficient to inhibit metabolic processes without triggering a full adaptive response. This pattern implies that *C. racemosa* may require a threshold level of metal stress to activate its detoxification mechanisms effectively.

Comparative studies support the superior bioremediation performance of *C. racemosa* over other macroalgae, including *Gracilaria* sp. (Yulianto et al 2018), likely due to its morphological advantages (larger surface area) and biochemical traits favorable to metal binding. Its efficiency in reducing other metals, such as zinc (Zn), has also been documented (Landi et al 2022), reinforcing its versatility in addressing multiple contaminants.

Despite its promise, the practical deployment of *C. racemosa* for phytoremediation requires standardization of protocols and deeper insights into its metal uptake physiology. As emphasized by Said et al (2025), implementation at larger scale should be supported by improved understanding of bioremediation conditions and uptake dynamics, including potential interactions among metal species and environmental factors.

Conclusions. *Caulerpa racemosa* effectively reduced lead (Pb) and cadmium (Cd) concentrations in seawater, achieving maximum removal efficiencies of 96.17% and 99.91%, respectively, particularly at elevated contamination levels (10 ppm Pb and 1 ppm and 10 ppm Cd). Although initial biomass decreased under metal exposure, the species exhibited adaptive recovery in specific growth rates after 10 days, notably in treatments with 10 ppm Pb and 1 ppm Cd. The study revealed distinct concentration-dependent responses: for Cd, remediation efficiency improved significantly between 0.1 and 1 ppm, with no additional benefit observed at 10 ppm, while Pb showed progressive enhancement with increasing concentrations, indicating a strong dose-response relationship. For practical bioremediation applications, optimizing outcomes while balancing resource efficiency would prioritize 1 ppm Cd and 10 ppm Pb. These findings underscore *Caulerpa racemosa* potential as a sustainable bioremediation agent for heavy metal-polluted coastal ecosystems. Further research is recommended to evaluate long-term metal tolerance and validate these results in field-scale implementations under natural conditions.

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Conflict of interest. The authors declare that there is no conflict of interest.

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Authors:
Ratna Indria Sari, Directorate for Laboratory Management, Research Facilities, and Science and Technology Park, National Research and Innovation Agency, Babarsari Street, Tambak Bayan, Caturtunggal, Depok District, Sleman Regency, Special Region of Yogyakarta 55281, Indonesia, e-mail: ratn024@brin.go.id
Ardhani Dyah Wahyuningtyas, Directorate for Laboratory Management, Research Facilities, and Science and Technology Park, National Research and Innovation Agency, Babarsari Street, Tambak Bayan, Caturtunggal, Depok District, Sleman Regency, Special Region of Yogyakarta 55281, Indonesia, e-mail: ardh004@brin.go.id
Indrian Rizka Amalia, Directorate for Laboratory Management, Research Facilities, and Science and Technology Park, National Research and Innovation Agency, Babarsari Street, Tambak Bayan, Caturtunggal, Depok District, Sleman Regency, Special Region of Yogyakarta 55281, Indonesia, e-mail: indr059@brin.go.id
Dian Permana, Research Center for Fishery, National Research and Innovation Agency, Jakarta-Bogor Street KM 46, Cibinong, Bogor Regency, West Java 16911, Indonesia, e-mail: dian088@brin.go.id
Endah Soetanti, Research Center for Fishery, National Research and Innovation Agency, Jakarta-Bogor Street KM 46, Cibinong, Bogor Regency, West Java 16911, Indonesia, e-mail: enda058@brin.go.id
Rahma Aulia, Research Center for Fishery, National Research and Innovation Agency, Jakarta-Bogor Street KM 46, Cibinong, Bogor Regency, West Java 16911, Indonesia; Fisheries Department, Faculty of Agriculture, Universitas Gadjah Mada, Yogyakarta, Indonesia, e-mail: rahma.aulia@brin.go.id
Zaenal Arifin Siregar, Research Center for Marine and Land Bioindustry, National Research and Innovation Agency, Jakarta-Bogor Street KM 46, Cibinong, Bogor Regency, West Java 16911, Indonesia, e-mail: zaen009@brin.go.id
Dasep Habullah, Research Center for Marine and Land Bioindustry, National Research and Innovation Agency, Jakarta-Bogor Street KM 46, Cibinong, Bogor Regency, West Java 16911, Indonesia, e-mail: dase003@brin.go.id
Gagan Garnawansah, Research Center for Marine and Land Bioindustry, National Research and Innovation Agency, Jakarta-Bogor Street KM 46, Cibinong, Bogor Regency, West Java 16911, Indonesia, e-mail: gaga005@brin.go.id

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