Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Thank you for considering Elsevier as your publishing partner!

1 pesan

Toxicology Reports <STMJournals@author.email.elsevier.com> 31 Oktober 2024 pukul 18.04
Balas Ke: stmjournals <stmjournals@elsevier.com>
Kepada: rozirwan@unsri.ac.id

If you are unable to view this message correctly, click here

ELSEVIER

Thank you for considering Elsevier as your publishing partner!

Dear Author,

Thank you for your submission. We handle each article with the utmost care and dedication, ensuring your work receives the attention it deserves so your article *Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones* is in safe hands.

Your paper will be considered by the editor and if it passes initial screening, it will be sent for peer review by experts in your field. You can track the status of your submitted paper online using the same system to which you submitted. Simply use the reference number you received post-submission.

As you await the outcome, take some time to explore the resources we've thoughtfully assembled for you. The Elsevier Researcher Academy is an entirely free e-learning platform designed to support researchers through each stage of the research and publishing cycle. Also check out Authors' Update for updates and stories on industry developments, support and training.

Researcher Academy

Authors' Update

Is there anything else we can help you with?

Visit our help page

Thank you for selecting Elsevier for your publication. We wish you the best with your research.

Sincerely,
The Researcher Engagement Team

Elsevier supports responsible sharing:
Responsible sharing in line with copyright enables publishers to sustain high quality journals and the services they provide to the research community. Find out how you can share your article in Elsevier journals .

- Find useful tools and resources: Author Resources .
- For assistance, please visit our Customer Support site, where you can search for solutions on a range of topics and find answers to frequently asked questions.

Would you like to **update your information**? Amend your profile or publication history by visiting the Scopus profile and content corrections Support Center .

ELSEVIER

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Track the status of your submission to Toxicology Reports

1 pesan

Track your Elsevier submission <no-reply@submissions.elsevier.com> 2 November 2024 pukul 20.13
Kepada: rozirwan@unsri.ac.id

Manuscript Number: TOXREP-D-24-00875
Manuscript Title: Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones
Journal: Toxicology Reports

Dear Rozirwan Rozirwan,

Your submitted manuscript is currently under review. You can track the status of your submission in Editorial Manager, or track the review status in more detail using Track your submission here:
https://track.authorhub.elsevier.com?uuid=dd2fe2b1-f8d8-4709-85eb-95cc4ced5517

This page will remain active until the peer review process for your submission is completed. You can visit the page whenever you like to check the progress of your submission. The page does not require a login, so you can also share the link with your co-authors.

If you are a WeChat user, then you can also receive status updates via WeChat. To do this please click the following link; you will be taken to Elsevier China's website where further instructions will guide you on how to give permission to have your submission's details made visible in WeChat. Note that by clicking the link no submission data is transferred to the WeChat platform. If you have any questions about using Track your submission with WeChat please visit 在线咨询 https://cn.service.elsevier.com/app/chat/chat_launch/supporthub/publishing/session/ - Journal Article Publishing 支持中心

https://webapps.elsevier.cn/st-wechat/subscribe?signature=1730552797-452e1c520a8f20fe65572e8bfe889d99&uuid=dd2fe2b1-f8d8-4709-85eb-95cc4ced5517

We hope you find this service useful.

Kind regards,
Journal Office of Toxicology Reports
Elsevier B.V.

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

TOXREP-D-24-00875 - Confirming your submission to Toxicology Reports

2 pesan

Toxicology Reports <em@editorialmanager.com> 29 Oktober 2024 pukul 11.24
Balas Ke: Toxicology Reports <support@elsevier.com>
Kepada: Rozirwan Rozirwan <rozirwan@unsri.ac.id>

This is an automated message.

Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

Dear Dr. Rozirwan,

We have received the above referenced manuscript you submitted to Toxicology Reports. It has been assigned the following manuscript number: **TOXREP-D-24-00875**.

To track the status of your manuscript, please log in as an author at https://www.editorialmanager.com/toxrep/, and navigate to the "Submissions Being Processed" folder.

Thank you for submitting your work to this journal.

Kind regards,
Toxicology Reports

FAQ: How can I reset a forgotten password?
https://service.elsevier.com/app/answers/detail/a_id/28452/supporthub/publishing/
For further assistance, please visit our customer service site: https://service.elsevier.com/app/home/supporthub/publishing/
Here you can search for solutions on a range of topics, find answers to frequently asked questions, and learn more about Editorial Manager via interactive tutorials. You can also talk 24/7 to our customer support team by phone and 24/7 by live chat and email

This journal uses the Elsevier Article Transfer Service. This means that if an editor feels your manuscript is more suitable for an alternative journal, then you might be asked to consider transferring the manuscript to such a journal. The recommendation might be provided by a Journal Editor, a dedicated Scientific Managing Editor, a tool assisted recommendation, or a combination. For more details see the journal guide for authors.

At Elsevier, we want to help all our authors to stay safe when publishing. Please be aware of fraudulent messages requesting money in return for the publication of your paper. If you are publishing open access with Elsevier, bear in mind that we will never request payment before the paper has been accepted. We have prepared some guidelines (https://www.elsevier.com/connect/authors-update/seven-top-tips-on-stopping-apc-scams) that you may find helpful, including a short video on Identifying fake acceptance letters (https://www.youtube.com/watch?v=o5l8thD9XtE). Please remember that you can contact Elsevier s Researcher Support team (https://service.elsevier.com/app/home/supporthub/publishing/) at any time if you have questions about your manuscript, and you can log into Editorial Manager to check the status of your manuscript (https://service.elsevier.com/app/answers/detail/a_id/29155/c/10530/supporthub/publishing/kw/status/).
#AU_TOXREP#
To ensure this email reaches the intended recipient, please do not delete the above code

---

In compliance with data protection regulations, you may request that we remove your personal registration details at any time. (Remove my information/details). Please contact the publication office if you have any questions.

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id> 2 Januari 2025 pukul 12.54
Kepada: Toxicology Reports <support@elsevier.com>

Dear Editor,

After a few months ago we submitted our article, we would like to inquire about the progress of my submitted manuscript entitled " Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones".

Manuscript No: **TOXREP-D-24-00875**

Thank you
Best regards
[Kutipan teks disembunyikan]
--
Prof. Dr. Rozirwan
Head of Marine Bioecology Laboratory
Department of Marine Science
Faculty of Mathematics and Natural Sciences
Sriwijaya University
Jalan Raya Palembang-Prabumulih KM 32, Indralaya
Ogan Ilir, Sumatera Selatan, Indonesia, Pos Code: 30862
Email: rozirwan@unsri.ac.id, rozirwan@gmail.com

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Re: TOXREP-D-24-00875 - Confirming your submission to Toxicology Reports [250102-006855]

2 pesan

Researcher Support <support@elsevier.com> 2 Januari 2025 pukul 12.54
Balas Ke: Researcher Support <support@elsevier.com>
Kepada: rozirwan@unsri.ac.id

Hello!

Thank you for contacting Elsevier Researcher Support.

To help us jump right into the solution, please ensure you have provided as much information as possible.

While you wait, you can take a look at our Journal Article Publishing Support Center where you can review FAQs and 'how to' videos.

To help ensure a fast response, please do not change the subject line of this email when replying. For any future correspondence, remember to quote your unique reference number provided in the subject line.

Regards,

Elsevier Researcher Support

From: Rozirwan Rozirwan
Date: 02/01/2025 05.54 AM

Dear Editor,

After a few months ago we submitted our article, we would like to inquire about the progress of my submitted manuscript entitled " Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones".
Manuscript No: **TOXREP-D-24-00875**

Thank you
Best regards

Pada Sel, 29 Okt 2024 pukul 11.25 Toxicology Reports <em@editorialmanager.com> menulis:

> *This is an automated message.*
>
> Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones
>
> Dear Dr. Rozirwan,
>
> We have received the above referenced manuscript you submitted to Toxicology Reports. It has been assigned the following manuscript number: **TOXREP-D-24-00875**.
>
> To track the status of your manuscript, please log in as an author at

https://www.editorialmanager.com/toxrep/, and navigate to the "Submissions Being Processed" folder.

Thank you for submitting your work to this journal.

Kind regards,
Toxicology Reports

FAQ: How can I reset a forgotten password?
https://service.elsevier.com/app/answers/detail/a_id/28452/supporthub/publishing/
For further assistance, please visit our customer service site: https://service.elsevier.com/app/home/supporthub/publishing/
Here you can search for solutions on a range of topics, find answers to frequently asked questions, and learn more about Editorial Manager via interactive tutorials. You can also talk 24/7 to our customer support team by phone and 24/7 by live chat and email

This journal uses the Elsevier Article Transfer Service. This means that if an editor feels your manuscript is more suitable for an alternative journal, then you might be asked to consider transferring the manuscript to such a journal. The recommendation might be provided by a Journal Editor, a dedicated Scientific Managing Editor, a tool assisted recommendation, or a combination. For more details see the journal guide for authors.

At Elsevier, we want to help all our authors to stay safe when publishing. Please be aware of fraudulent messages requesting money in return for the publication of your paper. If you are publishing open access with Elsevier, bear in mind that we will never request payment before the paper has been accepted. We have prepared some guidelines (https://www.elsevier.com/connect/authors-update/seven-top-tips-on-stopping-apc-scams) that you may find helpful, including a short video on Identifying fake acceptance letters (https://www.youtube.com/watch?v=o5l8thD9XtE). Please remember that you can contact Elsevier s Researcher Support team (https://service.elsevier.com/app/home/supporthub/publishing/) at any time if you have questions about your manuscript, and you can log into Editorial Manager to check the status of your manuscript (https://service.elsevier.com/app/answers/detail/a_id/29155/c/10530/supporthub/publishing/kw/status/).
#AU_TOXREP#
To ensure this email reaches the intended recipient, please do not delete the above code

---

--
Prof. Dr. Rozirwan
Head of Marine Bioecology Laboratory
Department of Marine Science
Faculty of Mathematics and Natural Sciences
Sriwijaya University
Jalan Raya Palembang-Prabumulih KM 32, Indralaya
Ogan Ilir, Sumatera Selatan, Indonesia, Pos Code: 30862
Email: rozirwan@unsri.ac.id, rozirwan@gmail.com

AuthorSupportGlobal (ELS) <AuthorSupport@elsevier.com> 3 Januari 2025 pukul 00.25
Balas Ke: "AuthorSupportGlobal (ELS)" <AuthorSupport@elsevier.com>
Kepada: rozirwan@unsri.ac.id

Dear Dr Rozirwan,

Thank you for contacting us regarding on your manuscript TOXREP-D-24-00875.

I understand the importance of a swift editorial decision, and work hard to ensure articles are reviewed quickly.

From checking, your paper is under review. Currently, we have received review comments from 1 reviewer. We are waiting for the required reviews to be completed before a decision can be made.

In line with this, I have contacted the Editor regarding on your manuscript to expedite the process.

There are several factors that may influence the review time, such as the availability and responsiveness of referees.

Please be assured that the Editor and reviewers receive regular reminders on your submission. You will be notified of a decision as soon as it has been made.

Please do not hesitate to contact us if you have any further queries. We appreciate your patience and understanding throughout the process.

Kind regards,

Veronique Reigne Carandang
Researcher Support Agent
ELSEVIER

Visit the Author Guide to Editorial Manager for a guided walkthrough of author key tasks, such as manuscript submission process and how to track your manuscript.
Visit the Reviewer Guide to Editorial Manager for a guided walkthrough of reviewer key tasks.

From: Administrator
Date: Thursday, January 02, 2025 05:54 AM GMT

Hello!

Thank you for contacting Elsevier Researcher Support.

To help us jump right into the solution, please ensure you have provided as much information as possible.

While you wait, you can take a look at our Journal Article Publishing Support Center where you can review FAQs and 'how to' videos.

To help ensure a fast response, please do not change the subject line of this email when replying. For any future correspondence, remember to quote your unique reference number provided in the subject line.

Regards,

Elsevier Researcher Support

From: Rozirwan Rozirwan
Date: Thursday, January 02, 2025 05:54 AM GMT

[Kutipan teks disembunyikan]

[Kutipan teks disembunyikan]

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Decision on submission to Toxicology Reports

1 pesan

Toxicology Reports <em@editorialmanager.com> 9 Februari 2025 pukul 21.27
Balas Ke: Toxicology Reports <support@elsevier.com>
Kepada: Rozirwan Rozirwan <rozirwan@unsri.ac.id>

CC: l.h.lash@wayne.edu, nbasaran@hacettepe.edu.tr, anbasaran@baskent.edu.tr

Manuscript Number: **TOXREP-D-24-00875**

Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

Dear Dr Rozirwan,

Thank you for submitting your manuscript to Toxicology Reports.

I have completed my evaluation of your manuscript. The reviewers recommend reconsideration of your manuscript following major revision. I invite you to resubmit your manuscript after addressing the comments below. Please resubmit your revised manuscript by **Mar 02, 2025**.

When revising your manuscript, please consider all issues mentioned in the reviewers' comments carefully: please outline every change made in response to their comments and provide suitable rebuttals for any comments not addressed. Please note that your revised submission may need to be re-reviewed.

To submit your revised manuscript, please log in as an author at https://www.editorialmanager.com/toxrep/, and navigate to the "Submissions Needing Revision" folder.

Toxicology Reports values your contribution and I look forward to receiving your revised manuscript.

Research Elements (optional)
This journal encourages you to share research objects - including your raw data, methods, protocols, software, hardware and more – which support your original research article in a Research Elements journal. Research Elements are open access, multidisciplinary, peer-reviewed journals which make the objects associated with your research more discoverable, trustworthy and promote replicability and reproducibility. As open access journals, there may be an Article Publishing Charge if your paper is accepted for publication. Find out more about the Research Elements journals at https://www.elsevier.com/authors/tools-and-resources/research-elements-journals?dgcid=ec_em_research_elements_email.

Kind regards,

Lawrence Lash
Editor-in-Chief
Toxicology Reports

Editor and Reviewer comments:

Reviewer #1: Research highlights need improvement, and the graphical abstract should be of high quality.

How does this study differ from previous research on mangrove species, metals, and biomarkers? What is the necessity of conducting research in this specific location, and how extensively has this area been investigated in terms of metal contamination?

The sampling map should indicate the sampling stations (Station 1 and Station 2).

The methods section should detail the sampling procedures, including how the mangrove samples and sediment were collected. Please specify how many mangrove samples were taken. Additionally, the author should clarify whether roots or leaves were collected for sampling. The author previously mentioned roots but later referred to leaves.

How long were the sediments air-dried at room temperature?

The author must clearly describe how the mangrove leaves or roots were dried in indirect sunlight. Furthermore, the author needs to include a section on heavy metals analysis, as this part is currently missing from the methods.

The use of "inhibition" should be revised in Equation 5, and the column name in Table 8 on page 30, line 51, should be adjusted to proper English.
The word of "inhibition" in eq 5, column name Table 8, and section title line 51 page 30, please kindly adjust to English

How does the dataset in this study fulfill the criteria for parametric analysis?

In the figure depicting mangrove leaves, the author should include a scale for better visualization.

What is the role of industrial activities in the accumulation of fine particles, specifically clay particles?

How do unmanaged anthropogenic activities contribute to the increase of copper (Cu)?

How do mangroves regulate copper in their system?

In the discussion, the author states that metal concentration shows a negative correlation with antioxidant activity, yet the abstract claims that heavy metal concentration increases antioxidant activity. This discrepancy needs clarification.

Reviewer #2: Review report for: Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

The study addresses a significant environmental concern—heavy metal pollution in mangrove ecosystems—and its biological response through antioxidant activity. The study aims to analyze the correlation between Pb and Cu concentration and antioxidant activity in Avicennia alba and Excoecaria agallocha. The results provide useful insights into bioaccumulation, pollution indices, and biochemical responses of mangroves to heavy metal stress.

Areas for Improvement and Suggested Revisions

The writing should be more fluid and concise. Some sentences are lengthy or unclear.

In the abstract section

"Mangroves can mitigate the impact of free radicals by producing antioxidant compounds" can be written as "Mangroves produce antioxidant compounds to mitigatethe impact of free radicals."

"The correlation analysis between heavy metal concentrations and antioxidant activity indicates that as heavy metal concentrations increase, antioxidant activity and total phenol content also increase." can be written as "Correlation analysis shows that higher heavy metal concentrations correspond to increased antioxidant activity and total phenol content."

Rearrange some details for logical flow: The sentence about Pearson correlation analysis should come after mentioning heavy metal concentration and antioxidant activity measurements.

The concentration values for Pb and Cu should be clearly formatted:

Instead of Pb values of 0.67 ± 0.16 -18.70 ± 0.48 mg / kg and Cu values of 3.39 ± 0.20 - 6.07 ± 0.37 mg / kg, write Pb values of 0.67 ± 0.16 to 18.70 ± 0.48 mg/kg and Cu values of 3.39 ± 0.20 - 6.07 ± 0.37 mg/kg for clarity.

In the sentence:"The results of sediment pollution assessment for heavy metals Pb and Cu at Igeo < 0, 1 < Cf < 3, and PLI 0-2." Define Igeo, Cf, and PLI for readers unfamiliar with these indices.
"BCF < 1" should be clarified: Does this mean bioaccumulation is low?

The Pearson correlation analysis result should be explicitly stated (e.g., $r = X$, $p < 0.05$).

Introduction

Some sentences are long and could be more concise for better readability.
Example: "Several previous studies reported that human activities that occur in coastal areas involve various industrial sectors such as fertilizer processing, oil and gas, fiberboard, and crude palm oil."
Suggestion: "Previous studies report that industrial activities like fertilizer processing, oil and gas, and crude palm oil production contribute to coastal pollution."

Some references are inconsistently formatted, e.g., [8,[9][10] instead of [8,9,10].
Some citations lack integration into the sentence structure. Instead of "According to [15]...", it should be "According to

Smith et al. (2015)..."

"environmental stresse" should be "environmental stress"

"making them valuable indicators for assessing pollution levels in coastal waters [18,19]. Their ability to absorb and store these pollutants..." (Consider merging these two sentences for smoother flow.)

The introduction lacks a clear research gap. What specific knowledge gap does this study address that hasn't been explored before?

Materials and methods

"Leaves sampling" should be "Leaf Sampling" for consistency with "Sediment Sampling."

"Sediment grain size measurement" should be "Sediment Grain Size Analysis" to match scientific terminology.

"This area was selected due to the significant accumulation of heavy metals resulting from industrial activities along the Musi River." could be written as "This area was chosen due to the high accumulation of heavy metals from industrial activities along the Musi River."

"Additionally, sediment substrate types (gravel, sand, silt, and clay) were identified using Shepard's triangle analysis, which was processed with Microsoft Excel V.2021." could be written as "Sediment types (gravel, sand, silt, and clay) were classified using Shepard's triangle analysis and processed with Microsoft Excel V.2021."

Ensure all formulas are formatted correctly. For example, Igeo's formula should be written properly in LaTeX or inline notation.

Ensure units are consistently reported (e.g., ppm, µM, µg/ml).

Results and discussion

Figures and tables should be directly referenced within the text. Example., "Figure 2 shows the morphological differences between A. alba and E. agallocha" instead of "These differences are particularly evident in their leaf types (Figure 2) "
.
Table 2 should be described with more interpretation rather than just restating numbers.

In Table 3, use "Station" instead of "St." for clarity.

Strengthen the discussion by comparing findings with similar studies. This will help validate your results and provide broader ecological relevance.

The increase in Cu levels is mentioned but not fully explained. What anthropogenic activities specifically contribute to this? Providing more context will enhance the scientific argument.

The bioaccumulation factor (BCF), geoaccumulation index (Igeo), contamination factor (Cf), and pollution load index (PLI) are mentioned, but their ecological implications are unclear. Briefly explain what these values indicate in relation to contamination risk. Compare these index values with other mangrove ecosystems to provide context on pollution levels.

The study states that the area is "not polluted" based on the PLI but also suggests potential bioaccumulation risks. This needs clarification.

Recommend future monitoring frequency and how this data could inform environmental policies.

24/7 by live chat and email

At Elsevier, we want to help all our authors to stay safe when publishing. Please be aware of fraudulent messages requesting money in return for the publication of your paper. If you are publishing open access with Elsevier, bear in mind that we will never request payment before the paper has been accepted. We have prepared some guidelines (https://www.elsevier.com/connect/authors-update/seven-top-tips-on-stopping-apc-scams) that you may find helpful, including a short video on Identifying fake acceptance letters (https://www.youtube.com/watch?v=o5l8thD9XtE). Please remember that you can contact Elsevier s Researcher Support team (https://service.elsevier.com/app/home/supporthub/publishing/) at any time if you have questions about your manuscript, and you can log into Editorial Manager to check the status of your manuscript (https://service.elsevier.com/app/answers/detail/a_id/29155/c/10530/supporthub/publishing/kw/status/).

#AU_TOXREP#

To ensure this email reaches the intended recipient, please do not delete the above code

---

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Revision of "Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones" is due soon

2 pesan

Lawrence Lash <em@editorialmanager.com> 23 Februari 2025 pukul 13.23
Balas Ke: Lawrence Lash <l.h.lash@wayne.edu>
Kepada: Rozirwan Rozirwan <rozirwan@unsri.ac.id>

This is an automated message.

Manuscript Number: **TOXREP-D-24-00875**
Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

Dear Dr. Rozirwan,

We would like to remind you that on **Feb 09, 2025** we asked you to revise your above referenced manuscript and your revision is due by **Mar 02, 2025**.

Toxicology Reports values your contribution and we look forward to receiving your revised manuscript.

To submit your revision, please log in as an author at https://www.editorialmanager.com/TOXREP/, and navigate to the "Submissions Needing Revision" folder under the Author Main Menu. You will also find the decision letter and comments available there.

If you do not plan to revise your manuscript, please click "Decline to Revise" in the "Submissions Needing Revision" folder.

If you require more time, please contact the journal office by replying to this email.

Kind regards,
Toxicology Reports

Have questions or need assistance?
For further assistance, please visit Elsevier Support Center for Author Support. Here you can search for solutions on a range of topics, find answers to frequently asked questions, and learn more about Editorial Manager via interactive tutorials.
You can also talk to our customer support team 24/7 by live chat, email and phone.

#AU_TOXREP#

To ensure this email reaches the intended recipient, please do not delete the above code

---

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id> 23 Februari 2025 pukul 22.10
Kepada: Lawrence Lash <l.h.lash@wayne.edu>

Dear Editor,

Thank you for the reminder regarding the revision of manuscript TOXREP-D-24-00875. We appreciate your continued support.

I would like to inform you that we are currently in the process of revising the manuscript, and we are working diligently to address the reviewers' comments. We will ensure that the revised manuscript is submitted before the deadline of March 2, 2025.

Thank you once again for your patience and for the opportunity to revise our work. We look forward to submitting the updated manuscript shortly.

Best regards,

[Kutipan teks disembunyikan]

--

Prof. Dr. Rozirwan
Head of Marine Bioecology Laboratory
Department of Marine Science
Faculty of Mathematics and Natural Sciences
Sriwijaya University
Jalan Raya Palembang-Prabumulih KM 32, Indralaya
Ogan Ilir, Sumatera Selatan, Indonesia, Pos Code: 30862
Email: rozirwan@unsri.ac.id, rozirwan@gmail.com

Unsri Google Apps

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Revision of "Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones" is due soon

1 pesan

Lawrence Lash <em@editorialmanager.com> 27 Februari 2025 pukul 13.58
Balas Ke: Lawrence Lash <l.h.lash@wayne.edu>
Kepada: Rozirwan Rozirwan <rozirwan@unsri.ac.id>

This is an automated message.

Manuscript Number: **TOXREP-D-24-00875R1**
Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

Dear Dr. Rozirwan,

We would like to remind you that on **Feb 09, 2025** we asked you to revise your above referenced manuscript and your revision is due by **Mar 02, 2025**.

Toxicology Reports values your contribution and we look forward to receiving your revised manuscript.

To submit your revision, please log in as an author at https://www.editorialmanager.com/TOXREP/, and navigate to the "Submissions Needing Revision" folder under the Author Main Menu. You will also find the decision letter and comments available there.

If you do not plan to revise your manuscript, please click "Decline to Revise" in the "Submissions Needing Revision" folder.

If you require more time, please contact the journal office by replying to this email.

Kind regards,
Toxicology Reports

Have questions or need assistance?
For further assistance, please visit Elsevier Support Center for Author Support. Here you can search for solutions on a range of topics, find answers to frequently asked questions, and learn more about Editorial Manager via interactive tutorials.
You can also talk to our customer support team 24/7 by live chat, email and phone.

#AU_TOXREP#

To ensure this email reaches the intended recipient, please do not delete the above code

Table of Responses

No.	Questions	Answears
	Reviewer #1	
1.	Research highlights need improvement, and the graphical abstract should be of high quality.	We have revised and improved the research highlights as per your recommendation. Additionally, we have enhanced the graphical abstract to ensure high quality and clarity.
2.	How does this study differ from previous research on mangrove species, metals, and biomarkers? What is the necessity of conducting research in this specific location, and how extensively has this area been investigated in terms of metal contamination?	This study differs from previous research on mangrove species, metals, and biomarkers by examining two mangrove species with distinct morphological and habitat characteristics. It focuses on the bioaccumulation of Pb and Cu, metals that are commonly found due to anthropogenic activities. While previous studies primarily focused on metal concentrations, this research also considers the physiological responses of mangroves to these contaminants, filling a gap in the literature. The study is conducted in two different locations to assess whether areas with high anthropogenic influence exhibit higher contamination and physiological responses, providing a more comprehensive understanding of how environmental stressors impact mangrove ecosystems.
3.	The sampling map should indicate the sampling stations (Station 1 and Station 2).	We have updated the sampling map to show the sampling stations (Station 1 and Station 2) (Page 6).
4.	The methods section should detail the sampling procedures, including how the mangrove samples and sediment were collected. Please specify how many mangrove samples were taken. Additionally, the author should clarify whether roots or leaves were collected for sampling. The author previously mentioned roots but later referred to leaves.	We have now provided a more detailed description of the sampling procedures in the Methods section, including how the mangrove and sediment samples were collected. Additionally, we have specified the number of mangrove samples taken. We sincerely apologize for the previous inconsistency regarding the

		sampled plant parts. To clarify, our study focused solely on mangrove leaves, not roots (Page 7).
5.	How long were the sediments air-dried at room temperature?	We have now specified the duration of air-drying the sediments at room temperature (72 hours) to clarify the methodology (Page 8).
6.	The author must clearly describe how the mangrove leaves or roots were dried in indirect sunlight. Furthermore, the author needs to include a section on heavy metals analysis, as this part is currently missing from the methods.	We have added a clearer description of the drying process for mangrove leaves using indirect sunlight, ensuring that the procedure is more detailed and understandable. Additionally, we have included a section on heavy metals analysis in the methodology, which was previously missing (Page 8).
7.	The use of "inhibition" should be revised in Equation 5, and the column name in Table 8 on page 30, line 51, should be adjusted to proper English.	We have revised (Page 10, 29)
8.	How does the dataset in this study fulfill the criteria for parametric analysis?	The dataset in this study meets the criteria for parametric analysis, proven by the results of the assumption test, which show a normal distribution. This ensures that the statistical parameters used in the correlation analysis are accurate. In addition, the Pearson correlation test (r) and coefficient of determination (Kd) further validate the analyzed relationship.
9.	In the figure depicting mangrove leaves, the author should include a scale for better visualization.	We have now included a scale in the figure to enhance visualization and provide a clearer reference for the leaf sizes (Page 13).
10.	What is the role of industrial activities in the accumulation of fine particles, specifically clay particles?	We have carefully revised the manuscript according to the reviewers' comments. Specifically, in response to the concern regarding the role of industrial activities in fine particle accumulation, we have clarified that the dominant contributors in our study area are fertilizer processing, oil and gas industries, crude palm oil

		production, port operations, and related activities (Page 13).
11.	How do unmanaged anthropogenic activities contribute to the increase of copper (Cu)?	We have revised the paragraph to clarify how unmanaged anthropogenic activities contribute to increasing Cu concentrations in the study area. Specifically, unregulated industrial waste disposal, improper wastewater treatment, and uncontrolled agricultural runoff serve as major sources of Cu pollution. Industrial activities discharge Cu-containing effluents directly into water bodies, while antifouling paints from ship maintenance release Cu into the environment. Additionally, agricultural runoff carrying Cu-based pesticides exacerbates contamination. Once introduced, Cu binds to suspended particles and accumulates in sediments, leading to long-term environmental pollution (Page 19).
12.	How do mangroves regulate copper in their system?	We have incorporated the requested explanation regarding how mangroves regulate Pb and Cu in their system. The revised discussion now elaborates on Pb exclusion mechanisms, including its limited uptake and accumulation in roots, as well as Cu regulation through controlled absorption, detoxification, and antioxidant responses (Page 19).
13.	In the discussion, the author states that metal concentration shows a negative correlation with antioxidant activity, yet the abstract claims that heavy metal concentration increases antioxidant activity. This discrepancy needs clarification.	The negative correlation mentioned in the discussion refers specifically to the DPPH assay values, where a lower DPPH value indicates stronger antioxidant activity. This means that although the numerical correlation appears negative, the actual antioxidant strength remains high. In other words, as heavy metal concentrations increase, antioxidant activity also intensifies, aligning with the statement in the abstract.

Reviewer #2		
1.	"Mangroves can mitigate the impact of free radicals by producing antioxidant compounds" can be written as "Mangroves produce antioxidant compounds to mitigatethe impact of free radicals."	We have revised (Page 1).
2.	"The correlation analysis between heavy metal concentrations and antioxidant activity indicates that as heavy metal concentrations increase, antioxidant activity and total phenol content also increase." can be written as "Correlation analysis shows that higher heavy metal concentrations correspond to increased antioxidant activity and total phenol content."	We have revised (Page 1).
3.	Instead of Pb values of 0.67 ± 0.16 -18.70 ± 0.48 mg / kg and Cu values of 3.39 ± 0.20 - 6.07 ± 0.37 mg / kg, write Pb values of 0.67 ± 0.16 to 18.70 ± 0.48 mg/kg and Cu values of 3.39 ± 0.20 - 6.07 ± 0.37 mg/kg for clarity.	We have revised (Page 1).
4.	In the sentence:"The results of sediment pollution assessment for heavy metals Pb and Cu at Igeo < 0, $1 < Cf < 3$, and PLI 0-2." Define Igeo, Cf, and PLI for readers unfamiliar with these indices. "BCF < 1" should be clarified: Does this mean bioaccumulation is low?	We have revised the sentence to define Igeo, Cf, and PLI for better clarity, as well as to explain that BCF < 1 indicates low bioaccumulation, meaning that the mangrove species studied function more as excluders rather than accumulators of Pb and Cu (Page 1).
5.	The Pearson correlation analysis result should be explicitly stated (e.g., $r = X$, $p < 0.05$).	We acknowledge the importance of providing statistical details for clarity. However, given that all correlation values (r) in our analysis are nonzero ($r \neq 0$), we initially summarized this in the abstract to avoid excessive numerical data. To ensure transparency while maintaining conciseness, we have now revised the abstract to include a representative correlation value (e.g., $r \neq 0$, $p < 0.05$) while keeping the full

		statistical details within the results section (Page 1).
6.	Some sentences are long and could be more concise for better readability. Example: "Several previous studies reported that human activities that occur in coastal areas involve various industrial sectors such as fertilizer processing, oil and gas, fiberboard, and crude palm oil." Suggestion: "Previous studies report that industrial activities like fertilizer processing, oil and gas, and crude palm oil production contribute to coastal pollution."	We have revised (Page 1)
7.	Some references are inconsistently formatted, e.g., [8,[9][10] instead of [8,9,10].	We have revised (Page 3).
8.	Some citations lack integration into the sentence structure. Instead of "According to [15]...", it should be "According to Smith et al. (2015)..."	We have revised
9.	"making them valuable indicators for assessing pollution levels in coastal waters [18,19]. Their ability to absorb and store these pollutants..." (Consider merging these two sentences for smoother flow.)	We have revised (Page 3).
10.	The introduction lacks a clear research gap. What specific knowledge gap does this study address that hasn't been explored before?	We have added aspects to the gaps that existed in previous studies which only studied the heavy metal content in mangroves without considering their physiological responses. Apart from that, this research also uses two types of mangroves and two different regional conditions, which is innovation and novelty in this research (Page 4).
11.	"Leaves sampling" should be "Leaf Sampling" for consistency with "Sediment Sampling."	We have revised (Page 5).
12.	"Sediment grain size measurement" should be "Sediment Grain Size Analysis" to match scientific terminology.	We have revised (Page 7).

13.	"This area was selected due to the significant accumulation of heavy metals resulting from industrial activities along the Musi River." could be written as "This area was chosen due to the high accumulation of heavy metals from industrial activities along the Musi River."	We have revised (Page 5).
14.	"Additionally, sediment substrate types (gravel, sand, silt, and clay) were identified using Shepard's triangle analysis, which was processed with Microsoft Excel V.2021." could be written as "Sediment types (gravel, sand, silt, and clay) were classified using Shepard's triangle analysis and processed with Microsoft Excel V.2021."	We have revised (Page 7).
15.	Ensure all formulas are formatted correctly. For example, Igeo's formula should be written properly in LaTeX or inline notation.	We have revised the text to ensure that all formulas are now written correctly using inline notation (Page 8,9,10).
16.	Ensure units are consistently reported (e.g., ppm, µM, µg/ml).	We have revised
17.	Figures and tables should be directly referenced within the text. Example., "Figure 2 shows the morphological differences between A. alba and E. agallocha" instead of "These differences are particularly evident in their leaf types (Figure 2) "	We have revised (Page 12).
18.	Table 2 should be described with more interpretation rather than just restating numbers.	We have revised Table 2 as per your suggestion by adding more interpretation and contextualizing the data. Rather than merely restating the numbers, we have now provided an analysis that discusses the implications of the sediment fractions and grain size in both the industrial area and conservation zone (Pag 16).
19.	In Table 3, use "Station" instead of "St." for clarity.	We have revised (Page 18).
20.	Strengthen the discussion by comparing findings with similar studies. This will help	We have incorporated similar studies in the discussion to strengthen the

	validate your results and provide broader ecological relevance.	findings (In page results and discussion).
21.	The increase in Cu levels is mentioned but not fully explained. What anthropogenic activities specifically contribute to this? Providing more context will enhance the scientific argument.	We have revised the sentence to provide clearer context on the anthropogenic activities contributing to Cu level increases. Specifically, we have included references to ship hull cleaning and the use of Cu-coated nets in fisheries, which are known to release Cu into the marine environment (Page 19).
22.	The bioaccumulation factor (BCF), geoaccumulation index (Igeo), contamination factor (Cf), and pollution load index (PLI) are mentioned, but their ecological implications are unclear. Briefly explain what these values indicate in relation to contamination risk. Compare these index values with other mangrove ecosystems to provide context on pollution levels.	We have clarified the ecological implications of the bioaccumulation factor (BCF), geoaccumulation index (Igeo), contamination factor (Cf), and pollution load index (PLI) in our manuscript. The higher BCF values suggesting greater ecological risk, particularly for toxic metals like Cu. The geoaccumulation index (Igeo) reflects sediment contamination levels, with high values indicating significant anthropogenic input and potential long-term ecological risks, particularly for Pb. The contamination factor (Cf) highlights the relative pollution risk, with higher values for Pb in industrial areas suggesting greater susceptibility to pollution compared to Cu. The pollution load index (PLI) provides an overall assessment of pollution, with higher values in industrial areas indicating elevated contamination. Comparisons with other mangrove ecosystems have also been presented (Page 22-23).
23.	The study states that the area is "not polluted" based on the PLI but also suggests potential bioaccumulation risks. This needs clarification.	We have revised the paragraph to clarify the distinction between the PLI classification and the potential bioaccumulation risks. While the PLI indicates that the area is "not polluted" based on sediment contamination

		levels, it does not fully account for the bioavailability and potential uptake of heavy metals by aquatic organisms. Even at relatively low sediment concentrations, metals like Cu and Pb can accumulate in biota over time, posing ecological risks (Page 23).
24.	Recommend future monitoring frequency and how this data could inform environmental policies.	We have added the recommended section regarding future monitoring and its implications for environmental policies in the final paragraph of the discussion (Page 36).

Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

Rozirwan[1*], Nadila Nur Khotimah[2], Wike Ayu Eka Putri[1], Fauziyah[1], Riris Aryawati[1], Gusti Diansyah[1], Redho Yoga Nugroho[1]

[1]Department of Marine Science, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya, Indralaya 30862, South Sumatra, Indonesia

[2]Environmental Management Study Program, Graduate Program, Universitas Sriwijaya, Palembang 30139, Indonesia

*Corresponding author's e-mail : rozirwan@unsri.ac.id

Abstract

Heavy metal contamination from industrial activities in coastal regions can lead to pollution in mangrove ecosystems. Mangroves produce antioxidant compounds to mitigate the impact of free radicals. ~~Mangroves can mitigate the impact of free radicals by producing antioxidant compounds~~This study aimed to analyze the correlation between the concentration of heavy metals Pb and Cu and antioxidant activity in *Avicennia alba* and *Excoecaria agallocha* mangroves from areas affected by industrial activities and conservation areas, Banyuasin, South Sumatra, Indonesia. This study was conducted in September 2023 with sampling locations in the Payung Island area and the Barong River conservation area, Berbak Sembilang National Park. The samples taken included sediment and mangrove leaves. The concentration of heavy metals Pb and Cu was measured by atomic absorption spectrometry. Antioxidant activity test using the DPPH test, total phenol using the Folin-Ciocalteu method, and phytochemical profile screening using GCMS. Statistical analysis of the correlation between antioxidant activity and heavy metal concentration using the Pearson correlation. The results showed that the highest concentration of heavy metals in sediment and mangrove leaves was found in the area affected by industrial activity, with a range of Pb values of 0.67 ± 0.16 to 18.70 ± 0.48 mg/kg and Cu values of 3.39 ± 0.20 to 6.07 ± 0.37 mg / kg. The results of sediment pollution assessment for heavy metals Pb and Cu at Igeo < 0 indicates uncontaminated, 1 < Cf < 3 indicates low contamination, and PLI 0-2 indicates not polluted. While the results of heavy metal bioaccumulation in leaves were BCF < 1, indicates low bioaccumulation. *E. agallocha* leaves from the Pulau Payung area showed very strong antioxidant activity of 21.63 µg/ml, and the highest total phenol content reached 398.80 mg GAE/g. Analysis of compounds with the highest antioxidant activity identified the presence of esters, aldehydes, alcohols, fatty acids, glycosides, flavonoids, terpenoids, and steroids. Correlation analysis shows that higher heavy metal concentrations correspond to increased antioxidant activity and total phenol content (r ≠ 0)~~The correlation analysis between heavy metal concentrations and antioxidant activity indicates that as heavy metal concentrations increase, antioxidant activity and total phenol content also increase~~. These findings are expected to contribute to scientific knowledge that enhances environmental sustainability, supporting effective management of coastal natural resources.

Keywords: Biomarkers, conservation zones, heavy metals, industrial activities, mangrove

Introduction

Coastal areas are transitional areas between land and sea that have abundant biodiversity and unique ecosystems [1,2]. Coastal areas face great pressure from various anthropogenic activities that can cause pollution [3,4]. Previous studies report that industrial activities like fertilizer processing, oil and gas, and crude palm oil production contribute to coastal pollution..

Several previous studies reported that human activities that occur in coastal areas involve various industrial sectors such as fertilizer processing, oil and gas, fiberboard, and crude palm oil [3,5,6]. In addition, there are also agricultural activities, ports, shipping, loading and unloading of coal raw materials and their products, and households [7]. Continuous anthropogenic activities in coastal areas can produce pollutants, such as microplastics, heavy metals, as well as various organic and inorganic contaminants [8, 9, 10]. Among various pollutant types, heavy metals are categorized as persistent pollutants due to their resistance to decomposition [11]. Heavy metals initially present in the water column gradually settle to the sediment and eventually accumulate in aquatic organisms [12]. This condition may have adverse impacts, particularly if it exceeds environmental quality standards. These adverse impacts can affect aquatic ecosystems, including mangroves [13,14]. According to Xu et al. (2024) , as the largest plant community in coastal areas, mangroves are also directly affected by pollution.

Mangrove ecosystems play a vital role in coastal protection, supporting biological diversity, and contributing to the socio-economic development of local communities [16,17]. Additionally, their capacity to accumulate pollutants makes them valuable indicators for assessing pollution levels in coastal waters, as they can absorb and store these pollutants in their tissues, enhancing their role in monitoring environmental health [18,19, 20]. Additionally, mangroves possess the capacity to accumulate pollutants, making them valuable indicators for assessing pollution levels in coastal waters [18,19]. Their ability to absorb and store these pollutants in their tissues enhances their role in monitoring environmental health [20]. Roots and leaves are important parts of mangroves in the absorption, accumulation, and response to pollutants [21]. Roots are the first part exposed to pollutants from their growth media. Furthermore, roots also have the ability to translocate pollutants to the leaves. Leaves are the primary site for photosynthesis in plants, supplying the energy essential for cell development, and overall plant function [22]. High concentrations of pollutants in roots and leaves can potentially increase excessive reactive oxygen species (ROS), resulting in oxidative stress in mangroves [23,24]. Oxidative stress arises from an imbalance between ROS production and detoxification, potentially leading to harmful cellular damage [25,26]. Although oxidative stress can be detrimental, plants also have a resistance response mechanism against free radicals [27]. This process involves producing antioxidant enzymes and molecules to counteract the harmful effects of free radicals. In response to environmental changes, plants enhance the activity of antioxidant defenses, including both enzymatic and non-enzymatic components such as superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), glutathione peroxidase (GPx), and phenolic compounds. These antioxidants serve as protective mechanisms against various environmental stress [28,29].

Research on the specific physiological adaptations of various mangrove species to pollutants is still limited. Most previous studies only focused on the accumulation of heavy metals in mangroves without exploring in depth the biochemical defense mechanisms they employ [30, 31, 32]. However, studies on how different mangrove species respond to industrial pollution in environments with varying levels of pollution have not yet been conducted. In addition, most studies only examine one mangrove species without comparing the adaptability of different species in the face of heavy metal contamination [33, 34].

This study aimed to evaluate the accumulation of heavy metals (Pb and Cu) in two mangrove species (*Avicennia alba* and *Excoecaria agallocha*) and assess their antioxidant activity in industrial and conservation zones. The selection of these two species was based on their prevalence in the research location as well as differences in habitat zones and morphological characteristics [35, 36]. This study was carried out in the mangrove ecosystem, which includes areas influenced by industrial activities such as Payung Island as well as conservation areas in the Berbak Sembilang National Park [37, 38].

Field Code Changed

Formatted: Font: Italic

Formatted: Font: Italic

By assessing biomarkers, new insights are provided into how mangrove species adapt to environmental stress caused by heavy metal pollution. Additionally, the research explores the impact of heavy metal contamination on the physiological responses of mangroves, focusing on their biochemical defense mechanisms. The findings aim to enhance understanding of mangrove adaptation strategies in response to pollution and offer valuable implications for coastal ecosystem conservation and environmental pollution management.

Formatted: Indent: First line: 0 cm

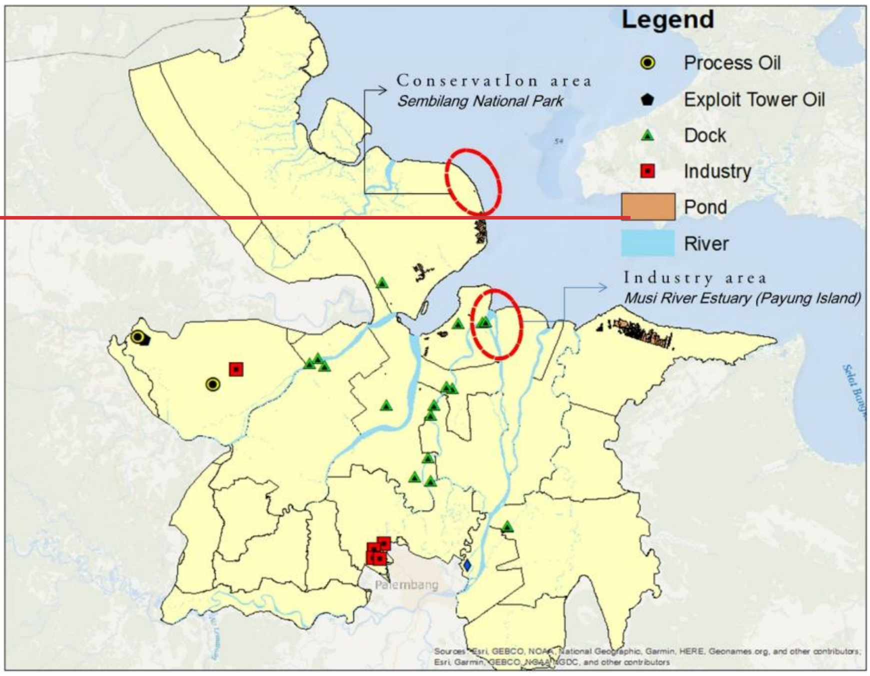
Materials and Method

Leaves Leaf sampling

This study was conducted in September 2023. The samples included *Avicennia alba*, *Excoecaria agallocha*, and sediments collected from industrial and conservation zones in Banyuasin, South Sumatra, Indonesia (Figure 1). The first area is the mangrove ecosystem on Payung Island. This area was chosen due to the high accumulation of heavy metals from industrial activities along the Musi River. This area was selected due to the significant accumulation of heavy metals resulting from industrial activities along the Musi River. Additionally, the area includes agricultural activities, ports, fish ponds, and settlements [39, 40]. The second area is the conservation forest in Sungai Barong, Sembilang National Park, which represents a natural area and protects flora and fauna from the threat of damage, scarcity, or deforestation [41, 42, 43].

Formatted: Font: Italic

Formatted: Font: Italic



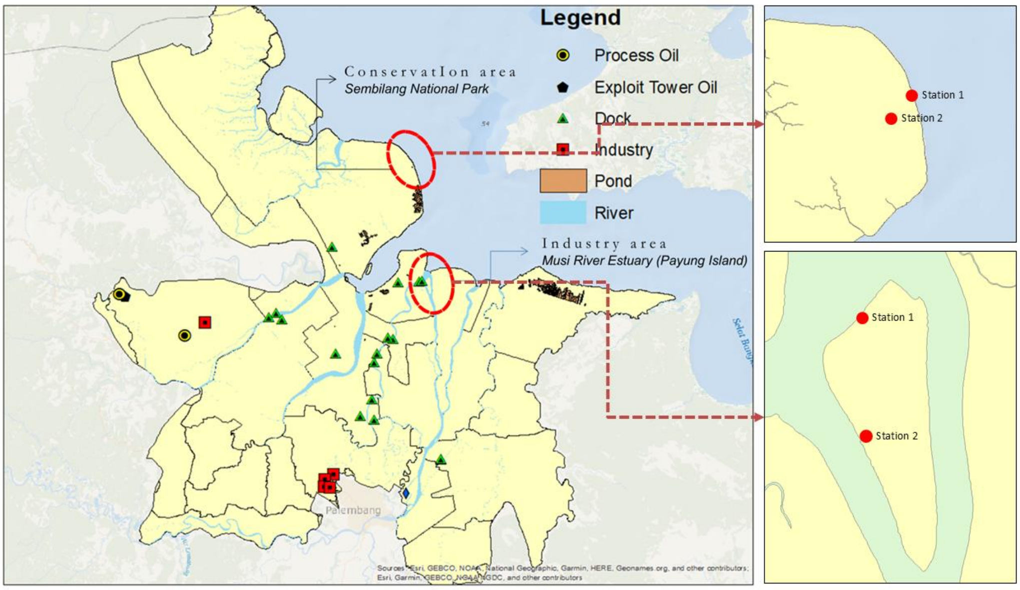


Fig.1. Map of sample collection

The sampling stages include collecting sediment samples and mangrove leaves. Sediment samples were taken as supporting data to determine the concentration of heavy metals in the mangrove growth media. The availability of heavy metals in sediments has a direct effect on the bioaccumulation and biomagnification processes in aquatic organisms. Sediment data helps understand the level of risk and potential impacts to organisms in mangrove ecosystems. Sediment samples were taken using a grab pipe at a depth of ± 10 cm from the surface [44]. Sediment depth shows a very significant impact on heavy metal content, with a greater decrease in heavy metal content as sediment depth increases [45]. amples were taken at three location points for each station, which were considered as replications. Samples were taken compositely together (taken as needed, 500 g) and placed into a polyethylene plastic container and stored in a cool box for analysis in the laboratory.

The method for collecting mangrove leaves taken from the field uses a random sampling method [46]. The random sampling method can be used if the sample studied is homogeneous. The mangrove species taken were *A. alba* and *E. agallocha*. The samples taken consisted of ± 1 kg of leaves and were put in polyethylene plastic.

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Not Bold

Formatted: Indent: First line: 1 cm

Sediment grain size ~~measurement~~ analysis

Grain size analysis was conducted using the sieving and pipetting methods as outlined by [47]. Sediment types (gravel, sand, silt, and clay) were classified using Shepard's triangle analysis and processed with Microsoft Excel V.2021 ~~Additionally, sediment substrate types (gravel, sand, silt, and clay) were identified using Shepard's triangle analysis, which was processed with Microsoft Excel V.2021~~, following the protocols established by [48, 49]. The sediment fraction type was determined by identifying the most dominant composition from the analysis results.

Sample preparation

Sediment sample preparation involved removing foreign objects such as plastic fragments and leaves. The sediment was then air dried at room temperature for 72 hours until fully dry, ground to a homogeneous consistency, and stored in a tightly sealed polyethylene bottle. They were then air-dried in a shaded, well-ventilated area for five days, ensuring indirect exposure to sunlight to prevent the degradation of bioactive compounds. The drying process was conducted at ambient temperature with sufficient airflow to facilitate moisture evaporation. Once dried, the samples were ground into a fine powder and stored in sealed containers for further analysis. The mangrove leaves were first cleaned and then dried in indirect sunlight before grinding. The extraction of heavy metals (Pb and Cu) from the sediment samples and mangrove leaves was performed using the wet destruction method, following the procedures outlined by [8, 50].

Formatted: Font: Not Bold

Formatted: Font: Not Bold

Atomic absorption spectroscopic measurement

Measuring the concentration of heavy metals Pb and Cu using an atomic absorption spectrophotometer with a wavelength of 283.3 nm for Pb and 324.7 nm for Cu.

Formatted: Indent: First line: 1 cm

Determination of heavy metals in leaves and sediments

Determination of sediment pollution

Geoacumulation index (I_{geo})

The Igeo (geo-accumulation index) quantitatively evaluates the degree of heavy metal contamination and classifies the level of pollution based on detailed categorization [51].

$$Igeo = \log_2 (Cn/1.5\ Bn) \quad (1)$$

Formatted: Subscript

$$I_{geo} = \log_2 \left(\frac{Concentration\ heavy\ metals\ in\ sediment}{1{,}5.Background}\right) \quad (1)$$

The classification of Igeo values includes the following categories: uncontaminated (Igeo ≤ 0), uncontaminated to moderately contaminated (Igeo 0–1), moderately contaminated (Igeo 1–2), moderately to highly contaminated (Igeo 2–3), highly contaminated (Igeo 3–4), highly contaminated to very highly contaminated (Igeo 4–5), and very highly contaminated (Igeo ≥ 5) [52].

Contamination factor (Cf)

The contamination factor is determined experimentally as the ratio of the element concentration in the sample to its background concentration [53].

Cf = (Cn/Bn) (2)

Contamination factor (Cf) = $\frac{Concentration\ of\ heavy\ metals\ in\ sediment}{Background}$ (2)

The contamination factor (Cf) classifications are as follows: [54]: Cf < 1 = low contamination; 1 < Cf < 3 = moderate contamination; 3 < Cf < 6 = sufficient contamination; Cf > 6 = very high contamination.

Pollution load index (PLI)

The pollution load index (PLI) is utilized to assess pollution quality in a given area. The pollution load index value uses the formula [55].

PLI = $[\ Cf1\ x\ Cf2\ x\ Cf3 \ldots.\ x\ Cfn]^{1/n}$ (3)

Pollution load index (PLI) = $[\ Cf1\ x\ Cf2\ x\ Cf3 \ldots.\ x\ Cfn]^{1/n}$ (3)

Pollution load index (PLI) criteria: PLI 8-10 = severely polluted; PLI 4-8 = heavily polluted; PLI 2-4 = moderately polluted; PLI 0-2 = not polluted to lightly polluted; PLI < 0 = not polluted.

Bioaccumulation of metal in leaves

Bioconcentration factor (BCF)

The absorption of metals by leaf from sediment occurs through a process known as bioaccumulation. The Bioconcentration Factor (BCF) values are utilized to assess the extent of metal bioaccumulation in mangrove leaf originating from sediment [56].

BCF = (Cn.leaf/Cn. sediment) (4)

$$BCF = \frac{Concentration\ of\ leaf}{Concentration\ of\ sediment} \quad (4)$$

BCF > 1 hyperaccumulator; BCF = 1 indicator; BCF < 1 is an excluder [57].

Analysis of antioxidant non-enzymes in leaves

Antioxidant activity evaluated by DPPH assay

Antioxidant activity analysis was carried out using ethanol solvent based on a method adapted from [58]. A 50 ml 0.1 μM DPPH solution was prepared, followed by the preparation of a sample stock solution and a 10 ml pure ascorbic acid stock solution of 2000 ppm, which was homogenized. Furthermore, a series of solutions were made with concentrations of 1000 ppm, 500 ppm, 250 ppm, 125 ppm, and 62.5 ppm. At each concentration, 1 ml of 0.1 μM DPPH solution was added to the mixture, which was then homogenized and incubated in the dark for 30 minutes. After incubation, the absorbance was measured using a UV-Vis spectrophotometer at a wavelength of 517 nm. The antioxidant activity of the extract is expressed as IC_{50}, which quantifies the strength of its antioxidant capacity (Table 1). The IC_{50} value is calculated using the following formula:

Formatted: Subscript

Formatted: Subscript

$$\%\ inhibition\ inhibisi = \frac{blank\ abs - sample\ abs.}{blank\ abs} \times 100\% \quad (5)$$

The IC_{50} value was derived by inputting the data into a linear regression equation, where the sample concentration was plotted on the X-axis and the percentage of inhibition of antioxidant activity on the Y-axis. The regression equation used is represented as y=ax + b [59].

Table 1

Characteristic value of IC_{50}

Concentration (µg/ml)	Characteristic
<50	Very strong
50-100	Strong
100-150	Moderate
150-200	Low

Determination of phenol content

The analysis of total phenol content in the samples was conducted using the Folin-Ciocalteu method, as outlined in the literature [60, 61, 62]. A standard solution of 1000 ppm gallic acid as much as 50 ml was prepared, then variations in concentrations of 10 ppm, 20 ppm, 30 ppm, 40 ppm, and 50 ppm were made, each as much as 5 ml. For each concentration variation, 1 ml, 2 ml, 3 ml, 4 ml, and 5 ml were pipetted into a 10 ml measuring flask containing a standard solution of 100 ppm gallic acid. A total of 50 mg of sample was weighed, then 2 ml of methanol and 5 ml of distilled water were added, then homogenized in a 10 ml measuring flask. In both the standard series and sample variations, 0.5 ml of 50% Folin-Ciocalteu reagent was added, followed by the addition of distilled water up to the mark. The mixture was then allowed to stand for 5 minutes. Next, one ml of a 5% Na2CO3 solution was added and incubated in a dark place for one hour. After incubation, the absorbance of the sample was measured using a UV-Vis spectrophotometer at a wavelength of 750 nm.

Pearson correlation analysis (*correlation bivariate*)

The use of Pearson correlation analysis (bivariate correlation) is a method used to evaluate the relationship between two variables [63, 64], in this case to see the relationship between antioxidant activity and heavy metal concentrations. This analysis was carried out using SPSS software version 28.

Result and Discussion

Description of mangrove leaves

The mangrove species *A. alba* and *E. agallocha* found at the sampling location exhibit distinct characteristics. Figure 2 shows the morphological differences between *A. alba* and *E. agallocha*. These differences are particularly evident in their leaf types (Figure 2).

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Centred, Indent: First line: 0 cm

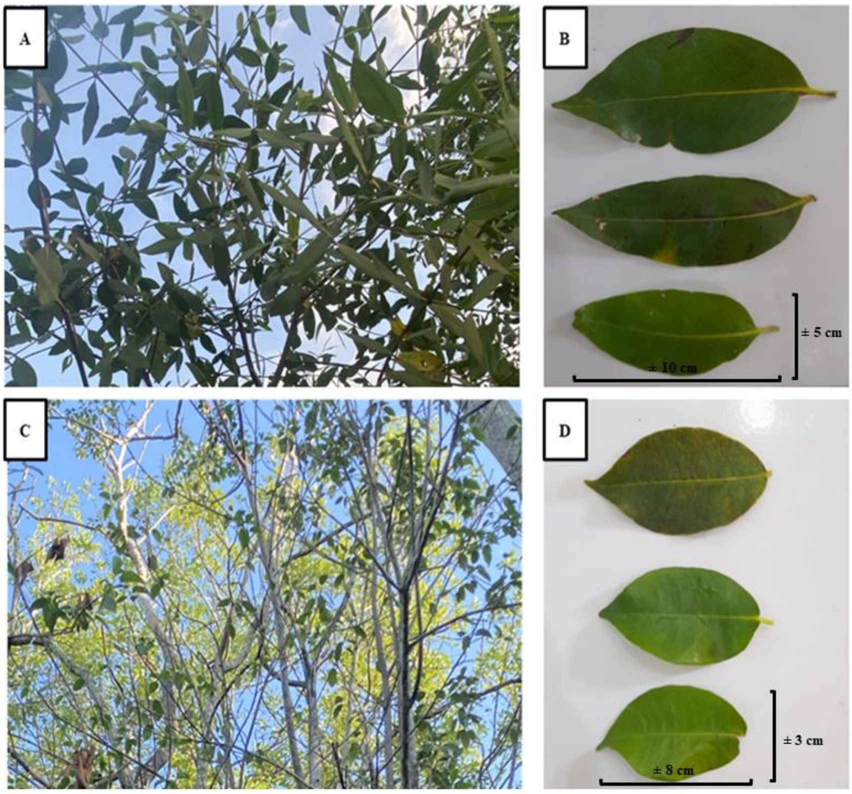


Fig.2. Leaves description. A-B). *A. alba*, C-D). *E. agallocha*

Leaves are the part that characterizes a mangrove species. When identifying each type of mangrove, observation of the morphology of the leaf shape is very important to understand the characteristics and differences in each type of leaf [31, 65]. *A. alba* leaves have a green surface with a smooth and slippery texture, while the underside is yellowish green with a rough texture. The morphology of the leaves is elliptical, almost oval, with a tapered tip. Based on observations, the length of the leaves ranges from 10 to 13 cm, and the width of the leaves ranges from 4 to 5 cm. *E. agallocha* leaves are elliptical and dark green in color, with finely serrated edges and tapered tips. The observed leaf sizes ranged from 8 to 10 cm in length and

3 to 4.5 cm in width. Old leaves were selected as samples for the study of heavy metal content and bioactive compounds due to several considerations related to their maturity and potential accumulation of pollutants and compounds of interest. According to [66], plants tend to produce bioactive compounds in higher amounts in older parts. This could be a plant strategy to protect itself from pests, diseases, or the external environment [67, 68]. Older leaves may have more stable chemical conditions, thus facilitating analysis and minimizing variability in results.

Sediment grain size

The determination of substrate types in the sampling was conducted using the Shepard triangle method (Figure 3). In the mangrove ecosystem of both industrial and conservation areas, sediment substrates were categorized into four types: gravel, sand, mud, and clay. The results indicated that the predominant substrate type in both areas was clay.

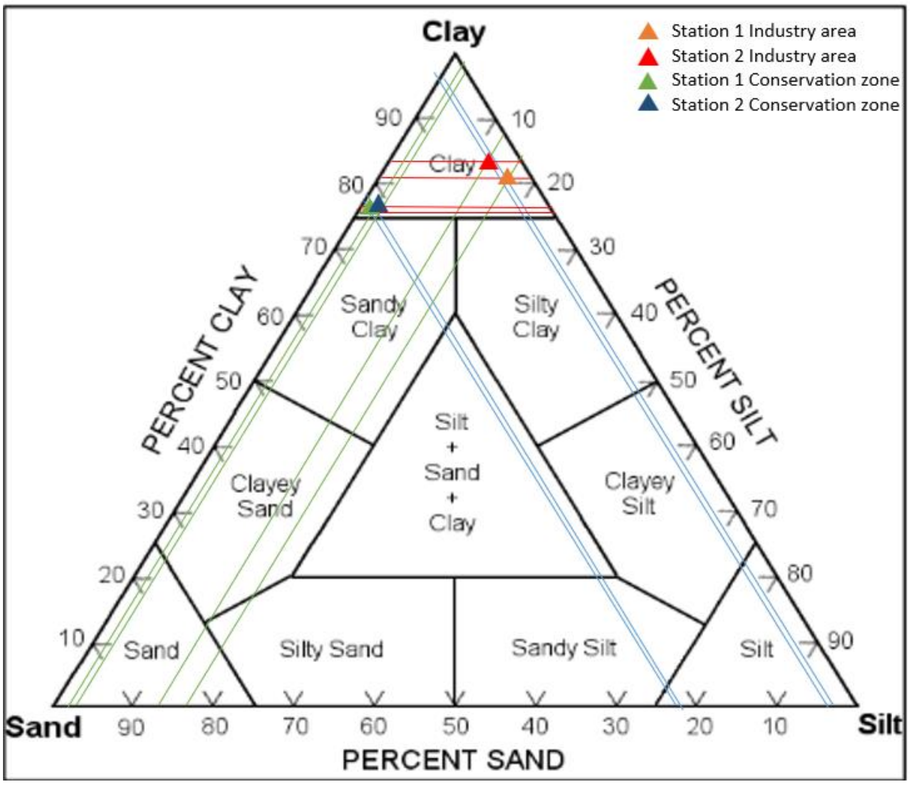


Fig.3. Classifications of sediment type with shepard triangle method

The sediment substrate surrounding the mangrove ecosystem in both areas is predominantly clay, with clay percentages ranging from 80,5% to 84,03%. The highest clay content was observed at station 1 in the industrial area (Table 2).

Tabel 2

Sediment grain size in each station

Location	Station	Sediment fraction (%)				Grain size
		Gravel	Sand	Mud	Clay	

Industry area	St.1 (*A. alba*)	0,00	3,6	12,37	84,03	Clay
	St.2 (*E. agallocha*)	0,00	3,36	16,14	80,5	Clay
Conservation zone	St.1 (*A. alba*)	0,00	22,5	1,95	75,55	Clay
	St.2 (*E. agallocha*)	0,00	21,91	2,02	76,07	Clay

Based on the results of Table 2, distribution of sediment fractions and grain sizes at two different locations, which represents two stations with different mangrove species (*A. alba* and *E. agallocha*). In the industrial area, most of the sediments consist of clay with a very low sand content (3.6% for Station 1 and 3.36% for Station 2), which indicates the predominance of fine materials that can influence the mobility of heavy metals and nutrients in the sediments. In contrast, in the conservation zone, although the sediment composition is still dominated by clay, the sand content is higher (22.5% for Station 1 and 21.91% for Station 2), indicating differences in sedimentation processes and a higher potential for water infiltration.

In the industrial area, both stations (*A. alba* and *E. agallocha*) showed a dominance of clay fractions with a very high percentage. The dominant clay fractions indicate that the sediment in this area consists of fine particles, which may be caused by the accumulation of fine particles from industrial activities around this location. Industries such as fertilizer processing, oil and gas, crude palm oil production, agricultural activities, ports, shipping, loading and unloading of coal raw materials and their products, and households contribute to the presence of fine particles in sediments [3, 5, 6, 7]. Port activities involve frequent vessel movement, dredging, and cargo handling, all of which can resuspend fine particles and increase sedimentation rates [69, 70]. Crude oil processing and petroleum industries may contribute to fine particle deposition through air emissions, which settle via atmospheric deposition [71]. Additionally, agricultural activities, particularly palm oil plantations, can contribute to

Formatted: Font: Times New Roman, 12 pt

Formatted: Font: Times New Roman, 12 pt, Italic

Formatted: Font: Italic

Formatted: Font: Times New Roman, 12 pt, Italic

Formatted: Font: Times New Roman, 12 pt

Formatted: Font: Times New Roman, 12 pt, Italic

Formatted: Font: Italic

Formatted: Font: Times New Roman, 12 pt, Italic

Formatted: Font: Times New Roman, 12 pt

Formatted: Font: +Body (Calibri), English (United increased fine particle accumulation through soil erosion and runoff carrying clay-rich sediments into adjacent water systems, particularly during heavy rainfall [72, 73].

Fine particles such as clay are usually carried by water and can accumulate in areas with slow water movement, such as near mangrove roots [74, 75]. In the conservation zone, the clay fraction also dominates, although with a slightly lower percentage than the industrial area. The conservation zone may also have less influence from human activities, so the sediment pattern is more natural than the industrial area. Clay is a sediment particle with a very fine grain size and a large surface area [76, 77]. Due to its small size and its tendency to be negatively charged, clay has a high adsorption capacity, which allows clay particles to attract and bind heavy metal ions such as Hg, Pb, Cd, Cu, and others [78, 79, 80]. Consequently, sediments dominated by clay fractions tend to accumulate more heavy metals than larger sediment fractions [81, 82].

Determination of heavy metals

The results of the heavy metal concentration analysis for Pb and Cu in sediments and mangrove leaves from both areas are summarized in Table 3. The concentrations of heavy metals, specifically Pb and Cu, in sediments from both the industrial area and the conservation zone exhibit variability; however, they generally remain below hazardous thresholds (ERL, ERM, TEL, and PEL). In the industrial area, the highest Pb concentration was found at Station 2 (18.70 ± 0.48 mg/kg), while in the conservation zone, the highest concentrations of Pb and Cu were each at Station 2 (Pb 14.22 ± 0.16 mg/kg; Cu 5.17 ± 0.17 mg/kg). For metal accumulation in mangrove leaves, Cu was recorded higher than Pb at all stations. In the industrial area, *A. alba* (Station 1) had Pb 0.67 ± 0.17 mg/kg and Cu 3.39 ± 0.20 mg/kg, while *E. agallocha* (Station 2) showed Pb 1.27 ± 0.31 mg/kg and Cu 3.73 ± 0.16 mg/kg. In the conservation zone, the highest accumulation of Cu in mangrove leaves was 3.69 ± 0.23 mg/kg at Station 2.

Tabel 3

Average concentrations of heavy metals (mg/kg) in mangrove sediments and leaves

	Pb	Cu
Sediments		
Station.1 Industry area	12.63±0.01	5.58±0.05
Station.2 Industry area	18.70±0.48	6.07±0.37
Station.1 Conservation zone	12.61±0.32	4.21±0.03
Station.2 Conservation zone	14.22±0.16	5.17±0.17
ERL	46.7	34
ERM	218	270
TEL	30.2	18.7
PEL	112	108.2
Mangrove leaves		
Station.1 Industry area (*A. alba*)	0.67±0.17	3.39±0.20
Station.2 Industry area (*E. agallocha*)	1.27±0.31	3.73±0.16
Station.1 Conservation zone (*A. alba*)	0.84±0.12	3.50±0.35
Station.2 Conservation zone (*E. agallocha*)	0.99±0.37	3.69±0.23

The industrially impacted area in the Musi River Estuary is affected by high anthropogenic activities, making it susceptible to accumulating pollutants, especially heavy metals such as Pb and Cu. Sediments in this area tend to contain higher pollutants than water and biota, influenced by domestic, industrial, and river transportation activities that pollute the environment [83, 84]. Ship and coastal building maintenance activities, including the use of anti-rust materials, electronic waste, and pipe corrosion, are the main sources of Pb, while sources of Cu in the aquatic environment come from antifouling paint, agricultural pesticides, and industrial waste [85, 86]. In addition, previous studies report that cleaning ship hulls can release Cu into the marine environment [87, 88]. Fisheries sector that uses Cu-coated nets to prevent biofouling can also contribute to increasing Cu levels in waters [89, 90].

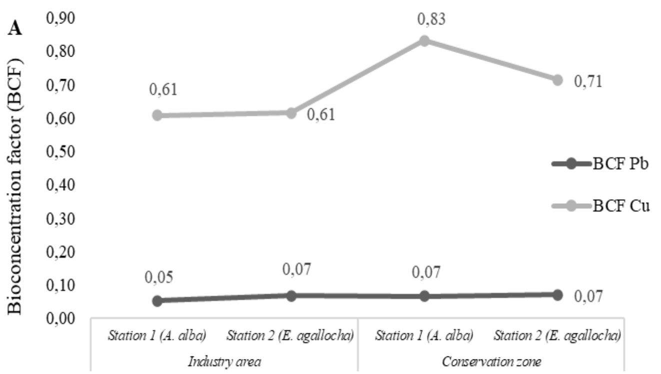
The conservation area in the Barong River is also exposed to heavy metal pollution, although at a lower level, considering that some human activities such as fishing are still ongoing [91]. Unmanaged anthropogenic activities, including unregulated industrial waste disposal, improper wastewater treatment, and uncontrolled agricultural runoff, have contributed to the increasing Cu concentrations observed in both locations, as indicated by the findings of this study and previous research [7, 50]. These activities introduce Cu into the aquatic system, where it binds to suspended particles and accumulates in sediments, further exacerbating environmental pollution.

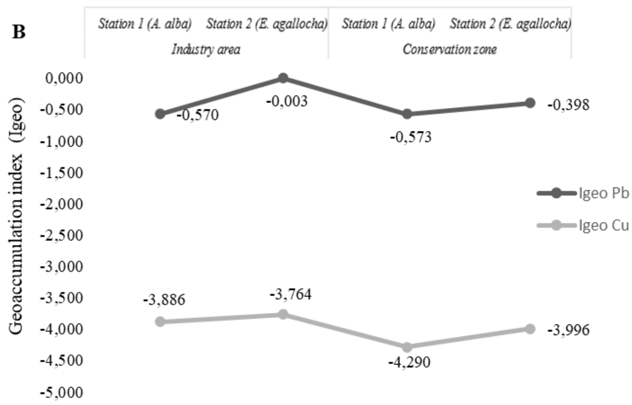
Formatted: English (United States)

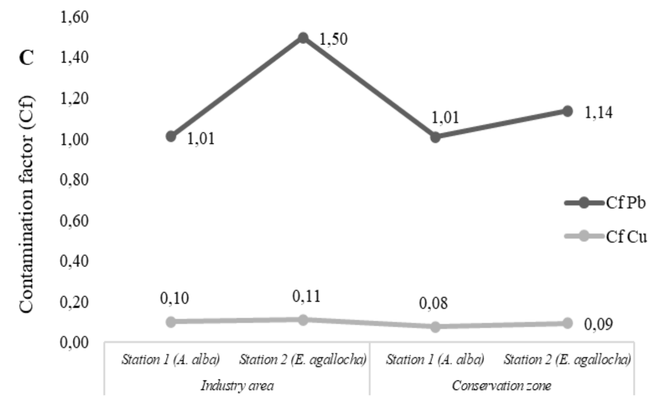
In mangrove leaves, Pb was detected at low concentrations. Plants regulate Pb primarily by limiting its uptake and translocation. Because Pb is a non-essential and highly toxic metal, most of it accumulates in the roots rather than being transported to the leaves [92]. In contrast, Cu an important micronutrient for plants, is regulated through controlled absorption and detoxification mechanisms [93, 94]. Plants manage excess Cu by binding it to metallothionein and phytochelatin, storing it in vacuoles, and activating the antioxidant defense system to fight oxidative stress [95]. Although heavy metal concentrations vary between locations, they are still below the threshold, indicating a relatively low risk of contamination. However, long-term monitoring is essential to track bioaccumulation trends in mangrove ecosystems.

Sediment quality indices

The results of the sediment quality index assessment are summarized in Figure 4. The results of the leaf bioconcentration factor (BCF) in bioaccumulating Pb and Cu metals from sediment with a BCF value <1 indicating low bioaccumulation. The geoaccumulation index shows uncontaminated properties for Pb and Cu with an Igeo value <0 indicating uncontaminated. The contamination factor (Cf) shows that contamination is low and moderate in Pb and Cu with a value of 1 <Cf <3 indicating low contamination. The PLI ranges from 0 to 2 indicating that both areas are not polluted.







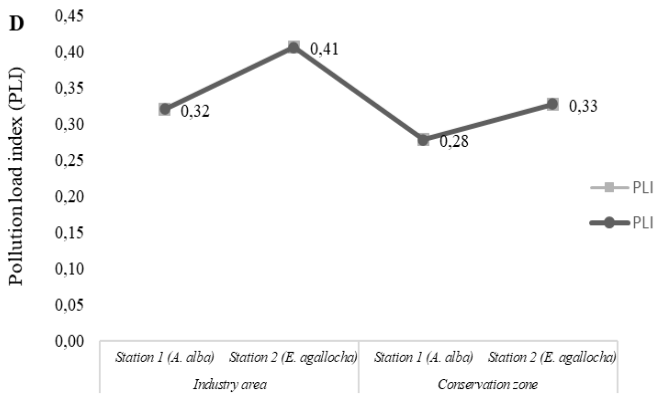


Fig.4. Sediment quality indices. A). Bioconcentration factor (BCF), B). Geoaccumulation index (Igeo), C). Contamination factor (Cf), and D). Pollution load index (PLI).

The difference in bioconcentration factor (BCF) between Cu and Pb can be explained by the chemical properties of each metal. Cu accumulates more easily in biota tissues than Pb. Cu is an essential element for organisms, although at higher concentrations it can be toxic [96]. In contrast, Pb is a non-essential heavy metal that tends not to accumulate much in biota tissues

[97]. The previous studies stated that essential heavy metals are more easily absorbed by organisms because they have physiological mechanisms to regulate the concentration of these elements [98, 99]. Analuddin et al. (2023) have also examined BCF in mangrove ecosystems, with results showing that the BCF values for Hg, Cu, Mn, Pb, and Zn > 1. This finding is thought to be related to the impact of anthropogenic activities in Kendari City, which has a high population density.

The Igeo index shows higher Pb contamination than Cu in industrial areas. Pb is thought to originate from human activities such as ports, agriculture, ship transportation, and household waste that tends to settle in sediments [8, 32]. A high Igeo value indicate an anthropogenic contamination and show sediments contaminated heavy metal [101]. In addition, long-term exposure to these heavy metals can change community structure and disrupt ecosystem function through bioaccumulation and biomagnification in the food chain [102, 103].

The high value of the Pb contamination factor (Cf) in industrial areas indicates that this environment is more susceptible to Pb pollution than Cu. Relevan study by Hasan et al. (2023) that the CF value of Pb (0.76) > Cu (0.68) in core sediment from a mangrove at the Pasur River. Cu is more likely to be bound to organic particles and accumulate in the tissues of benthic organisms, which may explain the lower Cf Cu value. The areas suspected of being polluted tend to have higher anthropogenic activity than conservation zones, which causes significant differences in the levels of contamination and accumulation of heavy metals [105]. Industries around mangrove areas may contribute to elevated levels of heavy metals. Meanwhile, the conservation zone which is relatively protected from industrial activities, shows lower contamination values, although there are still traces of pollution due to remote pollution sources [106, 107].

The PLI value in the industrial area is higher than the conservation zone. This indicates that industrial activities play a role in elevating heavy metal pollution in the area. Industrial areas are usually exposed to pollution sources such as factory waste, air pollution, and surface runoff that carry heavy metals into the sediment [108, 109]. Although both stations are in the same area, there is a difference in the PLI value between Station 1 and Station 2 at both locations. Local factors, including water movement, sediment composition, and proximity to pollution sources, significantly influence the distribution of heavy metals. [110]. The PLI in the conservation zone still shows heavy metal pollution. This could be due to atmospheric deposition from industrial activities in the surrounding area or pollutants carried by water currents from more contaminated areas [111, 112]. This suggests that although the conservation zone has better protection, it is not completely protected from the impacts of nearby industrial pollution.

The study indicate that both areas are classified as not polluted. In line with these findings by Karmakar et al. (2025) , the PLI value in mangrove planting areas due to heavy metals from ship demolition activities is still below 1. Even though the PLI reflects low levels of pollution over time, it can increase the potential for absorption by aquatic organisms and pose ecological risks. therefore, continuous monitoring is required to identify dynamic changes in heavy metal concentrations

Antioxidant non-enzyme activities

The results of percentage of depreciation data for the *A. alba* species taken from the industrial area were 66%, and the conservation zone was 65.8%. While for the *E. agallocha* species from the industrial area it was 68.5% and the conservation zone was 67.9% in the conservation zone. Conversely, the findings of the percentage of dry weight of *A. alba* in the industrial area were 34%, and the conservation zone was 34.3%. In the *E. agallocha*, the percentage of dry weight in the industrial area was recorded at 31.5% and the zone was 32.1% (Table 4).

Table 4

Depreciation percentage of weight

Location	Sample leaves	Sample weight (g)		Depreciation percentage (%)	Weight percentage (%)
		Wet	Dry		
Industry area	*A. alba*	800	272	66	34
	E. agallocha	800	252	68.5	31.5
Conservation zone	*A. alba*	800	274	65.8	34.3
	E. agallocha	800	257	67.9	32.1

The removal of water content from the sample can be achieved by drying it until all moisture is eliminated, as the presence of water can influence the stability of bioactive compounds during extraction. Certain compounds may remain more stable or be less prone to chemical degradation or oxidation in dry conditions. The extraction of leaf samples from *A. alba* and *E. agallocha* was performed using ethanol as the solvent. The results indicated that the extract yield from the *A. alba* leaves was the highest at 8.80%, which was obtained from the conservation area (Table 5).

Table 5

Percentage of etanol extract

Location	Sample leaves	Extract weight (g)		Depreciation percentage (%)	Extract percentage (%)
		Dry powder	Crude extract		
Industry area	*A. alba*	250	22.01	91.20	8.80
	E. agallocha	250	17.33	93.07	6.93

Conservation	*A. alba*	250	13.17	94.73	5.27
zone	*E. agallocha*	250	21.42	91.43	8.57

Based on Table 5, these results indicate that environmental conditions, both in industrial areas and conservation zones, have the potential to affect the weight of crude extracts and the percentage of depreciation of *A. alba* and *E. agallocha* leaves, with the possibility of differences in the composition of bioactive compounds in each location. The maceration and extraction processes are important steps in testing the content of bioactive compounds in samples, especially in separating compound components from mangrove extracts [114]. The use of solvents such as ethanol, which are amphipathic, allows the dissolution of both polar and nonpolar compounds, so that it is optimal for obtaining various bioactive compounds from mangroves, which contain various types of compounds with these properties [115, 116, 117]. A high percentage of extraction weight indicates the effectiveness of the extraction method, indicating the method's ability to obtain active compounds from the sample optimally [118]. High extraction results also indicate a high content of active compounds in the sample, which possess the capability to have biological value and other practical applications [119].

The potential antioxidant content is illustrated by the percentage value of free radical scavenging inhibition along with the IC_{50} value. The results of the antioxidant test on mangrove leaves using the DPPH radical scavenging method using ethanol solvent (Table 6). The IC_{50} value content in the industrial area for *A. alba* of 137.8 µg/ml is classified as a moderate and *E. agallocha* of 21.63 µg/ml is classified as a very strong. While in the conservation area, *A. alba* of 64.32 µg/ml is classified as a strong and *E. agallocha* of 41.43 µg/ml is also classified as a very strong.

Formatted: Subscript

Formatted: Subscript

Table 6

Classification of IC_{50}

Location	Sample leaves	Linear regression a	b	R^2	IC_{50} (µg/ml)	Category
Industry area	*A. alba*	36,277	128,7	0,9429	137,8	Moderate
	E. agallocha	30,953	45,165	0,9419	21,63	Very strong
Conservation zone	*A. alba*	28,726	69,611	0,8905	64,32	Strong
	E. agallocha	18,425	18,661	0,904	41,43	Very strong

Formatted: Subscript

The IC_{50} classification results indicate that *A. alba* leaves from both areas fall into the strong-moderate category, while *E. agallocha* is classified as very strong. According to Kodikara et al. (2020) , the difference in the strength of antioxidant activity in each species is thought to be because mangroves have different tolerances to certain environmental conditions, and this can affect the extent to which they can overcome heavy metal toxicity. Previous research explained that the genus Avicennia is a mangrove found in the front zone and directly facing the waters [121]. *Avicennia spp.* has strong and dense aerial roots so that it is able to efficiently capture and bind mud and various pollutants carried by water [122, 123]. As a type of plant that is periodically submerged in water, the roots of mangroves are able to take, absorb, or reduce contaminants through the dilution process [124, 125]. Therefore, it is hypothesized that contaminants absorbed by roots do not induce excessive oxidative stress and do not increase the production of secondary metabolites.

Formatted: Subscript

Another study in the Island of Weno area, Chuuk State of Micronesia, for the antioxidant activity of *Rhizophora stylosa* roots was 41.3% and *Sonneratia alba* 40.7% [60]. While the IC_{50} value of the *E. agallocha* in both areas is included in the high category. *E. agallocha* in this study was found in the ladward zone. This zone is rarely submerged by seawater and is more often affected by lower tides. This is thought to be the cause of the low water content in the leaves of *E. agallocha* as presented in Table 4, so that the pollutants absorbed are greater and last longer in the leaves. Therefore, the roots act to mitigate stress effectively by producing antioxidant activity [126]. The concentration of antioxidant activity (IC_{50}) in the leaves showed different values in the two areas. The differences that occur in the ability to produce antioxidant activity in each mangrove as a form of self-defense against oxidative stress are due to differences in morphology, habitat, tides, sediment substrates, and environmental conditions [127, 128]. Differences in IC_{50} classification results can reflect differences in the level of heavy metal exposure in the two locations.

In addition to testing antioxidant activity using the DPPH method, this activity can also be analyzed by calculating total phenol. Measuring the total phenol content is done by adding Folin-ciocalteu reagent to the solution sample being tested (Table 7). Phenols possess antioxidant properties that play a role in protecting plant tissues from damage induced by free radicals. Therefore, the total phenol test can provide information about the potential antioxidant activity of mangrove leaf extracts. In this study, the highest quantitative phenol value was found in *E. agallocha* at 398.80 mg GAE/gr from the industrial area and the smallest in *A. alba* at 21.85 mg GAE/gr from the conservation forest area.

Table 7

Total phenol of mangrove leaves extract

Location	Sample leaves	Phenol (mg GAE/g)
Industry	*A. alba*	36.68
	E. agallocha	398.80
Conservation	*A. alba*	21.85
	E. agallocha	320.44

The total phenol obtained in this study has a positive relationship with antioxidant activity, as indicated by the IC_{50} value in Table 7. The antioxidant activity of this mangrove is influenced by its total phenol content. The total phenol content is positively correlated with antioxidant activity, where the higher the total phenol content, the higher the antioxidant activity in the sample [129]. Based on this study, *A. alba* has a lower total phenol content than *E. agallocha*, which is strongly suspected due to differences in environmental factors. Mangroves in the pioneer zone more pressure from pollutants and the physicochemical conditions of the habitat. This is in line with previous findings, where the total phenol content in the roots of *A. marina* in the pioneer zone was 26.11 mg GAE/g, lower than *B. gymnorrhiza* in the landward zone with 344.02 mg GAE/g [130]. Mangrove ecosystems located in the pioneer zone tend to have special adaptations to survive in coastal environments that are often inundated by sea tides [131, 132]. Mangroves mitigate pollutants by reducing their concentration and toxicity through internal water content regulation, preventing excessive accumulation of absorbed contaminants [133]. According to Laoué et al. (2022)], non-enzymatic antioxidant activity is not produced exclusively because there is a certain limit for excess free radicals. However, the non-enzymatic antioxidant system is usually activated when free radical levels or oxidative stress exceed normal defense capacity [26].

GC-MS analysis using *E. agallocha* mangrove leaf samples from industrial areas because they are included in the IC_{50} classification is very strong among others. The graph revealed 15 peak points identifying compounds such as flavonoids, lipids, glycosides, glucosinolates, glucose, esters, terpenoids, and fatty acids (Figure 5). The identified compounds, based on chromatogram peak heights and mass spectra from the analysis, match those in the WILEY 7 database library (Table 8).

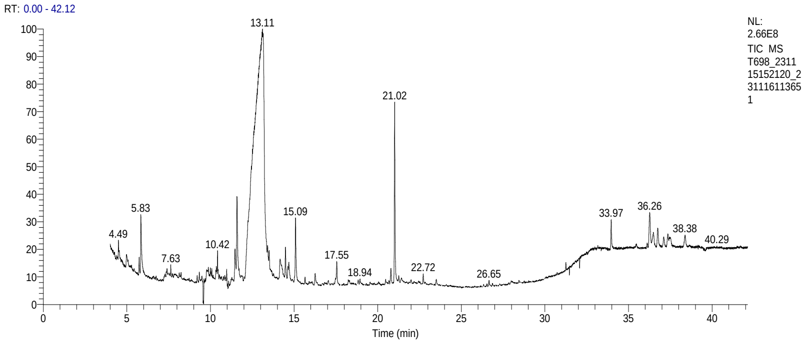


Figure 5. GC-MS chromatogram of bioactive compounds in mangrove leaves E. agallocha (Industry area)

Table 8

Retetion time, peak area, -compound name, formula, and compound group (Daun *E. agallocha*)

Ret. time	*Peak Area %*	Compound name	Formula	Compound group
5.84	2.45	4H-Pyran-4-one, 2,3-dihydro-3,5-dihydroxy-6-methyl	$C_6H_8O_4$	Flavonoid
9.49	1.68	2-Myristynoyl pantetheine	$C_{23}H_{45}N_2O_4S$	Lipid
9.77	1.65	Paromomycin	$C_{23}H_{45}N_5O_{14}$	Glikosida
9.87	1.17	2-Myristynoyl pantetheine	$C_{23}H_{45}N_2O_4S$	Lipid
11.46	1.16	Desulphosinigrin	$C_{11}H_{21}NO_9S_2$	Glukosinolat
11.59	3.31	2-O-Methyl-D-mannopyranosa	$C_7H_{14}O_6$	Glikosida

Formatted: Font colour: Auto

13.10	73.97	3-O-Methyl-d-glucose	$C_7H_{14}O_6$	Glukosa
14.16	1.84	3-O-Methyl-d-glucose	$C_7H_{14}O_6$	Glukosa
14.48	0.99	7-Methyl-Z-tetradecen-1-ol acetate	$C_{17}H_{34}O_2$	Ester
14.69	1.05	9-Octadecenoic acid, (2-phenyl-1,3-dioxolan-4-yl)methyl ester, trans-	$C_{28}H_{44}O_4$	Ester
15.09	2.29	2,6,8-Trimethylbicyclo[4.2.0]oct-2-ene -1,8-diol	$C_{11}H_{18}O_2$	Terpenoid
17.55	0.98	Hexadecanoic acid, methyl ester	$C_{17}H_{34}O_2$	Asam lemak
21.01	4.87	Phytol	$C_{20}H_{40}O$	Terpenoid
33.97	0.94	9-Desoxo-9-x-acetoxy-3,8,12-tri-O-ac etylingol	$C_{21}H_{30}O_9$	Glikosida
36.27	1.65	1-Monolinoleoylglycerol trimethylsilyl ether	$C_{21}H_{44}O_4Si$	Ester

Formatted: Font colour: Auto

Formatted: Font colour: Auto

Based on Table 8, 8 groups of compounds were found. The groups of compounds that are thought to be formed in response to the environment that increases antioxidant activity, such as flavonoids, lipids, glycosides, glucosinolates, glucose, esters, terpenoids, and fatty acids. The compound 4H-Pyran-4-one, 2,3-dihydro-3,5-dihydroxy-6-methyl found in these leaves is classified as a flavonoid. Flavonoids are specialized metabolites commonly found in plants, serving multiple functions such as defense and signaling, particularly under stress conditions [135]. Flavonoids are categorized into several groups, including chalcones, aurones, flavanonols, flavones, isoflavones, flavanols, flavonols, anthocyanins, proanthocyanidins, and leucoanthocyanidins. They can exist as aglycones, glycosides, and methylated derivatives. The compounds 2-Myristynoyl pantetheine and 2-O-Methyl-D-mannopyranose are classified as lipids. Lipid compounds can exhibit antioxidant activity, especially through mechanisms involving phenols and other structures that modulate oxidative stress and lipid peroxidation processes [136].

The compounds Paromomycin, 2-O-Methyl-D-mannopyranose, and 9-Desoxo-9-x-acetoxy-3,8,12-tri-O-ac etylingol are classified as glycoside compounds. Based on the results of the study of Yang et al. (2018), flavonoid glycosides are widely distributed in plants, where they function as phytoalexins to combat biotic stress. Desulphosinigrin is a glucosinolate known to exhibit anticancer and antimicrobial properties [138]. 4-methylsulfinylbutyl glucosinolate is a glucosinolate derived from the amino acid methionine, which has antioxidant, antifungal, and antimicrobial activities [139]. The compounds 7-Methyl-Z-tetradecen-1-ol acetate, 9-Octadecenoic acid, (2-phenyl-1,3-dioxolan-4-yl) methyl ester, trans-, and 1-Monolinoleoylglycerol trimethylsilyl ether are classified as esters. Clearly show that ester groups with different aromatic and alkyl chains will increase antioxidant capacity. e compound 2-[4-methyl-6-(2,6,6-trimethylcyclohex-1-enyl)hexa-1,3,5-trienyl]cyclohex-1-en-1 carboxaldehyde is categorized as an aldehyde. This type of compound is commonly found in various essential oils and contributes a distinctive aroma to certain plants. Several phenolic aldehydes and derivatives have antioxidant activity [140].

Compounds 2,6,8-Trimethylbicyclo[4.2.0]oct-2-ene -1,8-diol and phytol belong to the terpenoid compound group. Terpenoids are promising lead compounds for further structural modification and optimization because of their potent anti-inflammatory effects [141, 142].

Terpenoids (such as monoterpenes and carotenoids) and polyphenols (such as quercetin and other flavonoids) are important phytochemicals with various antioxidant effects [143]. Hexadecanoic acid, methyl ester compounds are classified as fatty acid compounds. Fatty acids have been found to be associated with various biological activities such as anti-inflammatory, antioxidant, antifeedant, antimicrobial, and neuroprotective [144]. While compounds that have no relationship with antioxidant activity are the glucose compound group found in leaf extracts. Glucose produced through photosynthesis and other carbohydrate processes can be used as an energy source to maintain cell vitality [145].

Correlation of heavy metal concentrations and biomarkers

The relationship between heavy metal concentrations and antioxidant activities in mangrove leaves in both areas using Pearson correlation analysis, which begins with assumption testing (Table 9). The test results were obtained for all variables with significance > 0.05, and if the skewness and quasi-sequence ratios are in the range of -1.96 and +1.96, it can be concluded that the data distribution is normal.

Table 9

Assumption test results

Sample	Variable	Mean	St.Dev	*Sig.2 tailed*	Skewness Kurtosis	Values
Leaves	Pb	0.94	0.12	0.927	0.55 dan 0.55	Normal
	Cu	3.57	0.080	0.498	0.33 dan 1.35	Normal
	IC50	66.35	25.19	0.457	1.31 dan 0.69	Normal
	Total Phenol	194.44	193.48	0.182	0.13 dan 1.93	Normal

Based on the results of the assumption test, the normal distribution of the data can explain that the statistical parameters used in the correlation analysis provide an accurate picture of the center and distribution of the data. Furthermore, the results of the Pearson correlation test (r) and the coefficient of determination (Kd) are summarized in Table 10.

Formatted: Indent: First line: 1 cm

Table 10

Results of the Pearson correlation test (r) and coefficient of determination (Kd)

Sample	Variable (X-Y)	r	Kd (%)	Interpretation
Leaves	Pb – IC_{50}	-0.906	82.08	Strong correlation
	Cu – IC_{50}	-0.937	87.79	Strong correlation
	Pb – Total Phenol	0.904	81.72	Strong correlation
	Cu – Total Phenol	0.949	90.06	Strong correlation

The results of the correlation test is a significant correlation or relationship between heavy metals and physiological responses ($r \neq 0$). The relationship between Pb and Cu to antioxidant activity in mangrove leaves produced from both areas has a very high negative correlation direction of -0.906 and -0.937. The relationship between Pb and Cu to total phenol in leaf samples is also very strong, with a very high positive correlation value of 0.904 and 0.949. In addition, the percentage of the determination coefficient (Kd) indicates that variables X and Y have a strong relationship. The Kd value of mangrove leaf samples ranges from 81.72% to 90.06%. This indicates that most of the variations in IC_{50} and total phenol can be explained by the Pb and Cu variables in both types of samples.

A high correlation indicates a strong relationship between the variables concerned and significantly supports the hypothesis. A negative relationship with IC_{50} indicates that the higher the concentration of Pb or Cu, the lower the IC_{50} value (higher antioxidant potential). A positive relationship with total phenol indicates that the higher the concentration of Pb or Cu, the total phenol content also increases. Furthermore, the results of GCMS screening also showed the presence of compounds such as flavonoids, lipids, glycosides, glucosinolates, glucose, esters, terpenoids, and fatty acids. Previous studies have shown that some of these compounds, especially the flavonoid and terpenoid groups, have significant antioxidant activity [146]. Therefore, increasing concentrations of heavy metals can indirectly affect the profile of secondary metabolite compounds in mangrove plants, which in turn can affect antioxidant activity and response to oxidative stress. Excessive concentrations of heavy metals cause the formation of ROS and affect the activity of antioxidants involved in plant metabolism [147]. According to Georgiadou et al. (2018), detoxification of ROS due to heavy metal contamination by producing antioxidant enzymes plays a central and vital role in protection in mangrove species.

In line with the research by [149], that under abiotic stress conditions, such as heavy metal contamination, the production of reactive oxygen species (ROS) increases in plants, resulting in the induction of oxidative stress, and plants initiate antioxidant production that significantly delays or prevents oxidative stress. According to Angon et al. (2024) , secondary metabolite compounds are involved in plant responses to biotic and abiotic stresses and contribute significantly to the antioxidant activity of plant tissues. Antioxidant activity is a common approach used to increase heavy metal tolerance, strengthening the defense system against oxidative stress [151, 152]. Several previous studies have found a relationship between heavy metal pollution and the physiological response of plants, especially mangroves. The decline in sediment quality due to heavy metal pollution in a gradual pattern that has the potential to have a negative impact on the biogeochemical cycle, with potentially fatal consequences for the survival of biodiversity (*A. marina*) [153] . Furthermore, the results of the study by Ghosh et al. (2021) also stated that there was a statistically significant relationship between the activity of antioxidant enzymes, photosynthetic pigments, and heavy metal contamination, resulting in the biotic response of riparian mangroves characterized by reduced photosynthetic pigments (chlorophyll a and b) and increased activity of antioxidant stress enzymes (POD, CAT, and SOD). The response of two tropical medicinal plant species to heavy metal accumulation can increase hydrogen peroxide (H_2O_2) activity, malondialdehyde content, enzymatic activity, and nonenzymatic antioxidants [154].

Mangroves cause trigger antioxidant defenses to overcome heavy metal absorption and normalize excessive production of oxidative stress mediated by reactive oxygen species (ROS) [155]. However, antioxidant responses in mangroves vary depending on the concentration and type of heavy metals, plant species, and duration of exposure [156]. Previous findings related to plant reactions to higher concentrations of heavy metals in the soil. For example, Kulbat-Warycha et al. (2020) observed that an increase in the concentration of heavy metals (Ni, Cu, Zn) caused a decrease in the concentration of phenols in oregano, which was associated with the induction of severe oxidative stress. According to Mansoor et al. (2023), excessive ROS production due to severe oxidative stress can cause damage to the mitochondrial respiratory chain, uncoupling of oxidative phosphorylation, and mitochondrial death in plants. However, this can also experience a decrease in the antioxidant activity defense system of the mangrove itself if the contamination of absorbed pollutants exceeds the threshold and severe oxidative stress occurs, which can cause damage and death to the mangrove ecosystem [159, 160].

The correlation between heavy metals and antioxidant activity in mangroves illustrates the complex relationship between heavy metal pollution and plant responses to oxidative stress. In this context, high concentrations of heavy metals can trigger ROS production, which in turn affects plant antioxidant activity. Excessive ROS can induce oxidative stress that activates the plant defense system to increase the production of antioxidant compounds. Thus, the relationship between heavy metals and antioxidant activity, total phenols, and secondary metabolite compound profiles in mangroves provides a deeper understanding of the mechanism of the plant's response to heavy metal pollution and oxidative stress. Therefore, if there is an indication that pollutant contamination exceeds the threshold and causes severe oxidative stress, some coastal environmental management policies can be expected in response to these findings.

To ensure the sustainability of mangrove ecosystems and mitigate the impact of heavy metal pollution, routine monitoring is recommended every 3–6 months to capture seasonal variations in heavy metal concentrations and antioxidant responses. Additionally, long-term monitoring (≥5 years) is necessary to identify trends in heavy metal accumulation and its effects on coastal ecosystems. Supplemental monitoring is also advised following specific events, such as industrial waste spills or land-use changes, to assess their immediate environmental impact. The data from this study can serve as a basis for environmental policy development, including updating regulations on heavy metal thresholds in sediments and coastal biota, strengthening conservation and mangrove rehabilitation policies, and improving industrial zone management in coastal areas. Furthermore, these findings can be utilized to raise public awareness about the importance of protecting coastal ecosystems and promoting sustainable resource management practices.

Conclusion

Heavy metal pollution of Pb and Cu resulting from areas affecting industrial and conservation activities has a significant effect on antioxidant activity in mangroves, especially *A. alba* and *E. agallocha*. Sediment pollution assessment showed that the Igeo value was at a low level, while the concentration factor (Cf) and Pollution Load Index (PLI) showed a relatively moderate level of pollution (Cf between 1 and 3, and PLI between 0 and 2). The bioaccumulation value of heavy metals in mangrove leaves was low (BCF < 1), indicating moderate accumulation of heavy metals in leaf tissue. The antioxidant activity of *E. agallocha* leaves from the industrial area was very strong and had the highest total phenol content. The compounds identified as having high antioxidant activity included flavonoids, lipids, glycosides, glucosinolates, glucose, esters, terpenoids, and fatty acids. Correlation analysis showed that increasing heavy metal concentrations were directly proportional to increasing antioxidant activity and total phenol content in mangrove leaves. This study contributes to our understanding of the potential of mangroves to respond to heavy metal exposure through increased antioxidant activity, which can support conservation efforts and sustainable management of coastal natural resources.

Author statement

The authors hereby declare that the work presented in this article is original and that any liability for claims relating to the content of this article will be borne by them.

CRediT authorship contribution statement

Rozirwan: Writing – review & editing, Supervision, Project administration, Conceptualization. **Redho Yoga Nugroho**: Resources, Formal analysis, Data curation. **Nadila Nur Khotimah**: Validation, Resources, Data curation. **Fauziyah**: Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Wike Ayu Eka Putri**: Writing – original draft, Software, Investigation. **Riris Aryawati**: Methodology, Data curation. **Gusti Diansyah**: Software, Investigation.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

The data supporting the findings of this study can be obtained from the corresponding author upon a reasonable request.

Acknowledgments

The reseacrh/publication of this article was funded by DIPA of Public Service Agency of Universitas Sriwijaya 2024. Nomor SP DIPA 023.17.2.677515/2024, On November 24, 2023. In accordance with the Rector's Degree Number: 0013/UN9/LP2M.PT/2024, On May 20, 2024.

References

[1] R. Ramesh *et al.*, "Land–Ocean Interactions in the Coastal Zone: Past, present & future," *Anthropocene*, vol. 12, pp. 85–98, 2015, doi: https://doi.org/10.1016/j.ancene.2016.01.005.

[2] R. Gotama, D. M. Baker, I. Guibert, S. E. McIlroy, and B. D. Russell, "How a coastal megacity affects marine biodiversity and ecosystem function: Impacts of reduced water quality and other anthropogenic stressors," *Ecol. Indic.*, vol. 160, p. 111683, 2024, doi: https://doi.org/10.1016/j.ecolind.2024.111683.

[3] Q. He and B. R. Silliman, "Climate Change, Human Impacts, and Coastal Ecosystems in the Anthropocene," *Curr. Biol.*, vol. 29, no. 19, pp. R1021–R1035, 2019, doi: https://doi.org/10.1016/j.cub.2019.08.042.

[4] N. S. Victoria, T. Sree Devi Kumari, and B. Lazarus, "Assessment on impact of sewage in coastal pollution and distribution of fecal pathogenic bacteria with reference to antibiotic resistance in the coastal area of Cape Comorin, India," *Mar. Pollut. Bull.*, vol. 175, p. 113123, 2022, doi: https://doi.org/10.1016/j.marpolbul.2021.113123.

[5] T. Zhai, J. Wang, Y. Fang, Y. Qin, L. Huang, and Y. Chen, "Assessing ecological risks caused by human activities in rapid urbanization coastal areas: Towards an integrated approach to determining key areas of terrestrial-oceanic ecosystems preservation and restoration," *Sci. Total Environ.*, vol. 708, p. 135153, 2020, doi: https://doi.org/10.1016/j.scitotenv.2019.135153.

[6] N. Andrews *et al.*, "Oil, fisheries and coastal communities: A review of impacts on the environment, livelihoods, space and governance," *Energy Res. Soc. Sci.*, vol. 75, p. 102009, 2021, doi: https://doi.org/10.1016/j.erss.2021.102009.

[7] W. A. E. Putri and A. I. S. Purwiyanto, "Cu and Pb Concentrations in Water Column and Plankton of Downstream Section of the Musi River," *J. Ilmu dan Teknol. Kelaut. Trop.*, vol. 8, no. 2, pp. 773–780, 2016.

[8] Rozirwan *et al.*, "An Assessment of Pb and Cu in Waters, Sediments, and Mud Crabs (Scylla serrata) from Mangrove Ecosystem Near Tanjung Api-Api Port Area, South Sumatra, Indonesia," *Sci. Technol. Indones.*, vol. 8, no. 4, pp. 675–683, 2023, doi: 10.26554/sti.2023.8.4.675-683.

[9] A. A. Galindo Montero, L. C. Costa-Redondo, O. Vasco-Echeverri, and V. A. Arana, "Microplastic pollution in coastal areas of Colombia: Review," *Mar. Environ. Res.*, vol. 190, p. 106027, 2023, doi: https://doi.org/10.1016/j.marenvres.2023.106027.

[10] Y. Choi, M.-Y. Lee, and T.-H. Kim, "Evaluating total organic carbon as an indicator for organic pollutant management in the marine environment: A case study on wastewater treatment plant effluent input into the coastal ocean," *Sci. Total Environ.*, vol. 919, p. 170704, 2024, doi: https://doi.org/10.1016/j.scitotenv.2024.170704.

[11] H. Wu *et al.*, "Trace metals in sediments and benthic animals from aquaculture ponds near a mangrove wetland in Southern China," *Mar. Pollut. Bull.*, vol. 117, no. 1–2, pp. 486–491, Apr. 2017, doi: 10.1016/J.MARPOLBUL.2017.01.026.

[12] J. Pandiyan *et al.*, “An assessment of level of heavy metals pollution in the water, sediment and aquatic organisms: A perspective of tackling environmental threats for food security,” *Saudi J. Biol. Sci.*, vol. 28, no. 2, pp. 1218–1225, Feb. 2021, doi: 10.1016/J.SJBS.2020.11.072.

[13] E. Ramazanova, Y. Bahetnur, K. Yessenbayeva, S. H. Lee, and W. Lee, “Spatiotemporal evaluation of water quality and risk assessment of heavy metals in the northern Caspian Sea bounded by Kazakhstan,” *Mar. Pollut. Bull.*, vol. 181, no. November 2021, p. 113879, 2022, doi: 10.1016/j.marpolbul.2022.113879.

[14] A. P. Cahyaningsih, A. K. Deanova, C. M. Pristiawati, Y. I. Ulumuddin, L. Kusumawati, and A. D. Setyawan, “Review: Causes and impacts of anthropogenic activities on mangrove deforestation and degradation in Indonesia,” *Int. J. Bonorowo Wetl.*, vol. 12, no. 1, pp. 12–22, 2022, doi: 10.13057/bonorowo/w120102.

[15] M. Xu, C. Sun, Y. Zhan, and Y. Liu, “Impact and prediction of pollutant on mangrove and carbon stocks: A machine learning study based on urban remote sensing data,” *Geosci. Front.*, vol. 15, no. 3, p. 101665, 2024, doi: https://doi.org/10.1016/j.gsf.2023.101665.

[16] S. S. Ram, A. Aich, P. Sengupta, A. Chakraborty, and M. Sudarshan, “Assessment of trace metal contamination of wetland sediments from eastern and western coastal region of India dominated with mangrove forest,” *Chemosphere*, vol. 211, pp. 1113–1122, Nov. 2018, doi: 10.1016/J.CHEMOSPHERE.2018.07.201.

[17] Rozirwan, R. Y. Nugroho, M. Hendri, Fauziyah, W. A. E. Putri, and A. Agussalim, “Phytochemical profile and toxicity of extracts from the leaf of Avicennia marina (Forssk.) Vierh. collected in mangrove areas affected by port activities,” *South African J. Bot.*, vol. 150, pp. 903–919, 2022, doi: 10.1016/j.sajb.2022.08.037.

[18] S. Abdul Azeez *et al.*, “Multi-decadal changes of mangrove forest and its response to

the tidal dynamics of thane creek, Mumbai," *J. Sea Res.*, vol. 180, p. 102162, Feb. 2022, doi: 10.1016/J.SEARES.2021.102162.

[19] Rozirwan *et al.*, "Distribution of phytoplankton diversity and abundance in Maspari island waters, South Sumatera, Indonesia," *J. Phys. Conf. Ser.*, vol. 1282, no. 1, 2019, doi: 10.1088/1742-6596/1282/1/012105.

[20] M. B. Hossain *et al.*, "Heavy Metal Accumulation and Phytoremediation Potentiality of Some Selected Mangrove Species from the World's Largest Mangrove Forest," *Biology (Basel).*, vol. 11, no. 8, p. 1144, Aug. 2022, doi: 10.3390/BIOLOGY11081144/S1.

[21] A. Talukdar *et al.*, "Microplastics in mangroves with special reference to Asia: Occurrence, distribution, bioaccumulation and remediation options," *Sci. Total Environ.*, vol. 904, p. 166165, 2023, doi: https://doi.org/10.1016/j.scitotenv.2023.166165.

[22] I. Sanjosé *et al.*, "The Bioconcentration and the Translocation of Heavy Metals in Recently Consumed Salicornia ramosissima J. Woods in Highly Contaminated Estuary Marshes and Its Food Risk," *Diversity*, vol. 14, no. 6, p. 452, Jun. 2022, doi: 10.3390/D14060452/S1.

[23] A. Nguyen, O. Richter, B. V. Q. Le, N. T. K. Phuong, and K. C. Dinh, "Long-Term Heavy Metal Retention by Mangroves and Effect on Its Growth: A Field Inventory and Scenario Simulation," *Int. J. Environ. Res. Public Health*, vol. 17, no. 23, pp. 1–24, Dec. 2020, doi: 10.3390/IJERPH17239131.

[24] G. Llauradó Maury *et al.*, "Antioxidants in plants: A valorization potential emphasizing the need for the conservation of plant biodiversity in cuba," *Antioxidants*, vol. 9, no. 11, pp. 1–39, 2020, doi: 10.3390/antiox9111048.

[25] M. Sharifi-Rad *et al.*, "Lifestyle, Oxidative Stress, and Antioxidants: Back and Forth in the Pathophysiology of Chronic Diseases," *Front. Physiol.*, vol. 11, p. 694, Jul. 2020,

doi: 10.3389/FPHYS.2020.00694.

[26] K. Jomova *et al.*, "Reactive oxygen species, toxicity, oxidative stress, and antioxidants: chronic diseases and aging," *Arch. Toxicol. 2023 9710*, vol. 97, no. 10, pp. 2499–2574, Aug. 2023, doi: 10.1007/S00204-023-03562-9.

[27] K. Messaoudi, T. Benmeddour, and G. Flamini, "First report on the chemical composition and the free radical scavenging and antimicrobial activities of the essential oil of Ononis aurasiaca, an endemic plant of Algeria," *Nat. Prod. Res.*, 2023, doi: https://doi.org/10.1080/14786419.2023.2282113.

[28] G. Eswaraiah, K. A. Peele, S. Krupanidhi, R. B. Kumar, and T. C. Venkateswarulu, "Studies on phytochemical, antioxidant, antimicrobial analysis and separation of bioactive leads of leaf extract from the selected mangroves," *J. King Saud Univ. - Sci.*, vol. 32, no. 1, pp. 842–847, Jan. 2020, doi: 10.1016/J.JKSUS.2019.03.002.

[29] U. Sarker, M. M. Hossain, and S. Oba, "Nutritional and antioxidant components and antioxidant capacity in green morph Amaranthus leafy vegetable," *Sci. Reports 2020 101*, vol. 10, no. 1, pp. 1–10, Jan. 2020, doi: 10.1038/s41598-020-57687-3.

[30] M. Rezaei *et al.*, "Heavy metals concentration in mangrove tissues and associated sediments and seawater from the north coast of Persian Gulf, Iran: Ecological and health risk assessment," *Environ. Nanotechnology, Monit. Manag.*, vol. 15, p. 100456, May 2021, doi: 10.1016/J.ENMM.2021.100456.

[31] Rozirwan *et al.*, "Environmental risk assessment of Pb , Cu , Zn , and Cd concentrations accumulated in selected mangrove roots and surrounding their sediment," *Biodiversitas*, vol. 24, no. 12, pp. 6733–6742, 2023, doi: 10.13057/biodiv/d241236.

[32] N. N. Khotimah *et al.*, "Bioaccumulation and Ecological Risk Assessment of Heavy Metal Contamination (Lead and Copper) Build Up in the Roots of Avicennia alba and Excoecaria agallocha," *J. Ecol. Eng.*, vol. 25, no. 5, pp. 101–113, 2024, doi:

10.12911/22998993/185716.

[33] V. Patale and J. G. Tank, "Ecological assessment of heavy metals accumulation in sediments and leaves of Avicennia marina along the Diu coast of the northeast Arabian Sea," *Oceanologia*, vol. 64, no. 2, pp. 276–286, Apr. 2022, doi: 10.1016/J.OCEANO.2021.12.002.

[34] H. Abelardo Gonzalez-Ocampo, M. C. Parra-Olivas, E. Pérez-González, and G. D. Rodríguez-Meza, "Rhizophora mangle L. bioindicator of environmental exposure to heavy metals in the Navachiste lagoon complex, Sinaloa, Mexico," *Mar. Pollut. Bull.*, vol. 209, p. 117131, Dec. 2024, doi: 10.1016/J.MARPOLBUL.2024.117131.

[35] A. Afriyani, F. Fauziyah, M. Mazidah, and R. Wijayanti, "Keanekaragaman Vegetasi Hutan Mangrove di Pulau Payung Sungsang Banyuasin Sumatera Selatan," *J. Lahan Suboptimal*, vol. 6, no. 3, pp. 113–119, 2017.

[36] Y. H. Hutasoit and D. Sarno, "Struktur Vegetasi Mangrove Alami Di Areal Taman Nasional Sembilang Banyuasin Sumatera Selatan Natural Mangrove Vegetation Structure in Sembilang National Park, Banyuasin South Sumatera," *Maspari J. Mar. Sci. Res.*, vol. 9, no. 1, pp. 1–8, 2017.

[37] W. J. M. Verheugt, A. Purwoko, F. Danielsen, H. Skov, and R. Kadarisman, "Integrating mangrove and swamp forests conservation with coastal lowland development; the Banyuasin Sembilang swamps case study, South Sumatra Province, Indonesia," *Landsc. Urban Plan.*, vol. 20, no. 1–3, pp. 85–94, Jan. 1991, doi: 10.1016/0169-2046(91)90096-5.

[38] G. Gustaman, . F., and . I., "Efektifitas Perbedaan Warna Cahaya Lampu terhadap Hasil Tangkapan Bagan Tancap di Perairan Sungsang Sumatera Selatan," *Maspari J. Mar. Sci. Res.*, vol. 4, no. 1, pp. 92–102, 2012, doi: 10.56064/MASPARI.V4I1.1433.

[39] Rozirwan *et al.*, "Assessment of phytoplankton community structure in musi estuary,

south sumatra, indonesia," *AACL Bioflux*, vol. 14, no. 3, pp. 1451–1463, 2021.

[40] Rozirwan *et al.*, "Assessment distribution of the phytoplankton community structure at the fishing ground, Banyuasin estuary, Indonesia," *Acta Ecol. Sin.*, Mar. 2022, doi: 10.1016/J.CHNAES.2022.02.006.

[41] Rozirwan *et al.*, "An ecological assessment of crab's diversity among habitats of migratory birds at Berbak-Sembilang National Park Indonesia," *Int. J. Conserv. Sci.*, vol. 13 (3), 2022, Accessed: Oct. 05, 2022. [Online]. Available: www.ijcs.ro

[42] Y. Fitria, Rozirwan, M. Fitrani, R. Y. Nugroho, Fauziyah, and W. A. E. Putri, "Gastropods as bioindicators of heavy metal pollution in the Banyuasin estuary shrimp pond area, South Sumatra, Indonesia," *Acta Ecol. Sin.*, Jun. 2023, doi: 10.1016/J.CHNAES.2023.05.009.

[43] R. Rozirwan *et al.*, "Insecticidal Activity and Phytochemical Profiles of Avicennia marina and Excoecaria agallocha Leaves Extracts," *ILMU Kelaut. Indones. J. Mar. Sci. Vol 28, No 2 Ilmu KelautanDO - 10.14710/ik.ijms.28.2.148-160* , vol. 28, no. June, pp. 148–160, 2023, doi: 10.14710/ik.ijms.28.2.148-160.

[44] E. Indawan, R. I. Hapsari, K. Ahmadi, and D. N. Khaerudin, "Quality assessment of mangrove growing environment in Pasuruan of East Java," *J. Degrad. Min. LANDS Manag.*, vol. 4, no. 3, pp. 815–819, 2017, doi: 10.15243/jdmlm.2017.043.815.

[45] I. M. Siaka, "Correlation between sediment depth at Benoa Harbor and concentrations of heavy metals PB and Cu," *J. Kim.*, vol. 2, no. 2, pp. 61–70, 2008.

[46] Y. Xiao, M. He, J. Xie, L. Liu, and X. Zhang, "Effects of heavy metals and organic matter fractions on the fungal communities in mangrove sediments from Techeng Isle, South China," *Ecotoxicol. Environ. Saf.*, vol. 222, p. 112545, Oct. 2021, doi: 10.1016/J.ECOENV.2021.112545.

[47] E. Romano, M. C. Magno, and L. Bergamin, "Grain size data analysis of marine

sediments, from sampling to measuring and classifying. A critical review," *IMEKO TC19 Work. Metrol. Sea, MetroSea 2017 Learn. to Meas. Sea Heal. Parameters*, vol. 2017-Octob, pp. 173–178, 2017.

[48] L. J. Poppe and A. H. Eliason, "A Visual Basic program to plot sediment grain-size data on ternary diagrams $," *Comput. Geosci.*, vol. 34, pp. 561–565, 2008, doi: 10.1016/j.cageo.2007.03.019.

[49] R. R. Anggraini, U. Yanuhar, and Y. Risjani, "Characteristic of sediment at lekok coastal waters, Pasuruan Regency, East Java," *J. Ilmu dan Teknol. Kelaut. Trop.*, vol. 12, no. 1, pp. 235–246, Apr. 2020, doi: 10.29244/JITKT.V12I1.28705.

[50] Rozirwan *et al.*, "Ecological Risk Assessment of Heavy Metal (Pb, Cu) Contamination in Water, Sediment, and Polychaeta (Neoleanira Tetragona) from Coastal Areas Affected by Aquaculture, Urban Rivers, and Ports in South Sumatra," *J. Ecol. Eng.*, vol. 25, no. 1, pp. 303–319, 2024, doi: 10.12911/22998993/175365.

[51] R. Nagarajan *et al.*, "Geochemical Characterization of Beach Sediments of Miri, NW Borneo, SE Asia: Implications on Provenance, Weathering Intensity, and Assessment of Coastal Environmental Status," *Coast. Zo. Manag. Glob. Perspect. Reg. Process. Local Issues*, pp. 279–330, Jan. 2019, doi: 10.1016/B978-0-12-814350-6.00012-4.

[52] G. Muller, "Index of geo-accumulation in sediments of the Rhine river – ScienceOpen," *J. Geol.*, 1969, Accessed: Jan. 08, 2023. [Online]. Available: https://www.scienceopen.com/document?vid=4b875795-5729-4c05-9813-64951e2ca488

[53] V. Gopal *et al.*, "Assessment of heavy metal contamination in the surface sediments of the Vedaranyam coast, Southern India," *Reg. Stud. Mar. Sci.*, vol. 65, p. 103081, Dec. 2023, doi: 10.1016/J.RSMA.2023.103081.

[54] S. M. Shaheen, M. S. Shams, M. R. Khalifa, M. A. El-Dali, and J. Rinklebe, "Various

soil amendments and environmental wastes affect the (im)mobilization and phytoavailability of potentially toxic elements in a sewage effluent irrigated sandy soil," *Ecotoxicol. Environ. Saf.*, vol. 142, pp. 375–387, Aug. 2017, doi: 10.1016/J.ECOENV.2017.04.026.

[55] S. M. Shaheen *et al.*, "Potentially toxic elements in saltmarsh sediments and common reed (Phragmites australis) of Burullus coastal lagoon at North Nile Delta, Egypt: A survey and risk assessment," *Sci. Total Environ.*, vol. 649, pp. 1237–1249, Feb. 2019, doi: 10.1016/J.SCITOTENV.2018.08.359.

[56] S. K. Maiti, D. Ghosh, and D. Raj, "Phytoremediation of fly ash: bioaccumulation and translocation of metals in natural colonizing vegetation on fly ash lagoons," *Handb. Fly Ash*, pp. 501–523, Jan. 2022, doi: 10.1016/B978-0-12-817686-3.00011-6.

[57] H. Almahasheer, "High levels of heavy metals in Western Arabian Gulf mangrove soils," *Mol. Biol. Rep.*, vol. 46, no. 2, pp. 1585–1592, Apr. 2019, doi: 10.1007/S11033-019-04603-2/METRICS.

[58] R. Rozirwan *et al.*, "Antioxidant Activity, Total Phenolic, Phytochemical Content, and HPLC Profile of Selected Mangrove Species from Tanjung Api-Api Port Area, South Sumatra, Indonesia," *Trop. J. Nat. Prod. Res. Available*, vol. 7, no. 7, pp. 3482–3489, 2023.

[59] H. D. Salusu *et al.*, "Phytochemical screening and antioxidant activity of selekop (Lepisanthes amoena) fruit," *Agrivita*, vol. 39, no. 2, pp. 214–218, 2017, doi: 10.17503/agrivita.v39i2.810.

[60] S. S. Suh, J. Hwang, M. Park, H. S. Park, and T. K. Lee, "Phenol content, antioxidant and tyrosinase inhibitory activity of mangrove plants in Micronesia," *Asian Pac. J. Trop. Med.*, vol. 7, no. 7, pp. 531–535, Jul. 2014, doi: 10.1016/S1995-7645(14)60089-4.

[61] K. Sopalun, W. Laosripaiboon, A. Wachirachaikarn, and S. Iamtham, "Biological

potential and chemical composition of bioactive compounds from endophytic fungi associated with thai mangrove plants,” *South African J. Bot.*, vol. 141, pp. 66–76, Sep. 2021, doi: 10.1016/J.SAJB.2021.04.031.

[62] U. Kustiati, H. Wihadmadyatami, and D. L. Kusindarta, “Dataset of Phytochemical and secondary metabolite profiling of holy basil leaf (Ocimum sanctum Linn) ethanolic extract using spectrophotometry, thin layer chromatography, Fourier transform infrared spectroscopy, and nuclear magnetic resonance,” *Data Br.*, vol. 40, 2022, doi: 10.1016/j.dib.2021.107774.

[63] W. Kirch, “Pearson’s Correlation Coefficient,” *Encycl. Public Heal.*, pp. 1090–1091, 2008, doi: 10.1007/978-1-4020-5614-7_2569.

[64] D. Weisburd, C. Britt, D. B. Wilson, and A. Wooditch, “Measuring Association for Scaled Data: Pearson’s Correlation Coefficient,” in *Basic Statistics in Criminology and Criminal Justice*, Cham: Springer International Publishing, 2020, pp. 479–530. doi: 10.1007/978-3-030-47967-1_14.

[65] Rozirwan, S. Ramadani, W. Ayu, E. Putri, N. Nur, and R. Y. Nugroho, “Evaluation of Calcium and Phosphorus content in Scallop Shells (Placuna placenta) and Blood Cockle Shells (Anadara granosa) from Banyuasin Waters, South Sumatra,” *Egypt. J. Aquat. Biol. Fish. Zool. Dep. Fac. Sci.*, vol. 27, no. 3, pp. 1053–1068, 2023.

[66] Sumartini, P W Ratrinia, and Hutabarat R F, “The effect of mangrove types and leave maturity on the mangrove leaves (Sonneratia alba) and (Rhizophora mucronata) tea powder - IOPscience,” in *IOP Conference Series: Earth and Environmental Science*, 2022. Accessed: Oct. 03, 2022. [Online]. Available: https://iopscience.iop.org/article/10.1088/1755-1315/967/1/012018

[67] J. P. Yactayo-Chang, H. V. Tang, J. Mendoza, S. A. Christensen, and A. K. Block, “Plant Defense Chemicals against Insect Pests,” *Agron. 2020, Vol. 10, Page 1156*, vol. 10, no.

8, p. 1156, Aug. 2020, doi: 10.3390/AGRONOMY10081156.

[68] Anjali *et al.*, “Role of plant secondary metabolites in defence and transcriptional regulation in response to biotic stress,” *Plant Stress*, vol. 8, p. 100154, Jun. 2023, doi: 10.1016/J.STRESS.2023.100154.

[69] J. Srše, M. Perkovič, and A. Grm, “Sediment Resuspension Distribution Modelling Using a Ship Handling Simulation along with the MIKE 3 Application,” *J. Mar. Sci. Eng.*, vol. 11, no. 8, 2023, doi: 10.3390/jmse11081619.

[70] J. Srse and M. Perkovic, “Field Studies on Sediment Resuspension Induced by Shipping: Vessel Kinematic Measurements and Water Sampling in the Port of Koper,” *2024 IEEE Int. Work. Metrol. Sea, MetroSea 2024 - Proc.*, no. October, pp. 353–357, 2024, doi: 10.1109/MetroSea62823.2024.10765676.

[71] J. Yun, Q. Yang, C. Zhao, C. Chen, and G. Liu, “Atmospheric emissions of fine particle matter bound rare earth elements from industry,” *Nat. Commun.* , vol. 15, no. 1, pp. 1–10, 2024, doi: 10.1038/s41467-024-53684-6.

[72] A. M. Afandi, Y. Zuraidah, H. A. Z. A. Nurzuhaili, H. Zulkifli, and M. Yaqin, “Managing soil deterioration and erosion under oil palm,” *Oil Palm Bull. 75*, vol. 75, no. November, pp. 1–10, 2017.

[73] I. Comte, F. Colin, J. K. Whalen, O. Grünberger, and J. P. Caliman, “Agricultural Practices in Oil Palm Plantations and Their Impact on Hydrological Changes, Nutrient Fluxes and Water Quality in Indonesia: A Review,” *Adv. Agron.*, vol. 116, pp. 71–124, Jan. 2012, doi: 10.1016/B978-0-12-394277-7.00003-8.

[74] L. Ivorra, P. G. Cardoso, S. K. Chan, C. Cruzeiro, and K. A. Tagulao, “Can mangroves work as an effective phytoremediation tool for pesticide contamination? An interlinked analysis between surface water, sediments and biota,” *J. Clean. Prod.*, vol. 295, p. 126334, May 2021, doi: 10.1016/J.JCLEPRO.2021.126334.

[75] S. Partani *et al.*, “Identifying toxic elements in water, sediments, and roots of mangrove forest (Avicennia marina) in Chabahar Bay, Sea of Oman,” *Sci. Total Environ.*, vol. 954, p. 176635, 2024, doi: https://doi.org/10.1016/j.scitotenv.2024.176635.

[76] S. Wang, C. Pan, D. Xie, M. Xu, Y. Yan, and X. Li, “Grain size characteristics of surface sediment and its response to the dynamic sedimentary environment in Qiantang Estuary, China,” *Int. J. Sediment Res.*, vol. 37, no. 4, pp. 457–468, 2022, doi: https://doi.org/10.1016/j.ijsrc.2021.12.002.

[77] R. Rozirwan, I. Bahrudin, B. S. Barus, R. Y. Nugroho, and N. N. Khotimah, “First assesment of coral Mussidae in Kelagian Island waters, Lampung,” *Proc. 9TH Int. Symp. Innov. Bioprod. Indones. Biotechnol. Bioeng. 2022 Strength. Bioeconomy through Appl. Biotechnol. Bioeng. Biodivers.*, vol. 2972, no. 1, p. 040008, Dec. 2023, doi: 10.1063/5.0171642/2931856.

[78] M. K. Uddin, “A review on the adsorption of heavy metals by clay minerals, with special focus on the past decade,” *Chem. Eng. J.*, vol. 308, pp. 438–462, 2017, doi: https://doi.org/10.1016/j.cej.2016.09.029.

[79] X. Huang and G. Yang, “Charge reversal and anion effects during adsorption of metal ions at clay surfaces: Mechanistic aspects and influence factors,” *Chem. Phys.*, vol. 529, p. 110575, 2020, doi: https://doi.org/10.1016/j.chemphys.2019.110575.

[80] S. Khan, S. Ajmal, T. Hussain, and M. U. Rahman, “Clay-based materials for enhanced water treatment: adsorption mechanisms, challenges, and future directions,” *J. Umm Al-Qura Univ. Appl. Sci.*, 2023, doi: 10.1007/s43994-023-00083-0.

[81] Y. M. Chen, J. bo Gao, Y. Q. Yuan, J. Ma, and S. Yu, “Relationship between heavy metal contents and clay mineral properties in surface sediments: Implications for metal pollution assessment,” *Cont. Shelf Res.*, vol. 124, pp. 125–133, Aug. 2016, doi: 10.1016/J.CSR.2016.06.002.

[82] W. Que, L. Yi, Y. Wu, and Q. Li, “Analysis of heavy metals in sediments with different particle sizes and influencing factors in a mining area in Hunan Province,” *Sci. Rep.*, vol. 14, no. 1, p. 20318, 2024, doi: 10.1038/s41598-024-71502-3.

[83] Y. G. Gu and Y. P. Gao, “An unconstrained ordination- and GIS-based approach for identifying anthropogenic sources of heavy metal pollution in marine sediments,” *Mar. Pollut. Bull.*, vol. 146, pp. 100–105, Sep. 2019, doi: 10.1016/J.MARPOLBUL.2019.06.008.

[84] A. Tjahjono, R. Sugiharto, and O. Wahyuni, “Study of water and sediment surface quality on defilement of heavy metals Pb & Cd at a downstream section of Musi River, South Sumatera, Indonesia,” *Rev. Ambient. e Agua*, vol. 17, no. 1, pp. 1–20, 2022.

[85] E. R. Sulistya Dewi, K. Ni’Mah, and F. Kaswinarni, “The content of heavy metal lead (Pb) on baung fish (Hemibagrus nemurus) as biomonitoring pollution of Wulan River of Demak Regency,” *J. Phys. Conf. Ser.*, vol. 1217, no. 1, 2019, doi: 10.1088/1742-6596/1217/1/012128.

[86] L. Schröder, F. Hellweger, and A. Putschew, “Copper leaching from recreational vessel antifouling paints in freshwater: A Berlin case study,” *J. Environ. Manage.*, vol. 301, p. 113895, Jan. 2022, doi: 10.1016/J.JENVMAN.2021.113895.

[87] J. Zhao *et al.*, “Controllable release of Cu ions contributes to the enhanced environmentally-friendly performance of antifouling Cu-bearing stainless steel coating prepared using high-velocity air fuel,” *Surf. Coatings Technol.*, vol. 481, p. 130629, Apr. 2024, doi: 10.1016/J.SURFCOAT.2024.130629.

[88] Z. Y. Soon, J. H. Jung, A. Loh, C. Yoon, D. Shin, and M. Kim, “Seawater contamination associated with in-water cleaning of ship hulls and the potential risk to the marine environment,” *Mar. Pollut. Bull.*, vol. 171, p. 112694, Oct. 2021, doi: 10.1016/J.MARPOLBUL.2021.112694.

[89] I. Kalantzi *et al.*, "Assessment of the use of copper alloy aquaculture nets: Potential impacts on the marine environment and on the farmed fish," *Aquaculture*, vol. 465, pp. 209–222, Dec. 2016, doi: 10.1016/J.AQUACULTURE.2016.09.016.

[90] N. Bloecher and O. Floerl, "Efficacy testing of novel antifouling coatings for pen nets in aquaculture: How good are alternatives to traditional copper coatings?," *Aquaculture*, vol. 519, p. 734936, Mar. 2020, doi: 10.1016/J.AQUACULTURE.2020.734936.

[91] L. S. Herbeck, D. Unger, Y. Wu, and T. C. Jennerjahn, "Effluent, nutrient and organic matter export from shrimp and fish ponds causing eutrophication in coastal and back-reef waters of NE Hainan, tropical China," *Cont. Shelf Res.*, vol. 57, pp. 92–104, Apr. 2013, doi: 10.1016/J.CSR.2012.05.006.

[92] S. Ur Rahman *et al.*, "Pb uptake, accumulation, and translocation in plants: Plant physiological, biochemical, and molecular response: A review," *Heliyon*, vol. 10, no. 6, p. e27724, Mar. 2024, doi: 10.1016/J.HELIYON.2024.E27724.

[93] G. Yu *et al.*, "The Mechanism of Plant Resistance to Heavy Metal," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 310, no. 5, pp. 1–6, 2019, doi: 10.1088/1755-1315/310/5/052004.

[94] Z. Shabbir *et al.*, "Copper uptake, essentiality, toxicity, detoxification and risk assessment in soil-plant environment," *Chemosphere*, vol. 259, p. 127436, Nov. 2020, doi: 10.1016/J.CHEMOSPHERE.2020.127436.

[95] E. Xu *et al.*, "Molecular Mechanisms of Plant Responses to Copper: From Deficiency to Excess," *Int. J. Mol. Sci.*, vol. 25, no. 13, p. 6993, Jul. 2024, doi: 10.3390/IJMS25136993.

[96] V. Kumar *et al.*, "Copper bioavailability, uptake, toxicity and tolerance in plants: A comprehensive review," *Chemosphere*, vol. 262, p. 127810, 2021, doi: https://doi.org/10.1016/j.chemosphere.2020.127810.

[97] S. Collin *et al.*, “Bioaccumulation of lead (Pb) and its effects in plants: A review,” *J. Hazard. Mater. Lett.*, vol. 3, p. 100064, 2022, doi: https://doi.org/10.1016/j.hazl.2022.100064.

[98] S. Mitra *et al.*, “Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity,” *J. King Saud Univ. - Sci.*, vol. 34, no. 3, p. 101865, Apr. 2022, doi: 10.1016/J.JKSUS.2022.101865.

[99] A. B. Fulke, S. Ratanpal, and S. Sonker, “Understanding heavy metal toxicity: Implications on human health, marine ecosystems and bioremediation strategies,” *Mar. Pollut. Bull.*, vol. 206, p. 116707, 2024, doi: https://doi.org/10.1016/j.marpolbul.2024.116707.

[100] K. Analuddin *et al.*, “The carrying capacity of estuarine mangroves in maintaining the coastal urban environmental health of Southeast Sulawesi, Indonesia,” *Egypt. J. Aquat. Res.*, vol. 49, no. 3, pp. 327–338, Sep. 2023, doi: 10.1016/J.EJAR.2023.03.002.

[101] T. Crespo-Toledo, F. Avelar-González, A. Guerrero-Barrera, K. Mitchell, L. Yamamoto-Flores, and O. Flores-Amaro, “Integrative assessment of heavy metal risks in mining polluted sediments and soils of Aguascalientes, Mexico,” *Case Stud. Chem. Environ. Eng.*, vol. 11, p. 101130, Jun. 2025, doi: 10.1016/J.CSCEE.2025.101130.

[102] P. B. Angon *et al.*, “Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain,” *Heliyon*, vol. 10, no. 7, p. e28357, Apr. 2024, doi: 10.1016/J.HELIYON.2024.E28357.

[103] O. J. Popoola, O. D. Ogundele, E. A. Ladapo, and S. Senbore, “The Impact of Heavy Metal Contamination in Soils on Soil Microbial Communities and Its Potential Health Risks for Humans,” *Soil Microbiome Green Technol. Sustain.*, pp. 351–375, 2024, doi: 10.1007/978-3-031-71844-1_15.

[104] M. R. Hasan *et al.*, “Vertical distribution, contamination status and ecological risk

assessment of heavy metals in core sediments from a mangrove-dominated tropical river," *Mar. Pollut. Bull.*, vol. 189, p. 114804, Apr. 2023, doi: 10.1016/J.MARPOLBUL.2023.114804.

[105] P. B. Angon *et al.*, "Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain," *Heliyon*, vol. 10, no. 7, p. e28357, 2024, doi: https://doi.org/10.1016/j.heliyon.2024.e28357.

[106] S. Hoffmann, "Challenges and opportunities of area-based conservation in reaching biodiversity and sustainability goals," *Biodivers. Conserv.*, vol. 31, no. 2, pp. 325–352, 2022, doi: 10.1007/s10531-021-02340-2.

[107] G. Li *et al.*, "Mixed effectiveness of global protected areas in resisting habitat loss," *Nat. Commun.*, vol. 15, no. 1, p. 8389, 2024, doi: 10.1038/s41467-024-52693-9.

[108] J. Briffa, E. Sinagra, and R. Blundell, "Heavy metal pollution in the environment and their toxicological effects on humans," *Heliyon*, vol. 6, no. 9, p. e04691, Sep. 2020, doi: 10.1016/J.HELIYON.2020.E04691.

[109] Ramses, Ismarti, F. Amelia, Rozirwan, and Suheryanto, "Diversity and abundance of polychaetes in the west coast waters of batam island, Kepulauan Riau province-indonesia," *AACL Bioflux*, vol. 13, no. 1, pp. 381–391, 2020.

[110] L. S. Miranda, B. Wijesiri, G. A. Ayoko, P. Egodawatta, and A. Goonetilleke, "Water-sediment interactions and mobility of heavy metals in aquatic environments," *Water Res.*, vol. 202, p. 117386, 2021, doi: https://doi.org/10.1016/j.watres.2021.117386.

[111] F. Brugnone *et al.*, "Atmospheric Deposition around the Industrial Areas of Milazzo and Priolo Gargallo (Sicily–Italy)—Part B: Trace Elements," *Atmosphere (Basel).*, vol. 14, no. 4, 2023, doi: 10.3390/atmos14040737.

[112] P. Liu, Q. Wu, W. Hu, K. Tian, B. Huang, and Y. Zhao, "Effects of atmospheric deposition on heavy metals accumulation in agricultural soils: Evidence from field

monitoring and Pb isotope analysis," *Environ. Pollut.*, vol. 330, p. 121740, 2023, doi: https://doi.org/10.1016/j.envpol.2023.121740.

[113] S. Karmakar *et al.*, "Effectiveness of artificially planted mangroves on remediation of metals released from ship-breaking activities," *Mar. Pollut. Bull.*, vol. 212, p. 117587, Mar. 2025, doi: 10.1016/J.MARPOLBUL.2025.117587.

[114] S. Mitra, N. Naskar, and P. Chaudhuri, "A review on potential bioactive phytochemicals for novel therapeutic applications with special emphasis on mangrove species," *Phytomedicine Plus*, vol. 1, no. 4, p. 100107, 2021, doi: 10.1016/j.phyplu.2021.100107.

[115] N. P. E. Hikmawanti, S. Fatmawati, and A. W. Asri, "The effect of ethanol concentrations as the extraction solvent on antioxidant activity of Katuk (Sauropus androgynus (L.) Merr.) leaves extracts," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 755, no. 1, 2021, doi: 10.1088/1755-1315/755/1/012060.

[116] A. Altemimi, N. Lakhssassi, A. Baharlouei, D. G. Watson, and D. A. Lightfoot, "Phytochemicals: Extraction, Isolation, and Identification of Bioactive Compounds from Plant Extracts," *Plants*, vol. 6, no. 4, Dec. 2017, doi: 10.3390/PLANTS6040042.

[117] A. Acquaviva *et al.*, "Screening for Chemical Characterization and Pharmacological Properties of Different Extracts from Nepeta italica," *Plants*, vol. 12, no. 15, Aug. 2023, doi: 10.3390/PLANTS12152785/S1.

[118] Rozirwan, R. Y. Nugroho, M. Hendri, Fauziyah, W. A. E. Putri, and A. Agussalim, "Phytochemical profile and toxicity of extracts from the leaf of Avicennia marina (Forssk.) Vierh. collected in mangrove areas affected by port activities," *South African J. Bot.*, vol. 150, pp. 903–919, Nov. 2022, doi: 10.1016/J.SAJB.2022.08.037.

[119] K. A. Audah *et al.*, "Indonesian Mangrove Sonneratia caseolaris Leaves Ethanol Extract Is a Potential Super Antioxidant and Anti Methicillin-Resistant Staphylococcus aureus Drug," *Molecules*, vol. 27, no. 23, p. 8369, Dec. 2022, doi:

10.3390/MOLECULES27238369/S1.

[120] K. A. S. Kodikara *et al.*, “Oxidative stress, leaf photosynthetic capacity and dry matter content in young mangrove plant Rhizophora mucronata Lam. under prolonged submergence and soil water stress,” *Physiol. Mol. Biol. Plants*, vol. 26, no. 8, p. 1609, Aug. 2020, doi: 10.1007/S12298-020-00843-W.

[121] F. P. Sabdanawaty, Purnomo, and B. S. Daryono, “Species diversity and phenetic relationship among accessions of api-api (Avicennia spp.) in java based on morphological characters and issr markers,” *Biodiversitas*, vol. 22, no. 1, pp. 193–198, 2021, doi: 10.13057/biodiv/d220125.

[122] B. Nath, G. Birch, and P. Chaudhuri, “Assessment of sediment quality in Avicennia marina-dominated embayments of Sydney Estuary: The potential use of pneumatophores (aerial roots) as a bio-indicator of trace metal contamination,” *Sci. Total Environ.*, vol. 472, pp. 1010–1022, Feb. 2014, doi: 10.1016/J.SCITOTENV.2013.11.096.

[123] S. Hao, W. Su, and Q. Q. Li, “Adaptive roots of mangrove Avicennia marina: Structure and gene expressions analyses of pneumatophores,” *Sci. Total Environ.*, vol. 757, p. 143994, Feb. 2021, doi: 10.1016/J.SCITOTENV.2020.143994.

[124] R. Wilda, A. M. Hamdan, and R. Rahmi, “A review: The use of mangrove for biomonitoring on aquatic environment,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 980, no. 1, 2020, doi: 10.1088/1757-899X/980/1/012083.

[125] Rozirwan *et al.*, “Investigating the Antioxidant Activity, Total Phenolics and Phytochemical Profile in Avicennia Alba and Excoecaria Agallocha Root Extracts As a Defence Mechanism Against Pollutants,” *Farmacia*, vol. 72, no. 5, pp. 1216–1226, 2024, doi: 10.31925/farmacia.2024.5.25.

[126] S. J. Hossain *et al.*, “Antibacterial, Anti-Diarrhoeal, Analgesic, Cytotoxic Activities, and

GC-MS Profiling of Sonneratia apetala (Buch.-Ham.) Seed," *Prev. Nutr. food Sci.*, vol. 22, no. 3, pp. 157–165, Sep. 2017, doi: 10.3746/pnf.2017.22.3.157.

[127] M. R. Bomfim *et al.*, "Morphology, Physical and Chemical Characteristics of Mangrove Soil under Riverine and Marine Influence: A Case Study on Subaé River Basin, Bahia, Brazil," *Mangrove Ecosyst. Ecol. Funct.*, Nov. 2018, doi: 10.5772/INTECHOPEN.79142.

[128] I. Dewiyanti, D. Darmawi, Z. A. Muchlisin, T. Z. Helmi, I. Imelda, and C. N. Defira, "Physical and chemical characteristics of soil in mangrove ecosystem based on differences habitat in Banda Aceh and Aceh Besar," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 674, no. 1, p. 012092, Feb. 2021, doi: 10.1088/1755-1315/674/1/012092.

[129] Rozirwan *et al.*, "Phytochemical composition , total phenolic content and antioxidant activity of Anadara granosa (Linnaeus , 1758) collected from the east coast of South Sumatra , Indonesia Abstract :," *Baghdad Sci. J.*, pp. 1–8, 2023.

[130] M. F. Misrah *et al.*, "Evaluation of antioxidant activity and total phenolics of selected mangrove plants in Sabah," *Borneo Int. J. Biotechnol.*, vol. 2, no. December, pp. 14–21, 2022, [Online]. Available: https://doi.org/10.51200/bijb.v2i.3330

[131] Y. S. Wang and J. D. Gu, "Ecological responses, adaptation and mechanisms of mangrove wetland ecosystem to global climate change and anthropogenic activities," *Int. Biodeterior. Biodegradation*, vol. 162, p. 105248, Aug. 2021, doi: 10.1016/J.IBIOD.2021.105248.

[132] S. Sudhir, A. Arunprasath, and V. Sankara Vel, "A critical review on adaptations, and biological activities of the mangroves," *J. Nat. Pestic. Res.*, vol. 1, p. 100006, Jun. 2022, doi: 10.1016/J.NAPERE.2022.100006.

[133] M. Xu, C. Sun, Y. Zhan, and Y. Liu, "Impact and prediction of pollutant on mangrove and carbon stocks: A machine learning study based on urban remote sensing data,"

Geosci. Front., p. 101665, Jul. 2023, doi: 10.1016/J.GSF.2023.101665.

[134] O. M. Ighodaro and O. A. Akinloye, "First line defence antioxidants-superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPX): Their fundamental role in the entire antioxidant defence grid," *Alexandria J. Med.*, vol. 54, no. 4, pp. 287–293, Dec. 2018, doi: 10.1016/J.AJME.2017.09.001.

[135] J. Laoué, C. Fernandez, and E. Ormeño, "Plant Flavonoids in Mediterranean Species: A Focus on Flavonols as Protective Metabolites under Climate Stress," *Plants*, vol. 11, no. 2, Jan. 2022, doi: 10.3390/PLANTS11020172.

[136] L. Valgimigli, "Lipid Peroxidation and Antioxidant Protection," *Biomolecules*, vol. 13, no. 9, 2023, doi: 10.3390/biom13091291.

[137] B. Yang, H. Liu, J. Yang, V. K. Gupta, and Y. Jiang, "New insights on bioactivities and biosynthesis of flavonoid glycosides," *Trends Food Sci. Technol.*, vol. 79, pp. 116–124, Sep. 2018, doi: 10.1016/J.TIFS.2018.07.006.

[138] A. M. M. Youssef, D. A. M. Maaty, and Y. M. Al-Saraireh, "Phytochemistry and Anticancer Effects of Mangrove (Rhizophora mucronata Lam.) Leaves and Stems Extract against Different Cancer Cell Lines," *Pharmaceuticals*, vol. 16, no. 1, 2023, doi: 10.3390/ph16010004.

[139] A. Elaiyaraja and G. Chandramohan, "Comparative phytochemical profile of crinum defixum ker-gawler leaves using gc-ms," *J. Drug Deliv. Ther.*, vol. 8, no. 4, pp. 365–380, Aug. 2018, doi: 10.22270/JDDT.V8I4.1758.

[140] R. Borgohain, A. K. Guha, S. Pratihar, and J. G. Handique, "Antioxidant activity of some phenolic aldehydes and their diimine derivatives: A DFT study," *Comput. Theor. Chem.*, vol. 1060, pp. 17–23, May 2015, doi: 10.1016/J.COMPTC.2015.02.014.

[141] J. Ge *et al.*, "Natural terpenoids with anti-inflammatory activities: Potential leads for anti-inflammatory drug discovery," *Bioorg. Chem.*, vol. 124, p. 105817, Jul. 2022, doi:

10.1016/J.BIOORG.2022.105817.

[142] R. Rozirwan *et al.*, "Anti-Inflammatory Activity and Phytochemical Profile from the Leaves of the Mangrove Sonneratia caseolaris (L.) Engl. for Future Drug Discovery," *Sci. Technol. Indones.*, vol. 9, no. 2, pp. 502–516, Apr. 2024, doi: 10.26554/STI.2024.9.2.502-516.

[143] I. Gutiérrez-Del-río *et al.*, "Terpenoids and Polyphenols as Natural Antioxidant Agents in Food Preservation," *Antioxidants*, vol. 10, no. 8, Aug. 2021, doi: 10.3390/ANTIOX10081264.

[144] V. Venepally and R. C. Reddy Jala, "An insight into the biological activities of heterocyclic–fatty acid hybrid molecules," *Eur. J. Med. Chem.*, vol. 141, pp. 113–137, Dec. 2017, doi: 10.1016/J.EJMECH.2017.09.069.

[145] A. Cherkas, S. Holota, T. Mdzinarashvili, R. Gabbianelli, and N. Zarkovic, "Glucose as a Major Antioxidant: When, What for and Why It Fails?," *Antioxidants (Basel, Switzerland)*, vol. 9, no. 2, Feb. 2020, doi: 10.3390/antiox9020140.

[146] N. Shen, T. Wang, Q. Gan, S. Liu, L. Wang, and B. Jin, "Plant flavonoids: Classification, distribution, biosynthesis, and antioxidant activity," *Food Chem.*, vol. 383, p. 132531, Jul. 2022, doi: 10.1016/J.FOODCHEM.2022.132531.

[147] I. Makuch-Pietraś, D. Grabek-Lejko, A. Górka, and I. Kasprzyk, "Antioxidant activities in relation to the transport of heavy metals from the soil to different parts of Betula pendula (Roth.)," *J. Biol. Eng.*, vol. 17, no. 1, pp. 1–25, 2023, doi: 10.1186/s13036-022-00322-8.

[148] E. C. Georgiadou *et al.*, "Influence of heavy metals (Ni, Cu, and Zn) on nitro-oxidative stress responses, proteome regulation and allergen production in basil (ocimum basilicum L.) plants," *Front. Plant Sci.*, vol. 9, p. 374129, Jul. 2018, doi: 10.3389/FPLS.2018.00862/BIBTEX.

[149] D. M. Kasote, S. S. Katyare, M. V. Hegde, and H. Bae, “Significance of Antioxidant Potential of Plants and its Relevance to Therapeutic Applications,” *Int. J. Biol. Sci.*, vol. 11, no. 8, p. 982, Jun. 2015, doi: 10.7150/IJBS.12096.

[150] Z. Cai, A. Kastell, C. Speiser, and I. Smetanska, “Enhanced resveratrol production in Vitis vinifera cell suspension cultures by heavy metals without loss of cell viability,” *Appl. Biochem. Biotechnol.*, vol. 171, no. 2, pp. 330–340, 2013, doi: 10.1007/s12010-013-0354-4.

[151] A. Koźmińska, A. Wiszniewska, E. Hanus-Fajerska, and E. Muszyńska, “Recent strategies of increasing metal tolerance and phytoremediation potential using genetic transformation of plants,” *Plant Biotechnol. Rep.*, vol. 12, no. 1, Feb. 2018, doi: 10.1007/S11816-017-0467-2.

[152] S. Mansoor *et al.*, “Phytoremediation at Molecular Level,” *Phytoremediation Biotechnol. Strateg. Promot. Invigorating Environs*, pp. 65–90, Jan. 2022, doi: 10.1016/B978-0-323-89874-4.00011-X.

[153] M. O. Aljahdali, A. B. Alhassan, and Z. Zhang, “Environmental Factors Causing Stress in Avicennia marina Mangrove in Rabigh Lagoon Along the Red Sea: Based on a Multi-Approach Study,” *Front. Mar. Sci.*, vol. 8, p. 328, May 2021, doi: 10.3389/FMARS.2021.646993/BIBTEX.

[154] S. Ghosh, M. Bakshi, S. Mahanty, and P. Chaudhuri, “Understanding potentially toxic metal (PTM) induced biotic response in two riparian mangrove species Sonneratia caseolaris and Avicennia officinalis along river Hooghly, India: Implications for sustainable sediment quality management,” *Mar. Environ. Res.*, vol. 172, no. June, p. 105486, 2021, doi: 10.1016/j.marenvres.2021.105486.

[155] S. Ur Rahman *et al.*, “Adaptation and remediation strategies of mangroves against heavy metal contamination in global coastal ecosystems: A review,” *J. Clean. Prod.*, vol. 441,

p. 140868, Feb. 2024, doi: 10.1016/J.JCLEPRO.2024.140868.

[156] Z. Yan, X. Sun, Y. Xu, Q. Zhang, and X. Li, "Accumulation and Tolerance of Mangroves to Heavy Metals: a Review," *Curr. Pollut. Reports 2017 34*, vol. 3, no. 4, pp. 302–317, Aug. 2017, doi: 10.1007/S40726-017-0066-4.

[157] K. Kulbat-Warycha, E. C. Georgiadou, D. Mańkowska, B. Smolińska, V. Fotopoulos, and J. Leszczyńska, "Response to stress and allergen production caused by metal ions (Ni, Cu and Zn) in oregano (Origanum vulgare L.) plants," *J. Biotechnol.*, vol. 324, pp. 171–182, Dec. 2020, doi: 10.1016/J.JBIOTEC.2020.10.025.

[158] S. Mansoor *et al.*, "Heavy Metal Induced Oxidative Stress Mitigation and ROS Scavenging in Plants," *Plants*, vol. 12, no. 16, Aug. 2023, doi: 10.3390/PLANTS12163003.

[159] H. N. Thatoi, J. K. Patra, and S. K. Das, "Free radical scavenging and antioxidant potential of mangrove plants: A review," *Acta Physiol. Plant.*, vol. 36, no. 3, pp. 561–579, 2014, doi: 10.1007/s11738-013-1438-z.

[160] J. Liu and T. Myat, "Contaminants and heavy metals along the mangrove area of Dongzhai Harbor, China: distribution and assessment," *SN Appl. Sci.*, vol. 3, no. 10, pp. 1–12, Oct. 2021, doi: 10.1007/S42452-021-04802-2/FIGURES/6.

Unsri Google Apps

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Confirming submission to Toxicology Reports

1 pesan

Toxicology Reports <em@editorialmanager.com> 27 Februari 2025 pukul 15.15
Balas Ke: Toxicology Reports <support@elsevier.com>
Kepada: Rozirwan Rozirwan <rozirwan@unsri.ac.id>

This is an automated message.

Manuscript Number: **TOXREP-D-24-00875R1**

Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

Dear Dr. Rozirwan,

We have received the above referenced manuscript you submitted to Toxicology Reports.

To track the status of your manuscript, please log in as an author at https://www.editorialmanager.com/toxrep/, and navigate to the "Revisions Being Processed" folder.

Thank you for submitting your revision to this journal.

Kind regards,
Toxicology Reports

Have questions or need assistance?
For further assistance, please visit Elsevier Support Center for Author Support. Here you can search for solutions on a range of topics, find answers to frequently asked questions, and learn more about Editorial Manager via interactive tutorials.
You can also talk to our customer support team 24/7 by live chat, email and phone.

#AU_TOXREP#

To ensure this email reaches the intended recipient, please do not delete the above code

---

In compliance with data protection regulations, you may request that we remove your personal registration details at any time. (Remove my information/details). Please contact the publication office if you have any questions.

Unsri Google Apps

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Decision on submission to Toxicology Reports

1 pesan

Toxicology Reports <em@editorialmanager.com> 28 Februari 2025 pukul 22.37
Balas Ke: Toxicology Reports <support@elsevier.com>
Kepada: Rozirwan Rozirwan <rozirwan@unsri.ac.id>

CC: l.h.lash@wayne.edu

Manuscript Number: **TOXREP-D-24-00875R1**

Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

Dear Dr Rozirwan,

Thank you for submitting your manuscript to Toxicology Reports.

I have completed my evaluation of your manuscript. The reviewers recommend reconsideration of your manuscript following major revision. I invite you to resubmit your manuscript after addressing the comments below. Please resubmit your revised manuscript by **Mar 14, 2025**.

When revising your manuscript, please consider all issues mentioned in the reviewers' comments carefully: please outline every change made in response to their comments and provide suitable rebuttals for any comments not addressed. Please note that your revised submission may need to be re-reviewed.

To submit your revised manuscript, please log in as an author at https://www.editorialmanager.com/toxrep/, and navigate to the "Submissions Needing Revision" folder.

Toxicology Reports values your contribution and I look forward to receiving your revised manuscript.

Research Elements (optional)
This journal encourages you to share research objects - including your raw data, methods, protocols, software, hardware and more – which support your original research article in a Research Elements journal. Research Elements are open access, multidisciplinary, peer-reviewed journals which make the objects associated with your research more discoverable, trustworthy and promote replicability and reproducibility. As open access journals, there may be an Article Publishing Charge if your paper is accepted for publication. Find out more about the Research Elements journals at https://www.elsevier.com/authors/tools-and-resources/research-elements-journals?dgcid=ec_em_research_elements_email.

Kind regards,

Lawrence Lash
Editor-in-Chief
Toxicology Reports

Editor comments:

We also need a version of the manuscript with all changes accepted and tracking turned off (i.e., a Clean version). The tracked changes version can be submitted as a supplemental file. We cannot send this out for re-review with only the tracked changes version.

More information and support

FAQ: How do I revise my submission in Editorial Manager?
https://service.elsevier.com/app/answers/detail/a_id/28463/supporthub/publishing/

FAQ: How can I reset a forgotten password?

https://service.elsevier.com/app/answers/detail/a_id/28452/supporthub/publishing/
For further assistance, please visit our customer service site: https://service.elsevier.com/app/home/supporthub/publishing/
Here you can search for solutions on a range of topics, find answers to frequently asked questions, and learn more about Editorial Manager via interactive tutorials. You can also talk 24/7 to our customer support team by phone and 24/7 by live chat and email

At Elsevier, we want to help all our authors to stay safe when publishing. Please be aware of fraudulent messages requesting money in return for the publication of your paper. If you are publishing open access with Elsevier, bear in mind that we will never request payment before the paper has been accepted. We have prepared some guidelines (https://www.elsevier.com/connect/authors-update/seven-top-tips-on-stopping-apc-scams) that you may find helpful, including a short video on Identifying fake acceptance letters (https://www.youtube.com/watch?v=o5l8thD9XtE). Please remember that you can contact Elsevier s Researcher Support team (https://service.elsevier.com/app/home/supporthub/publishing/) at any time if you have questions about your manuscript, and you can log into Editorial Manager to check the status of your manuscript (https://service.elsevier.com/app/answers/detail/a_id/29155/c/10530/supporthub/publishing/kw/status/).

#AU_TOXREP#

To ensure this email reaches the intended recipient, please do not delete the above code

---

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Revision of "Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones" is due soon

1 pesan

Lawrence Lash <em@editorialmanager.com> 11 Maret 2025 pukul 12.50
Balas Ke: Lawrence Lash <l.h.lash@wayne.edu>
Kepada: Rozirwan Rozirwan <rozirwan@unsri.ac.id>

This is an automated message.

Manuscript Number: **TOXREP-D-24-00875R1**
Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

Dear Dr. Rozirwan,

We would like to remind you that on **Feb 28, 2025** we asked you to revise your above referenced manuscript and your revision is due by **Mar 14, 2025**.

Toxicology Reports values your contribution and we look forward to receiving your revised manuscript.

To submit your revision, please log in as an author at https://www.editorialmanager.com/TOXREP/, and navigate to the "Submissions Needing Revision" folder under the Author Main Menu. You will also find the decision letter and comments available there.

If you do not plan to revise your manuscript, please click "Decline to Revise" in the "Submissions Needing Revision" folder.

If you require more time, please contact the journal office by replying to this email.

Kind regards,
Toxicology Reports

Have questions or need assistance?
For further assistance, please visit Elsevier Support Center for Author Support. Here you can search for solutions on a range of topics, find answers to frequently asked questions, and learn more about Editorial Manager via interactive tutorials.
You can also talk to our customer support team 24/7 by live chat, email and phone.

#AU_TOXREP#

To ensure this email reaches the intended recipient, please do not delete the above code

---

Unsri Google Apps

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Confirming submission to Toxicology Reports

1 pesan

Toxicology Reports <em@editorialmanager.com> 12 Maret 2025 pukul 13.37
Balas Ke: Toxicology Reports <support@elsevier.com>
Kepada: Rozirwan Rozirwan <rozirwan@unsri.ac.id>

This is an automated message.

Manuscript Number: **TOXREP-D-24-00875R2**

Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

Dear Dr. Rozirwan,

We have received the above referenced manuscript you submitted to Toxicology Reports.

To track the status of your manuscript, please log in as an author at https://www.editorialmanager.com/toxrep/, and navigate to the "Revisions Being Processed" folder.

Thank you for submitting your revision to this journal.

Kind regards,
Toxicology Reports

Have questions or need assistance?
For further assistance, please visit Elsevier Support Center for Author Support. Here you can search for solutions on a range of topics, find answers to frequently asked questions, and learn more about Editorial Manager via interactive tutorials.
You can also talk to our customer support team 24/7 by live chat, email and phone.

#AU_TOXREP#

To ensure this email reaches the intended recipient, please do not delete the above code

---

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Decision on submission to Toxicology Reports

1 pesan

Toxicology Reports <em@editorialmanager.com> 17 Maret 2025 pukul 16.07
Balas Ke: Toxicology Reports <support@elsevier.com>
Kepada: Rozirwan Rozirwan <rozirwan@unsri.ac.id>

CC: l.h.lash@wayne.edu, nbasaran@hacettepe.edu.tr, anbasaran@baskent.edu.tr

Manuscript Number: **TOXREP-D-24-00875R2**

Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

Dear Rozirwan,

Thank you for submitting your manuscript to Toxicology Reports.

I have completed my evaluation of your manuscript. The reviewers recommend reconsideration of your manuscript following minor revision and modification. I invite you to resubmit your manuscript after addressing the comments below. Please resubmit your revised manuscript by **Mar 31, 2025**.

When revising your manuscript, please consider all issues mentioned in the reviewers' comments carefully: please outline every change made in response to their comments and provide suitable rebuttals for any comments not addressed. Please note that your revised submission may need to be re-reviewed.

To submit your revised manuscript, please log in as an author at https://www.editorialmanager.com/toxrep/, and navigate to the "Submissions Needing Revision" folder under the Author Main Menu.

Research Elements (optional)
This journal encourages you to share research objects - including your raw data, methods, protocols, software, hardware and more – which support your original research article in a Research Elements journal. Research Elements are open access, multidisciplinary, peer-reviewed journals which make the objects associated with your research more discoverable, trustworthy and promote replicability and reproducibility. As open access journals, there may be an Article Publishing Charge if your paper is accepted for publication. Find out more about the Research Elements journals at https://www.elsevier.com/authors/tools-and-resources/research-elements-journals?dgcid=ec_em_research_elements_email.

Toxicology Reports values your contribution and I look forward to receiving your revised manuscript.

Kind regards,

Lawrence Lash
Editor-in-Chief
Toxicology Reports

Editor and Reviewer comments:

Reviewer #1: Kindly, recreate the graphical abstract. Please visit the link https://doi.org/10.1016/j.ecss.2019.106403
Regarding to previous study on biomarker which involve sediment and mangrove this reference ((https://doi.org/10.1016/j.ecss.2019.106403) may strengthen the manuscript
Please kindly correct this word (ample) Line 57 - Leaf sampling section
Please kindly reorganize Line 1 - 10 - Atomic absorption and determination of heavy metals
Please kindly mention the detail in AAS instrument (e.g. Shimidzu or etc)
Please kindly added detail in measurement procedure on using AAS

More information and support

FAQ: How do I revise my submission in Editorial Manager?

https://service.elsevier.com/app/answers/detail/a_id/28463/supporthub/publishing/

FAQ: How can I reset a forgotten password?
https://service.elsevier.com/app/answers/detail/a_id/28452/supporthub/publishing/
For further assistance, please visit our customer service site: https://service.elsevier.com/app/home/supporthub/publishing/
Here you can search for solutions on a range of topics, find answers to frequently asked questions, and learn more about Editorial Manager via interactive tutorials. You can also talk 24/7 to our customer support team by phone and 24/7 by live chat and email

At Elsevier, we want to help all our authors to stay safe when publishing. Please be aware of fraudulent messages requesting money in return for the publication of your paper. If you are publishing open access with Elsevier, bear in mind that we will never request payment before the paper has been accepted. We have prepared some guidelines (https://www.elsevier.com/connect/authors-update/seven-top-tips-on-stopping-apc-scams) that you may find helpful, including a short video on Identifying fake acceptance letters (https://www.youtube.com/watch?v=o5l8thD9XtE). Please remember that you can contact Elsevier s Researcher Support team (https://service.elsevier.com/app/home/supporthub/publishing/) at any time if you have questions about your manuscript, and you can log into Editorial Manager to check the status of your manuscript (https://service.elsevier.com/app/answers/detail/a_id/29155/c/10530/supporthub/publishing/kw/status/).

#AU_TOXREP#

To ensure this email reaches the intended recipient, please do not delete the above code

---

Table of Responses

No.	Questions	Answears
	Reviewer #1	
1.	Kindly, recreate the graphical abstract	We have carefully revised the graphical abstract.
2.	Regarding to previous study on biomarker which involve sediment and mangrove this reference ((https://doi.org/10.1016/j.ecss.2019.106403) may strengthen the manuscript	We have now incorporated the reference into our manuscript, particularly in the Results and Discussion section related to antioxidant activity and total phenol content.
3.	Please kindly correct this word (ample) Line 57 - Leaf sampling section	We have revised.
4.	Please kindly reorganize Line 1 - 10 - Atomic absorption and determination of heavy metals	We have revised.
5.	Please kindly mention the detail in AAS instrument (e.g. Shimidzu or etc)	We have made specifications for the equipment used, namely the Atomic Absorption Spectrophotometer (Shimadzu AA-7000).
6.	Please kindly added detail in measurement procedure on using AAS	We have added details in the measurement procedure using AAS by citing references from the book Fundamentals of Analytical Chemistry.

Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

Rozirwan[1*], Nadila Nur Khotimah[2], Wike Ayu Eka Putri[1], Fauziyah[1], Riris Aryawati[1], Gusti Diansyah[1], Redho Yoga Nugroho[1]

[1]Department of Marine Science, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya, Indralaya 30862, South Sumatra, Indonesia

[2]Environmental Management Study Program, Graduate Program, Universitas Sriwijaya, Palembang 30139, Indonesia

*Corresponding author's e-mail : rozirwan@unsri.ac.id

Abstract

Heavy metal contamination from industrial activities in coastal regions can lead to pollution in mangrove ecosystems. Mangroves produce antioxidant compounds to mitigate the impact of free radicals. This study aimed to analyze the correlation between the concentration of heavy metals Pb and Cu and antioxidant activity in *Avicennia alba* and *Excoecaria agallocha* mangroves from areas affected by industrial activities and conservation areas, Banyuasin, South Sumatra, Indonesia. This study was conducted in September 2023 with sampling locations in the Payung Island area and the Barong River conservation area, Berbak Sembilang National Park. The samples taken included sediment and mangrove leaves. The concentration of heavy metals Pb and Cu was measured by atomic absorption spectrometry. Antioxidant activity test using the DPPH test, total phenol using the Folin-Ciocalteu method, and phytochemical profile screening using GCMS. Statistical analysis of the correlation between antioxidant activity and heavy metal concentration using the Pearson correlation. The results

showed that the highest concentration of heavy metals in sediment and mangrove leaves was found in the area affected by industrial activity, with a range of Pb values of 0.67 ± 0.16 to 18.70 ± 0.48 mg/kg and Cu values of 3.39 ± 0.20 to 6.07 ± 0.37 mg / kg. The results of sediment pollution assessment for heavy metals Pb and Cu at Igeo < 0 indicates uncontaminated, $1 < Cf < 3$ indicates low contamination, and PLI 0-2 indicates not polluted. While the results of heavy metal bioaccumulation in leaves were BCF < 1, indicates low bioaccumulation. *E. agallocha* leaves from the Pulau Payung area showed very strong antioxidant activity of 21.63 µg/ml, and the highest total phenol content reached 398.80 mg GAE/g. Analysis of compounds with the highest antioxidant activity identified the presence of esters, aldehydes, alcohols, fatty acids, glycosides, flavonoids, terpenoids, and steroids. Correlation analysis shows that higher heavy metal concentrations correspond to increased antioxidant activity and total phenol content ($r \neq 0$). These findings are expected to contribute to scientific knowledge that enhances environmental sustainability, supporting effective management of coastal natural resources.
Keywords: Biomarkers, conservation zones, heavy metals, industrial activities, mangrove

Introduction

Coastal areas are transitional areas between land and sea that have abundant biodiversity and unique ecosystems [1,2]. Coastal areas face great pressure from various anthropogenic activities that can cause pollution [3,4]. Previous studies report that industrial activities like fertilizer processing, oil and gas, and crude palm oil production contribute to coastal pollution. [3,5,6]. In addition, there are also agricultural activities, ports, shipping, loading and unloading of coal raw materials and their products, and households [7]. Continuous anthropogenic activities in coastal areas can produce pollutants, such as microplastics, heavy metals, as well as various organic and inorganic contaminants [8, 9, 10]. Among various pollutant types, heavy metals are categorized as persistent pollutants due to their resistance to decomposition [11].

Heavy metals initially present in the water column gradually settle to the sediment and eventually accumulate in aquatic organisms [12]. This condition may have adverse impacts, particularly if it exceeds environmental quality standards. These adverse impacts can affect aquatic ecosystems, including mangroves [13,14]. According to Xu et al. (2024) , as the largest plant community in coastal areas, mangroves are also directly affected by pollution.

Mangrove ecosystems play a vital role in coastal protection, supporting biological diversity, and contributing to the socio-economic development of local communities [16,17]. Additionally, their capacity to accumulate pollutants makes them valuable indicators for assessing pollution levels in coastal waters, as they can absorb and store these pollutants in their tissues, enhancing their role in monitoring environmental health [18,19, 20]. Roots and leaves are important parts of mangroves in the absorption, accumulation, and response to pollutants [21]. Roots are the first part exposed to pollutants from their growth media. Furthermore, roots also have the ability to translocate pollutants to the leaves. Leaves are the primary site for photosynthesis in plants, supplying the energy essential for cell development, and overall plant function [22]. High concentrations of pollutants in roots and leaves can potentially increase excessive reactive oxygen species (ROS), resulting in oxidative stress in mangroves [23,24]. Oxidative stress arises from an imbalance between ROS production and detoxification, potentially leading to harmful cellular damage [25,26]. Although oxidative stress can be detrimental, plants also have a resistance response mechanism against free radicals [27]. This process involves producing antioxidant enzymes and molecules to counteract the harmful effects of free radicals. In response to environmental changes, plants enhance the activity of antioxidant defenses, including both enzymatic and non-enzymatic components such as superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), glutathione peroxidase (GPx), and phenolic compounds. These antioxidants serve as protective mechanisms against various environmental stress [28,29].

Research on the specific physiological adaptations of various mangrove species to pollutants is still limited. Most previous studies only focused on the accumulation of heavy metals in mangroves without exploring in depth the biochemical defense mechanisms they employ [30, 31, 32]. However, studies on how different mangrove species respond to industrial pollution in environments with varying levels of pollution have not yet been conducted. In addition, most studies only examine one mangrove species without comparing the adaptability of different species in the face of heavy metal contamination [33, 34].

This study aimed to evaluate the accumulation of heavy metals (Pb and Cu) in two mangrove species (*Avicennia alba* and *Excoecaria agallocha*) and assess their antioxidant activity in industrial and conservation zones. The selection of these two species was based on their prevalence in the research location as well as differences in habitat zones and morphological characteristics [35, 36]. This study was carried out in the mangrove ecosystem, which includes areas influenced by industrial activities such as Payung Island as well as conservation areas in the Berbak Sembilang National Park [37, 38].

By assessing biomarkers, new insights are provided into how mangrove species adapt to environmental stress caused by heavy metal pollution. Additionally, the research explores the impact of heavy metal contamination on the physiological responses of mangroves, focusing on their biochemical defense mechanisms. The findings aim to enhance understanding of mangrove adaptation strategies in response to pollution and offer valuable implications for coastal ecosystem conservation and environmental pollution management.

Materials and Method

Leaf sampling

This study was conducted in September 2023. The samples included *Avicennia alba*, *Excoecaria agallocha*, and sediments collected from industrial and conservation zones in

Banyuasin, South Sumatra, Indonesia (Figure 1). The first area is the mangrove ecosystem on Payung Island. This area was chosen due to the high accumulation of heavy metals from industrial activities along the Musi River. Additionally, the area includes agricultural activities, ports, fish ponds, and settlements [39, 40]. The second area is the conservation forest in Sungai Barong, Sembilang National Park, which represents a natural area and protects flora and fauna from the threat of damage, scarcity, or deforestation [41, 42, 43].

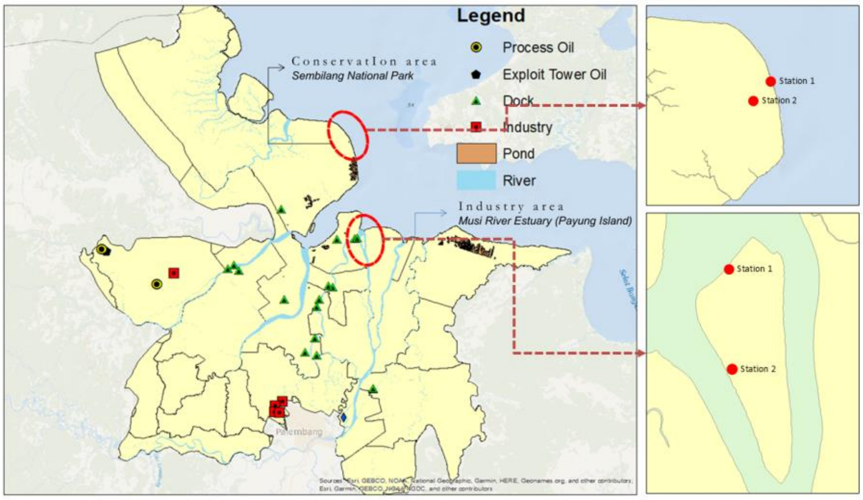


Fig.1. Map of sample collection

The sampling stages include collecting sediment samples and mangrove leaves. Sediment samples were taken as supporting data to determine the concentration of heavy metals in the mangrove growth media. The availability of heavy metals in sediments has a direct effect on the bioaccumulation and biomagnification processes in aquatic organisms. Sediment data helps understand the level of risk and potential impacts to organisms in mangrove ecosystems. Sediment samples were taken using a grab pipe at a depth of ± 10 cm from the surface [44]. Sediment depth shows a very significant impact on heavy metal content, with a greater decrease in heavy metal content as sediment depth increases [45]. Samples were taken at three location points for each station, which were considered as replications. Samples were taken compositely together (taken as needed, 500 g) and placed into a polyethylene plastic container and stored in a cool box for analysis in the laboratory.

The method for collecting mangrove leaves taken from the field uses a random sampling method [46]. The random sampling method can be used if the sample studied is homogeneous. The mangrove species taken were *A. alba* and *E. agallocha*. The samples taken consisted of ± 1 kg of leaves and were put in polyethylene plastic.

Sediment grain size analysis

Grain size analysis was conducted using the sieving and pipetting methods as outlined by [47]. Sediment types (gravel, sand, silt, and clay) were classified using Shepard's triangle analysis and processed with Microsoft Excel V.2021, following the protocols established by [48, 49]. The sediment fraction type was determined by identifying the most dominant composition from the analysis results.

Sample preparation

Sediment sample preparation involved removing foreign objects such as plastic fragments and leaves. The sediment was then air dried at room temperature for 72 hours until fully dry, ground to a homogeneous consistency, and stored in a tightly sealed polyethylene bottle. They were then air-dried in a shaded, well-ventilated area for five days, ensuring indirect exposure to sunlight to prevent the degradation of bioactive compounds. The drying process was conducted at ambient temperature with sufficient airflow to facilitate moisture evaporation. Once dried, the samples were ground into a fine powder and stored in sealed containers for further analysis. . The extraction of heavy metals (Pb and Cu) from the sediment samples and mangrove leaves was performed using the wet destruction method, following the procedures outlined by [8, 50].

Atomic absorption spectroscopic measurement

Measuring the concentration of heavy metals Pb and Cu using an atomic absorption spectrophotometer with a wavelength of 283.3 nm for Pb and 324.7 nm for Cu Measuring the concentration of heavy metals Pb and Cu using an Atomic Absorption Spectrophotometer (Shimadzu AA-7000). Operational parameters: Pb (283.3 nm, 5 mA lamp current) and Cu (324.7 nm, 4 mA), slit width 0.5 nm, air-acetylene flame (2.0 L/min air; 1.5 L/min acetylene), burner height 5–7 mm. After 15–20 min warm-up, calibration was performed using blank and standard solutions (0.1–2.0 ppm Pb; 0.05–1.0 ppm Cu), achieving $R^2 \geq 0.995$. Samples were aspirated in triplicate with 15-sec distilled water rinsing between measurements and acid blank checks every 5 samples. Quality control included spike recovery (85–115%), duplicate analyses (RSD <5%), and certified reference materials (NIST SRM 1640a/2711a). LODs: 0.02 ppm Pb; 0.01 ppm Cu (3×SD blank) [51].

Determination of heavy metals in leaves and sediments

Determination of sediment pollution

Geoacumulation index (I_{geo})

The Igeo (geo-accumulation index) quantitatively evaluates the degree of heavy metal contamination and classifies the level of pollution based on detailed categorization [52].

$$Igeo = \log_2 (Cn/1.5\ Bn) \quad (1)$$

The classification of Igeo values includes the following categories: uncontaminated (Igeo ≤ 0), uncontaminated to moderately contaminated (Igeo 0–1), moderately contaminated (Igeo 1–2), moderately to highly contaminated (Igeo 2–3), highly contaminated (Igeo 3–4), highly contaminated to very highly contaminated (Igeo 4–5), and very highly contaminated (Igeo ≥ 5) [53].

Contamination factor (Cf)

The contamination factor is determined experimentally as the ratio of the element concentration in the sample to its background concentration [54].

$$Cf = (Cn/Bn) \qquad (2)$$

The contamination factor (Cf) classifications are as follows: [55]: Cf < 1 = low contamination; 1 < Cf < 3 = moderate contamination; 3 < Cf < 6 = sufficient contamination; Cf > 6 = very high contamination.

Pollution load index (PLI)

The pollution load index (PLI) is utilized to assess pollution quality in a given area. The pollution load index value uses the formula [56].

$$PLI = [\, Cf1 \times Cf2 \times Cf3 \ldots \times Cfn\,]^{1/n} \qquad (3)$$

Pollution load index (PLI) criteria: PLI 8-10 = severely polluted; PLI 4-8 = heavily polluted; PLI 2-4 = moderately polluted; PLI 0-2 = not polluted to lightly polluted; PLI < 0 = not polluted.

Bioaccumulation of metal in leaves

Bioconcentration factor (BCF)

The absorption of metals by leaf from sediment occurs through a process known as bioaccumulation. The Bioconcentration Factor (BCF) values are utilized to assess the extent of metal bioaccumulation in mangrove leaf originating from sediment [57].

$$BCF = (Cn.leaf/Cn.\ sediment) \qquad (4)$$

BCF > 1 hyperaccumulator; BCF = 1 indicator; BCF < 1 is an excluder [58].

Analysis of antioxidant non-enzymes in leaves

Antioxidant activity evaluated by DPPH assay

Antioxidant activity analysis was carried out using ethanol solvent based on a method adapted from [59]. A 50 ml 0.1 μM DPPH solution was prepared, followed by the preparation of a sample stock solution and a 10 ml pure ascorbic acid stock solution of 2000 ppm, which was homogenized. Furthermore, a series of solutions were made with concentrations of 1000 ppm, 500 ppm, 250 ppm, 125 ppm, and 62.5 ppm. At each concentration, 1 ml of 0.1 μM DPPH solution was added to the mixture, which was then homogenized and incubated in the dark for 30 minutes. After incubation, the absorbance was measured using a UV-Vis spectrophotometer (Shimadzu UV-1900, Japan) at a wavelength of 517 nm. The antioxidant activity of the extract is expressed as IC_{50}, which quantifies the strength of its antioxidant capacity (Table 1). The IC_{50} value is calculated using the following formula:

$$\%\,inhibition = \frac{blank\ abs - sample\ abs.}{blank\ abs} \times 100\% \quad (5)$$

The IC_{50} value was derived by inputting the data into a linear regression equation, where the sample concentration was plotted on the X-axis and the percentage of inhibition of antioxidant activity on the Y-axis. The regression equation used is represented as y=ax + b [60].

Table 1

Characteristic value of IC_{50}

Concentration (μg/ml)	Characteristic

<50	Very strong
50-100	Strong
100-150	Moderate
150-200	Low

Determination of phenol content

The analysis of total phenol content in the samples was conducted using the Folin-Ciocalteu method, as outlined in the literature [60, 61, 62]. A standard solution of 1000 ppm gallic acid as much as 50 ml was prepared, then variations in concentrations of 10 ppm, 20 ppm, 30 ppm, 40 ppm, and 50 ppm were made, each as much as 5 ml. For each concentration variation, 1 ml, 2 ml, 3 ml, 4 ml, and 5 ml were pipetted into a 10 ml measuring flask containing a standard solution of 100 ppm gallic acid. A total of 50 mg of sample was weighed, then 2 ml of methanol and 5 ml of distilled water were added, then homogenized in a 10 ml measuring flask. In both the standard series and sample variations, 0.5 ml of 50% Folin-Ciocalteu reagent was added, followed by the addition of distilled water up to the mark. The mixture was then allowed to stand for 5 minutes. Next, one ml of a 5% Na2CO3 solution was added and incubated in a dark place for one hour. After incubation, the absorbance of the sample was measured using a UV-Vis spectrophotometer at a wavelength of 750 nm.

Pearson correlation analysis (*correlation bivariate*)

The use of Pearson correlation analysis (bivariate correlation) is a method used to evaluate the relationship between two variables [63, 64], in this case to see the relationship between antioxidant activity and heavy metal concentrations. This analysis was carried out using SPSS software version 28.

Result and Discussion

Description of mangrove leaves

The mangrove species *A. alba* and *E. agallocha* found at the sampling location exhibit distinct characteristics. Figure 2 shows the morphological differences between *A. alba* and *E. agallocha*.

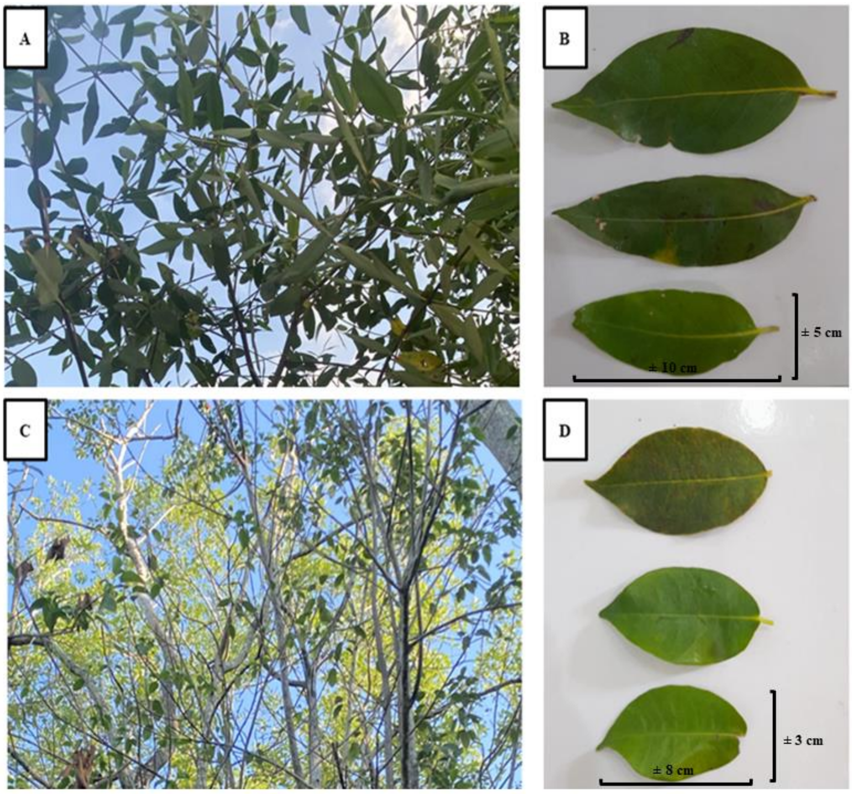


Fig.2. Leaves description. A-B). *A. alba*, C-D). *E. agallocha*

Leaves are the part that characterizes a mangrove species. When identifying each type of mangrove, observation of the morphology of the leaf shape is very important to understand the characteristics and differences in each type of leaf [31, 65]. *A. alba* leaves have a green surface with a smooth and slippery texture, while the underside is yellowish green with a rough texture. The morphology of the leaves is elliptical, almost oval, with a tapered tip. Based on observations, the length of the leaves ranges from 10 to 13 cm, and the width of the leaves ranges from 4 to 5 cm. *E. agallocha* leaves are elliptical and dark green in color, with finely serrated edges and tapered tips. The observed leaf sizes ranged from 8 to 10 cm in length and 3 to 4.5 cm in width. Old leaves were selected as samples for the study of heavy metal content and bioactive compounds due to several considerations related to their maturity and potential accumulation of pollutants and compounds of interest. According to [67], plants tend to produce bioactive compounds in higher amounts in older parts. This could be a plant strategy to protect itself from pests, diseases, or the external environment [67, 68]. Older leaves may have more stable chemical conditions, thus facilitating analysis and minimizing variability in results.

Sediment grain size

The determination of substrate types in the sampling was conducted using the Shepard triangle method (Figure 3). In the mangrove ecosystem of both industrial and conservation areas, sediment substrates were categorized into four types: gravel, sand, mud, and clay. The results indicated that the predominant substrate type in both areas was clay.

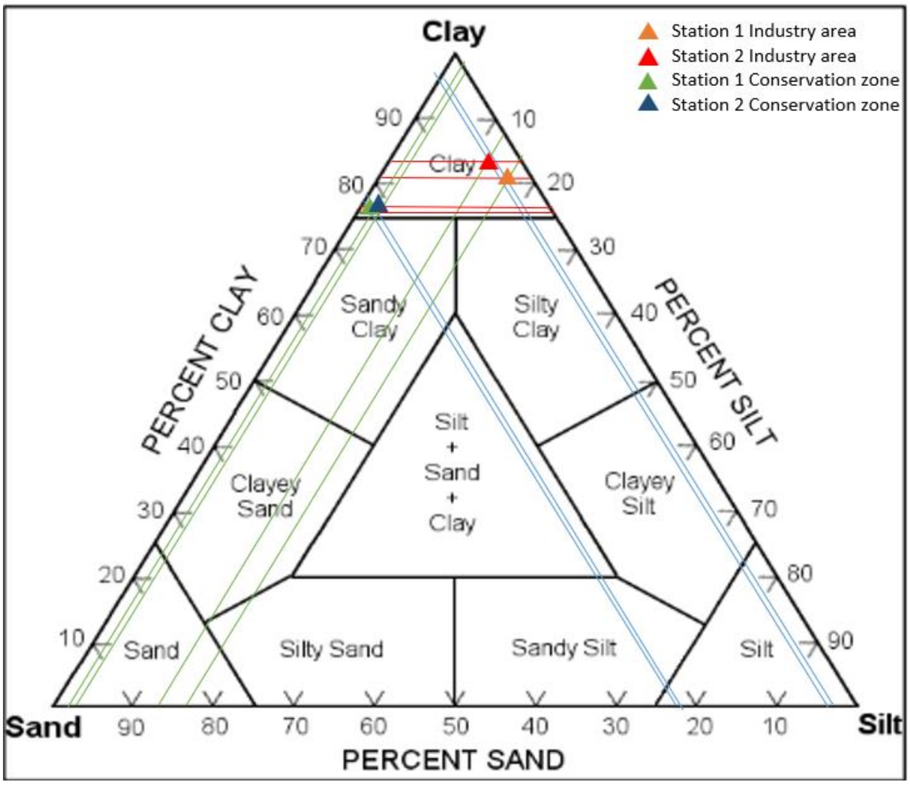


Fig.3. Classifications of sediment type with shepard triangle method

The sediment substrate surrounding the mangrove ecosystem in both areas is predominantly clay, with clay percentages ranging from 80,5% to 84,03%. The highest clay content was observed at station 1 in the industrial area (Table 2).

Tabel 2

Sediment grain size in each station

Location	Station	Sediment fraction (%)				Grain size
		Gravel	Sand	Mud	Clay	

Industry area	1 (*A. alba*)	0,00	3,6	12,37	84,03	Clay
	2 (*E. agallocha*)	0,00	3,36	16,14	80,5	Clay
Conservation zone	1 (*A. alba*)	0,00	22,5	1,95	75,55	Clay
	2 (*E. agallocha*)	0,00	21,91	2,02	76,07	Clay

Based on the results of Table 2, distribution of sediment fractions and grain sizes at two different locations, which represents two stations with different mangrove species *(A. alba* and *E. agallocha*). In the industrial area, most of the sediments consist of clay with a very low sand content (3.6% for Station 1 and 3.36% for Station 2), which indicates the predominance of fine materials that can influence the mobility of heavy metals and nutrients in the sediments. In contrast, in the conservation zone, although the sediment composition is still dominated by clay, the sand content is higher (22.5% for Station 1 and 21.91% for Station 2), indicating differences in sedimentation processes and a higher potential for water infiltration.

In the industrial area, both stations (*A. alba* and *E. agallocha*) showed a dominance of clay fractions with a very high percentage. The dominant clay fractions indicate that the sediment in this area consists of fine particles, which may be caused by the accumulation of fine particles from industrial activities around this location. Industries such as fertilizer processing, oil and gas, crude palm oil production, agricultural activities, ports, shipping, loading and unloading of coal raw materials and their products, and households contribute to the presence of fine particles in sediments [3, 5, 6, 7]. Port activities involve frequent vessel movement, dredging, and cargo handling, all of which can resuspend fine particles and increase sedimentation rates [69, 70]. Crude oil processing and petroleum industries may contribute to fine particle deposition through air emissions, which settle via atmospheric deposition [72]. Additionally, agricultural activities, particularly palm oil plantations, can contribute to increased fine particle accumulation through soil erosion and runoff carrying clay-rich sediments into adjacent water systems, particularly during heavy rainfall [72, 73].

Fine particles such as clay are usually carried by water and can accumulate in areas with slow water movement, such as near mangrove roots [74, 75]. In the conservation zone, the clay fraction also dominates, although with a slightly lower percentage than the industrial area. The conservation zone may also have less influence from human activities, so the sediment pattern is more natural than the industrial area. Clay is a sediment particle with a very fine grain size and a large surface area [76, 77]. Due to its small size and its tendency to be negatively charged, clay has a high adsorption capacity, which allows clay particles to attract and bind heavy metal ions such as Hg, Pb, Cd, Cu, and others [78, 79, 80]. Consequently, sediments dominated by clay fractions tend to accumulate more heavy metals than larger sediment fractions [81, 82].

Determination of heavy metals

The results of the heavy metal concentration analysis for Pb and Cu in sediments and mangrove leaves from both areas are summarized in Table 3. The concentrations of heavy metals, specifically Pb and Cu, in sediments from both the industrial area and the conservation zone exhibit variability; however, they generally remain below hazardous thresholds (ERL, ERM, TEL, and PEL). In the industrial area, the highest Pb concentration was found at Station 2 (18.70 ± 0.48 mg/kg), while in the conservation zone, the highest concentrations of Pb and Cu were each at Station 2 (Pb 14.22 ± 0.16 mg/kg; Cu 5.17 ± 0.17 mg/kg). For metal accumulation in mangrove leaves, Cu was recorded higher than Pb at all stations. In the industrial area, *A. alba* (Station 1) had Pb 0.67 ± 0.17 mg/kg and Cu 3.39 ± 0.20 mg/kg, while *E. agallocha* (Station 2) showed Pb 1.27 ± 0.31 mg/kg and Cu 3.73 ± 0.16 mg/kg. In the conservation zone, the highest accumulation of Cu in mangrove leaves was 3.69 ± 0.23 mg/kg at Station 2.

Tabel 3

Average concentrations of heavy metals (mg/kg) in mangrove sediments and leaves

	Pb	Cu
Sediments		
Station.1 Industry area	12.63±0.01	5.58±0.05
Station.2 Industry area	18.70±0.48	6.07±0.37
Station.1 Conservation zone	12.61±0.32	4.21±0.03
Station.2 Conservation zone	14.22±0.16	5.17±0.17
ERL	46.7	34
ERM	218	270
TEL	30.2	18.7
PEL	112	108.2
Mangrove leaves		
Station.1 Industry area (*A. alba*)	0.67±0.17	3.39±0.20
Station.2 Industry area (*E. agallocha*)	1.27±0.31	3.73±0.16
Station.1 Conservation zone (*A. alba*)	0.84±0.12	3.50±0.35
Station.2 Conservation zone (*E. agallocha*)	0.99±0.37	3.69±0.23

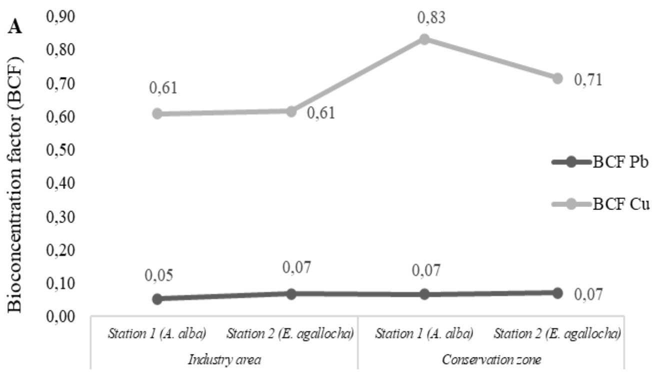
The industrially impacted area in the Musi River Estuary is affected by high anthropogenic activities, making it susceptible to accumulating pollutants, especially heavy metals such as Pb and Cu. Sediments in this area tend to contain higher pollutants than water and biota, influenced by domestic, industrial, and river transportation activities that pollute the environment [83, 84]. Ship and coastal building maintenance activities, including the use of anti-rust materials, electronic waste, and pipe corrosion, are the main sources of Pb, while sources of Cu in the aquatic environment come from antifouling paint, agricultural pesticides, and industrial waste [85, 86]. In addition, previous studies report that cleaning ship hulls can release Cu into the marine environment [87, 88]. Fisheries sector that uses Cu-coated nets to prevent biofouling can also contribute to increasing Cu levels in waters [89, 90].

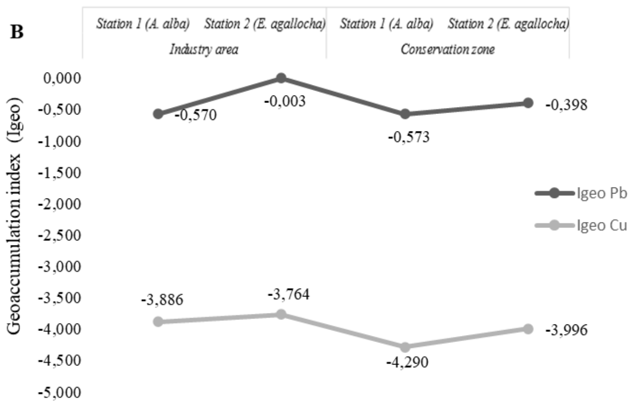
The conservation area in the Barong River is also exposed to heavy metal pollution, although at a lower level, considering that some human activities such as fishing are still ongoing [92]. Unmanaged anthropogenic activities, including unregulated industrial waste disposal, improper wastewater treatment, and uncontrolled agricultural runoff, have contributed to the increasing Cu concentrations observed in both locations, as indicated by the findings of this study and previous research [7, 50]. These activities introduce Cu into the aquatic system, where it binds to suspended particles and accumulates in sediments, further exacerbating environmental pollution.

In mangrove leaves, Pb was detected at low concentrations. Plants regulate Pb primarily by limiting its uptake and translocation. Because Pb is a non-essential and highly toxic metal, most of it accumulates in the roots rather than being transported to the leaves [93]. In contrast, Cu an important micronutrient for plants, is regulated through controlled absorption and detoxification mechanisms [93, 94]. Plants manage excess Cu by binding it to metallothionein and phytochelatin, storing it in vacuoles, and activating the antioxidant defense system to fight oxidative stress [96]. Although heavy metal concentrations vary between locations, they are still below the threshold, indicating a relatively low risk of contamination. However, long-term monitoring is essential to track bioaccumulation trends in mangrove ecosystems.

Sediment quality indices

The results of the sediment quality index assessment are summarized in Figure 4. The results of the leaf bioconcentration factor (BCF) in bioaccumulating Pb and Cu metals from sediment with a BCF value <1 indicating low bioaccumulation. The geoaccumulation index shows uncontaminated properties for Pb and Cu with an Igeo value <0 indicating uncontaminated. The contamination factor (Cf) shows that contamination is low and moderate in Pb and Cu with a value of 1 <Cf <3 indicating low contamination. The PLI ranges from 0 to 2 indicating that both areas are not polluted.





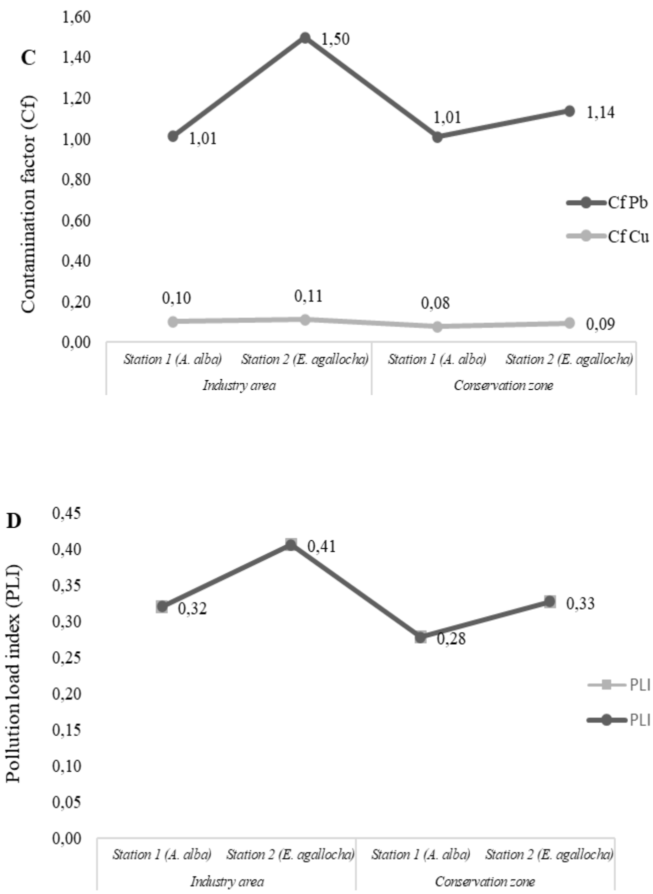


Fig.4. Sediment quality indices. A). Bioconcentration factor (BCF), B). Geoaccumulation index (Igeo), C). Contamination factor (Cf), and D). Pollution load index (PLI).

The difference in bioconcentration factor (BCF) between Cu and Pb can be explained by the chemical properties of each metal. Cu accumulates more easily in biota tissues than Pb. Cu is an essential element for organisms, although at higher concentrations it can be toxic [97]. In contrast, Pb is a non-essential heavy metal that tends not to accumulate much in biota tissues

[98]. The previous studies stated that essential heavy metals are more easily absorbed by organisms because they have physiological mechanisms to regulate the concentration of these elements [98, 99]. Analuddin et al. (2023) have also examined BCF in mangrove ecosystems, with results showing that the BCF values for Hg, Cu, Mn, Pb, and Zn > 1. This finding is thought to be related to the impact of anthropogenic activities in Kendari City, which has a high population density.

The Igeo index shows higher Pb contamination than Cu in industrial areas. Pb is thought to originate from human activities such as ports, agriculture, ship transportation, and household waste that tends to settle in sediments [8, 32]. A high Igeo value indicate an anthropogenic contamination and show sediments contaminated heavy metal [102]. In addition, long-term exposure to these heavy metals can change community structure and disrupt ecosystem function through bioaccumulation and biomagnification in the food chain [102, 103].

The high value of the Pb contamination factor (Cf) in industrial areas indicates that this environment is more susceptible to Pb pollution than Cu. Relevan study by Hasan et al. (2023) that the CF value of Pb (0.76) > Cu (0.68) in core sediment from a mangrove at the Pasur River. Cu is more likely to be bound to organic particles and accumulate in the tissues of benthic organisms, which may explain the lower Cf Cu value. The areas suspected of being polluted tend to have higher anthropogenic activity than conservation zones, which causes significant differences in the levels of contamination and accumulation of heavy metals [106]. Industries around mangrove areas may contribute to elevated levels of heavy metals. Meanwhile, the conservation zone which is relatively protected from industrial activities, shows lower contamination values, although there are still traces of pollution due to remote pollution sources [106, 107].

The PLI value in the industrial area is higher than the conservation zone. This indicates that industrial activities play a role in elevating heavy metal pollution in the area. Industrial areas are usually exposed to pollution sources such as factory waste, air pollution, and surface runoff that carry heavy metals into the sediment [108, 109]. Although both stations are in the same area, there is a difference in the PLI value between Station 1 and Station 2 at both locations. Local factors, including water movement, sediment composition, and proximity to pollution sources, significantly influence the distribution of heavy metals. [111]. The PLI in the conservation zone still shows heavy metal pollution. This could be due to atmospheric deposition from industrial activities in the surrounding area or pollutants carried by water currents from more contaminated areas [111, 112]. This suggests that although the conservation zone has better protection, it is not completely protected from the impacts of nearby industrial pollution.

The study indicate that both areas are classified as not polluted. In line with these findings by Karmakar et al. (2025) , the PLI value in mangrove planting areas due to heavy metals from ship demolition activities is still below 1. Even though the PLI reflects low levels of pollution over time, it can increase the potential for absorption by aquatic organisms and pose ecological risks. therefore, continuous monitoring is required to identify dynamic changes in heavy metal concentrations

Antioxidant non-enzyme activities

The results of percentage of depreciation data for the *A. alba* species taken from the industrial area were 66%, and the conservation zone was 65.8%. While for the *E. agallocha* species from the industrial area it was 68.5% and the conservation zone was 67.9% in the conservation zone. Conversely, the findings of the percentage of dry weight of *A. alba* in the industrial area were 34%, and the conservation zone was 34.3%. In the *E. agallocha*, the percentage of dry weight in the industrial area was recorded at 31.5% and the zone was 32.1% (Table 4).

Table 4

Depreciation percentage of weight

Location	Sample leaves	Sample weight (g)		Depreciation percentage (%)	Weight percentage (%)
		Wet	Dry		
Industry area	*A. alba*	800	272	66	34
	E. agallocha	800	252	68.5	31.5
Conservation zone	*A. alba*	800	274	65.8	34.3
	E. agallocha	800	257	67.9	32.1

The removal of water content from the sample can be achieved by drying it until all moisture is eliminated, as the presence of water can influence the stability of bioactive compounds during extraction. Certain compounds may remain more stable or be less prone to chemical degradation or oxidation in dry conditions. The extraction of leaf samples from *A. alba* and *E. agallocha* was performed using ethanol as the solvent. The results indicated that the extract yield from the *A. alba* leaves was the highest at 8.80%, which was obtained from the conservation area (Table 5).

Table 5

Percentage of etanol extract

Location	Sample leaves	Extract weight (g)		Depreciation percentage (%)	Extract percentage (%)
		Dry powder	Crude extract		
Industry area	*A. alba*	250	22.01	91.20	8.80
	E. agallocha	250	17.33	93.07	6.93
	A. alba	250	13.17	94.73	5.27

Conservation zone	*E. agallocha*	250	21.42	91.43	8.57

Based on Table 5, these results indicate that environmental conditions, both in industrial areas and conservation zones, have the potential to affect the weight of crude extracts and the percentage of depreciation of *A. alba* and *E. agallocha* leaves, with the possibility of differences in the composition of bioactive compounds in each location. The maceration and extraction processes are important steps in testing the content of bioactive compounds in samples, especially in separating compound components from mangrove extracts [115]. The use of solvents such as ethanol, which are amphipathic, allows the dissolution of both polar and nonpolar compounds, so that it is optimal for obtaining various bioactive compounds from mangroves, which contain various types of compounds with these properties [115, 116, 117]. A high percentage of extraction weight indicates the effectiveness of the extraction method, indicating the method's ability to obtain active compounds from the sample optimally [119]. High extraction results also indicate a high content of active compounds in the sample, which possess the capability to have biological value and other practical applications [120].

The potential antioxidant content is illustrated by the percentage value of free radical scavenging inhibition along with the IC_{50} value. The results of the antioxidant test on mangrove leaves using the DPPH radical scavenging method using ethanol solvent (Table 6). The IC_{50} value content in the industrial area for *A. alba* of 137.8 µg/ml is classified as a moderate and *E. agallocha* of 21.63 µg/ml is classified as a very strong. While in the conservation area, *A. alba* of 64.32 µg/ml is classified as a strong and *E. agallocha* of 41.43 µg/ml is also classified as a very strong.

Table 6

Classification of IC_{50}

Location	Sample leaves	Linear regression a	b	R^2	IC_{50} (µg/ml)	Category
Industry area	*A. alba*	36,277	128,7	0,9429	137,8	Moderate
	E. agallocha	30,953	45,165	0,9419	21,63	Very strong
Conservation zone	*A. alba*	28,726	69,611	0,8905	64,32	Strong
	E. agallocha	18,425	18,661	0,904	41,43	Very strong

The IC_{50} classification results indicate that *A. alba* leaves from both areas fall into the strong-moderate category, while *E. agallocha* is classified as very strong. According to Kodikara et al. (2020) , the difference in the strength of antioxidant activity in each species is thought to be because mangroves have different tolerances to certain environmental conditions, and this can affect the extent to which they can overcome heavy metal toxicity. Previous research explained that the genus Avicennia is a mangrove found in the front zone and directly facing the waters [122]. *Avicennia spp.* has strong and dense aerial roots so that it is able to efficiently capture and bind mud and various pollutants carried by water [122, 123]. As a type of plant that is periodically submerged in water, the roots of mangroves are able to take, absorb, or reduce contaminants through the dilution process [124, 125]. Therefore, it is hypothesized that contaminants absorbed by roots do not induce excessive oxidative stress and do not increase the production of secondary metabolites.

Another study in the Island of Weno area, Chuuk State of Micronesia, for the antioxidant activity of *Rhizophora stylosa* roots was 41.3% and *Sonneratia alba* 40.7% [61]. While the IC_{50} value of the *E. agallocha* in both areas is included in the high category. *E. agallocha* in this study was found in the ladward zone. This zone is rarely submerged by seawater and is more often affected by lower tides. This is thought to be the cause of the low water content in the leaves of *E. agallocha* as presented in Table 4, so that the pollutants absorbed are greater and last longer in the leaves. Therefore, the roots act to mitigate stress effectively by producing antioxidant activity [127]. The concentration of antioxidant activity (IC_{50}) in the leaves showed different values in the two areas. The differences that occur in the ability to produce antioxidant activity in each mangrove as a form of self-defense against oxidative stress are due to differences in morphology, habitat, tides, sediment substrates, and environmental conditions [127, 128]. Kumar et al. (2019) also found that mangrove sediments in intertidal zones are rich in organic matter, including phenolic compounds and triterpenoids, which contribute to antioxidant potential. The presence of triterpenoids such as taraxerol acetate, germanicol, and β-amyrin suggests a strong chemotaxonomic link between mangrove-derived organic matter and plant defense mechanisms against oxidative stress. Differences in IC_{50} classification results can reflect differences in the level of heavy metal exposure in the two locations.

Formatted: Font: Not Bold

In addition to testing antioxidant activity using the DPPH method, this activity can also be analyzed by calculating total phenol. Measuring the total phenol content is done by adding Folin-ciocalteu reagent to the solution sample being tested (Table 7). Phenols possess antioxidant properties that play a role in protecting plant tissues from damage induced by free radicals. Therefore, the total phenol test can provide information about the potential antioxidant activity of mangrove leaf extracts. In this study, the highest quantitative phenol value was found in *E. agallocha* at 398.80 mg GAE/gr from the industrial area and the smallest in *A. alba* at 21.85 mg GAE/gr from the conservation forest area.

Table 7

Total phenol of mangrove leaves extract

Location	Sample leaves	Phenol (mg GAE/g)

Industry	*A. alba*	36.68
	E. agallocha	398.80
Conservation	*A. alba*	21.85
	E. agallocha	320.44

The total phenol obtained in this study has a positive relationship with antioxidant activity, as indicated by the IC_{50} value in Table 7. The antioxidant activity of this mangrove is influenced by its total phenol content. The total phenol content is positively correlated with antioxidant activity, where the higher the total phenol content, the higher the antioxidant activity in the sample [131]. Based on this study, *A. alba* has a lower total phenol content than *E. agallocha*, which is strongly suspected due to differences in environmental factors. Mangroves in the pioneer zone more pressure from pollutants and the physicochemical conditions of the habitat. This is in line with previous findings, where the total phenol content in the roots of *A. marina* in the pioneer zone was 26.11 mg GAE/g, lower than *B. gymnorrhiza* in the landward zone with 344.02 mg GAE/g [132]. Mangrove ecosystems located in the pioneer zone tend to have special adaptations to survive in coastal environments that are often inundated by sea tides [131, 132]. Mangrove sediments in intertidal zones are rich in organic matter originating from terrestrial vascular plants, including phenolic compounds and triterpenoids, which contribute to their antioxidant potential [130]. Mangroves mitigate pollutants by reducing their concentration and toxicity through internal water content regulation, preventing excessive accumulation of absorbed contaminants [135]. According to Laoué et al. (2022)], non-enzymatic antioxidant activity is not produced exclusively because there is a certain limit for excess free radicals. However, the non-enzymatic antioxidant system is usually activated when free radical levels or oxidative stress exceed normal defense capacity [26].

GC-MS analysis using *E. agallocha* mangrove leaf samples from industrial areas because they are included in the IC_{50} classification is very strong among others. The graph revealed 15 peak points identifying compounds such as flavonoids, lipids, glycosides, glucosinolates, glucose, esters, terpenoids, and fatty acids (Figure 5). The identified compounds, based on chromatogram peak heights and mass spectra from the analysis, match those in the WILEY 7 database library (Table 8).

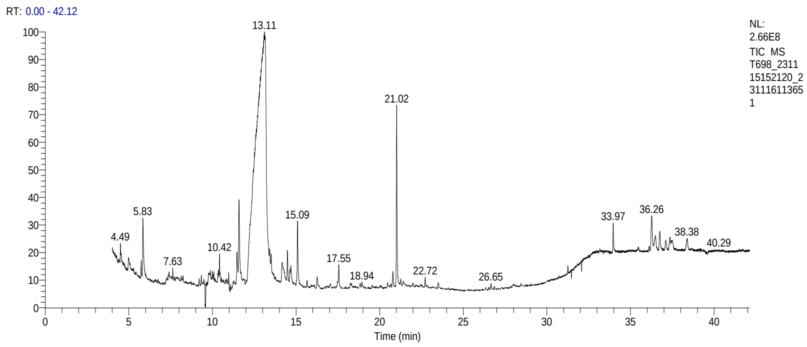


Figure 5. GC-MS chromatogram of bioactive compounds in mangrove leaves E. agallocha (Industry area)

Table 8

Retetion time, peak area, compound name, formula, and compound group (Daun *E. agallocha*)

Ret. time	*Peak Area %*	Compound name	Formula	Compound group
5.84	2.45	4H-Pyran-4-one, 2,3-dihydro-3,5-dihydroxy-6-methyl	$C_6H_8O_4$	Flavonoid
9.49	1.68	2-Myristynoyl pantetheine	$C_{23}H_{45}N_2O_4S$	Lipid

9.77	1.65	Paromomycin	$C_{23}H_{45}N_5O_{14}$	Glikosida
9.87	1.17	2-Myristynoyl pantetheine	$C_{23}H_{45}N_2O_4S$	Lipid
11.46	1.16	Desulphosinigrin	$C_{11}H_{21}NO_9S_2$	Glukosinolat
11.59	3.31	2-O-Methyl-D-mannopyranosa	$C_7H_{14}O_6$	Glikosida
13.10	73.97	3-O-Methyl-d-glucose	$C_7H_{14}O_6$	Glukosa
14.16	1.84	3-O-Methyl-d-glucose	$C_7H_{14}O_6$	Glukosa
14.48	0.99	7-Methyl-Z-tetradecen-1-ol acetate	$C_{17}H_{34}O_2$	Ester
14.69	1.05	9-Octadecenoic acid, (2-phenyl-1,3-dioxolan-4-yl)methyl ester, trans-	$C_{28}H_{44}O_4$	Ester
15.09	2.29	2,6,8-Trimethylbicyclo[4.2.0]oct-2-ene -1,8-diol	$C_{11}H_{18}O_2$	Terpenoid
17.55	0.98	Hexadecanoic acid, methyl ester	$C_{17}H_{34}O_2$	Asam lemak
21.01	4.87	Phytol	$C_{20}H_{40}O$	Terpenoid
33.97	0.94	9-Desoxo-9-x-acetoxy-3,8,12-tri-O-ac etylingol	$C_{21}H_{30}O_9$	Glikosida
36.27	1.65	1-Monolinoleoylglycerol trimethylsilyl ether	$C_{21}H_{44}O_4Si$	Ester

Based on Table 8, 8 groups of compounds were found. The groups of compounds that are thought to be formed in response to the environment that increases antioxidant activity, such as flavonoids, lipids, glycosides, glucosinolates, glucose, esters, terpenoids, and fatty acids. The compound 4H-Pyran-4-one, 2,3-dihydro-3,5-dihydroxy-6-methyl found in these leaves is classified as a flavonoid. Flavonoids are specialized metabolites commonly found in plants, serving multiple functions such as defense and signaling, particularly under stress conditions [137]. Flavonoids are categorized into several groups, including chalcones, aurones, flavanonols, flavones, isoflavones, flavanols, flavonols, anthocyanins, proanthocyanidins, and leucoanthocyanidins. They can exist as aglycones, glycosides, and methylated derivatives. The compounds 2-Myristynoyl pantetheine and 2-O-Methyl-D-mannopyranose are classified as lipids. Lipid compounds can exhibit antioxidant activity, especially through mechanisms involving phenols and other structures that modulate oxidative stress and lipid peroxidation processes [138].

The compounds Paromomycin, 2-O-Methyl-D-mannopyranose, and 9-Desoxo-9-x-acetoxy-3,8,12-tri-O-ac etylingol are classified as glycoside compounds. Based on the results of the study of Yang et al. (2018), flavonoid glycosides are widely distributed in plants, where they function as phytoalexins to combat biotic stress. Desulphosinigrin is a glucosinolate known to exhibit anticancer and antimicrobial properties [140]. 4-methylsulfinylbutyl glucosinolate is a glucosinolate derived from the amino acid methionine, which has antioxidant, antifungal, and antimicrobial activities [141]. The compounds 7-Methyl-Z-tetradecen-1-ol acetate, 9-Octadecenoic acid, (2-phenyl-1,3-dioxolan-4-yl) methyl ester, trans-, and 1-Monolinoleoylglycerol trimethylsilyl ether are classified as esters. Clearly show that ester groups with different aromatic and alkyl chains will increase antioxidant capacity. e compound 2-[4-methyl-6-(2,6,6-trimethylcyclohex-1-enyl)hexa-1,3,5-trienyl]cyclohex-1-en-1 carboxaldehyde is categorized as an aldehyde. This type of compound is commonly found in various essential oils and contributes a distinctive aroma to certain plants. Several phenolic aldehydes and derivatives have antioxidant activity [142].

Compounds 2,6,8-Trimethylbicyclo[4.2.0]oct-2-ene -1,8-diol and phytol belong to the terpenoid compound group. Terpenoids are promising lead compounds for further structural modification and optimization because of their potent anti-inflammatory effects [141, 142]. Terpenoids (such as monoterpenes and carotenoids) and polyphenols (such as quercetin and other flavonoids) are important phytochemicals with various antioxidant effects [145]. Hexadecanoic acid, methyl ester compounds are classified as fatty acid compounds. Fatty acids have been found to be associated with various biological activities such as anti-inflammatory, antioxidant, antifeedant, antimicrobial, and neuroprotective [146]. While compounds that have no relationship with antioxidant activity are the glucose compound group found in leaf extracts. Glucose produced through photosynthesis and other carbohydrate processes can be used as an energy source to maintain cell vitality [147].

Correlation of heavy metal concentrations and biomarkers

The relationship between heavy metal concentrations and antioxidant activities in mangrove leaves in both areas using Pearson correlation analysis, which begins with assumption testing (Table 9). The test results were obtained for all variables with significance > 0.05, and if the skewness and quasi-sequence ratios are in the range of -1.96 and +1.96, it can be concluded that the data distribution is normal.

Table 9

Assumption test results

Sample	Variable	Mean	St.Dev	*Sig.2 tailed*	Skewness	Values

					Kurtosis	
Leaves	Pb	0.94	0.12	0.927	0.55 dan 0.55	Normal
	Cu	3.57	0.080	0.498	0.33 dan 1.35	Normal
	IC50	66.35	25.19	0.457	1.31 dan 0.69	Normal
	Total Phenol	194.44	193.48	0.182	0.13 dan 1.93	Normal

Based on the results of the assumption test, the normal distribution of the data can explain that the statistical parameters used in the correlation analysis provide an accurate picture of the center and distribution of the data. Furthermore, the results of the Pearson correlation test (r) and the coefficient of determination (Kd) are summarized in Table 10.

Table 10

Results of the Pearson correlation test (r) and coefficient of determination (Kd)

Sample	Variable (X-Y)	r	Kd (%)	Interpretation
Leaves	Pb – IC_{50}	-0.906	82.08	Strong correlation
	Cu – IC_{50}	-0.937	87.79	Strong correlation
	Pb – Total Phenol	0.904	81.72	Strong correlation
	Cu – Total Phenol	0.949	90.06	Strong correlation

The results of the correlation test is a significant correlation or relationship between heavy metals and physiological responses ($r \neq 0$). The relationship between Pb and Cu to antioxidant activity in mangrove leaves produced from both areas has a very high negative correlation direction of -0.906 and -0.937. The relationship between Pb and Cu to total phenol in leaf samples is also very strong, with a very high positive correlation value of 0.904 and 0.949. In addition, the percentage of the determination coefficient (Kd) indicates that variables

X and Y have a strong relationship. The Kd value of mangrove leaf samples ranges from 81.72% to 90.06%. This indicates that most of the variations in IC_{50} and total phenol can be explained by the Pb and Cu variables in both types of samples.

A high correlation indicates a strong relationship between the variables concerned and significantly supports the hypothesis. A negative relationship with IC_{50} indicates that the higher the concentration of Pb or Cu, the lower the IC_{50} value (higher antioxidant potential). A positive relationship with total phenol indicates that the higher the concentration of Pb or Cu, the total phenol content also increases. Furthermore, the results of GCMS screening also showed the presence of compounds such as flavonoids, lipids, glycosides, glucosinolates, glucose, esters, terpenoids, and fatty acids. Previous studies have shown that some of these compounds, especially the flavonoid and terpenoid groups, have significant antioxidant activity [148]. Therefore, increasing concentrations of heavy metals can indirectly affect the profile of secondary metabolite compounds in mangrove plants, which in turn can affect antioxidant activity and response to oxidative stress. Excessive concentrations of heavy metals cause the formation of ROS and affect the activity of antioxidants involved in plant metabolism [149]. According to Georgiadou et al. (2018), detoxification of ROS due to heavy metal contamination by producing antioxidant enzymes plays a central and vital role in protection in mangrove species.

In line with the research by [151], that under abiotic stress conditions, such as heavy metal contamination, the production of reactive oxygen species (ROS) increases in plants, resulting in the induction of oxidative stress, and plants initiate antioxidant production that significantly delays or prevents oxidative stress. According to Angon et al. (2024) , secondary metabolite compounds are involved in plant responses to biotic and abiotic stresses and contribute significantly to the antioxidant activity of plant tissues. Antioxidant activity is a common approach used to increase heavy metal tolerance, strengthening the defense system against oxidative stress [151, 152]. Several previous studies have found a relationship between heavy metal pollution and the physiological response of plants, especially mangroves. The decline in sediment quality due to heavy metal pollution in a gradual pattern that has the potential to have a negative impact on the biogeochemical cycle, with potentially fatal consequences for the survival of biodiversity (*A. marina*) [155] . Furthermore, the results of the study by Ghosh et al. (2021) also stated that there was a statistically significant relationship between the activity of antioxidant enzymes, photosynthetic pigments, and heavy metal contamination, resulting in the biotic response of riparian mangroves characterized by reduced photosynthetic pigments (chlorophyll a and b) and increased activity of antioxidant stress enzymes (POD, CAT, and SOD). The response of two tropical medicinal plant species to heavy metal accumulation can increase hydrogen peroxide (H_2O_2) activity, malondialdehyde content, enzymatic activity, and nonenzymatic antioxidants [156].

Mangroves cause trigger antioxidant defenses to overcome heavy metal absorption and normalize excessive production of oxidative stress mediated by reactive oxygen species (ROS) [157]. However, antioxidant responses in mangroves vary depending on the concentration and type of heavy metals, plant species, and duration of exposure [158]. Previous findings related to plant reactions to higher concentrations of heavy metals in the soil. For example, Kulbat-Warycha et al. (2020) observed that an increase in the concentration of heavy metals (Ni, Cu, Zn) caused a decrease in the concentration of phenols in oregano, which was associated with the induction of severe oxidative stress. According to Mansoor et al. (2023), excessive ROS production due to severe oxidative stress can cause damage to the mitochondrial respiratory chain, uncoupling of oxidative phosphorylation, and mitochondrial death in plants. However, this can also experience a decrease in the antioxidant activity defense system of the mangrove itself if the contamination of absorbed pollutants exceeds the threshold and severe oxidative stress occurs, which can cause damage and death to the mangrove ecosystem [159, 160].

The correlation between heavy metals and antioxidant activity in mangroves illustrates the complex relationship between heavy metal pollution and plant responses to oxidative stress. In this context, high concentrations of heavy metals can trigger ROS production, which in turn affects plant antioxidant activity. Excessive ROS can induce oxidative stress that activates the plant defense system to increase the production of antioxidant compounds. Thus, the relationship between heavy metals and antioxidant activity, total phenols, and secondary metabolite compound profiles in mangroves provides a deeper understanding of the mechanism of the plant's response to heavy metal pollution and oxidative stress. Therefore, if there is an indication that pollutant contamination exceeds the threshold and causes severe oxidative stress, some coastal environmental management policies can be expected in response to these findings.

To ensure the sustainability of mangrove ecosystems and mitigate the impact of heavy metal pollution, routine monitoring is recommended every 3–6 months to capture seasonal variations in heavy metal concentrations and antioxidant responses. Additionally, long-term monitoring (≥5 years) is necessary to identify trends in heavy metal accumulation and its effects on coastal ecosystems. Supplemental monitoring is also advised following specific events, such as industrial waste spills or land-use changes, to assess their immediate environmental impact. The data from this study can serve as a basis for environmental policy development, including updating regulations on heavy metal thresholds in sediments and coastal biota, strengthening conservation and mangrove rehabilitation policies, and improving industrial zone management in coastal areas. Furthermore, these findings can be utilized to raise public awareness about the importance of protecting coastal ecosystems and promoting sustainable resource management practices.

Conclusion

Heavy metal pollution of Pb and Cu resulting from areas affecting industrial and conservation activities has a significant effect on antioxidant activity in mangroves, especially *A. alba* and *E. agallocha*. Sediment pollution assessment showed that the Igeo value was at a low level, while the concentration factor (Cf) and Pollution Load Index (PLI) showed a relatively moderate level of pollution (Cf between 1 and 3, and PLI between 0 and 2). The bioaccumulation value of heavy metals in mangrove leaves was low (BCF < 1), indicating moderate accumulation of heavy metals in leaf tissue. The antioxidant activity of *E. agallocha* leaves from the industrial area was very strong and had the highest total phenol content. The compounds identified as having high antioxidant activity included flavonoids, lipids, glycosides, glucosinolates, glucose, esters, terpenoids, and fatty acids. Correlation analysis showed that increasing heavy metal concentrations were directly proportional to increasing antioxidant activity and total phenol content in mangrove leaves. This study contributes to our understanding of the potential of mangroves to respond to heavy metal exposure through increased antioxidant activity, which can support conservation efforts and sustainable management of coastal natural resources.

Author statement

The authors hereby declare that the work presented in this article is original and that any liability for claims relating to the content of this article will be borne by them.

CRediT authorship contribution statement

Rozirwan: Writing – review & editing, Supervision, Project administration, Conceptualization. **Redho Yoga Nugroho**: Resources, Formal analysis, Data curation. **Nadila Nur Khotimah**: Validation, Resources, Data curation. **Fauziyah**: Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Wike Ayu Eka Putri**: Writing – original draft, Software, Investigation. **Riris Aryawati**: Methodology, Data curation. **Gusti Diansyah**: Software, Investigation.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

The data supporting the findings of this study can be obtained from the corresponding author upon a reasonable request.

Acknowledgments

The reseacrh/publication of this article was funded by DIPA of Public Service Agency of Universitas Sriwijaya 2024. Nomor SP DIPA 023.17.2.677515/2024, On November 24, 2023. In accordance with the Rector's Degree Number: 0013/UN9/LP2M.PT/2024, On May 20, 2024.

References

[1] R. Ramesh *et al.*, "Land–Ocean Interactions in the Coastal Zone: Past, present & future," *Anthropocene*, vol. 12, pp. 85–98, 2015, doi: https://doi.org/10.1016/j.ancene.2016.01.005.

[2] R. Gotama, D. M. Baker, I. Guibert, S. E. McIlroy, and B. D. Russell, "How a coastal megacity affects marine biodiversity and ecosystem function: Impacts of reduced water quality and other anthropogenic stressors," *Ecol. Indic.*, vol. 160, p. 111683, 2024, doi: https://doi.org/10.1016/j.ecolind.2024.111683.

[3] Q. He and B. R. Silliman, "Climate Change, Human Impacts, and Coastal Ecosystems

in the Anthropocene," *Curr. Biol.*, vol. 29, no. 19, pp. R1021–R1035, 2019, doi: https://doi.org/10.1016/j.cub.2019.08.042.

[4] N. S. Victoria, T. Sree Devi Kumari, and B. Lazarus, "Assessment on impact of sewage in coastal pollution and distribution of fecal pathogenic bacteria with reference to antibiotic resistance in the coastal area of Cape Comorin, India," *Mar. Pollut. Bull.*, vol. 175, p. 113123, 2022, doi: https://doi.org/10.1016/j.marpolbul.2021.113123.

[5] T. Zhai, J. Wang, Y. Fang, Y. Qin, L. Huang, and Y. Chen, "Assessing ecological risks caused by human activities in rapid urbanization coastal areas: Towards an integrated approach to determining key areas of terrestrial-oceanic ecosystems preservation and restoration," *Sci. Total Environ.*, vol. 708, p. 135153, 2020, doi: https://doi.org/10.1016/j.scitotenv.2019.135153.

[6] N. Andrews *et al.*, "Oil, fisheries and coastal communities: A review of impacts on the environment, livelihoods, space and governance," *Energy Res. Soc. Sci.*, vol. 75, p. 102009, 2021, doi: https://doi.org/10.1016/j.erss.2021.102009.

[7] W. A. E. Putri and A. I. S. Purwiyanto, "Cu and Pb Concentrations in Water Column and Plankton of Downstream Section of the Musi River," *J. Ilmu dan Teknol. Kelaut. Trop.*, vol. 8, no. 2, pp. 773–780, 2016.

[8] Rozirwan *et al.*, "An Assessment of Pb and Cu in Waters, Sediments, and Mud Crabs (Scylla serrata) from Mangrove Ecosystem Near Tanjung Api-Api Port Area, South Sumatra, Indonesia," *Sci. Technol. Indones.*, vol. 8, no. 4, pp. 675–683, 2023, doi: 10.26554/sti.2023.8.4.675-683.

[9] A. A. Galindo Montero, L. C. Costa-Redondo, O. Vasco-Echeverri, and V. A. Arana, "Microplastic pollution in coastal areas of Colombia: Review," *Mar. Environ. Res.*, vol. 190, p. 106027, 2023, doi: https://doi.org/10.1016/j.marenvres.2023.106027.

[10] Y. Choi, M.-Y. Lee, and T.-H. Kim, "Evaluating total organic carbon as an indicator

for organic pollutant management in the marine environment: A case study on wastewater treatment plant effluent input into the coastal ocean," *Sci. Total Environ.*, vol. 919, p. 170704, 2024, doi: https://doi.org/10.1016/j.scitotenv.2024.170704.

[11] H. Wu *et al.*, "Trace metals in sediments and benthic animals from aquaculture ponds near a mangrove wetland in Southern China," *Mar. Pollut. Bull.*, vol. 117, no. 1–2, pp. 486–491, Apr. 2017, doi: 10.1016/J.MARPOLBUL.2017.01.026.

[12] J. Pandiyan *et al.*, "An assessment of level of heavy metals pollution in the water, sediment and aquatic organisms: A perspective of tackling environmental threats for food security," *Saudi J. Biol. Sci.*, vol. 28, no. 2, pp. 1218–1225, Feb. 2021, doi: 10.1016/J.SJBS.2020.11.072.

[13] E. Ramazanova, Y. Bahetnur, K. Yessenbayeva, S. H. Lee, and W. Lee, "Spatiotemporal evaluation of water quality and risk assessment of heavy metals in the northern Caspian Sea bounded by Kazakhstan," *Mar. Pollut. Bull.*, vol. 181, no. November 2021, p. 113879, 2022, doi: 10.1016/j.marpolbul.2022.113879.

[14] A. P. Cahyaningsih, A. K. Deanova, C. M. Pristiawati, Y. I. Ulumuddin, L. Kusumawati, and A. D. Setyawan, "Review: Causes and impacts of anthropogenic activities on mangrove deforestation and degradation in Indonesia," *Int. J. Bonorowo Wetl.*, vol. 12, no. 1, pp. 12–22, 2022, doi: 10.13057/bonorowo/w120102.

[15] M. Xu, C. Sun, Y. Zhan, and Y. Liu, "Impact and prediction of pollutant on mangrove and carbon stocks: A machine learning study based on urban remote sensing data," *Geosci. Front.*, vol. 15, no. 3, p. 101665, 2024, doi: https://doi.org/10.1016/j.gsf.2023.101665.

[16] S. S. Ram, A. Aich, P. Sengupta, A. Chakraborty, and M. Sudarshan, "Assessment of trace metal contamination of wetland sediments from eastern and western coastal region of India dominated with mangrove forest," *Chemosphere*, vol. 211, pp. 1113–

1122, Nov. 2018, doi: 10.1016/J.CHEMOSPHERE.2018.07.201.

[17] Rozirwan, R. Y. Nugroho, M. Hendri, Fauziyah, W. A. E. Putri, and A. Agussalim, "Phytochemical profile and toxicity of extracts from the leaf of Avicennia marina (Forssk.) Vierh. collected in mangrove areas affected by port activities," *South African J. Bot.*, vol. 150, pp. 903–919, 2022, doi: 10.1016/j.sajb.2022.08.037.

[18] S. Abdul Azeez *et al.*, "Multi-decadal changes of mangrove forest and its response to the tidal dynamics of thane creek, Mumbai," *J. Sea Res.*, vol. 180, p. 102162, Feb. 2022, doi: 10.1016/J.SEARES.2021.102162.

[19] Rozirwan *et al.*, "Distribution of phytoplankton diversity and abundance in Maspari island waters, South Sumatera, Indonesia," *J. Phys. Conf. Ser.*, vol. 1282, no. 1, 2019, doi: 10.1088/1742-6596/1282/1/012105.

[20] M. B. Hossain *et al.*, "Heavy Metal Accumulation and Phytoremediation Potentiality of Some Selected Mangrove Species from the World's Largest Mangrove Forest," *Biology (Basel).*, vol. 11, no. 8, p. 1144, Aug. 2022, doi: 10.3390/BIOLOGY11081144/S1.

[21] A. Talukdar *et al.*, "Microplastics in mangroves with special reference to Asia: Occurrence, distribution, bioaccumulation and remediation options," *Sci. Total Environ.*, vol. 904, p. 166165, 2023, doi: https://doi.org/10.1016/j.scitotenv.2023.166165.

[22] I. Sanjosé *et al.*, "The Bioconcentration and the Translocation of Heavy Metals in Recently Consumed Salicornia ramosissima J. Woods in Highly Contaminated Estuary Marshes and Its Food Risk," *Diversity*, vol. 14, no. 6, p. 452, Jun. 2022, doi: 10.3390/D14060452/S1.

[23] A. Nguyen, O. Richter, B. V. Q. Le, N. T. K. Phuong, and K. C. Dinh, "Long-Term Heavy Metal Retention by Mangroves and Effect on Its Growth: A Field Inventory and

Scenario Simulation," *Int. J. Environ. Res. Public Health*, vol. 17, no. 23, pp. 1–24, Dec. 2020, doi: 10.3390/IJERPH17239131.

[24] G. Llauradó Maury *et al.*, "Antioxidants in plants: A valorization potential emphasizing the need for the conservation of plant biodiversity in cuba," *Antioxidants*, vol. 9, no. 11, pp. 1–39, 2020, doi: 10.3390/antiox9111048.

[25] M. Sharifi-Rad *et al.*, "Lifestyle, Oxidative Stress, and Antioxidants: Back and Forth in the Pathophysiology of Chronic Diseases," *Front. Physiol.*, vol. 11, p. 694, Jul. 2020, doi: 10.3389/FPHYS.2020.00694.

[26] K. Jomova *et al.*, "Reactive oxygen species, toxicity, oxidative stress, and antioxidants: chronic diseases and aging," *Arch. Toxicol. 2023 9710*, vol. 97, no. 10, pp. 2499–2574, Aug. 2023, doi: 10.1007/S00204-023-03562-9.

[27] K. Messaoudi, T. Benmeddour, and G. Flamini, "First report on the chemical composition and the free radical scavenging and antimicrobial activities of the essential oil of Ononis aurasiaca, an endemic plant of Algeria," *Nat. Prod. Res.*, 2023, doi: https://doi.org/10.1080/14786419.2023.2282113.

[28] G. Eswaraiah, K. A. Peele, S. Krupanidhi, R. B. Kumar, and T. C. Venkateswarulu, "Studies on phytochemical, antioxidant, antimicrobial analysis and separation of bioactive leads of leaf extract from the selected mangroves," *J. King Saud Univ. - Sci.*, vol. 32, no. 1, pp. 842–847, Jan. 2020, doi: 10.1016/J.JKSUS.2019.03.002.

[29] U. Sarker, M. M. Hossain, and S. Oba, "Nutritional and antioxidant components and antioxidant capacity in green morph Amaranthus leafy vegetable," *Sci. Reports 2020 101*, vol. 10, no. 1, pp. 1–10, Jan. 2020, doi: 10.1038/s41598-020-57687-3.

[30] M. Rezaei *et al.*, "Heavy metals concentration in mangrove tissues and associated sediments and seawater from the north coast of Persian Gulf, Iran: Ecological and health risk assessment," *Environ. Nanotechnology, Monit. Manag.*, vol. 15, p. 100456,

May 2021, doi: 10.1016/J.ENMM.2021.100456.

[31] Rozirwan *et al.*, “Environmental risk assessment of Pb , Cu , Zn , and Cd concentrations accumulated in selected mangrove roots and surrounding their sediment,” *Biodiversitas*, vol. 24, no. 12, pp. 6733–6742, 2023, doi: 10.13057/biodiv/d241236.

[32] N. N. Khotimah *et al.*, “Bioaccumulation and Ecological Risk Assessment of Heavy Metal Contamination (Lead and Copper) Build Up in the Roots of Avicennia alba and Excoecaria agallocha,” *J. Ecol. Eng.*, vol. 25, no. 5, pp. 101–113, 2024, doi: 10.12911/22998993/185716.

[33] V. Patale and J. G. Tank, “Ecological assessment of heavy metals accumulation in sediments and leaves of Avicennia marina along the Diu coast of the northeast Arabian Sea,” *Oceanologia*, vol. 64, no. 2, pp. 276–286, Apr. 2022, doi: 10.1016/J.OCEANO.2021.12.002.

[34] H. Abelardo Gonzalez-Ocampo, M. C. Parra-Olivas, E. Pérez-González, and G. D. Rodríguez-Meza, “Rhizophora mangle L. bioindicator of environmental exposure to heavy metals in the Navachiste lagoon complex, Sinaloa, Mexico,” *Mar. Pollut. Bull.*, vol. 209, p. 117131, Dec. 2024, doi: 10.1016/J.MARPOLBUL.2024.117131.

[35] A. Afriyani, F. Fauziyah, M. Mazidah, and R. Wijayanti, “Keanekaragaman Vegetasi Hutan Mangrove di Pulau Payung Sungsang Banyuasin Sumatera Selatan,” *J. Lahan Suboptimal*, vol. 6, no. 3, pp. 113–119, 2017.

[36] Y. H. Hutasoit and D. Sarno, “Struktur Vegetasi Mangrove Alami Di Areal Taman Nasional Sembilang Banyuasin Sumatera Selatan Natural Mangrove Vegetation Structure in Sembilang National Park, Banyuasin South Sumatera,” *Maspari J. Mar. Sci. Res.*, vol. 9, no. 1, pp. 1–8, 2017.

[37] W. J. M. Verheugt, A. Purwoko, F. Danielsen, H. Skov, and R. Kadarisman,

"Integrating mangrove and swamp forests conservation with coastal lowland development; the Banyuasin Sembilang swamps case study, South Sumatra Province, Indonesia," *Landsc. Urban Plan.*, vol. 20, no. 1–3, pp. 85–94, Jan. 1991, doi: 10.1016/0169-2046(91)90096-5.

[38] G. Gustaman, . F., and . I., "Efektifitas Perbedaan Warna Cahaya Lampu terhadap Hasil Tangkapan Bagan Tancap di Perairan Sungsang Sumatera Selatan," *Maspari J. Mar. Sci. Res.*, vol. 4, no. 1, pp. 92–102, 2012, doi: 10.56064/MASPARI.V4I1.1433.

[39] Rozirwan *et al.*, "Assessment of phytoplankton community structure in musi estuary, south sumatra, indonesia," *AACL Bioflux*, vol. 14, no. 3, pp. 1451–1463, 2021.

[40] Rozirwan *et al.*, "Assessment distribution of the phytoplankton community structure at the fishing ground, Banyuasin estuary, Indonesia," *Acta Ecol. Sin.*, Mar. 2022, doi: 10.1016/J.CHNAES.2022.02.006.

[41] Rozirwan *et al.*, "AN ECOLOGICAL ASSESSMENT OF CRAB'S DIVERSITY AMONG HABITATS OF MIGRATORY BIRDS AT BERBAK-SEMBILANG NATIONAL PARK INDONESIA," *Int. J. Conserv. Sci.*, vol. 13 (3), 2022, Accessed: Oct. 05, 2022. [Online]. Available: www.ijcs.ro

[42] Y. Fitria, Rozirwan, M. Fitrani, R. Y. Nugroho, Fauziyah, and W. A. E. Putri, "Gastropods as bioindicators of heavy metal pollution in the Banyuasin estuary shrimp pond area, South Sumatra, Indonesia," *Acta Ecol. Sin.*, Jun. 2023, doi: 10.1016/J.CHNAES.2023.05.009.

[43] R. Rozirwan *et al.*, "Insecticidal Activity and Phytochemical Profiles of Avicennia marina and Excoecaria agallocha Leaves Extracts," *ILMU Kelaut. Indones. J. Mar. Sci. Vol 28, No 2 Ilmu KelautanDO - 10.14710/ik.ijms.28.2.148-160* , vol. 28, no. June, pp. 148–160, 2023, doi: 10.14710/ik.ijms.28.2.148-160.

[44] E. Indawan, R. I. Hapsari, K. Ahmadi, and D. N. Khaerudin, "Quality assessment of

mangrove growing environment in Pasuruan of East Java," *J. Degrad. Min. LANDS Manag.*, vol. 4, no. 3, pp. 815–819, 2017, doi: 10.15243/jdmlm.2017.043.815.

[45] I. M. Siaka, "KORELASI ANTARA KEDALAMAN SEDIMEN DI PELABUHAN BENOA DAN KONSENTRASI LOGAM BERAT Pb DAN Cu," *J. Kim.*, vol. 2, no. 2, pp. 61–70, 2008.

[46] Y. Xiao, M. He, J. Xie, L. Liu, and X. Zhang, "Effects of heavy metals and organic matter fractions on the fungal communities in mangrove sediments from Techeng Isle, South China," *Ecotoxicol. Environ. Saf.*, vol. 222, p. 112545, Oct. 2021, doi: 10.1016/J.ECOENV.2021.112545.

[47] E. Romano, M. C. Magno, and L. Bergamin, "Grain size data analysis of marine sediments, from sampling to measuring and classifying. A critical review," *IMEKO TC19 Work. Metrol. Sea, MetroSea 2017 Learn. to Meas. Sea Heal. Parameters*, vol. 2017-Octob, pp. 173–178, 2017.

[48] L. J. Poppe and A. H. Eliason, "A Visual Basic program to plot sediment grain-size data on ternary diagrams $," *Comput. Geosci.*, vol. 34, pp. 561–565, 2008, doi: 10.1016/j.cageo.2007.03.019.

[49] R. R. Anggraini, U. Yanuhar, and Y. Risjani, "CHARACTERISTIC OF SEDIMENT AT LEKOK COASTAL WATERS, PASURUAN REGENCY, EAST JAVA," *J. Ilmu dan Teknol. Kelaut. Trop.*, vol. 12, no. 1, pp. 235–246, Apr. 2020, doi: 10.29244/JITKT.V12I1.28705.

[50] Rozirwan *et al.*, "Ecological Risk Assessment of Heavy Metal (Pb, Cu) Contamination in Water, Sediment, and Polychaeta (Neoleanira Tetragona) from Coastal Areas Affected by Aquaculture, Urban Rivers, and Ports in South Sumatra," *J. Ecol. Eng.*, vol. 25, no. 1, pp. 303–319, 2024, doi: 10.12911/22998993/175365.

[51] D. A. Skoog, D. M. West, F. J. Holler, and S. R. Crouch, *Fundamentals of Analytical*

Chemistry. Cengage Learning, 2013. [Online]. Available: https://books.google.co.id/books?id=8bIWAAAAQBAJ

[52] R. Nagarajan *et al.*, "Geochemical Characterization of Beach Sediments of Miri, NW Borneo, SE Asia: Implications on Provenance, Weathering Intensity, and Assessment of Coastal Environmental Status," *Coast. Zo. Manag. Glob. Perspect. Reg. Process. Local Issues*, pp. 279–330, Jan. 2019, doi: 10.1016/B978-0-12-814350-6.00012-4.

[53] G. Muller, "Index of geo-accumulation in sediments of the Rhine river – ScienceOpen," *J. Geol.*, 1969, Accessed: Jan. 08, 2023. [Online]. Available: https://www.scienceopen.com/document?vid=4b875795-5729-4c05-9813-64951e2ca488

[54] V. Gopal *et al.*, "Assessment of heavy metal contamination in the surface sediments of the Vedaranyam coast, Southern India," *Reg. Stud. Mar. Sci.*, vol. 65, p. 103081, Dec. 2023, doi: 10.1016/J.RSMA.2023.103081.

[55] S. M. Shaheen, M. S. Shams, M. R. Khalifa, M. A. El-Dali, and J. Rinklebe, "Various soil amendments and environmental wastes affect the (im)mobilization and phytoavailability of potentially toxic elements in a sewage effluent irrigated sandy soil," *Ecotoxicol. Environ. Saf.*, vol. 142, pp. 375–387, Aug. 2017, doi: 10.1016/J.ECOENV.2017.04.026.

[56] S. M. Shaheen *et al.*, "Potentially toxic elements in saltmarsh sediments and common reed (Phragmites australis) of Burullus coastal lagoon at North Nile Delta, Egypt: A survey and risk assessment," *Sci. Total Environ.*, vol. 649, pp. 1237–1249, Feb. 2019, doi: 10.1016/J.SCITOTENV.2018.08.359.

[57] S. K. Maiti, D. Ghosh, and D. Raj, "Phytoremediation of fly ash: bioaccumulation and translocation of metals in natural colonizing vegetation on fly ash lagoons," *Handb. Fly Ash*, pp. 501–523, Jan. 2022, doi: 10.1016/B978-0-12-817686-3.00011-6.

[58] H. Almahasheer, “High levels of heavy metals in Western Arabian Gulf mangrove soils,” *Mol. Biol. Rep.*, vol. 46, no. 2, pp. 1585–1592, Apr. 2019, doi: 10.1007/S11033-019-04603-2/METRICS.

[59] R. Rozirwan *et al.*, “Antioxidant Activity, Total Phenolic, Phytochemical Content, and HPLC Profile of Selected Mangrove Species from Tanjung Api-Api Port Area, South Sumatra, Indonesia,” *Trop. J. Nat. Prod. Res. Available*, vol. 7, no. 7, pp. 3482–3489, 2023.

[60] H. D. Salusu *et al.*, “Phytochemical screening and antioxidant activity of selekop (Lepisanthes amoena) fruit,” *Agrivita*, vol. 39, no. 2, pp. 214–218, 2017, doi: 10.17503/agrivita.v39i2.810.

[61] S. S. Suh, J. Hwang, M. Park, H. S. Park, and T. K. Lee, “Phenol content, antioxidant and tyrosinase inhibitory activity of mangrove plants in Micronesia,” *Asian Pac. J. Trop. Med.*, vol. 7, no. 7, pp. 531–535, Jul. 2014, doi: 10.1016/S1995-7645(14)60089-4.

[62] K. Sopalun, W. Laosripaiboon, A. Wachirachaikarn, and S. Iamtham, “Biological potential and chemical composition of bioactive compounds from endophytic fungi associated with thai mangrove plants,” *South African J. Bot.*, vol. 141, pp. 66–76, Sep. 2021, doi: 10.1016/J.SAJB.2021.04.031.

[63] U. Kustiati, H. Wihadmadyatami, and D. L. Kusindarta, “Dataset of Phytochemical and secondary metabolite profiling of holy basil leaf (Ocimum sanctum Linn) ethanolic extract using spectrophotometry, thin layer chromatography, Fourier transform infrared spectroscopy, and nuclear magnetic resonance,” *Data Br.*, vol. 40, 2022, doi: 10.1016/j.dib.2021.107774.

[64] W. Kirch, “Pearson’s Correlation Coefficient,” *Encycl. Public Heal.*, pp. 1090–1091, 2008, doi: 10.1007/978-1-4020-5614-7_2569.

[65] D. Weisburd, C. Britt, D. B. Wilson, and A. Wooditch, “Measuring Association for Scaled Data: Pearson’s Correlation Coefficient,” in *Basic Statistics in Criminology and Criminal Justice*, Cham: Springer International Publishing, 2020, pp. 479–530. doi: 10.1007/978-3-030-47967-1_14.

[66] Rozirwan, S. Ramadani, W. Ayu, E. Putri, N. Nur, and R. Y. Nugroho, “Evaluation of Calcium and Phosphorus content in Scallop Shells (Placuna placenta) and Blood Cockle Shells (Anadara granosa) from Banyuasin Waters, South Sumatra,” *Egypt. J. Aquat. Biol. Fish. Zool. Dep. Fac. Sci.*, vol. 27, no. 3, pp. 1053–1068, 2023.

[67] Sumartini, P W Ratrinia, and Hutabarat R F, “The effect of mangrove types and leave maturity on the mangrove leaves (Sonneratia alba) and (Rhizophora mucronata) tea powder - IOPscience,” in *IOP Conference Series: Earth and Environmental Science*, 2022. Accessed: Oct. 03, 2022. [Online]. Available: https://iopscience.iop.org/article/10.1088/1755-1315/967/1/012018

[68] J. P. Yactayo-Chang, H. V. Tang, J. Mendoza, S. A. Christensen, and A. K. Block, “Plant Defense Chemicals against Insect Pests,” *Agron. 2020, Vol. 10, Page 1156*, vol. 10, no. 8, p. 1156, Aug. 2020, doi: 10.3390/AGRONOMY10081156.

[69] Anjali *et al.*, “Role of plant secondary metabolites in defence and transcriptional regulation in response to biotic stress,” *Plant Stress*, vol. 8, p. 100154, Jun. 2023, doi: 10.1016/J.STRESS.2023.100154.

[70] J. Srše, M. Perkovič, and A. Grm, “Sediment Resuspension Distribution Modelling Using a Ship Handling Simulation along with the MIKE 3 Application,” *J. Mar. Sci. Eng.*, vol. 11, no. 8, 2023, doi: 10.3390/jmse11081619.

[71] J. Srse and M. Perkovic, “Field Studies on Sediment Resuspension Induced by Shipping: Vessel Kinematic Measurements and Water Sampling in the Port of Koper,” *2024 IEEE Int. Work. Metrol. Sea, MetroSea 2024 - Proc.*, no. October, pp. 353–357,

2024, doi: 10.1109/MetroSea62823.2024.10765676.

[72] J. Yun, Q. Yang, C. Zhao, C. Chen, and G. Liu, “Atmospheric emissions of fine particle matter bound rare earth elements from industry,” *Nat. Commun.* , vol. 15, no. 1, pp. 1–10, 2024, doi: 10.1038/s41467-024-53684-6.

[73] A. M. Afandi, Y. Zuraidah, H. A. Z. A. Nurzuhaili, H. Zulkifli, and M. Yaqin, “Managing soil deterioration and erosion under oil palm,” *Oil Palm Bull. 75*, vol. 75, no. November, pp. 1–10, 2017.

[74] I. Comte, F. Colin, J. K. Whalen, O. Grünberger, and J. P. Caliman, “Agricultural Practices in Oil Palm Plantations and Their Impact on Hydrological Changes, Nutrient Fluxes and Water Quality in Indonesia: A Review,” *Adv. Agron.*, vol. 116, pp. 71–124, Jan. 2012, doi: 10.1016/B978-0-12-394277-7.00003-8.

[75] L. Ivorra, P. G. Cardoso, S. K. Chan, C. Cruzeiro, and K. A. Tagulao, “Can mangroves work as an effective phytoremediation tool for pesticide contamination? An interlinked analysis between surface water, sediments and biota,” *J. Clean. Prod.*, vol. 295, p. 126334, May 2021, doi: 10.1016/J.JCLEPRO.2021.126334.

[76] S. Partani *et al.*, “Identifying toxic elements in water, sediments, and roots of mangrove forest (Avicennia marina) in Chabahar Bay, Sea of Oman,” *Sci. Total Environ.*, vol. 954, p. 176635, 2024, doi: https://doi.org/10.1016/j.scitotenv.2024.176635.

[77] S. Wang, C. Pan, D. Xie, M. Xu, Y. Yan, and X. Li, “Grain size characteristics of surface sediment and its response to the dynamic sedimentary environment in Qiantang Estuary, China,” *Int. J. Sediment Res.*, vol. 37, no. 4, pp. 457–468, 2022, doi: https://doi.org/10.1016/j.ijsrc.2021.12.002.

[78] R. Rozirwan, I. Bahrudin, B. S. Barus, R. Y. Nugroho, and N. N. Khotimah, “First assesment of coral Mussidae in Kelagian Island waters, Lampung,” *Proc. 9TH Int.*

Symp. Innov. Bioprod. Indones. Biotechnol. Bioeng. 2022 Strength. Bioeconomy through Appl. Biotechnol. Bioeng. Biodivers., vol. 2972, no. 1, p. 040008, Dec. 2023, doi: 10.1063/5.0171642/2931856.

[79] M. K. Uddin, "A review on the adsorption of heavy metals by clay minerals, with special focus on the past decade," *Chem. Eng. J.*, vol. 308, pp. 438–462, 2017, doi: https://doi.org/10.1016/j.cej.2016.09.029.

[80] X. Huang and G. Yang, "Charge reversal and anion effects during adsorption of metal ions at clay surfaces: Mechanistic aspects and influence factors," *Chem. Phys.*, vol. 529, p. 110575, 2020, doi: https://doi.org/10.1016/j.chemphys.2019.110575.

[81] S. Khan, S. Ajmal, T. Hussain, and M. U. Rahman, "Clay-based materials for enhanced water treatment: adsorption mechanisms, challenges, and future directions," *J. Umm Al-Qura Univ. Appl. Sci.*, 2023, doi: 10.1007/s43994-023-00083-0.

[82] Y. M. Chen, J. bo Gao, Y. Q. Yuan, J. Ma, and S. Yu, "Relationship between heavy metal contents and clay mineral properties in surface sediments: Implications for metal pollution assessment," *Cont. Shelf Res.*, vol. 124, pp. 125–133, Aug. 2016, doi: 10.1016/J.CSR.2016.06.002.

[83] W. Que, L. Yi, Y. Wu, and Q. Li, "Analysis of heavy metals in sediments with different particle sizes and influencing factors in a mining area in Hunan Province," *Sci. Rep.*, vol. 14, no. 1, p. 20318, 2024, doi: 10.1038/s41598-024-71502-3.

[84] Y. G. Gu and Y. P. Gao, "An unconstrained ordination- and GIS-based approach for identifying anthropogenic sources of heavy metal pollution in marine sediments," *Mar. Pollut. Bull.*, vol. 146, pp. 100–105, Sep. 2019, doi: 10.1016/J.MARPOLBUL.2019.06.008.

[85] A. Tjahjono, R. Sugiharto, and O. Wahyuni, "Study of water and sediment surface quality on defilement of heavy metals Pb & Cd at a downstream section of Musi River,

South Sumatera, Indonesia,” *Rev. Ambient. e Agua*, vol. 17, no. 1, pp. 1–20, 2022.

[86] E. R. Sulistya Dewi, K. Ni’Mah, and F. Kaswinarni, “The content of heavy metal lead (Pb) on baung fish (Hemibagrus nemurus) as biomonitoring pollution of Wulan River of Demak Regency,” *J. Phys. Conf. Ser.*, vol. 1217, no. 1, 2019, doi: 10.1088/1742-6596/1217/1/012128.

[87] L. Schröder, F. Hellweger, and A. Putschew, “Copper leaching from recreational vessel antifouling paints in freshwater: A Berlin case study,” *J. Environ. Manage.*, vol. 301, p. 113895, Jan. 2022, doi: 10.1016/J.JENVMAN.2021.113895.

[88] J. Zhao *et al.*, “Controllable release of Cu ions contributes to the enhanced environmentally-friendly performance of antifouling Cu-bearing stainless steel coating prepared using high-velocity air fuel,” *Surf. Coatings Technol.*, vol. 481, p. 130629, Apr. 2024, doi: 10.1016/J.SURFCOAT.2024.130629.

[89] Z. Y. Soon, J. H. Jung, A. Loh, C. Yoon, D. Shin, and M. Kim, “Seawater contamination associated with in-water cleaning of ship hulls and the potential risk to the marine environment,” *Mar. Pollut. Bull.*, vol. 171, p. 112694, Oct. 2021, doi: 10.1016/J.MARPOLBUL.2021.112694.

[90] I. Kalantzi *et al.*, “Assessment of the use of copper alloy aquaculture nets: Potential impacts on the marine environment and on the farmed fish,” *Aquaculture*, vol. 465, pp. 209–222, Dec. 2016, doi: 10.1016/J.AQUACULTURE.2016.09.016.

[91] N. Bloecher and O. Floerl, “Efficacy testing of novel antifouling coatings for pen nets in aquaculture: How good are alternatives to traditional copper coatings?,” *Aquaculture*, vol. 519, p. 734936, Mar. 2020, doi: 10.1016/J.AQUACULTURE.2020.734936.

[92] L. S. Herbeck, D. Unger, Y. Wu, and T. C. Jennerjahn, “Effluent, nutrient and organic matter export from shrimp and fish ponds causing eutrophication in coastal and back-

reef waters of NE Hainan, tropical China," *Cont. Shelf Res.*, vol. 57, pp. 92–104, Apr. 2013, doi: 10.1016/J.CSR.2012.05.006.

[93] S. Ur Rahman *et al.*, "Pb uptake, accumulation, and translocation in plants: Plant physiological, biochemical, and molecular response: A review," *Heliyon*, vol. 10, no. 6, p. e27724, Mar. 2024, doi: 10.1016/J.HELIYON.2024.E27724.

[94] G. Yu *et al.*, "The Mechanism of Plant Resistance to Heavy Metal," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 310, no. 5, pp. 1–6, 2019, doi: 10.1088/1755-1315/310/5/052004.

[95] Z. Shabbir *et al.*, "Copper uptake, essentiality, toxicity, detoxification and risk assessment in soil-plant environment," *Chemosphere*, vol. 259, p. 127436, Nov. 2020, doi: 10.1016/J.CHEMOSPHERE.2020.127436.

[96] E. Xu *et al.*, "Molecular Mechanisms of Plant Responses to Copper: From Deficiency to Excess," *Int. J. Mol. Sci.*, vol. 25, no. 13, p. 6993, Jul. 2024, doi: 10.3390/IJMS25136993.

[97] V. Kumar *et al.*, "Copper bioavailability, uptake, toxicity and tolerance in plants: A comprehensive review," *Chemosphere*, vol. 262, p. 127810, 2021, doi: https://doi.org/10.1016/j.chemosphere.2020.127810.

[98] S. Collin *et al.*, "Bioaccumulation of lead (Pb) and its effects in plants: A review," *J. Hazard. Mater. Lett.*, vol. 3, p. 100064, 2022, doi: https://doi.org/10.1016/j.hazl.2022.100064.

[99] S. Mitra *et al.*, "Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity," *J. King Saud Univ. - Sci.*, vol. 34, no. 3, p. 101865, Apr. 2022, doi: 10.1016/J.JKSUS.2022.101865.

[100] A. B. Fulke, S. Ratanpal, and S. Sonker, "Understanding heavy metal toxicity: Implications on human health, marine ecosystems and bioremediation strategies," *Mar.*

Pollut. Bull., vol. 206, p. 116707, 2024, doi: https://doi.org/10.1016/j.marpolbul.2024.116707.

[101] K. Analuddin *et al.*, “The carrying capacity of estuarine mangroves in maintaining the coastal urban environmental health of Southeast Sulawesi, Indonesia,” *Egypt. J. Aquat. Res.*, vol. 49, no. 3, pp. 327–338, Sep. 2023, doi: 10.1016/J.EJAR.2023.03.002.

[102] T. Crespo-Toledo, F. Avelar-González, A. Guerrero-Barrera, K. Mitchell, L. Yamamoto-Flores, and O. Flores-Amaro, “Integrative assessment of heavy metal risks in mining polluted sediments and soils of Aguascalientes, Mexico,” *Case Stud. Chem. Environ. Eng.*, vol. 11, p. 101130, Jun. 2025, doi: 10.1016/J.CSCEE.2025.101130.

[103] P. B. Angon *et al.*, “Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain,” *Heliyon*, vol. 10, no. 7, p. e28357, Apr. 2024, doi: 10.1016/J.HELIYON.2024.E28357.

[104] O. J. Popoola, O. D. Ogundele, E. A. Ladapo, and S. Senbore, “The Impact of Heavy Metal Contamination in Soils on Soil Microbial Communities and Its Potential Health Risks for Humans,” *Soil Microbiome Green Technol. Sustain.*, pp. 351–375, 2024, doi: 10.1007/978-3-031-71844-1_15.

[105] M. R. Hasan *et al.*, “Vertical distribution, contamination status and ecological risk assessment of heavy metals in core sediments from a mangrove-dominated tropical river,” *Mar. Pollut. Bull.*, vol. 189, p. 114804, Apr. 2023, doi: 10.1016/J.MARPOLBUL.2023.114804.

[106] P. B. Angon *et al.*, “Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain,” *Heliyon*, vol. 10, no. 7, p. e28357, 2024, doi: https://doi.org/10.1016/j.heliyon.2024.e28357.

[107] S. Hoffmann, “Challenges and opportunities of area-based conservation in reaching biodiversity and sustainability goals,” *Biodivers. Conserv.*, vol. 31, no. 2, pp. 325–352,

2022, doi: 10.1007/s10531-021-02340-2.

[108] G. Li *et al.*, “Mixed effectiveness of global protected areas in resisting habitat loss,” *Nat. Commun.*, vol. 15, no. 1, p. 8389, 2024, doi: 10.1038/s41467-024-52693-9.

[109] J. Briffa, E. Sinagra, and R. Blundell, “Heavy metal pollution in the environment and their toxicological effects on humans,” *Heliyon*, vol. 6, no. 9, p. e04691, Sep. 2020, doi: 10.1016/J.HELIYON.2020.E04691.

[110] Ramses, Ismarti, F. Amelia, Rozirwan, and Suheryanto, “Diversity and abundance of polychaetes in the west coast waters of batam island, Kepulauan Riau province-indonesia,” *AACL Bioflux*, vol. 13, no. 1, pp. 381–391, 2020.

[111] L. S. Miranda, B. Wijesiri, G. A. Ayoko, P. Egodawatta, and A. Goonetilleke, “Water-sediment interactions and mobility of heavy metals in aquatic environments,” *Water Res.*, vol. 202, p. 117386, 2021, doi: https://doi.org/10.1016/j.watres.2021.117386.

[112] F. Brugnone *et al.*, “Atmospheric Deposition around the Industrial Areas of Milazzo and Priolo Gargallo (Sicily–Italy)—Part B: Trace Elements,” *Atmosphere (Basel).*, vol. 14, no. 4, 2023, doi: 10.3390/atmos14040737.

[113] P. Liu, Q. Wu, W. Hu, K. Tian, B. Huang, and Y. Zhao, “Effects of atmospheric deposition on heavy metals accumulation in agricultural soils: Evidence from field monitoring and Pb isotope analysis,” *Environ. Pollut.*, vol. 330, p. 121740, 2023, doi: https://doi.org/10.1016/j.envpol.2023.121740.

[114] S. Karmakar *et al.*, “Effectiveness of artificially planted mangroves on remediation of metals released from ship-breaking activities,” *Mar. Pollut. Bull.*, vol. 212, p. 117587, Mar. 2025, doi: 10.1016/J.MARPOLBUL.2025.117587.

[115] S. Mitra, N. Naskar, and P. Chaudhuri, “A review on potential bioactive phytochemicals for novel therapeutic applications with special emphasis on mangrove species,” *Phytomedicine Plus*, vol. 1, no. 4, p. 100107, 2021, doi:

10.1016/j.phyplu.2021.100107.

[116] N. P. E. Hikmawanti, S. Fatmawati, and A. W. Asri, “The effect of ethanol concentrations as the extraction solvent on antioxidant activity of Katuk (Sauropus androgynus (L.) Merr.) leaves extracts,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 755, no. 1, 2021, doi: 10.1088/1755-1315/755/1/012060.

[117] A. Altemimi, N. Lakhssassi, A. Baharlouei, D. G. Watson, and D. A. Lightfoot, “Phytochemicals: Extraction, Isolation, and Identification of Bioactive Compounds from Plant Extracts,” *Plants*, vol. 6, no. 4, Dec. 2017, doi: 10.3390/PLANTS6040042.

[118] A. Acquaviva *et al.*, “Screening for Chemical Characterization and Pharmacological Properties of Different Extracts from Nepeta italica,” *Plants*, vol. 12, no. 15, Aug. 2023, doi: 10.3390/PLANTS12152785/S1.

[119] Rozirwan, R. Y. Nugroho, M. Hendri, Fauziyah, W. A. E. Putri, and A. Agussalim, “Phytochemical profile and toxicity of extracts from the leaf of Avicennia marina (Forssk.) Vierh. collected in mangrove areas affected by port activities,” *South African J. Bot.*, vol. 150, pp. 903–919, Nov. 2022, doi: 10.1016/J.SAJB.2022.08.037.

[120] K. A. Audah *et al.*, “Indonesian Mangrove Sonneratia caseolaris Leaves Ethanol Extract Is a Potential Super Antioxidant and Anti Methicillin-Resistant Staphylococcus aureus Drug,” *Molecules*, vol. 27, no. 23, p. 8369, Dec. 2022, doi: 10.3390/MOLECULES27238369/S1.

[121] K. A. S. Kodikara *et al.*, “Oxidative stress, leaf photosynthetic capacity and dry matter content in young mangrove plant Rhizophora mucronata Lam. under prolonged submergence and soil water stress,” *Physiol. Mol. Biol. Plants*, vol. 26, no. 8, p. 1609, Aug. 2020, doi: 10.1007/S12298-020-00843-W.

[122] F. P. Sabdanawaty, Purnomo, and B. S. Daryono, “Species diversity and phenetic relationship among accessions of api-api (Avicennia spp.) in java based on

morphological characters and issr markers," *Biodiversitas*, vol. 22, no. 1, pp. 193–198, 2021, doi: 10.13057/biodiv/d220125.

[123] B. Nath, G. Birch, and P. Chaudhuri, "Assessment of sediment quality in Avicennia marina-dominated embayments of Sydney Estuary: The potential use of pneumatophores (aerial roots) as a bio-indicator of trace metal contamination," *Sci. Total Environ.*, vol. 472, pp. 1010–1022, Feb. 2014, doi: 10.1016/J.SCITOTENV.2013.11.096.

[124] S. Hao, W. Su, and Q. Q. Li, "Adaptive roots of mangrove Avicennia marina: Structure and gene expressions analyses of pneumatophores," *Sci. Total Environ.*, vol. 757, p. 143994, Feb. 2021, doi: 10.1016/J.SCITOTENV.2020.143994.

[125] R. Wilda, A. M. Hamdan, and R. Rahmi, "A review: The use of mangrove for biomonitoring on aquatic environment," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 980, no. 1, 2020, doi: 10.1088/1757-899X/980/1/012083.

[126] Rozirwan *et al.*, "Investigating the Antioxidant Activity, Total Phenolics and Phytochemical Profile in Avicennia Alba and Excoecaria Agallocha Root Extracts As a Defence Mechanism Against Pollutants," *Farmacia*, vol. 72, no. 5, pp. 1216–1226, 2024, doi: 10.31925/farmacia.2024.5.25.

[127] S. J. Hossain *et al.*, "Antibacterial, Anti-Diarrhoeal, Analgesic, Cytotoxic Activities, and GC-MS Profiling of Sonneratia apetala (Buch.-Ham.) Seed," *Prev. Nutr. food Sci.*, vol. 22, no. 3, pp. 157–165, Sep. 2017, doi: 10.3746/pnf.2017.22.3.157.

[128] M. R. Bomfim *et al.*, "Morphology, Physical and Chemical Characteristics of Mangrove Soil under Riverine and Marine Influence: A Case Study on Subaé River Basin, Bahia, Brazil," *Mangrove Ecosyst. Ecol. Funct.*, Nov. 2018, doi: 10.5772/INTECHOPEN.79142.

[129] I. Dewiyanti, D. Darmawi, Z. A. Muchlisin, T. Z. Helmi, I. Imelda, and C. N. Defira,

"Physical and chemical characteristics of soil in mangrove ecosystem based on differences habitat in Banda Aceh and Aceh Besar," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 674, no. 1, p. 012092, Feb. 2021, doi: 10.1088/1755-1315/674/1/012092.

[130] M. Kumar *et al.*, "Biomarkers as indicators of sedimentary organic matter sources and early diagenetic transformation of pentacyclic triterpenoids in a tropical mangrove ecosystem," *Estuar. Coast. Shelf Sci.*, vol. 229, p. 106403, 2019, doi: 10.1016/j.ecss.2019.106403.

[131] Rozirwan *et al.*, "Phytochemical composition , total phenolic content and antioxidant activity of Anadara granosa (Linnaeus , 1758) collected from the east coast of South Sumatra , Indonesia Abstract :," *Baghdad Sci. J.*, pp. 1–8, 2023.

[132] M. F. Misrah *et al.*, "Evaluation of antioxidant activity and total phenolics of selected mangrove plants in Sabah," *Borneo Int. J. Biotechnol.*, vol. 2, no. December, pp. 14–21, 2022, [Online]. Available: https://doi.org/10.51200/bijb.v2i.3330

[133] Y. S. Wang and J. D. Gu, "Ecological responses, adaptation and mechanisms of mangrove wetland ecosystem to global climate change and anthropogenic activities," *Int. Biodeterior. Biodegradation*, vol. 162, p. 105248, Aug. 2021, doi: 10.1016/J.IBIOD.2021.105248.

[134] S. Sudhir, A. Arunprasath, and V. Sankara Vel, "A critical review on adaptations, and biological activities of the mangroves," *J. Nat. Pestic. Res.*, vol. 1, p. 100006, Jun. 2022, doi: 10.1016/J.NAPERE.2022.100006.

[135] M. Xu, C. Sun, Y. Zhan, and Y. Liu, "Impact and prediction of pollutant on mangrove and carbon stocks: A machine learning study based on urban remote sensing data," *Geosci. Front.*, p. 101665, Jul. 2023, doi: 10.1016/J.GSF.2023.101665.

[136] O. M. Ighodaro and O. A. Akinloye, "First line defence antioxidants-superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPX): Their

fundamental role in the entire antioxidant defence grid," *Alexandria J. Med.*, vol. 54, no. 4, pp. 287–293, Dec. 2018, doi: 10.1016/J.AJME.2017.09.001.

[137] J. Laoué, C. Fernandez, and E. Ormeño, "Plant Flavonoids in Mediterranean Species: A Focus on Flavonols as Protective Metabolites under Climate Stress," *Plants*, vol. 11, no. 2, Jan. 2022, doi: 10.3390/PLANTS11020172.

[138] L. Valgimigli, "Lipid Peroxidation and Antioxidant Protection," *Biomolecules*, vol. 13, no. 9, 2023, doi: 10.3390/biom13091291.

[139] B. Yang, H. Liu, J. Yang, V. K. Gupta, and Y. Jiang, "New insights on bioactivities and biosynthesis of flavonoid glycosides," *Trends Food Sci. Technol.*, vol. 79, pp. 116–124, Sep. 2018, doi: 10.1016/J.TIFS.2018.07.006.

[140] A. M. M. Youssef, D. A. M. Maaty, and Y. M. Al-Saraireh, "Phytochemistry and Anticancer Effects of Mangrove (Rhizophora mucronata Lam.) Leaves and Stems Extract against Different Cancer Cell Lines," *Pharmaceuticals*, vol. 16, no. 1, 2023, doi: 10.3390/ph16010004.

[141] A. Elaiyaraja and G. Chandramohan, "COMPARATIVE PHYTOCHEMICAL PROFILE OF CRINUM DEFIXUM KER-GAWLER LEAVES USING GC-MS," *J. Drug Deliv. Ther.*, vol. 8, no. 4, pp. 365–380, Aug. 2018, doi: 10.22270/JDDT.V8I4.1758.

[142] R. Borgohain, A. K. Guha, S. Pratihar, and J. G. Handique, "Antioxidant activity of some phenolic aldehydes and their diimine derivatives: A DFT study," *Comput. Theor. Chem.*, vol. 1060, pp. 17–23, May 2015, doi: 10.1016/J.COMPTC.2015.02.014.

[143] J. Ge *et al.*, "Natural terpenoids with anti-inflammatory activities: Potential leads for anti-inflammatory drug discovery," *Bioorg. Chem.*, vol. 124, p. 105817, Jul. 2022, doi: 10.1016/J.BIOORG.2022.105817.

[144] R. Rozirwan *et al.*, "Anti-Inflammatory Activity and Phytochemical Profile from the

Leaves of the Mangrove Sonneratia caseolaris (L.) Engl. for Future Drug Discovery," *Sci. Technol. Indones.*, vol. 9, no. 2, pp. 502–516, Apr. 2024, doi: 10.26554/STI.2024.9.2.502-516.

[145] I. Gutiérrez-Del-río *et al.*, "Terpenoids and Polyphenols as Natural Antioxidant Agents in Food Preservation," *Antioxidants*, vol. 10, no. 8, Aug. 2021, doi: 10.3390/ANTIOX10081264.

[146] V. Venepally and R. C. Reddy Jala, "An insight into the biological activities of heterocyclic–fatty acid hybrid molecules," *Eur. J. Med. Chem.*, vol. 141, pp. 113–137, Dec. 2017, doi: 10.1016/J.EJMECH.2017.09.069.

[147] A. Cherkas, S. Holota, T. Mdzinarashvili, R. Gabbianelli, and N. Zarkovic, "Glucose as a Major Antioxidant: When, What for and Why It Fails?," *Antioxidants (Basel, Switzerland)*, vol. 9, no. 2, Feb. 2020, doi: 10.3390/antiox9020140.

[148] N. Shen, T. Wang, Q. Gan, S. Liu, L. Wang, and B. Jin, "Plant flavonoids: Classification, distribution, biosynthesis, and antioxidant activity," *Food Chem.*, vol. 383, p. 132531, Jul. 2022, doi: 10.1016/J.FOODCHEM.2022.132531.

[149] I. Makuch-Pietraś, D. Grabek-Lejko, A. Górka, and I. Kasprzyk, "Antioxidant activities in relation to the transport of heavy metals from the soil to different parts of Betula pendula (Roth.)," *J. Biol. Eng.*, vol. 17, no. 1, pp. 1–25, 2023, doi: 10.1186/s13036-022-00322-8.

[150] E. C. Georgiadou *et al.*, "Influence of heavy metals (Ni, Cu, and Zn) on nitro-oxidative stress responses, proteome regulation and allergen production in basil (ocimum basilicum L.) plants," *Front. Plant Sci.*, vol. 9, p. 374129, Jul. 2018, doi: 10.3389/FPLS.2018.00862/BIBTEX.

[151] D. M. Kasote, S. S. Katyare, M. V. Hegde, and H. Bae, "Significance of Antioxidant Potential of Plants and its Relevance to Therapeutic Applications," *Int. J. Biol. Sci.*,

vol. 11, no. 8, p. 982, Jun. 2015, doi: 10.7150/IJBS.12096.

[152] Z. Cai, A. Kastell, C. Speiser, and I. Smetanska, "Enhanced resveratrol production in Vitis vinifera cell suspension cultures by heavy metals without loss of cell viability," *Appl. Biochem. Biotechnol.*, vol. 171, no. 2, pp. 330–340, 2013, doi: 10.1007/s12010-013-0354-4.

[153] A. Koźmińska, A. Wiszniewska, E. Hanus-Fajerska, and E. Muszyńska, "Recent strategies of increasing metal tolerance and phytoremediation potential using genetic transformation of plants," *Plant Biotechnol. Rep.*, vol. 12, no. 1, Feb. 2018, doi: 10.1007/S11816-017-0467-2.

[154] S. Mansoor *et al.*, "Phytoremediation at Molecular Level," *Phytoremediation Biotechnol. Strateg. Promot. Invigorating Environs*, pp. 65–90, Jan. 2022, doi: 10.1016/B978-0-323-89874-4.00011-X.

[155] M. O. Aljahdali, A. B. Alhassan, and Z. Zhang, "Environmental Factors Causing Stress in Avicennia marina Mangrove in Rabigh Lagoon Along the Red Sea: Based on a Multi-Approach Study," *Front. Mar. Sci.*, vol. 8, p. 328, May 2021, doi: 10.3389/FMARS.2021.646993/BIBTEX.

[156] S. Ghosh, M. Bakshi, S. Mahanty, and P. Chaudhuri, "Understanding potentially toxic metal (PTM) induced biotic response in two riparian mangrove species Sonneratia caseolaris and Avicennia officinalis along river Hooghly, India: Implications for sustainable sediment quality management," *Mar. Environ. Res.*, vol. 172, no. June, p. 105486, 2021, doi: 10.1016/j.marenvres.2021.105486.

[157] S. Ur Rahman *et al.*, "Adaptation and remediation strategies of mangroves against heavy metal contamination in global coastal ecosystems: A review," *J. Clean. Prod.*, vol. 441, p. 140868, Feb. 2024, doi: 10.1016/J.JCLEPRO.2024.140868.

[158] Z. Yan, X. Sun, Y. Xu, Q. Zhang, and X. Li, "Accumulation and Tolerance of

Mangroves to Heavy Metals: a Review," *Curr. Pollut. Reports 2017 34*, vol. 3, no. 4, pp. 302–317, Aug. 2017, doi: 10.1007/S40726-017-0066-4.

[159] K. Kulbat-Warycha, E. C. Georgiadou, D. Mańkowska, B. Smolińska, V. Fotopoulos, and J. Leszczyńska, "Response to stress and allergen production caused by metal ions (Ni, Cu and Zn) in oregano (Origanum vulgare L.) plants," *J. Biotechnol.*, vol. 324, pp. 171–182, Dec. 2020, doi: 10.1016/J.JBIOTEC.2020.10.025.

[160] S. Mansoor *et al.*, "Heavy Metal Induced Oxidative Stress Mitigation and ROS Scavenging in Plants," *Plants*, vol. 12, no. 16, Aug. 2023, doi: 10.3390/PLANTS12163003.

[161] H. N. Thatoi, J. K. Patra, and S. K. Das, "Free radical scavenging and antioxidant potential of mangrove plants: A review," *Acta Physiol. Plant.*, vol. 36, no. 3, pp. 561–579, 2014, doi: 10.1007/s11738-013-1438-z.

[162] J. Liu and T. Myat, "Contaminants and heavy metals along the mangrove area of Dongzhai Harbor, China: distribution and assessment," *SN Appl. Sci.*, vol. 3, no. 10, pp. 1–12, Oct. 2021, doi: 10.1007/S42452-021-04802-2/FIGURES/6.

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Confirming submission to Toxicology Reports

1 pesan

Toxicology Reports <em@editorialmanager.com> 23 Maret 2025 pukul 23.02
Balas Ke: Toxicology Reports <support@elsevier.com>
Kepada: Rozirwan Rozirwan <rozirwan@unsri.ac.id>

This is an automated message.

Manuscript Number: **TOXREP-D-24-00875R3**

Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

Dear Dr. Rozirwan,

We have received the above referenced manuscript you submitted to Toxicology Reports.

To track the status of your manuscript, please log in as an author at https://www.editorialmanager.com/toxrep/, and navigate to the "Revisions Being Processed" folder.

Thank you for submitting your revision to this journal.

Kind regards,
Toxicology Reports

Have questions or need assistance?
For further assistance, please visit Elsevier Support Center for Author Support. Here you can search for solutions on a range of topics, find answers to frequently asked questions, and learn more about Editorial Manager via interactive tutorials.
You can also talk to our customer support team 24/7 by live chat, email and phone.

#AU_TOXREP#

To ensure this email reaches the intended recipient, please do not delete the above code

---

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

IMPORTANT – Track your article [TOXREP_102011]

1 pesan

Toxicology Reports <toxrep@elsevier.com> 25 Maret 2025 pukul 07.05
Kepada: rozirwan@unsri.ac.id

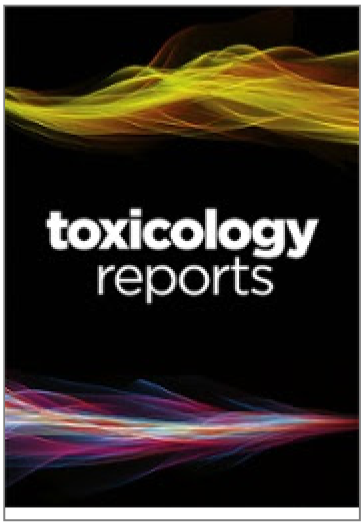
ELSEVIER

Track your article!

Paper Accepted in the Editorial system › Paper Received in Production › Proofs are being created › Proofs are Ready for Approval › Corrections to the Proof Submitted › Paper is Finalised › Issue is Finalised

Title: *Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones*
Reference: *TOXREP_102011*

Dear Dr. Rozirwan,



We're looking forward to your article *Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones* soon being published in Toxicology Reports.

You can follow your article's journey throughout the publication process by using our article tracking service.

https://authors.elsevier.com/tracking/article/details.do?aid=102011&jid=TOXREP&surname=Rozirwan

For help with article tracking, please visit Elsevier Support at Elsevier Support.

WHAT HAPPENS NEXT?
We are committed to publishing your article as quickly as possible and will send you an alert at each step in the production process where your involvement is required. We're currently working on the proof of your article and will be in touch shortly to let you know when we expect it to be ready.

Yours sincerely,

Nalini Kannan
Toxicology Reports

For further help and/or information please visit our Author hub here.

Have questions or need assistance?
Please do not reply to this automated message.
For further assistance, please visit our Elsevier Support Center where you can search for solutions on a

range of topics and find answers to frequently asked questions.
From here you can also contact our Researcher Support team via 24/7 live chat, email or phone support.

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Decision on submission to Toxicology Reports

2 pesan

Toxicology Reports <em@editorialmanager.com> 25 Maret 2025 pukul 04.39
Balas Ke: Toxicology Reports <support@elsevier.com>
Kepada: Rozirwan Rozirwan <rozirwan@unsri.ac.id>

CC: l.h.lash@wayne.edu, nbasaran@hacettepe.edu.tr, anbasaran@baskent.edu.tr

Manuscript Number: **TOXREP-D-24-00875R3**

Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

Dear Dr Rozirwan,

Thank you for submitting your manuscript to Toxicology Reports.

I am pleased to inform you that your manuscript has been accepted for publication.

Your accepted manuscript will now be transferred to our production department. We will create a proof which you will be asked to check, and you will also be asked to complete a number of online forms required for publication. If we need additional information from you during the production process, we will contact you directly.

We appreciate you submitting your manuscript to Toxicology Reports and hope you will consider us again for future submissions.

We encourage authors of original research papers to share the research objects – including raw data, methods, protocols, software, hardware and other outputs – associated with their paper. More information on how our open access Research Elements journals can help you do this is available at https://www.elsevier.com/authors/tools-and-resources/research-elements-journals?dgcid=ec_em_research_elements_email.

Kind regards,

Lawrence Lash
Editor-in-Chief
Toxicology Reports

More information and support

FAQ: When and how will I receive the proofs of my article?
https://service.elsevier.com/app/answers/detail/a_id/6007/p/10592/supporthub/publishing/related/

FAQ: How can I reset a forgotten password?
https://service.elsevier.com/app/answers/detail/a_id/28452/supporthub/publishing/
For further assistance, please visit our customer service site: https://service.elsevier.com/app/home/supporthub/publishing/
Here you can search for solutions on a range of topics, find answers to frequently asked questions, and learn more about Editorial Manager via interactive tutorials. You can also talk 24/7 to our customer support team by phone and 24/7 by live chat and email

At Elsevier, we want to help all our authors to stay safe when publishing. Please be aware of fraudulent messages requesting money in return for the publication of your paper. If you are publishing open access with Elsevier, bear in mind that we will never request payment before the paper has been accepted. We have prepared some guidelines (https://www.elsevier.com/connect/authors-update/seven-top-tips-on-stopping-apc-scams) that you may find helpful, including a short video on Identifying fake acceptance letters (https://www.youtube.com/watch?v=o5l8thD9XtE). Please remember that you can contact Elsevier s Researcher Support team (https://service.elsevier.com/app/home/supporthub/publishing/) at any time if you have questions about your manuscript, and you can log into Editorial Manager to check the status of your manuscript (https://service.elsevier.com/app/answers/detail/a_id/29155/c/10530/supporthub/publishing/kw/status/).

#AU_TOXREP#

To ensure this email reaches the intended recipient, please do not delete the above code

---

In compliance with data protection regulations, you may request that we remove your personal registration details at any time. (Remove my information/details). Please contact the publication office if you have any questions.

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id> 25 Maret 2025 pukul 10.22
Kepada: Toxicology Reports <support@elsevier.com>

Dear Editor,

Thank you for your kind email and for accepting our manuscript for publication in *Toxicology Reports*. We are truly grateful for the opportunity to contribute to your esteemed journal.

We look forward to the next steps in the production process and will carefully review the proof once it is available. Please do not hesitate to reach out if any additional information or forms are required from our side.

Once again, we sincerely appreciate the editorial and review team's efforts in evaluating our work. We hope to continue collaborating with *Toxicology Reports* in the future.

Best regards,

[Kutipan teks disembunyikan]

--

Prof. Dr. Rozirwan
Head of Marine Bioecology Laboratory
Department of Marine Science
Faculty of Mathematics and Natural Sciences
Sriwijaya University
Jalan Raya Palembang-Prabumulih KM 32, Indralaya
Ogan Ilir, Sumatera Selatan, Indonesia, Pos Code: 30862
Email: rozirwan@unsri.ac.id, rozirwan@gmail.com

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Re: Decision on submission to Toxicology Reports [250325-012110]

1 pesan

Researcher Support <support@elsevier.com> 25 Maret 2025 pukul 10.22
Balas Ke: Researcher Support <support@elsevier.com>
Kepada: rozirwan@unsri.ac.id

Hello!

Thank you for contacting Elsevier Researcher Support.

To help us jump right into the solution, please ensure you have provided as much information as possible.

While you wait, you can take a look at our Journal Article Publishing Support Center where you can review FAQs and 'how to' videos.

To help ensure a fast response, please do not change the subject line of this email when replying. For any future correspondence, remember to quote your unique reference number provided in the subject line.

Regards,

Elsevier Researcher Support

From: Rozirwan Rozirwan
Date: 25/03/2025 03.22 AM

Dear Editor,

Thank you for your kind email and for accepting our manuscript for publication in *Toxicology Reports*. We are truly grateful for the opportunity to contribute to your esteemed journal.

We look forward to the next steps in the production process and will carefully review the proof once it is available. Please do not hesitate to reach out if any additional information or forms are required from our side.

Once again, we sincerely appreciate the editorial and review team's efforts in evaluating our work. We hope to continue collaborating with *Toxicology Reports* in the future.

Best regards,

Pada Sel, 25 Mar 2025 pukul 04.39 Toxicology Reports <em@editorialmanager.com> menulis:

> CC: l.h.lash@wayne.edu, nbasaran@hacettepe.edu.tr, anbasaran@baskent.edu.tr
>
> Manuscript Number: **TOXREP-D-24-00875R3**
>
> Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones

Dear Dr Rozirwan,

Thank you for submitting your manuscript to Toxicology Reports.

I am pleased to inform you that your manuscript has been accepted for publication.

Your accepted manuscript will now be transferred to our production department. We will create a proof which you will be asked to check, and you will also be asked to complete a number of online forms required for publication. If we need additional information from you during the production process, we will contact you directly.

We appreciate you submitting your manuscript to Toxicology Reports and hope you will consider us again for future submissions.

We encourage authors of original research papers to share the research objects – including raw data, methods, protocols, software, hardware and other outputs – associated with their paper. More information on how our open access Research Elements journals can help you do this is available at https://www.elsevier.com/authors/tools-and-resources/research-elements-journals?dgcid=ec_em_research_elements_email.

Kind regards,

Lawrence Lash
Editor-in-Chief
Toxicology Reports

More information and support

FAQ: When and how will I receive the proofs of my article?
https://service.elsevier.com/app/answers/detail/a_id/6007/p/10592/supporthub/publishing/related/

FAQ: How can I reset a forgotten password?
https://service.elsevier.com/app/answers/detail/a_id/28452/supporthub/publishing/
For further assistance, please visit our customer service site: https://service.elsevier.com/app/home/supporthub/publishing/
Here you can search for solutions on a range of topics, find answers to frequently asked questions, and learn more about Editorial Manager via interactive tutorials. You can also talk 24/7 to our customer support team by phone and 24/7 by live chat and email

At Elsevier, we want to help all our authors to stay safe when publishing. Please be aware of fraudulent messages requesting money in return for the publication of your paper. If you are publishing open access with Elsevier, bear in mind that we will never request payment before the paper has been accepted. We have prepared some guidelines (https://www.elsevier.com/connect/authors-update/seven-top-tips-on-stopping-apc-scams) that you may find helpful, including a short video on Identifying fake acceptance letters (https://www.youtube.com/watch?v=o5l8thD9XtE). Please remember that you can contact Elsevier s Researcher Support team (https://service.elsevier.com/app/home/supporthub/publishing/) at any time if you have questions about your manuscript, and you can log into Editorial Manager to check the status of your manuscript (https://service.elsevier.com/app/answers/detail/a_id/29155/c/10530/supporthub/publishing/kw/status/).

#AU_TOXREP#

To ensure this email reaches the intended recipient, please do not delete the above code

---

In compliance with data protection regulations, you may request that we remove your personal registration details at any time. (Remove my information/details). Please contact the publication office if you have any questions.

--
Prof. Dr. Rozirwan
Head of Marine Bioecology Laboratory
Department of Marine Science
Faculty of Mathematics and Natural Sciences
Sriwijaya University
Jalan Raya Palembang-Prabumulih KM 32, Indralaya
Ogan Ilir, Sumatera Selatan, Indonesia, Pos Code: 30862
Email: rozirwan@unsri.ac.id, rozirwan@gmail.com

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

IMPORTANT PLEASE TAKE ACTION, Production has begun on your article [TOXREP_102011] in Toxicology Reports

1 pesan

P.Kaushik@elsevier.com <P.Kaushik@elsevier.com> 25 Maret 2025 pukul 14.51
Kepada: rozirwan@unsri.ac.id

Our reference: TOXREP 102011
Article reference: TOXREP_TOXREP-D-24-00875
Article title: Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones
To be published in: Toxicology Reports

Dear Dr Rozirwan,

Congratulations on your accepted paper! Thank you for choosing to publish in Toxicology Reports. Please read this e-mail carefully as it contains important information.

FINALIZE PUBLISHING YOUR ARTICLE:

We work hard to publish our authors' articles online as quickly as possible, so we're happy to report that processing of your manuscript has already begun. To ensure that we publish your article in accordance with your wishes, please now complete these forms

http://authors.elsevier.com/authorforms/TOXREP102011/39756c2bbe1841ea8f820d230c3f8715

If this link does not work, please copy the entire URL (noting that it may run on to a second line in this message) into your browser. You should log in with your Elsevier Profile credentials, which you may have already created when submitting your article.

CHECK YOUR CONTACT DETAILS:

Please check that your details listed below are correct so we can contact you if needed:

Dr Rozirwan Rozirwan
Universitas Sriwijaya
Indonesia
Phone: not available
Fax: not available
E-mail: rozirwan@unsri.ac.id

YOUR REFERENCE NUMBER:

To help us provide you with the best service, please make a note of your article's reference number TOXREP 102011 and quote it in all of your messages to us.

If you wish to find out more about the next steps in the publication process and for further help and / or information please visit our Author hub, link below:
https://service.elsevier.com/app/answers/detail/a_id/34514/c/10532/supporthub/publishing/

Thank you for your cooperation.

Kind regards,

MR Paras Kaushik

Elsevier
E-Mail: P.Kaushik@Elsevier.Com

HAVE QUESTIONS OR NEED ASSISTANCE?

For further assistance, Please feel free to talk to our Researcher support
team via 24/7 live chat and e-mail or avail our phone support for 24/7. Please visit
our Elsevier support Center where you can search for solutions on a range
of topics and find answers to frequently asked questions, Get started here:

http://service.elsevier.com/app/home/supporthub/publishing

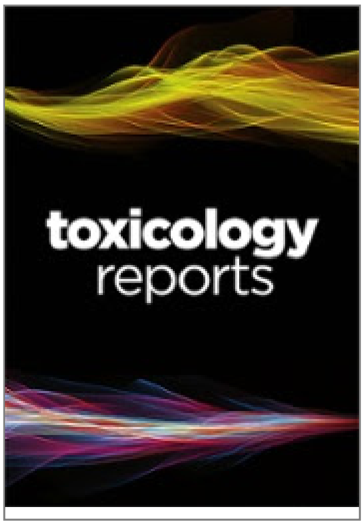
Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Publishing Agreement completed for your article [TOXREP_102011]

1 pesan

Elsevier - Author Forms <Article_Status@elsevier.com> 25 Maret 2025 pukul 22.21
Kepada: rozirwan@unsri.ac.id

ELSEVIER



Dear Dr Rozirwan,

Thank you for completing the Publishing Agreement Form for your article *Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones*. Please find attached a copy of the "Journal Publishing (License) Agreement" which you completed online on March 25, 2025.

If you have any questions, please do not hesitate to contact us. To help us assist you, please quote our article reference TOXREP_102011 in all correspondence.

Now that your article has been accepted, you will want to maximize the impact of your work. Elsevier facilitates and encourages authors to share their article responsibly. To learn about the many ways in which you can share your article whilst respecting copyright, visit: www.elsevier.com/sharing-articles.

We are committed to publishing your article as quickly as possible.

Kind regards,
Elsevier Researcher Support

Have questions or need assistance?
Please do not reply to this automated message.
For further assistance, please visit our Elsevier Support Center where you can search for solutions on a range of topics and find answers to frequently asked questions.
From here you can also contact our Researcher Support team via 24/7 live chat, email or phone support.

TOXREP102011.html
25K

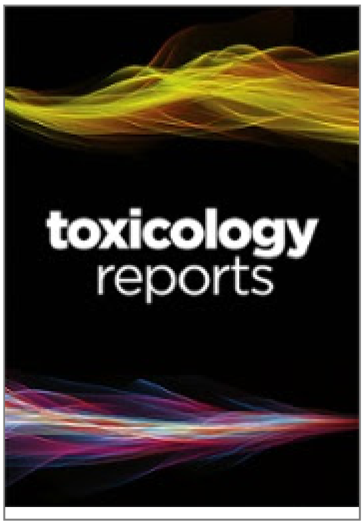
Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Rights and Access form completed for your article [TOXREP_102011]

1 pesan

Elsevier - Author Forms <oasupport@elsevier.com> 25 Maret 2025 pukul 22.21
Kepada: rozirwan@unsri.ac.id

ELSEVIER



Dear Dr Rozirwan,

Thank you for completing the Rights and Access Form for your article *Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones* on March 25, 2025.

The Order Summary is attached to this email. If you wish to make any changes, please contact our Researcher Support team immediately through one of the contact options mentioned on the support site: https://service.elsevier.com.

Your article will be free for everyone to read online as soon as it is published.

If you have any questions, please do not hesitate to contact us. Quote our article reference TOXREP_102011 in all correspondence.

Now that your article has been accepted, you will want to maximize the impact of your work. Elsevier facilitates and encourages authors to share their article responsibly. To learn about the many ways in which you can share your article while respecting copyright, visit: www.elsevier.com/sharing-articles.

Kind regards,
Elsevier Researcher Support

Seven strategies for you to create a brand and promote your research

Learn how to give your research the visibility it deserves with these seven strategies.

\> Access module now

Have questions or need assistance?
Please do not reply to this automated message.
For further assistance, please visit our Elsevier Support Center where you can search for solutions on a range of topics and find answers to frequently asked questions.
From here you can also contact our Researcher Support team via 24/7 live chat, email or phone support.

Order Confirmation.html
20K

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

Proofs of [TOXREP_102011]

1 pesan

corrections.esch@elsevier.macipd.com <corrections.esch@elsevier.macipd.com> 26 Maret 2025 pukul 18.34

Kepada: rozirwan@unsri.ac.id

PLEASE DO NOT ALTER THE SUBJECT LINE OF THIS E-MAIL ON REPLY

Dear Dr. Rozirwan Rozirwan,

Thank you for publishing with Toxicology Reports. We are pleased to inform you that the proof for your upcoming publication is ready for review via the link below. You will find instructions on the start page on how to make corrections directly on-screen or through PDF.

https://elsevier.proofcentral.com/en-us/landing-page.html?token=e06e645b80339bd059f20b24d2a66c

Please open this hyperlink using one of the following browser versions:
•Google Chrome 68+
•Mozilla Firefox 61+
•Safari 11+
•Microsoft Edge 79+

We ask you to check that you are satisfied with the accuracy of the copy-editing, and with the completeness and correctness of the text, tables and figures. To assist you with this, copy-editing changes have been highlighted.

You can save and return to your article at any time during the correction process. Once you make corrections and hit the SUBMIT button you can no longer make further corrections.

We will do everything possible to get your article published quickly and accurately. The sooner we hear from you, the sooner your corrected article will be published online. You can expect your corrected proof to appear online within a week after we receive your corrections.

We very much look forward to your response.

Yours sincerely,
Elsevier
E-mail: corrections.esch@elsevier.macipd.com

For further assistance, please visit our customer support site at http://support.elsevier.com. Here you can search for solutions on a range of topics. You will also find our 24/7 support contact details should you need any further assistance from one of our customer support representatives.

Rozirwan ROZIRWAN <rozirwan@unsri.ac.id>

FOR YOUR INFORMATION - Your article (Pre-Proof) is now available online [TOXREP_102011]

1 pesan

Toxicology Reports <toxrep@elsevier.com> 27 Maret 2025 pukul 07.21
Kepada: rozirwan@unsri.ac.id

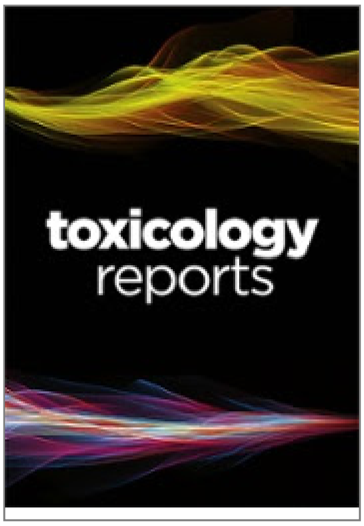
ELSEVIER

Your Article Is Now Available Online

Paper Accepted in the Editorial system → Paper Received in Production - Pre-proof available online → Proofs are being created → Proofs are Ready for Approval → Corrections to the Proof Submitted → Paper is Finalised → Issue is Finalised

Title: *Biomarkers of heavy metals pollution in mangrove ecosystems: comparative assessment in industrial impact and conservation zones*
Reference: *TOXREP_102011*

Dear Dr Rozirwan,



We are pleased to inform you that your article is now available online at:

https://authors.elsevier.com/sd/article/S2214-7500(25)00129-5

You may want to bookmark this permanent URL to your article.

The first published version has been made available so that you can view your article, but it is not intended to be the final version. Your article will now undergo copyediting and typesetting, after which you will have the opportunity to review the proof and provide corrections before final publication.

This version will be replaced by the final version as soon as this is available.

Your article can already be cited using the year of online availability and the DOI as follows: Author(s), Article Title, Journal (Year), DOI..

Once the full bibliographic details (including volume and page numbering) for citation purposes are available, you will be alerted by email. Elsevier facilitates and encourages authors to share their articles responsibly. To learn more about the many ways in which you can share your article whilst respecting copyright, visit https://www.elsevier.com/sharing-articles.

To track the status of your article throughout the publication process, please use our article tracking service:

https://authors.elsevier.com/tracking/article/details.do?aid=102011&jid=TOXREP&surname=Rozirwan

Yours sincerely,

Nalini Kannan
Toxicology Reports

For further help and/or information please visit our Author hub here.

Toxicology Reports 14 (2025) 102011

Contents lists available at ScienceDirect

Toxicology Reports

journal homepage: www.elsevier.com/locate/toxrep

Biomarkers of heavy metals pollution in mangrove ecosystems: Comparative assessment in industrial impact and conservation zones

Rozirwan [a,*], Nadila Nur Khotimah [b], Wike Ayu Eka Putri [a], Fauziyah [a], Riris Aryawati [a], Gusti Diansyah [a], Redho Yoga Nugroho [a]

[a] Department of Marine Science, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya, Indralaya, South Sumatra 30862, Indonesia
[b] Environmental Management Study Program, Graduate Program, Universitas Sriwijaya, Palembang 30139, Indonesia

ARTICLE INFO

Handling Editor: Prof. L.H. Lash

Keywords:
Biomarkers
Conservation zones
Heavy metals
Industrial activities
Mangrove

ABSTRACT

Heavy metal contamination from industrial activities in coastal regions can lead to pollution in mangrove ecosystems. Mangroves produce antioxidant compounds to mitigate the impact of free radicals. This study aimed to analyze the correlation between the concentration of heavy metals Pb and Cu and antioxidant activity in *Avicennia alba* and *Excoecaria agallocha* mangroves from areas affected by industrial activities and conservation areas, Banyuasin, South Sumatra, Indonesia. This study was conducted in September 2023 with sampling locations in the Payung Island area and the Barong River conservation area, Berbak Sembilang National Park. The samples taken included sediment and mangrove leaves. The concentration of heavy metals Pb and Cu was measured by atomic absorption spectrometry. Antioxidant activity test using the DPPH test, total phenol using the Folin-Ciocalteu method, and phytochemical profile screening using GCMS. Statistical analysis of the correlation between antioxidant activity and heavy metal concentration using the Pearson correlation. The results showed that the highest concentration of heavy metals in sediment and mangrove leaves was found in the area affected by industrial activity, with a range of Pb values of 0.67 ± 0.16–18.70 ± 0.48 mg/kg and Cu values of 3.39 ± 0.20–6.07 ± 0.37 mg / kg. The results of sediment pollution assessment for heavy metals Pb and Cu at Igeo < 0 indicates uncontaminated, $1 < Cf < 3$ indicates low contamination, and PLI 0–2 indicates not polluted. While the results of heavy metal bioaccumulation in leaves were BCF < 1, indicates low bioaccumulation. *E. agallocha* leaves from the Pulau Payung area showed very strong antioxidant activity of 21.63 μg/ml, and the highest total phenol content reached 398.80 mg GAE/g. Analysis of compounds with the highest antioxidant activity identified the presence of esters, aldehydes, alcohols, fatty acids, glycosides, flavonoids, terpenoids, and steroids. Correlation analysis shows that higher heavy metal concentrations correspond to increased antioxidant activity and total phenol content ($r \neq 0$). These findings are expected to contribute to scientific knowledge that enhances environmental sustainability, supporting effective management of coastal natural resources.

1. Introduction

Coastal areas are transitional areas between land and sea that have abundant biodiversity and unique ecosystems [1,2]. Coastal areas face great pressure from various anthropogenic activities that can cause pollution [3,4]. Previous studies report that industrial activities like fertilizer processing, oil and gas, and crude palm oil production contribute to coastal pollution [3,5,6]. In addition, there are also agricultural activities, ports, shipping, loading and unloading of coal raw materials and their products, and households [7]. Continuous anthropogenic activities in coastal areas can produce pollutants, such as microplastics, heavy metals, as well as various organic and inorganic contaminants [8–10]. Among various pollutant types, heavy metals are categorized as persistent pollutants due to their resistance to decomposition [11]. Heavy metals initially present in the water column gradually settle to the sediment and eventually accumulate in aquatic organisms [12]. This condition may have adverse impacts, particularly if it exceeds environmental quality standards. These adverse impacts can affect aquatic ecosystems, including mangroves [13,14]. According to Xu et al., [15], as the largest plant community in coastal areas, mangroves are also directly affected by pollution.

Mangrove ecosystems play a vital role in coastal protection,

* Corresponding author.
E-mail address: rozirwan@unsri.ac.id (Rozirwan).

https://doi.org/10.1016/j.toxrep.2025.102011
Received 29 October 2024; Received in revised form 23 March 2025; Accepted 24 March 2025
Available online 25 March 2025

supporting biological diversity, and contributing to the socio-economic development of local communities [16,17]. Additionally, their capacity to accumulate pollutants makes them valuable indicators for assessing pollution levels in coastal waters, as they can absorb and store these pollutants in their tissues, enhancing their role in monitoring environmental health [18–20]. Roots and leaves are important parts of mangroves in the absorption, accumulation, and response to pollutants [21]. Roots are the first part exposed to pollutants from their growth media. Furthermore, roots also have the ability to translocate pollutants to the leaves. Leaves are the primary site for photosynthesis in plants, supplying the energy essential for cell development, and overall plant function [22]. High concentrations of pollutants in roots and leaves can potentially increase excessive reactive oxygen species (ROS), resulting in oxidative stress in mangroves [23,24]. Oxidative stress arises from an imbalance between ROS production and detoxification, potentially leading to harmful cellular damage [25,26]. Although oxidative stress can be detrimental, plants also have a resistance response mechanism against free radicals [27]. This process involves producing antioxidant enzymes and molecules to counteract the harmful effects of free radicals. In response to environmental changes, plants enhance the activity of antioxidant defenses, including both enzymatic and non-enzymatic components such as superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), glutathione peroxidase (GPx), and phenolic compounds. These antioxidants serve as protective mechanisms against various environmental stress [28,29].

Research on the specific physiological adaptations of various mangrove species to pollutants is still limited. Most previous studies only focused on the accumulation of heavy metals in mangroves without exploring in depth the biochemical defense mechanisms they employ [30–32]. However, studies on how different mangrove species respond to industrial pollution in environments with varying levels of pollution have not yet been conducted. In addition, most studies only examine one mangrove species without comparing the adaptability of different species in the face of heavy metal contamination [33,34].

This study aimed to evaluate the accumulation of heavy metals (Pb and Cu) in two mangrove species (*Avicennia alba* and *Excoecaria agallocha*) and assess their antioxidant activity in industrial and conservation zones. The selection of these two species was based on their prevalence in the research location as well as differences in habitat zones and morphological characteristics [35,36]. This study was carried out in the mangrove ecosystem, which includes areas influenced by industrial activities such as Payung Island as well as conservation areas in the Berbak Sembilang National Park [37,38].

By assessing biomarkers, new insights are provided into how mangrove species adapt to environmental stress caused by heavy metal pollution. Additionally, the research explores the impact of heavy metal contamination on the physiological responses of mangroves, focusing on their biochemical defense mechanisms. The findings aim to enhance understanding of mangrove adaptation strategies in response to pollution and offer valuable implications for coastal ecosystem conservation and environmental pollution management.

2. Materials and method

2.1. Leaf sampling

This study was conducted in September 2023. The samples included *Avicennia alba*, *Excoecaria agallocha*, and sediments collected from industrial and conservation zones in Banyuasin, South Sumatra, Indonesia (Fig. 1). The first area is the mangrove ecosystem on Payung Island. This area was chosen due to the high accumulation of heavy metals from industrial activities along the Musi River. Additionally, the area includes agricultural activities, ports, fish ponds, and settlements [39,40]. The second area is the Barong River conservation area, Berbak Sembilang National Park, which represents a natural area and protects flora and fauna from the threat of damage, scarcity, or deforestation [41–43].

The sampling stages include collecting sediment samples and mangrove leaves. Sediment samples were taken as supporting data to determine the concentration of heavy metals in the mangrove growth media. The availability of heavy metals in sediments has a direct effect

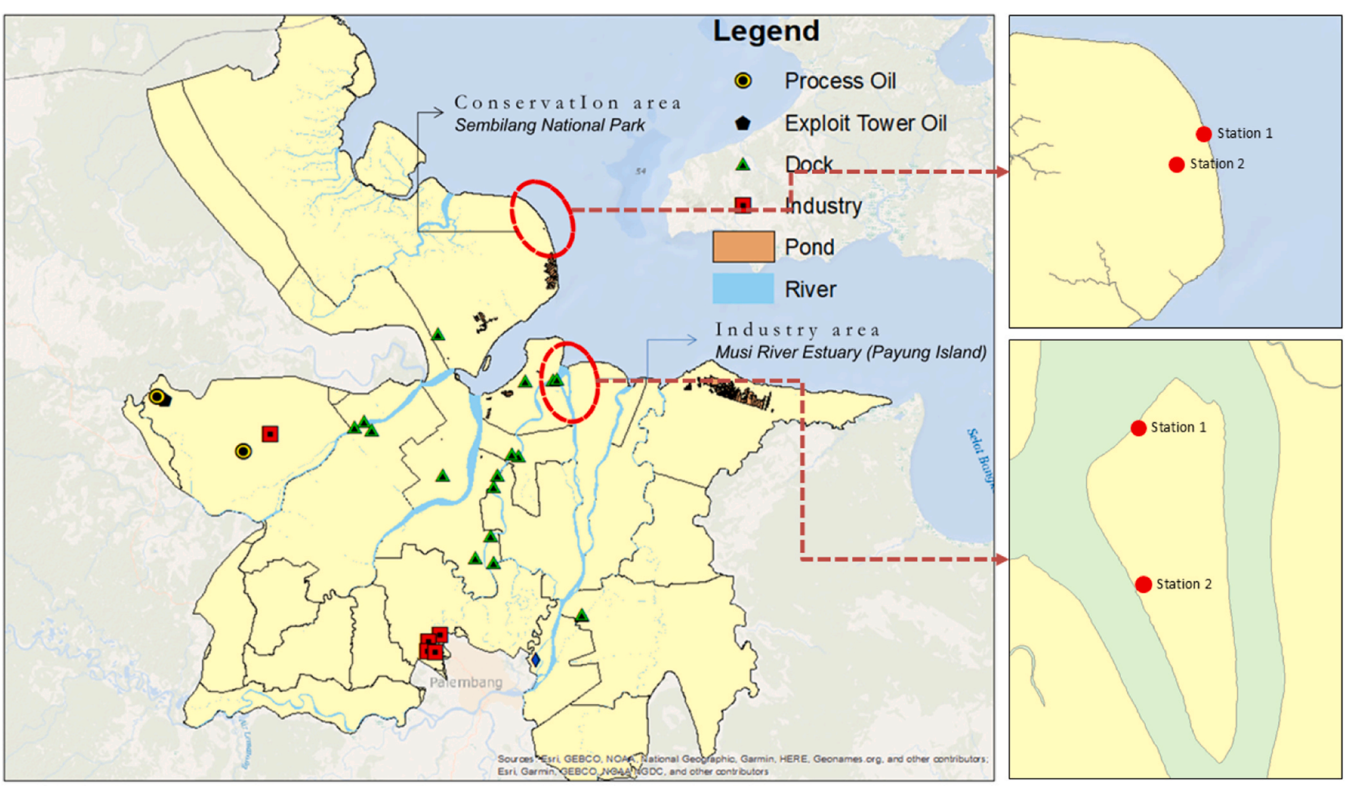


Fig. 1. Map of sample collection.

on the bioaccumulation and biomagnification processes in aquatic organisms. Sediment data helps understand the level of risk and potential impacts to organisms in mangrove ecosystems. Sediment samples were taken using a grab pipe at a depth of ± 10 cm from the surface [44]. Sediment depth shows a very significant impact on heavy metal content, with a greater decrease in heavy metal content as sediment depth increases [45]. Samples were taken at three location points for each station, which were considered as replications. Samples were taken compositely together (taken as needed, 500 g) and placed into a polyethylene plastic container and stored in a cool box for analysis in the laboratory.

The method for collecting mangrove leaves taken from the field uses a random sampling method [46]. The random sampling method can be used if the sample studied is homogeneous. The mangrove species taken were *A. alba* and *E. agallocha*. The samples taken consisted of ± 1 kg of leaves and were put in polyethylene plastic.

2.2. Sediment grain size analysis

Grain size analysis was conducted using the sieving and pipetting methods as outlined by [47]. Sediment types (gravel, sand, silt, and clay) were classified using Shepard's triangle analysis and processed with Microsoft Excel V.2021, following the protocols established by [48,49]. The sediment fraction type was determined by identifying the most dominant composition from the analysis results.

2.3. Sample preparation

Sediment sample preparation involved removing foreign objects such as plastic fragments and leaves. The sediment was then air dried at room temperature for 72 hours until fully dry, ground to a homogeneous consistency, and stored in a tightly sealed polyethylene bottle. They were then air-dried in a shaded, well-ventilated area for five days, ensuring indirect exposure to sunlight to prevent the degradation of bioactive compounds. The drying process was conducted at ambient temperature with sufficient airflow to facilitate moisture evaporation. Once dried, the samples were ground into a fine powder and stored in sealed containers for further analysis. The extraction of heavy metals (Pb and Cu) from the sediment samples and mangrove leaves was performed using the wet destruction method, following the procedures outlined by [8,50].

2.4. Atomic absorption spectroscopic measurement

Measuring the concentration of heavy metals Pb and Cu using an Atomic Absorption Spectrophotometer (Shimadzu AA-7000). Operational parameters: Pb (283.3 nm, 5 mA lamp current) and Cu (324.7 nm, 4 mA), slit width 0.5 nm, air-acetylene flame (2.0 L/min air; 1.5 L/min acetylene), burner height 5–7 mm. After 15–20 min warm-up, calibration was performed using blank and standard solutions (0.1–2.0 ppm Pb; 0.05–1.0 ppm Cu), achieving $R^2 \geq 0.995$. Samples were aspirated in triplicate with 15-sec distilled water rinsing between measurements and acid blank checks every 5 samples. Quality control included spike recovery (85–115 %), duplicate analyses (RSD <5 %). LODs: 0.02 ppm Pb; 0.01 ppm Cu (3 ×SD blank) [51].

2.5. Determination of heavy metals in leaves and sediments

2.5.1. Determination of sediment pollution

2.5.1.1. Geoacumulation index (I_{geo}). The Igeo (geo-accumulation index) quantitatively evaluates the degree of heavy metal contamination and classifies the level of pollution based on detailed categorization [52].

$$Igeo = \log_2 (Cn/1.5\ Bn) \quad (1)$$

The classification of Igeo values includes the following categories: uncontaminated (Igeo ≤ 0), uncontaminated to moderately contaminated (Igeo 0–1), moderately contaminated (Igeo 1–2), moderately to highly contaminated (Igeo 2–3), highly contaminated (Igeo 3–4), highly contaminated to very highly contaminated (Igeo 4–5), and very highly contaminated (Igeo ≥ 5) [53].

2.6. Contamination factor (Cf)

The contamination factor is determined experimentally as the ratio of the element concentration in the sample to its background concentration [54].

$$Cf = (Cn/Bn) \quad (2)$$

The contamination factor (Cf) classifications are as follows: [55]: Cf < 1 = low contamination; 1 < Cf < 3 = moderate contamination; 3 < Cf < 6 = sufficient contamination; Cf > 6 = very high contamination.

2.7. Pollution load index (PLI)

The pollution load index (PLI) is utilized to assess pollution quality in a given area. The pollution load index value uses the formula [56].

$$PLI = [Cf1\ x\ Cf2\ x\ Cf3\ldots\ x\ Cfn]^{1/n} \quad (3)$$

Pollution load index (PLI) criteria: PLI 8–10 = severely polluted; PLI 4–8 = heavily polluted; PLI 2–4 = moderately polluted; PLI 0–2 = not polluted to lightly polluted; PLI < 0 = not polluted.

2.8. Bioaccumulation of metal in leaves

2.8.1. Bioconcentration factor (BCF)

The absorption of metals by leaf from sediment occurs through a process known as bioaccumulation. The bioconcentration factor (BCF) values are utilized to assess the extent of metal bioaccumulation in mangrove leaf originating from sediment [57].

$$BCF = (Cn.leaf/Cn.\ sediment) \quad (4)$$

BCF > 1 hyperaccumulator; BCF = 1 indicator; BCF < 1 is an excluder [58].

2.9. Analysis of antioxidant non-enzymes in leaves

2.9.1. Antioxidant activity evaluated by DPPH assay

Antioxidant activity analysis was carried out using ethanol solvent based on a method adapted from [59]. A 50 ml 0.1 μM DPPH solution was prepared, followed by the preparation of a sample stock solution and a 10 ml pure ascorbic acid stock solution of 2000 ppm, which was homogenized. Furthermore, a series of solutions were made with concentrations of 1000 ppm, 500 ppm, 250 ppm, 125 ppm, and 62.5 ppm. At each concentration, 1 ml of 0.1 μM DPPH solution was added to the mixture, which was then homogenized and incubated in the dark for 30 minutes. After incubation, the absorbance was measured using a UV-Vis spectrophotometer (Shimadzu UV-1900, Japan) at a wavelength of 517 nm. The antioxidant activity of the extract is expressed as IC_{50}, which quantifies the strength of its antioxidant capacity (Table 1). The

Table 1
Characteristic value of IC_{50}.

Concentration (μg/ml)	Characteristic
< 50	Very strong
50–100	Strong
100–150	Moderate
150–200	Low

IC_{50} value is calculated using the following formula:

$$\%inhibition = \frac{blank\ abs - sample\ abs.}{blank\ abs} x100\% \quad (5)$$

The IC_{50} value was derived by inputting the data into a linear regression equation, where the sample concentration was plotted on the X-axis and the percentage of inhibition of antioxidant activity on the Y-axis. The regression equation used is represented as y = ax + b [60].

2.10. Determination of phenol content

The analysis of total phenol content in the samples was conducted using the Folin-Ciocalteu method, as outlined in the literature [60–62]. A standard solution of 1000 ppm gallic acid as much as 50 ml was prepared, then variations in concentrations of 10 ppm, 20 ppm, 30 ppm, 40 ppm, and 50 ppm were made, each as much as 5 ml. For each concentration variation, 1 ml, 2 ml, 3 ml, 4 ml, and 5 ml were pipetted into a 10 ml measuring flask containing a standard solution of 100 ppm gallic acid. A total of 50 mg of sample was weighed, then 2 ml of methanol and 5 ml of distilled water were added, then homogenized in a 10 ml measuring flask. In both the standard series and sample variations, 0.5 ml of 50 % Folin-Ciocalteu reagent was added, followed by the addition of distilled water up to the mark. The mixture was then allowed to stand for 5 minutes. Next, one ml of a 5 % Na_2CO_3 solution was added and incubated in a dark place for one hour. After incubation, the absorbance of the sample was measured using a UV-Vis spectrophotometer at a wavelength of 750 nm.

2.11. Pearson correlation analysis (correlation bivariate)

The use of pearson correlation analysis (bivariate correlation) is a method used to evaluate the relationship between two variables [63, 64], in this case to see the relationship between antioxidant activity and heavy metal concentrations. This analysis was carried out using SPSS software version 28.

3. Result and discussion

3.1. Description of mangrove leaves

The mangrove species *A. alba* and *E. agallocha* found at the sampling location exhibit distinct characteristics. Fig. 2 shows the characteristic differences between *A. alba* and *E. agallocha* leaves.

Leaves are the part that characterizes a mangrove species. When identifying each type of mangrove, observation of the morphology of the leaf shape is very important to understand the characteristics and differences in each type of leaf [65,66]. *A. alba* leaves have a green surface with a smooth and slippery texture, while the underside is yellowish green with a rough texture. The characteristics of the leaves is elliptical, almost oval, with a tapered tip. Based on observations, the length of the leaves ranges from 10 to 13 cm, and the width of the leaves ranges from 4 to 5 cm. *E. agallocha* leaves are elliptical and dark green in color, with finely serrated edges and tapered tips. The observed leaf sizes ranged from 8 to 10 cm in length and 3–4.5 cm in width. Old leaves were selected as samples for the study of heavy metal content and bioactive compounds due to several considerations related to their maturity and potential accumulation of pollutants and compounds of interest. According to [67], plants tend to produce bioactive compounds in higher amounts in older parts. This could be a plant strategy to protect itself from pests, diseases, or the external environment [68,69]. Older leaves may have more stable chemical conditions, thus facilitating analysis and minimizing variability in results.

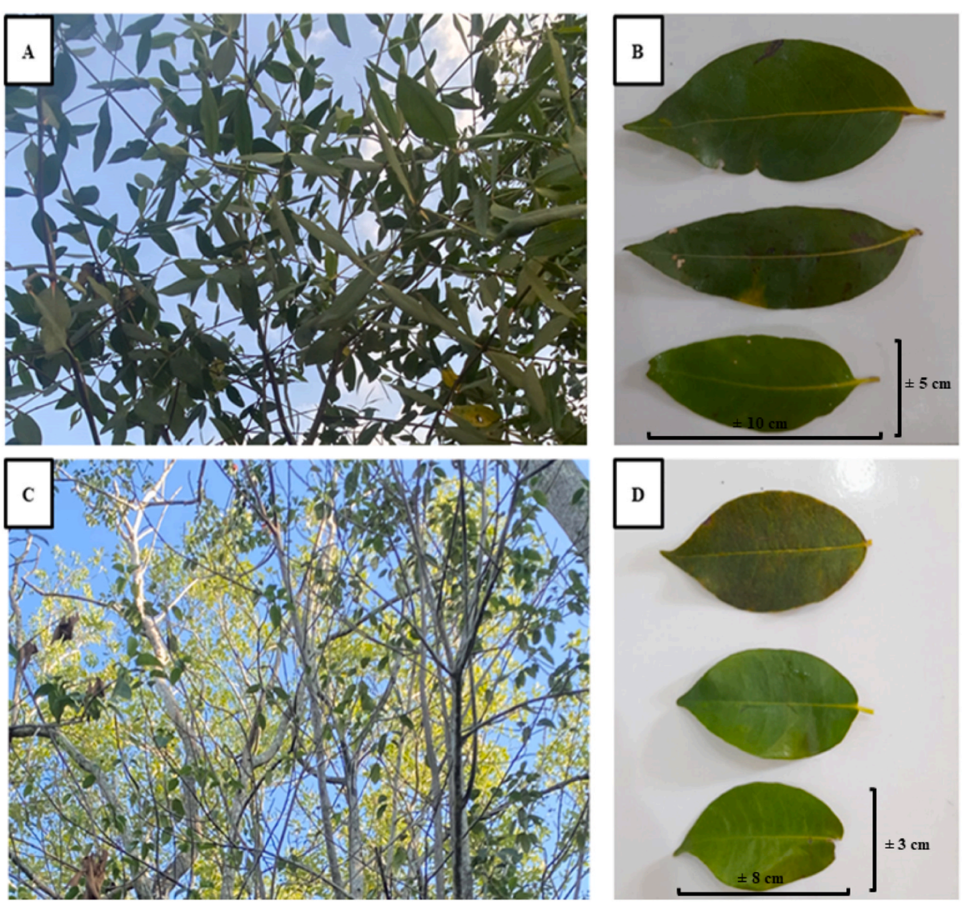


Fig. 2. Leaves description. A-B). *A. alba*, C-D). *E. agallocha*.

3.2. Sediment grain size

The determination of substrate types in the sampling was conducted using the Shepard triangle method (Fig. 3). In the mangrove ecosystem of both industrial and conservation areas, sediment substrates were categorized into four types: gravel, sand, mud, and clay. The results indicated that the predominant substrate type in both areas was clay.

The sediment substrate surrounding the mangrove ecosystem in both areas is predominantly clay, with clay percentages ranging from 80.5 % to 84.03 %. The highest clay content was observed at station 1 in the industrial area (Table 2).

Based on the results of Table 2, distribution of sediment fractions and grain sizes at two different locations, which represents two stations with different mangrove species *(A. alba* and *E. agallocha*). In the industrial area, most of the sediments consist of clay with a very low sand content (3.6 % for Station 1 and 3.36 % for Station 2), which indicates the predominance of fine materials that can influence the mobility of heavy metals and nutrients in the sediments. In contrast, in the conservation zone, although the sediment composition is still dominated by clay, the sand content is higher (22.5 % for Station 1 and 21.91 % for Station 2), indicating differences in sedimentation processes and a higher potential for water infiltration.

In the industrial area, both stations (*A. alba* and *E. agallocha*) showed a dominance of clay fractions with a very high percentage. The dominant clay fractions indicate that the sediment in this area consists of fine particles, which may be caused by the accumulation of fine particles from industrial activities around this location. Industries such as fertilizer processing, oil and gas, crude palm oil production, agricultural activities, ports, shipping, loading and unloading of coal raw materials and their products, and households contribute to the presence of fine particles in sediments [3,5–7]. Port activities involve frequent vessel movement, dredging, and cargo handling, all of which can resuspend fine particles and increase sedimentation rates [70,71]. Crude oil processing and petroleum industries may contribute to fine particle deposition through air emissions, which settle via atmospheric deposition [72]. Additionally, agricultural activities, particularly palm oil plantations,

Table 2
Sediment grain size in each station.

Location	Station	Sediment fraction (%)				Grain size
		Gravel	Sand	Mud	Clay	
Industry area	1 (*A. alba*)	0.00	3.6	12.37	84.03	Clay
	2 (*E. agallocha*)	0.00	3.36	16.14	80.5	Clay
Conservation zone	1 (*A. alba*)	0.00	22.5	1.95	75.55	Clay
	2 (*E. agallocha*)	0.00	21.91	2.02	76.07	Clay

can contribute to increased fine particle accumulation through soil erosion and runoff carrying clay-rich sediments into adjacent water systems, particularly during heavy rainfall [73,74].

Fine particles such as clay are usually carried by water and can accumulate in areas with slow water movement, such as near mangrove roots [75,76]. In the conservation zone, the clay fraction also dominates, although with a slightly lower percentage than the industrial area. The conservation zone may also have less influence from human activities, so the sediment pattern is more natural than the industrial area. Clay is a sediment particle with a very fine grain size and a large surface area [77,78]. Due to its small size and its tendency to be negatively charged, clay has a high adsorption capacity, which allows clay particles to attract and bind heavy metal ions such as Hg, Pb, Cd, Cu, and others [79–81]. Consequently, sediments dominated by clay fractions tend to accumulate more heavy metals than larger sediment fractions [82,83].

3.3. Determination of heavy metals

The results of the heavy metal concentration analysis for Pb and Cu in sediments and mangrove leaves from both areas are summarized in Table 3. The concentrations of heavy metals in sediments from both the industrial area and the conservation zone exhibit variability; however, they generally remain below hazardous thresholds (ERL, ERM, TEL, and PEL). In the industrial area, the highest Pb concentration was found at Station 2 (18.70 ± 0.48 mg/kg), while in the conservation zone, the

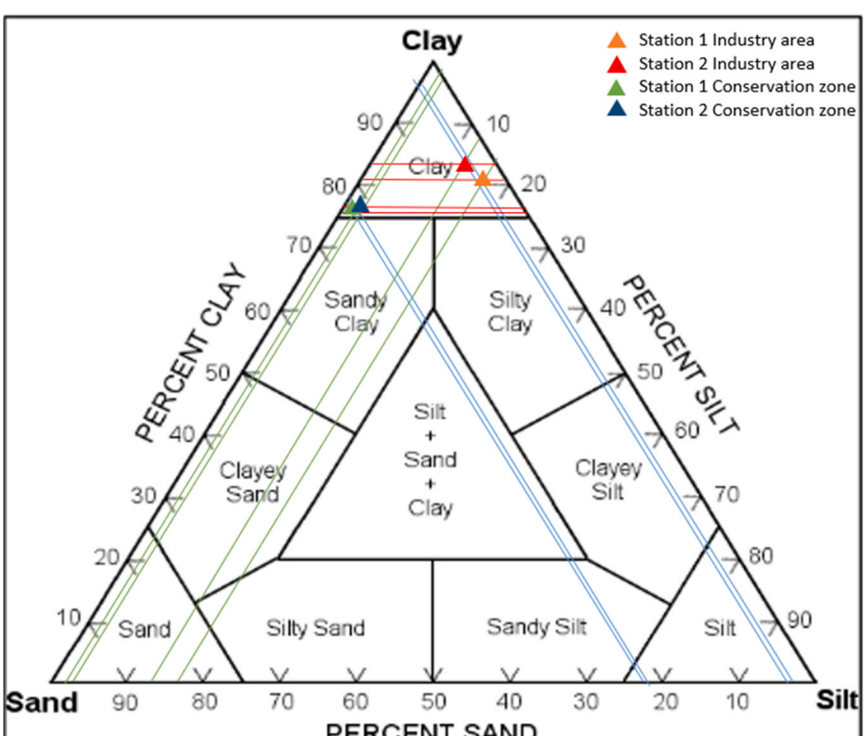


Fig. 3. Classifications of sediment type with shepard triangle method.

Table 3
Average concentrations of heavy metals (mg/kg) in mangrove sediments and leaves.

	Pb	Cu
Sediments		
Station.1 Industry area	12.63 ± 0.01	5.58 ± 0.05
Station.2 Industry area	18.70 ± 0.48	6.07 ± 0.37
Station.1 Conservation zone	12.61 ± 0.32	4.21 ± 0.03
Station.2 Conservation zone	14.22 ± 0.16	5.17 ± 0.17
ERL	46.7	34
ERM	218	270
TEL	30.2	18.7
PEL	112	108.2
Mangrove leaves		
Station.1 Industry area (*A. alba*)	0.67 ± 0.17	3.39 ± 0.20
Station.2 Industry area (*E. agallocha*)	1.27 ± 0.31	3.73 ± 0.16
Station.1 Conservation zone (*A. alba*)	0.84 ± 0.12	3.50 ± 0.35
Station.2 Conservation zone (*E. agallocha*)	0.99 ± 0.37	3.69 ± 0.23

highest concentrations of Pb and Cu were each at Station 2 (Pb 14.22 ± 0.16 mg/kg; Cu 5.17 ± 0.17 mg/kg). For metal accumulation in mangrove leaves, Cu was recorded higher than Pb at all stations. In the industrial area, *A. alba* (Station 1) had Pb 0.67 ± 0.17 mg/kg and Cu 3.39 ± 0.20 mg/kg, while *E. agallocha* (Station 2) showed Pb 1.27 ± 0.31 mg/kg and Cu 3.73 ± 0.16 mg/kg. In the conservation zone, the highest accumulation of Cu in mangrove leaves was 3.69 ± 0.23 mg/kg at Station 2.

The industrially impacted area in the Musi River Estuary is affected by high anthropogenic activities, making it susceptible to accumulating pollutants, especially heavy metals such as Pb and Cu. Sediments in this area tend to contain higher pollutants than water and biota, influenced by domestic, industrial, and river transportation activities that pollute the environment [84,85]. Ship and coastal building maintenance activities, including the use of anti-rust materials, electronic waste, and pipe corrosion, are the main sources of Pb, while sources of Cu in the aquatic environment come from antifouling paint, agricultural pesticides, and industrial waste [86,87]. In addition, previous studies report that cleaning ship hulls can release Cu into the marine environment [88,89]. Fisheries sector that uses Cu-coated nets to prevent biofouling can also contribute to increasing Cu levels in waters [90,91].

The conservation area in the Barong River is also exposed to heavy metal pollution, although at a lower level, considering that some human activities such as fishing are still ongoing [92]. Unmanaged anthropogenic activities, including unregulated industrial waste disposal, improper wastewater treatment, and uncontrolled agricultural runoff, have contributed to the increasing Cu concentrations observed in both locations, as indicated by the findings of this study and previous research [7,50]. These activities introduce Cu into the aquatic system, where it binds to suspended particles and accumulates in sediments, further exacerbating environmental pollution.

In mangrove leaves, Pb was detected at low concentrations. Plants regulate Pb primarily by limiting its uptake and translocation. Because Pb is a non-essential and highly toxic metal, most of it accumulates in the roots rather than being transported to the leaves [93]. In contrast, Cu an important micronutrient for plants, is regulated through controlled absorption and detoxification mechanisms [93,94]. Plants manage excess Cu by binding it to metallothionein and phytochelatin, storing it in vacuoles, and activating the antioxidant defense system to fight oxidative stress [95,96]. Although heavy metal concentrations vary between locations, they are still below the threshold, indicating a relatively low risk of contamination. However, long-term monitoring is essential to

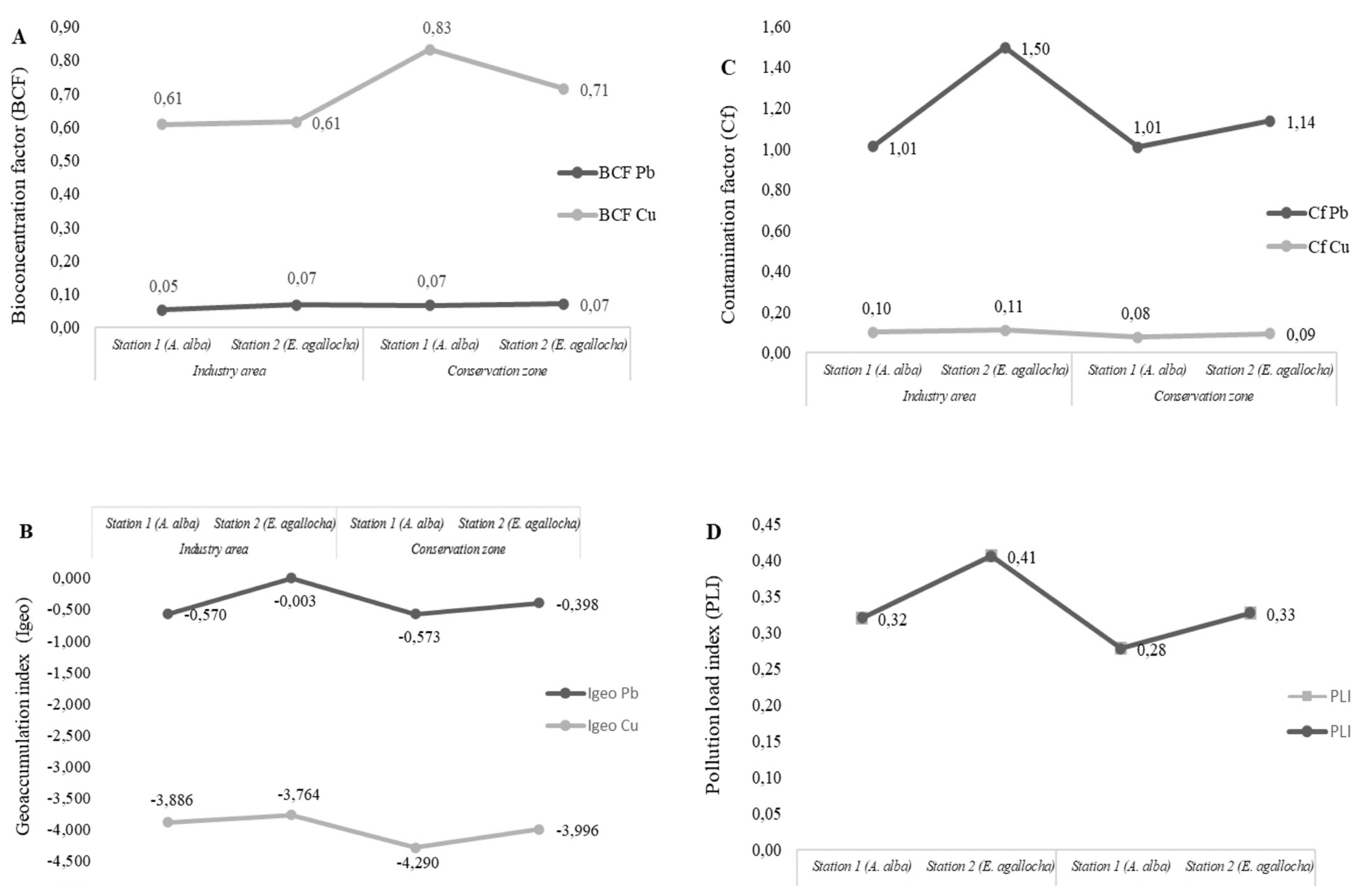


Fig. 4. Sediment quality indices. A). Bioconcentration factor (BCF), B). Geoaccumulation index (Igeo), C). Contamination factor (Cf), and D). Pollution load index (PLI).

track bioaccumulation trends in mangrove ecosystems.

3.4. Sediment quality indices

The results of the sediment quality index assessment are summarized in Fig. 4. The results of the leaf bioconcentration factor (BCF) in bioaccumulating Pb and Cu metals from sediment with a BCF value < 1 indicating low bioaccumulation. The geoaccumulation index shows uncontaminated properties for Pb and Cu with an Igeo value < 0 indicating uncontaminated. The contamination factor (Cf) shows that contamination is low and moderate in Pb and Cu with a value of 1 <Cf < 3 indicating low contamination. The PLI ranges from 0 to 2 indicating that both areas are not polluted.

The difference in bioconcentration factor (BCF) between Cu and Pb can be explained by the chemical properties of each metal. Cu accumulates more easily in biota tissues than Pb. Cu is an essential element for organisms, although at higher concentrations it can be toxic [97]. In contrast, Pb is a non-essential heavy metal that tends not to accumulate much in biota tissues [98]. The previous studies stated that essential heavy metals are more easily absorbed by organisms because they have physiological mechanisms to regulate the concentration of these elements [98,99]. Analuddin et al. [100] have also examined BCF in mangrove ecosystems, with results showing that the BCF values for Hg, Cu, Mn, Pb, and Zn > 1. This finding is thought to be related to the impact of anthropogenic activities in Kendari City, which has a high population density.

The Igeo index shows higher Pb contamination than Cu in industrial areas. Pb is thought to originate from human activities such as ports, agriculture, ship transportation, and household waste that tends to settle in sediments [32,79]. A high Igeo value indicate an anthropogenic contamination and show sediments contaminated heavy metal [101]. In addition, long-term exposure to these heavy metals can change community structure and disrupt ecosystem function through bioaccumulation and biomagnification in the food chain [102,103].

The high value of the Pb contamination factor (Cf) in industrial areas indicates that this environment is more susceptible to Pb pollution than Cu. Relevan study by Hasan et al. [104] that the CF value of Pb (0.76) > Cu (0.68) in core sediment from a mangrove at the Pasur River. Cu is more likely to be bound to organic particles and accumulate in the tissues of benthic organisms, which may explain the lower Cf Cu value. The areas suspected of being polluted tend to have higher anthropogenic activity than conservation zones, which causes significant differences in the levels of contamination and accumulation of heavy metals [105]. Industries around mangrove areas may contribute to elevated levels of heavy metals. Meanwhile, the conservation zone which is relatively protected from industrial activities, shows lower contamination values, although there are still traces of pollution due to remote pollution sources [105,106].

The PLI value in the industrial area is higher than the conservation zone. This indicates that industrial activities play a role in elevating heavy metal pollution in the area. Industrial areas are usually exposed to pollution sources such as factory waste, air pollution, and surface runoff that carry heavy metals into the sediment [107,108]. Although both stations are in the same area, there is a difference in the PLI value between Station 1 and Station 2 at both locations. Local factors, including water movement, sediment composition, and proximity to pollution sources, significantly influence the distribution of heavy metals [109]. The PLI in the conservation zone still shows heavy metal pollution. This could be due to atmospheric deposition from industrial activities in the surrounding area or pollutants carried by water currents from more contaminated areas [110,111]. This suggests that although the conservation zone has better protection, it is not completely protected from the impacts of nearby industrial pollution.

The study indicate that both areas are classified as not polluted. In line with these findings by Karmakar et al. [112], the PLI value in mangrove planting areas due to heavy metals from ship demolition activities is still below 1. Even though the PLI reflects low levels of pollution over time, it can increase the potential for absorption by aquatic organisms and pose ecological risks. therefore, continuous monitoring is required to identify dynamic changes in heavy metal concentrations

3.5. Antioxidant non-enzyme activities

The results of percentage of depreciation data for the *A. alba* species taken from the industrial area were 66 %, and the conservation zone was 65.8 %. While for the *E. agallocha* species from the industrial area it was 68.5 % and the conservation zone was 67.9 % in the conservation zone. Conversely, the findings of the percentage of dry weight of *A. alba* in the industrial area were 34 %, and the conservation zone was 34.3 %. In the *E. agallocha*, the percentage of dry weight in the industrial area was recorded at 31.5 % and the zone was 32.1 % (Table 4).

The removal of water content from the sample can be achieved by drying it until all moisture is eliminated, as the presence of water can influence the stability of bioactive compounds during extraction. Certain compounds may remain more stable or be less prone to chemical degradation or oxidation in dry conditions. The extraction of leaf samples from *A. alba* and *E. agallocha* was performed using ethanol as the solvent. The results indicated that the extract yield from the *A. alba* leaves was the highest at 8.80 %, which was obtained from the conservation area (Table 5).

Based on Table 5, these results indicate that environmental conditions, both in industrial areas and conservation zones, have the potential to affect the weight of crude extracts and the percentage of depreciation of *A. alba* and *E. agallocha* leaves, with the possibility of differences in the composition of bioactive compounds in each location. The maceration and extraction processes are important steps in testing the content of bioactive compounds in samples, especially in separating compound components from mangrove extracts [113]. The use of solvents such as ethanol, which are amphipathic, allows the dissolution of both polar and nonpolar compounds, so that it is optimal for obtaining various bioactive compounds from mangroves, which contain various types of compounds with these properties [113–115]. A high percentage of extraction weight indicates the effectiveness of the extraction method, indicating the method's ability to obtain active compounds from the sample optimally [116]. High extraction results also indicate a high content of active compounds in the sample, which possess the capability to have biological value and other practical applications [117].

The potential antioxidant content is illustrated by the percentage value of free radical scavenging inhibition along with the IC_{50} value. The results of the antioxidant test on mangrove leaves using the DPPH radical scavenging method using ethanol solvent (Table 6). The IC_{50} value content in the industrial area for *A. alba* of 137.8 μg/ml is classified as a moderate and *E. agallocha* of 21.63 μg/ml is classified as a very strong. While in the conservation area, *A. alba* of 64.32 μg/ml is classified as a strong and *E. agallocha* of 41.43 μg/ml is also classified as a very strong.

The IC_{50} classification results indicate that *A. alba* leaves from both areas fall into the strong-moderate category, while *E. agallocha* is classified as very strong. According to Kodikara et al. [118], the difference in the strength of antioxidant activity in each species is thought to be

Table 4
Depreciation percentage of weight.

Location	Sample leaves	Sample weight (g)		Depreciation percentage (%)	Weight percentage (%)
		Wet	Dry		
Industry area	*A. alba*	800	272	66	34
	E. agallocha	800	252	68.5	31.5
Conservation zone	*A. alba*	800	274	65.8	34.3
	E. agallocha	800	257	67.9	32.1

Table 5
Percentage of etanol extract.

Location	Sample leaves	Extract weight (g)		Depreciation percentage (%)	Extract percentage (%)
		Dry powder	Crude extract		
Industry area	*A. alba*	250	22.01	91.20	8.80
	E. agallocha	250	17.33	93.07	6.93
Conservation zone	*A. alba*	250	13.17	94.73	5.27
	E. agallocha	250	21.42	91.43	8.57

Table 6
Classification of IC_{50}.

Location	Sample leaves	Linear regression			IC_{50} (µg/ml)	Category
		a	b	R^2		
Industry area	*A. alba*	36.277	128.7	0.9429	137.8	Moderate
	E. agallocha	30.953	45.165	0.9419	21.63	Very strong
Conservation zone	*A. alba*	28.726	69.611	0.8905	64.32	Strong
	E. agallocha	18.425	18.661	0.904	41.43	Very strong

because mangroves have different tolerances to certain environmental conditions, and this can affect the extent to which they can overcome heavy metal toxicity. Previous research explained that the genus *Avicennia* is a mangrove found in the front zone and directly facing the waters [119]. *Avicennia spp.* has strong and dense aerial roots so that it is able to efficiently capture and bind mud and various pollutants carried by water [119,120]. As a type of plant that is periodically submerged in water, the roots of mangroves are able to take, absorb, or reduce contaminants through the dilution process [121,122]. Therefore, it is hypothesized that contaminants absorbed by roots do not induce excessive oxidative stress and do not increase the production of secondary metabolites.

Another study in the Island of Weno area, Chuuk State of Micronesia, for the antioxidant activity of *Rhizophora stylosa* roots was 41.3 % and *Sonneratia alba* 40.7 % [61]. While the IC_{50} value of the *E. agallocha* in both areas is included in the high category. *E. agallocha* in this study was found in the ladward zone. This zone is rarely submerged by seawater and is more often affected by lower tides. This is thought to be the cause of the low water content in the leaves of *E. agallocha* as presented in Table 4, so that the pollutants absorbed are greater and last longer in the leaves. Therefore, the roots act to mitigate stress effectively by producing antioxidant activity [123]. The concentration of antioxidant activity (IC_{50}) in the leaves showed different values in the two areas. The differences that occur in the ability to produce antioxidant activity in each mangrove as a form of self-defense against oxidative stress are due to differences in morphology, habitat, tides, sediment substrates, and environmental conditions [124,125]. Kumar et al. [126] also found that mangrove sediments in intertidal zones are rich in organic matter, including phenolic compounds and triterpenoids, which contribute to antioxidant potential. The presence of triterpenoids such as taraxerol acetate, germanicol, and β-amyrin suggests a strong chemotaxonomic link between mangrove-derived organic matter and plant defense mechanisms against oxidative stress. Differences in IC_{50} classification results can reflect differences in the level of heavy metal exposure in the two locations.

In addition to testing antioxidant activity using the DPPH method, this activity can also be analyzed by calculating total phenol. Measuring the total phenol content is done by adding Folin-ciocalteu reagent to the solution sample being tested (Table 7). Phenols possess antioxidant properties that play a role in protecting plant tissues from damage induced by free radicals. Therefore, the total phenol test can provide information about the potential antioxidant activity of mangrove leaf extracts. In this study, the highest quantitative phenol value was found in *E. agallocha* at 398.80 mg GAE/gr from the industrial area and the smallest in *A. alba* at 21.85 mg GAE/gr from the conservation area.

Table 7
Total phenol of mangrove leaves extract.

Location	Sample leaves	Phenol (mg GAE/g)
Industry area	*A. alba*	36.68
	E. agallocha	398.80
Conservation zone	*A. alba*	21.85
	E. agallocha	320.44

The total phenol obtained in this study has a positive relationship with antioxidant activity, as indicated by the IC_{50} value in Table 7. The antioxidant activity of this mangrove is influenced by its total phenol content. The total phenol content is positively correlated with antioxidant activity, where the higher the total phenol content, the higher the antioxidant activity in the sample [66]. Based on this study, *A. alba* has a lower total phenol content than *E. agallocha*, which is strongly suspected due to differences in environmental factors. Mangroves in the pioneer zone more pressure from pollutants and the physicochemical conditions of the habitat. This is in line with previous findings, where the total phenol content in the roots of *A. marina* in the pioneer zone was 26.11 mg GAE/g, lower than *B. gymnorrhiza* in the landward zone with 344.02 mg GAE/g [127]. Mangrove ecosystems located in the pioneer zone tend to have special adaptations to survive in coastal environments that are often inundated by sea tides [128,129]. Mangrove sediments in intertidal zones are rich in organic matter originating from terrestrial vascular plants, including phenolic compounds and triterpenoids, which contribute to their antioxidant potential [126]. Mangroves mitigate pollutants by reducing their concentration and toxicity through internal water content regulation, preventing excessive accumulation of absorbed contaminants [130]. According to Laoué et al. [131], non-enzymatic antioxidant activity is not produced exclusively because there is a certain limit for excess free radicals. However, the non-enzymatic antioxidant system is usually activated when free radical levels or oxidative stress exceed normal defense capacity [132].

GC-MS analysis using *E. agallocha* mangrove leaf samples from industrial areas because they are included in the IC_{50} classification is very strong among others. The graph revealed 15 peak points identifying compounds such as flavonoids, lipids, glycosides, glucosinolates, glucose, esters, terpenoids, and fatty acids (Fig. 5). The identified compounds, based on chromatogram peak heights and mass spectra from the analysis, match those in the WILEY 7 database library (Table 8).

Based on Table 8, 8 groups of compounds were found. The groups of compounds that are thought to be formed in response to the environment that increases antioxidant activity, such as flavonoids, lipids, glycosides, glucosinolates, glucose, esters, terpenoids, and fatty acids.

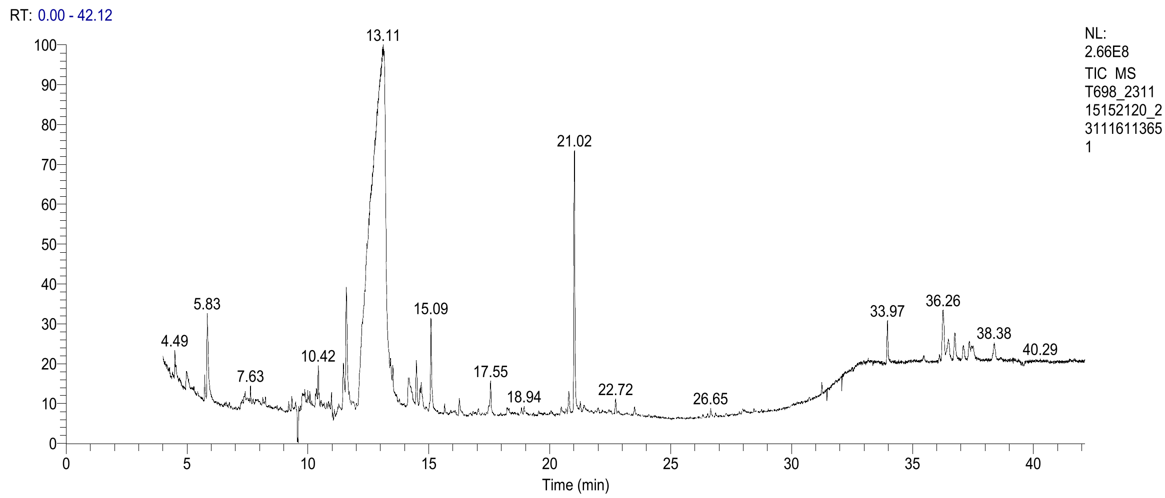


Fig. 5. GC-MS chromatogram of bioactive compounds in mangrove leaves *E. agallocha* (Industry area).

Table 8
Retetion time, peak area, compound name, formula, and compound group (*E. agallocha*).

Ret. time	*Peak Area %*	Compound name	Formula	Compound group
5.84	2.45	4H-Pyran−4-one, 2,3-dihydro−3,5-dihydroxy−6-methyl	$C_6H_8O_4$	Flavonoid
9.49	1.68	2-Myristynoyl pantetheine	$C_{23}H_{45}N_2O_4S$	Lipid
9.77	1.65	Paromomycin	$C_{23}H_{45}N_5O_{14}$	Glikosida
9.87	1.17	2-Myristynoyl pantetheine	$C_{23}H_{45}N_2O_4S$	Lipid
11.46	1.16	Desulphosinigrin	$C_{11}H_{21}NO_9S_2$	Glukosinolat
11.59	3.31	2-O-Methyl-D-mannopyranosa	$C_7H_{14}O_6$	Glikosida
13.10	73.97	3-O-Methyl-d-glucose	$C_7H_{14}O_6$	Glukosa
14.16	1.84	3-O-Methyl-d-glucose	$C_7H_{14}O_6$	Glukosa
14.48	0.99	7-Methyl-Z-tetradecen−1-ol acetate	$C_{17}H_{34}O_2$	Ester
14.69	1.05	9-Octadecenoic acid, (2-phenyl−1,3-dioxolan−4-yl) methyl ester, trans-	$C_{28}H_{44}O_4$	Ester
15.09	2.29	2,6,8-Trimethylbicyclo [4.2.0]oct−2-ene −1,8-diol	$C_{11}H_{18}O_2$	Terpenoid
17.55	0.98	Hexadecanoic acid, methyl ester	$C_{17}H_{34}O_2$	Asam lemak
21.01	4.87	Phytol	$C_{20}H_{40}O$	Terpenoid
33.97	0.94	9-Desoxo−9-x-acetoxy−3,8,12-tri-O-ac etylingol	$C_{21}H_{30}O_9$	Glikosida
36.27	1.65	1-Monolinoleoylglycerol trimethylsilyl ether	$C_{21}H_{44}O_4Si$	Ester

The compound 4H-Pyran-4-one, 2,3-dihydro-3,5-dihydroxy-6-methyl found in these leaves is classified as a flavonoid. Flavonoids are specialized metabolites commonly found in plants, serving multiple functions such as defense and signaling, particularly under stress conditions [131]. Flavonoids are categorized into several groups, including chalcones, aurones, flavanonols, flavones, isoflavones, flavanols, flavonols, anthocyanins, proanthocyanidins, and leucoanthocyanidins. They can exist as aglycones, glycosides, and methylated derivatives. The compounds 2-Myristynoyl pantetheine and 2-O-Methyl-D-mannopyranose are classified as lipids. Lipid compounds can exhibit antioxidant activity, especially through mechanisms involving phenols and other structures that modulate oxidative stress and lipid peroxidation processes [133].

The compounds Paromomycin, 2-O-Methyl-D-mannopyranose, and 9-Desoxo-9-x-acetoxy-3,8,12-tri-O-ac etylingol are classified as glycoside compounds. Based on the results of the study of Yang et al. [134], flavonoid glycosides are widely distributed in plants, where they function as phytoalexins to combat biotic stress. Desulphosinigrin is a glucosinolate known to exhibit anticancer and antimicrobial properties [135]. 4-methylsulfinylbutyl glucosinolate is a glucosinolate derived from the amino acid methionine, which has antioxidant, antifungal, and antimicrobial activities [136]. The compounds 7-Methyl-Z-tetradecen-1-ol acetate, 9-Octadecenoic acid, (2-phenyl-1,3-dioxolan-4-yl) methyl ester, trans-, and 1-Monolinoleoylglycerol trimethylsilyl ether are classified as esters. Clearly show that ester groups with different aromatic and alkyl chains will increase antioxidant capacity. e compound 2-[4-methyl-6-(2,6,6-trimethylcyclohex-1-enyl)hexa-1,3,5-trienyl]cyclohex-1-en-1 carboxaldehyde is categorized as an aldehyde. This type of compound is commonly found in various essential oils and contributes a distinctive aroma to certain plants. Several phenolic aldehydes and derivatives have antioxidant activity [137].

Compounds 2,6,8-Trimethylbicyclo[4.2.0]oct-2-ene −1,8-diol and phytol belong to the terpenoid compound group. Terpenoids are promising lead compounds for further structural modification and optimization because of their potent anti-inflammatory effects [138, 139]. Terpenoids (such as monoterpenes and carotenoids) and polyphenols (such as quercetin and other flavonoids) are important phytochemicals with various antioxidant effects [140]. Hexadecanoic acid, methyl ester compounds are classified as fatty acid compounds. Fatty acids have been found to be associated with various biological activities such as anti-inflammatory, antioxidant, antifeedant, antimicrobial, and neuroprotective [141]. While compounds that have no relationship with antioxidant activity are the glucose compound group found in leaf extracts. Glucose produced through photosynthesis and other carbohydrate processes can be used as an energy source to maintain cell vitality [142].

3.6. Correlation of heavy metal concentrations and biomarkers

The relationship between heavy metal concentrations and antioxidant activities in mangrove leaves in both areas using Pearson correlation analysis, which begins with assumption testing (Table 9). The test results were obtained for all variables with significance > 0.05, and if the skewness and quasi-sequence ratios are in the range of -1.96 and $+1.96$, it can be concluded that the data distribution is normal.

Based on the results of the assumption test, the normal distribution of the data can explain that the statistical parameters used in the correlation analysis provide an accurate picture of the center and distribution of the data. Furthermore, the results of the pearson correlation test (r) and the coefficient of determination (Kd) are summarized in Table 10.

Table 9
Assumption test results.

Sample	Variable	Mean	St.Dev	Sig.2 tailed	Skewness Kurtosis	Values
Leaves	Pb	0.94	0.12	0.927	0.55 dan 0.55	Normal
	Cu	3.57	0.080	0.498	0.33 dan 1.35	Normal
	IC50	66.35	25.19	0.457	1.31 dan 0.69	Normal
	Total Phenol	194.44	193.48	0.182	0.13 dan 1.93	Normal

Table 10
Results of the Pearson correlation test (r) and coefficient of determination (Kd).

Sample	Variable (X-Y)	r	Kd (%)	Interpretation
Leaves	Pb – IC_{50}	−0.906	82.08	Strong correlation
	Cu – IC_{50}	−0.937	87.79	Strong correlation
	Pb – Total Phenol	0.904	81.72	Strong correlation
	Cu – Total Phenol	0.949	90.06	Strong correlation

The results of the correlation test is a significant correlation or relationship between heavy metals and physiological responses ($r \neq 0$). The relationship between Pb and Cu to antioxidant activity in mangrove leaves produced from both areas has a very high negative correlation direction of −0.906 and −0.937. The relationship between Pb and Cu to total phenol in leaf samples is also very strong, with a very high positive correlation value of 0.904 and 0.949. In addition, the percentage of the determination coefficient (Kd) indicates that variables X and Y have a strong relationship. The Kd value of mangrove leaf samples ranges from 81.72 % to 90.06 %. This indicates that most of the variations in IC_{50} and total phenol can be explained by the Pb and Cu variables in both types of samples.

A high correlation indicates a strong relationship between the variables concerned and significantly supports the hypothesis. A negative relationship with IC_{50} indicates that the higher the concentration of Pb or Cu, the lower the IC_{50} value (higher antioxidant potential). A positive relationship with total phenol indicates that the higher the concentration of Pb or Cu, the total phenol content also increases. Furthermore, the results of GCMS screening also showed the presence of compounds such as flavonoids, lipids, glycosides, glucosinolates, glucose, esters, terpenoids, and fatty acids. Previous studies have shown that some of these compounds, especially the flavonoid and terpenoid groups, have significant antioxidant activity [143]. Therefore, increasing concentrations of heavy metals can indirectly affect the profile of secondary metabolite compounds in mangrove plants, which in turn can affect antioxidant activity and response to oxidative stress. Excessive concentrations of heavy metals cause the formation of ROS and affect the activity of antioxidants involved in plant metabolism [144]. According to Georgiadou et al. [145], detoxification of ROS due to heavy metal contamination by producing antioxidant enzymes plays a central and vital role in protection in mangrove species.

In line with the research by [146], that under abiotic stress conditions, such as heavy metal contamination, the production of reactive oxygen species (ROS) increases in plants, resulting in the induction of oxidative stress, and plants initiate antioxidant production that significantly delays or prevents oxidative stress. Secondary metabolite compounds are involved in plant responses to biotic and abiotic stresses and contribute significantly to the antioxidant activity of plant tissues [103]. Antioxidant activity is a common approach used to increase heavy metal tolerance, strengthening the defense system against oxidative stress [146,147]. Several previous studies have found a relationship between heavy metal pollution and the physiological response of plants, especially mangroves. The decline in sediment quality due to heavy metal pollution in a gradual pattern that has the potential to have a negative impact on the biogeochemical cycle, with potentially fatal consequences for the survival of biodiversity (*A. marina*) [148]. Furthermore, the results of the study by Ghosh et al. [149] also stated that there was a statistically significant relationship between the activity of antioxidant enzymes, photosynthetic pigments, and heavy metal contamination, resulting in the biotic response of riparian mangroves characterized by reduced photosynthetic pigments (chlorophyll a and b) and increased activity of antioxidant stress enzymes (POD, CAT, and SOD). The response of two tropical medicinal plant species to heavy metal accumulation can increase hydrogen peroxide (H_2O_2) activity, malondialdehyde content, enzymatic activity, and nonenzymatic antioxidants [149].

Mangroves cause trigger antioxidant defenses to overcome heavy metal absorption and normalize excessive production of oxidative stress mediated by reactive oxygen species (ROS) [150]. However, antioxidant responses in mangroves vary depending on the concentration and type of heavy metals, plant species, and duration of exposure [151]. Previous findings related to plant reactions to higher concentrations of heavy metals in the soil. For example, Kulbat-Warycha et al. [152] observed that an increase in the concentration of heavy metals (Ni, Cu, Zn) caused a decrease in the concentration of phenols in oregano, which was associated with the induction of severe oxidative stress. According to Mansoor et al. [153], excessive ROS production due to severe oxidative stress can cause damage to the mitochondrial respiratory chain, uncoupling of oxidative phosphorylation, and mitochondrial death in plants. However, this can also experience a decrease in the antioxidant activity defense system of the mangrove itself if the contamination of absorbed pollutants exceeds the threshold and severe oxidative stress occurs, which can cause damage and death to the mangrove ecosystem [154,155].

The correlation between heavy metals and antioxidant activity in mangroves illustrates the complex relationship between heavy metal pollution and plant responses to oxidative stress. In this context, high concentrations of heavy metals can trigger ROS production, which in turn affects plant antioxidant activity. Excessive ROS can induce oxidative stress that activates the plant defense system to increase the production of antioxidant compounds. Thus, the relationship between heavy metals and antioxidant activity, total phenols, and secondary metabolite compound profiles in mangroves provides a deeper understanding of the mechanism of the plant's response to heavy metal pollution and oxidative stress. Therefore, if there is an indication that pollutant contamination exceeds the threshold and causes severe oxidative stress, some coastal environmental management policies can be expected in response to these findings.

To ensure the sustainability of mangrove ecosystems and mitigate the impact of heavy metal pollution, routine monitoring is recommended every 3–6 months to capture seasonal variations in heavy metal concentrations and antioxidant responses. Additionally, long-term monitoring (≥5 years) is necessary to identify trends in heavy metal accumulation and its effects on coastal ecosystems. Supplemental monitoring is also advised following specific events, such as industrial waste spills or land-use changes, to assess their immediate environmental impact. The data from this study can serve as a basis for environmental policy development, including updating regulations on heavy metal thresholds in sediments and coastal biota, strengthening conservation and mangrove rehabilitation policies, and improving industrial zone management in coastal areas. Furthermore, these findings can be utilized to raise public awareness about the importance of protecting coastal ecosystems and promoting sustainable resource management practices.

4. Conclusion

Heavy metal pollution of Pb and Cu resulting from areas affecting industrial and conservation activities has a significant effect on antioxidant activity in mangroves (*A. alba* and *E. agallocha*). Sediment pollution assessment showed that the Igeo value was at a low level, while the contamination factor (Cf) and pollution load Index (PLI) showed a relatively moderate level of pollution (Cf between 1 and 3, and PLI between 0 and 2). The bioaccumulation value of heavy metals in mangrove leaves was low (BCF < 1), indicating moderate accumulation of heavy metals in leaf tissue. The antioxidant activity of *E. agallocha* leaves from the industrial area was very strong and had the highest total phenol content. The compounds identified as having high antioxidant activity included flavonoids, lipids, glycosides, glucosinolates, glucose, esters, terpenoids, and fatty acids. Correlation analysis showed that increasing heavy metal concentrations were directly proportional to increasing antioxidant activity and total phenol content in mangrove leaves. This study contributes to our understanding of the potential of mangroves to respond to heavy metal exposure through increased antioxidant activity, which can support conservation efforts and sustainable management of coastal natural resources.

Author statement

The authors hereby declare that the work presented in this article is original and that any liability for claims relating to the content of this article will be borne by them.

CRediT authorship contribution statement

Rozirwan: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Nadila Nur Khotimah:** Writing – original draft, Validation, Resources, Formal analysis, Data curation. **Wike Ayu Eka Putri:** Software, Investigation. **Fauziyah:** Supervision, Data curation. **Riris Aryawati:** Methodology, Data curation. **Gusti Diansyah:** Software, Investigation. **Redho Yoga Nugroho:** Writing – review & editing, Resources, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The research/publication of this article was funded by DIPA of Public Service Agency of Universitas Sriwijaya 2024. Nomor SP DIPA 023.17.2.677515/2024, On November 24, 2023. In accordance with the Rector's Degree Number: 0013/UN9/LP2M.PT/2024, On May 20, 2024.

Author declaration

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property. We further confirm that any aspect of the work covered in this manuscript that has involved either experimental animals or human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript. We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author.

Declaration of competing interest

The authors declare no conflict of interest.

Data Availability

No data was used for the research described in the article. The data supporting the findings of this study can be obtained from the corresponding author upon a reasonable request.

References

[1] R. Ramesh, et al., Land–ocean interactions in the coastal zone: past, present & future, Anthropocene 12 (2015) 85–98, https://doi.org/10.1016/j.ancene.2016.01.005.
[2] R. Gotama, D.M. Baker, I. Guibert, S.E. McIlroy, B.D. Russell, How a coastal megacity affects marine biodiversity and ecosystem function: Impacts of reduced water quality and other anthropogenic stressors, Ecol. Indic. 160 (2024) 111683, https://doi.org/10.1016/j.ecolind.2024.111683.
[3] Q. He, B.R. Silliman, Climate change, human impacts, and coastal ecosystems in the anthropocene, Curr. Biol. 29 (19) (2019) R1021–R1035, https://doi.org/10.1016/j.cub.2019.08.042.
[4] N.S. Victoria, T. Sree Devi Kumari, B. Lazarus, Assessment on impact of sewage in coastal pollution and distribution of fecal pathogenic bacteria with reference to antibiotic resistance in the coastal area of Cape Comorin, India, Mar. Pollut. Bull. 175 (2022) 113123, https://doi.org/10.1016/j.marpolbul.2021.113123.
[5] T. Zhai, J. Wang, Y. Fang, Y. Qin, L. Huang, Y. Chen, Assessing ecological risks caused by human activities in rapid urbanization coastal areas: towards an integrated approach to determining key areas of terrestrial-oceanic ecosystems preservation and restoration, Sci. Total Environ. 708 (2020) 135153, https://doi.org/10.1016/j.scitotenv.2019.135153.
[6] N. Andrews, et al., Oil, fisheries and coastal communities: a review of impacts on the environment, livelihoods, space and governance, Energy Res. Soc. Sci. 75 (2021) 102009, https://doi.org/10.1016/j.erss.2021.102009.
[7] W.A.E. Putri, A.I.S. Purwiyanto, Cu and Pb concentrations in water column and plankton of downstream section of the Musi River, J. Ilmu Dan. Teknol. Kelaut. Trop. 8 (2) (2016) 773–780.
[8] Rozirwan, et al., An assessment of Pb and Cu in waters, sediments, and mud crabs (Scylla serrata) from Mangrove Ecosystem Near Tanjung Api-Api Port Area, South Sumatra, Indonesia, Sci. Technol. Indones. 8 (4) (2023) 675–683, https://doi.org/10.26554/sti.2023.8.4.675-683.
[9] A.A. Galindo Montero, L.C. Costa-Redondo, O. Vasco-Echeverri, V.A. Arana, Microplastic pollution in coastal areas of Colombia: review, Mar. Environ. Res. 190 (2023) 106027, https://doi.org/10.1016/j.marenvres.2023.106027.
[10] Y. Choi, M.-Y. Lee, T.-H. Kim, Evaluating total organic carbon as an indicator for organic pollutant management in the marine environment: a case study on wastewater treatment plant effluent input into the coastal ocean, Sci. Total Environ. 919 (2024) 170704, https://doi.org/10.1016/j.scitotenv.2024.170704.
[11] H. Wu, et al., Trace metals in sediments and benthic animals from aquaculture ponds near a mangrove wetland in Southern China, Mar. Pollut. Bull. 117 (1–2) (2017) 486–491, https://doi.org/10.1016/J.MARPOLBUL.2017.01.026.
[12] J. Pandiyan, et al., An assessment of level of heavy metals pollution in the water, sediment and aquatic organisms: a perspective of tackling environmental threats for food security, Saudi J. Biol. Sci. 28 (2) (2021) 1218–1225, https://doi.org/10.1016/J.SJBS.2020.11.072.
[13] E. Ramazanova, Y. Bahetnur, K. Yessenbayeva, S.H. Lee, W. Lee, Spatiotemporal evaluation of water quality and risk assessment of heavy metals in the northern Caspian Sea bounded by Kazakhstan, Mar. Pollut. Bull. 181 (ember 2021) (2022) 113879, https://doi.org/10.1016/j.marpolbul.2022.113879.
[14] A.P. Cahyaningsih, A.K. Deanova, C.M. Pristiawati, Y.I. Ulumuddin, L. Kusumawati, A.D. Setyawan, Review: causes and impacts of anthropogenic activities on mangrove deforestation and degradation in Indonesia, Int. J. Bonorowo Wetl. 12 (1) (2022) 12–22, https://doi.org/10.13057/bonorowo/w120102.
[15] M. Xu, C. Sun, Y. Zhan, Y. Liu, Impact and prediction of pollutant on mangrove and carbon stocks: a machine learning study based on urban remote sensing data, Geosci. Front 15 (3) (2024) 101665, https://doi.org/10.1016/j.gsf.2023.101665.
[16] S.S. Ram, A. Aich, P. Sengupta, A. Chakraborty, M. Sudarshan, Assessment of trace metal contamination of wetland sediments from eastern and western coastal region of India dominated with mangrove forest (Nov), Chemosphere 211 (2018) 1113–1122, https://doi.org/10.1016/J.CHEMOSPHERE.2018.07.201.
[17] Rozirwan, R.Y. Nugroho, M. Hendri, Fauziyah, W.A.E. Putri, A. Agussalim, Phytochemical profile and toxicity of extracts from the leaf of Avicennia marina (Forssk.) Vierh. collected in mangrove areas affected by port activities, *South*

African, J. Bot. 150 (2022) 903–919, https://doi.org/10.1016/j.sajb.2022.08.037.

[18] S. Abdul Azeez, et al., Multi-decadal changes of mangrove forest and its response to the tidal dynamics of thane creek, Mumbai, J. Sea Res. 180 (2022) 102162, https://doi.org/10.1016/J.SEARES.2021.102162.

[19] Rozirwan, et al., Distribution of phytoplankton diversity and abundance in Maspari island waters, South Sumatera, Indonesia, J. Phys. Conf. Ser. 1282 (1) (2019), https://doi.org/10.1088/1742-6596/1282/1/012105.

[20] M.B. Hossain, et al., Heavy metal accumulation and phytoremediation potentiality of some selected Mangrove species from the world's largest Mangrove forest, Biol. (Basel). 11 (8) (2022) 1144, https://doi.org/10.3390/BIOLOGY11081144/S1.

[21] A. Talukdar, et al., Microplastics in mangroves with special reference to Asia: occurrence, distribution, bioaccumulation and remediation options, Sci. Total Environ. 904 (2023) 166165, https://doi.org/10.1016/j.scitotenv.2023.166165.

[22] I. Sanjosé, et al., The bioconcentration and the translocation of heavy metals in recently consumed Salicornia ramosissima J. woods in highly contaminated estuary marshes and its food risk (Jun), Diversity 14 (6) (2022) 452, https://doi.org/10.3390/D14060452/S1.

[23] A. Nguyen, O. Richter, B.V.Q. Le, N.T.K. Phuong, K.C. Dinh, Long-term heavy metal retention by mangroves and effect on its growth: a field inventory and scenario simulation, Int. J. Environ. Res. Public Health 17 (23) (2020) 1–24, https://doi.org/10.3390/IJERPH17239131.

[24] G. Llauradó Maury, et al., Antioxidants in plants: a valorization potential emphasizing the need for the conservation of plant biodiversity in cuba, Antioxidants 9 (11) (2020) 1–39, https://doi.org/10.3390/antiox9111048.

[25] M. Sharifi-Rad, et al., Lifestyle, oxidative stress, and antioxidants: back and forth in the pathophysiology of chronic diseases (Jul), Front. Physiol. 11 (2020) 694, https://doi.org/10.3389/FPHYS.2020.00694.

[26] K. Jomova, et al., Reactive oxygen species, toxicity, oxidative stress, and antioxidants: chronic diseases and aging, *2023 9710*, Arch. Toxicol. 97 (10) (2023) 2499–2574, https://doi.org/10.1007/S00204-023-03562-9.

[27] K. Messaoudi, T. Benmeddour, G. Flamini, First report on the chemical composition and the free radical scavenging and antimicrobial activities of the essential oil of Ononis aurasiaca, an endemic plant of Algeria, Nat. Prod. Res. (2023), https://doi.org/10.1080/14786419.2023.2282113.

[28] G. Eswaraiah, K.A. Peele, S. Krupanidhi, R.B. Kumar, T.C. Venkateswarulu, Studies on phytochemical, antioxidant, antimicrobial analysis and separation of bioactive leads of leaf extract from the selected mangroves, J. King Saud. Univ. - Sci. 32 (1) (2020) 842–847, https://doi.org/10.1016/J.JKSUS.2019.03.002.

[29] U. Sarker, M.M. Hossain, S. Oba, Nutritional and antioxidant components and antioxidant capacity in green morph Amaranthus leafy vegetable, *2020 101*, Sci. Rep. 10 (1) (2020) 1–10, https://doi.org/10.1038/s41598-020-57687-3.

[30] M. Rezaei, et al., Heavy metals concentration in mangrove tissues and associated sediments and seawater from the north coast of Persian Gulf, Iran: ecological and health risk assessment (May), Environ. Nanotechnol., Monit. Manag 15 (2021) 100456, https://doi.org/10.1016/J.ENMM.2021.100456.

[31] Rozirwan, et al., Environmental risk assessment of Pb, Cu, Zn, and Cd concentrations accumulated in selected mangrove roots and surrounding their sediment, Biodiversitas 24 (12) (2023) 6733–6742, https://doi.org/10.13057/biodiv/d241236.

[32] N.N. Khotimah, et al., Bioaccumulation and ecological risk assessment of heavy metal contamination (Lead and Copper) build up in the roots of Avicennia alba and Excoecaria agallocha, J. Ecol. Eng. 25 (5) (2024) 101–113, https://doi.org/10.12911/22998993/185716.

[33] V. Patale, J.G. Tank, Ecological assessment of heavy metals accumulation in sediments and leaves of Avicennia marina along the Diu coast of the northeast Arabian Sea, Oceanologia 64 (2) (2022) 276–286, https://doi.org/10.1016/J.OCEANO.2021.12.002.

[34] H. Abelardo Gonzalez-Ocampo, M.C. Parra-Olivas, E. Pérez-González, G. D. Rodríguez-Meza, Rhizophora mangle L. bioindicator of environmental exposure to heavy metals in the Navachiste lagoon complex, Sinaloa, Mexico (Dec), Mar. Pollut. Bull. 209 (2024) 117131, https://doi.org/10.1016/J.MARPOLBUL.2024.117131.

[35] A. Afriyani, F. Fauziyah, M. Mazidah, R. Wijayanti, Keanekaragaman Vegetasi Hutan Mangrove di Pulau Payung Sungsang Banyuasin Sumatera Selatan, J. Lahan Suboptimal 6 (3) (2017) 113–119.

[36] Y.H. Hutasoit, D. Sarno, Struktur Vegetasi Mangrove Alami Di Areal Taman Nasional Sembilang Banyuasin Sumatera Selatan Natural Mangrove Vegetation Structure in Sembilang National Park, Banyuasin South Sumatera, Maspari J. Mar. Sci. Res. 9 (1) (2017) 1–8.

[37] W.J.M. Verheugt, A. Purwoko, F. Danielsen, H. Skov, R. Kadarisman, Integrating mangrove and swamp forests conservation with coastal lowland development; the Banyuasin Sembilang swamps case study, South Sumatra Province, Indonesia, Landsc. Urban Plan 20 (1–3) (1991) 85–94, https://doi.org/10.1016/0169-2046(91)90096-5.

[38] G. Gustaman, F. I., Efektifitas Perbedaan Warna Cahaya Lampu terhadap Hasil Tangkapan Bagan Tancap di Perairan Sungsang Sumatera Selatan, Maspari J. Mar. Sci. Res. 4 (1) (2012) 92–102, doi:10.56064/MASPARI.V4I1.1433.

[39] Rozirwan, et al., Assessment of phytoplankton community structure in musi estuary, South Sumatra, Indonesia, AACL Bioflux 14 (3) (2021) 1451–1463.

[40] Rozirwan, et al., Assessment distribution of the phytoplankton community structure at the fishing ground, Banyuasin estuary, Indonesia, Acta Ecol. Sin. (2022), https://doi.org/10.1016/J.CHNAES.2022.02.006.

[41] Rozirwan, et al., An ecological assessment of crab's diversity among habitats of migratory birds at berbak-sembilang national park Indonesia, Int. J. Conserv. Sci. 13 (3) (2022). Accessed: Oct. 05, 2022. [Online]. Available: www.ijcs.ro.

[42] Y. Fitria, Rozirwan, M. Fitrani, R.Y. Nugroho, Fauziyah, W.A.E. Putri, Gastropods as bioindicators of heavy metal pollution in the Banyuasin estuary shrimp pond area, South Sumatra, Indonesia, Acta Ecol. Sin. (2023), https://doi.org/10.1016/J.CHNAES.2023.05.009.

[43] R. Rozirwan, et al., Insecticidal activity and phytochemical profiles of avicennia marina and excoecaria agallocha leaves extracts, *ILMU Kelaut*, No 2 Ilmu KelautanDO - 10.14710/ik.ijms.28.2.148-160, vol. 28, no. June, Indones. J. Mar. Sci. 28 (2023) 148–160, https://doi.org/10.14710/ik.ijms.28.2.148-160.

[44] E. Indawan, R.I. Hapsari, K. Ahmadi, D.N. Khaerudin, Quality assessment of mangrove growing environment in Pasuruan of East Java, J. Degrad. Min. LANDS Manag 4 (3) (2017) 815–819, https://doi.org/10.15243/jdmlm.2017.043.815.

[45] I.M. Siaka, Korelasi antara kedalaman sedimen di pelabuhan benoa dan konsentrasi logam berat Pb DAN Cu, J. Kim. 2 (2) (2008) 61–70.

[46] Y. Xiao, M. He, J. Xie, L. Liu, X. Zhang, Effects of heavy metals and organic matter fractions on the fungal communities in mangrove sediments from Techeng Isle, South China, Ecotoxicol. Environ. Saf. 222 (2021) 112545, https://doi.org/10.1016/J.ECOENV.2021.112545.

[47] E. Romano, M.C. Magno, L. Bergamin, Grain size data analysis of marine sediments, from sampling to measuring and classifying. A critical review, IMEKO TC19 Work. Metrol. Sea, MetroSea 2017 Learn. to Meas. Sea Heal. Parameters (2017) 173–178.

[48] L.J. Poppe, A.H. Eliason, A Visual Basic program to plot sediment grain-size data on ternary diagrams, Comput. Geosci. 34 (2008) 561–565, https://doi.org/10.1016/j.cageo.2007.03.019.

[49] R.R. Anggraini, U. Yanuhar, Y. Risjani, Characteristic of sediment at lekok coastal waters, pasuruan regency, East Java, J. Ilmu Dan. Teknol. Kelaut. Trop. 12 (1) (2020) 235–246, https://doi.org/10.29244/JITKT.V12I1.28705.

[50] Rozirwan, et al., Ecological Risk Assessment of Heavy Metal (Pb, Cu) Contamination in Water, Sediment, and Polychaeta (Neoleanira tetragona) from coastal areas affected by aquaculture, Urban Rivers, and Ports in South Sumatra, J. Ecol. Eng. 25 (1) (2024) 303–319, https://doi.org/10.12911/22998993/175365.

[51] D.A. Skoog, D.M. West, F.J. Holler, and S.R. Crouch, Fundamentals of analytical chemistry. Cengage Learning, 2013. [Online]. Available: 〈https://books.google.co.id/books?id= 8bIWAAAAQBAJ〉.

[52] R. Nagarajan, et al., Geochemical Characterization of Beach Sediments of Miri, NW Borneo, SE Asia: implications on provenance, weathering intensity, and assessment of coastal environmental status, Coast. Zo. Manag. Glob. Perspect. Reg. Process. Local Issues (2019) 279–330, https://doi.org/10.1016/B978-0-12-814350-6.00012-4.

[53] G. Muller, Index of geo-accumulation in sediments of the Rhine river – ScienceOpen, J. Geol. (1969). Accessed: Jan. 08, 2023. [Online]. Available: 〈https://www.scienceopen.com/document?vid= 4b875795-5729-4c05-9813-64951e2ca488〉.

[54] V. Gopal, et al., Assessment of heavy metal contamination in the surface sediments of the Vedaranyam coast, Southern India, Reg. Stud. Mar. Sci. 65 (2023) 103081, https://doi.org/10.1016/J.RSMA.2023.103081.

[55] S.M. Shaheen, M.S. Shams, M.R. Khalifa, M.A. El-Dali, J. Rinklebe, Various soil amendments and environmental wastes affect the (im)mobilization and phytoavailability of potentially toxic elements in a sewage effluent irrigated sandy soil, Ecotoxicol. Environ. Saf. 142 (2017) 375–387, https://doi.org/10.1016/J.ECOENV.2017.04.026.

[56] S.M. Shaheen, et al., Potentially toxic elements in saltmarsh sediments and common reed (Phragmites australis) of Burullus coastal lagoon at North Nile Delta, Egypt: a survey and risk assessment, Sci. Total Environ. 649 (2019) 1237–1249, https://doi.org/10.1016/J.SCITOTENV.2018.08.359.

[57] S.K. Maiti, D. Ghosh, D. Raj, Phytoremediation of fly ash: bioaccumulation and translocation of metals in natural colonizing vegetation on fly ash lagoons, Handb. Fly. Ash (2022) 501–523, https://doi.org/10.1016/B978-0-12-817686-3.00011-6.

[58] H. Almahasheer, High levels of heavy metals in Western Arabian Gulf mangrove soils, Mol. Biol. Rep. 46 (2) (2019) 1585–1592, https://doi.org/10.1007/S11033-019-04603-2/METRICS.

[59] R. Rozirwan, et al., Antioxidant activity, total phenolic, phytochemical content, and HPLC profile of selected mangrove species from Tanjung Api-Api Port Area, South Sumatra, Indonesia, Trop. J. Nat. Prod. Res. Available 7 (7) (2023) 3482–3489.

[60] H.D. Salusu, et al., Phytochemical screening and antioxidant activity of selekop (Lepisanthes amoena) fruit, Agrivita 39 (2) (2017) 214–218, https://doi.org/10.17503/agrivita.v39i2.810.

[61] S.S. Suh, J. Hwang, M. Park, H.S. Park, T.K. Lee, Phenol content, antioxidant and tyrosinase inhibitory activity of mangrove plants in Micronesia (Jul), Asian Pac. J. Trop. Med. 7 (7) (2014) 531–535, https://doi.org/10.1016/S1995-7645(14)60089-4.

[62] K. Sopalun, W. Laosripaiboon, A. Wachirachaikarn, S. Iamtham, Biological potential and chemical composition of bioactive compounds from endophytic fungi associated with thai mangrove plants, South Afr. J. Bot. 141 (2021) 66–76, https://doi.org/10.1016/J.SAJB.2021.04.031.

[63] U. Kustiati, H. Wihadmadyatami, D.L. Kusindarta, Dataset of Phytochemical and secondary metabolite profiling of holy basil leaf (Ocimum sanctum Linn) ethanolic extract using spectrophotometry, thin layer chromatography, Fourier transform infrared spectroscopy, and nuclear magnetic resonance, Data Br. 40 (2022), https://doi.org/10.1016/j.dib.2021.107774.

[64] W. Kirch, Pearson's correlation coefficient, Encycl. Public Heal (2008) 1090–1091, https://doi.org/10.1007/978-1-4020-5614-7_2569.

[65] D. Weisburd, C. Britt, D.B. Wilson, A. Wooditch, Measuring Association for Scaled Data: Pearson's Correlation Coefficient. Basic statistics in criminology and criminal justice, Springer International Publishing, Cham, 2020, pp. 479–530, https://doi.org/10.1007/978-3-030-47967-1_14.

[66] Rozirwan, et al., Phytochemical composition, total phenolic content and antioxidant activity of Anadara granosa (Linnaeus, 1758) collected from the east coast of South Sumatra, Indonesia Abstract, Baghdad Sci. J. (2023) 1–8.

[67] Sumartini, P.W. Ratrinia, and Hutabarat R.F., The effect of mangrove types and leave maturity on the mangrove leaves (Sonneratia alba) and (Rhizophora mucronata) tea powder - IOPscience, in IOP Conference Series: Earth and Environmental Science, 2022. Accessed: Oct. 03, 2022. [Online]. Available: ⟨https://iopscience.iop.org/article/10.1088/1755-1315/967/1/012018⟩.

[68] Rozirwan, S. Ramadani, W. Ayu, E. Putri, N. Nur, R.Y. Nugroho, Evaluation of Calcium and Phosphorus content in Scallop Shells (Placuna placenta) and Blood Cockle Shells (Anadara granosa) from Banyuasin Waters, South Sumatra, Egypt. J. Aquat. Biol. Fish. Zool. Dep. Fac. Sci. 27 (3) (2023) 1053–1068.

[69] J.P. Yactayo-Chang, H.V. Tang, J. Mendoza, S.A. Christensen, A.K. Block, Plant defense chemicals against insect pests, Agron 10 (8) (2020) 1156, https://doi.org/10.3390/AGRONOMY10081156.

[70] Anjali, et al., Role of plant secondary metabolites in defence and transcriptional regulation in response to biotic stress, Plant Stress 8 (2023) 100154, https://doi.org/10.1016/J.STRESS.2023.100154.

[71] J. Srše, M. Perkovič, A. Grm, Sediment resuspension distribution modelling using a ship handling simulation along with the MIKE 3 application, J. Mar. Sci. Eng. 11 (8) (2023), https://doi.org/10.3390/jmse11081619.

[72] J. Srse, M. Perkovic, Field Studies on Sediment Resuspension Induced by Shipping: Vessel Kinematic Measurements and Water Sampling in the Port of Koper, 2024 IEEE Int. Work. Metrol. Sea, MetroSea 2024 - Proc. (2024) 353–357. , no. October, doi: 10.1109/MetroSea62823.2024.10765676.

[73] J. Yun, Q. Yang, C. Zhao, C. Chen, G. Liu, Atmospheric emissions of fine particle matter bound rare earth elements from industry, Nat. Commun. 15 (1) (2024) 1–10, https://doi.org/10.1038/s41467-024-53684-6.

[74] A.M. Afandi, Y. Zuraidah, H.A.Z.A. Nurzuhaili, H. Zulkifli, M. Yaqin, Managing soil deterioration and erosion under oil palm, *75*, Oil Palm. Bull. 75 (ember) (2017) 1–10.

[75] I. Comte, F. Colin, J.K. Whalen, O. Grünberger, J.P. Caliman, Agricultural practices in oil palm plantations and their impact on hydrological changes, nutrient fluxes and water quality in Indonesia, A Rev., *Adv. Agron.* 116 (2012) 71–124, https://doi.org/10.1016/B978-0-12-394277-7.00003-8.

[76] L. Ivorra, P.G. Cardoso, S.K. Chan, C. Cruzeiro, K.A. Tagulao, Can mangroves work as an effective phytoremediation tool for pesticide contamination? An interlinked analysis between surface water, sediments and biota, J. Clean. Prod. 295 (2021) 126334, https://doi.org/10.1016/J.JCLEPRO.2021.126334.

[77] S. Partani, et al., Identifying toxic elements in water, sediments, and roots of mangrove forest (Avicennia marina) in Chabahar Bay, Sea of Oman, Sci. Total Environ. 954 (2024) 176635, https://doi.org/10.1016/j.scitotenv.2024.176635.

[78] S. Wang, C. Pan, D. Xie, M. Xu, Y. Yan, X. Li, Grain size characteristics of surface sediment and its response to the dynamic sedimentary environment in Qiantang Estuary, China, Int. J. Sediment Res. 37 (4) (2022) 457–468, https://doi.org/10.1016/j.ijsrc.2021.12.002.

[79] R. Rozirwan, I. Bahrudin, B.S. Barus, R.Y. Nugroho, and N.N. Khotimah, First assesment of coral Mussidae in Kelagian Island waters, Lampung, Proc. 9TH Int. Symp. Innov. Bioprod. Indones. Biotechnol. Bioeng. 2022 Strength. Bioeconomy through Appl. Biotechnol. Bioeng. Biodivers., vol. 2972, no. 1, p. 040008, Dec. 2023a, doi: 10.1063/5.0171642/2931856.

[80] M.K. Uddin, A review on the adsorption of heavy metals by clay minerals, with special focus on the past decade, Chem. Eng. J. 308 (2017) 438–462, https://doi.org/10.1016/j.cej.2016.09.029.

[81] X. Huang, G. Yang, Charge reversal and anion effects during adsorption of metal ions at clay surfaces: mechanistic aspects and influence factors, Chem. Phys. 529 (2020) 110575, https://doi.org/10.1016/j.chemphys.2019.110575.

[82] S. Khan, S. Ajmal, T. Hussain, M.U. Rahman, Clay-based materials for enhanced water treatment: adsorption mechanisms, challenges, and future directions, J. Umm Al-Qura Univ. Appl. Sci. (2023), https://doi.org/10.1007/s43994-023-00083-0.

[83] Y.M. Chen, J. Bo Gao, Y.Q. Yuan, J. Ma, S. Yu, Relationship between heavy metal contents and clay mineral properties in surface sediments: Implications for metal pollution assessment, Cont. Shelf Res. 124 (2016) 125–133, https://doi.org/10.1016/J.CSR.2016.06.002.

[84] W. Que, L. Yi, Y. Wu, Q. Li, Analysis of heavy metals in sediments with different particle sizes and influencing factors in a mining area in Hunan Province, Sci. Rep. 14 (1) (2024) 20318, https://doi.org/10.1038/s41598-024-71502-3.

[85] Y.G. Gu, Y.P. Gao, An unconstrained ordination- and GIS-based approach for identifying anthropogenic sources of heavy metal pollution in marine sediments (Sep), Mar. Pollut. Bull. 146 (2019) 100–105, https://doi.org/10.1016/J.MARPOLBUL.2019.06.008.

[86] A. Tjahjono, R. Sugiharto, O. Wahyuni, Study of water and sediment surface quality on defilement of heavy metals Pb & Cd at a downstream section of Musi River, South Sumatera, Indonesia, Rev. Ambient. e Agua 17 (1) (2022) 1–20.

[87] E.R. Sulistya Dewi, K. Ni'Mah, F. Kaswinarni, The content of heavy metal lead (Pb) on baung fish (Hemibagrus nemurus) as biomonitoring pollution of Wulan River of Demak Regency, J Phys. Conf. Ser. 1217 (1) (2019) doi: 10.1088/1742-6596/1217/1/012128.

[88] L. Schröder, F. Hellweger, A. Putschew, Copper leaching from recreational vessel antifouling paints in freshwater: a Berlin case study, J. Environ. Manag. 301 (2022) 113895, https://doi.org/10.1016/J.JENVMAN.2021.113895.

[89] J. Zhao, et al., Controllable release of Cu ions contributes to the enhanced environmentally-friendly performance of antifouling Cu-bearing stainless steel coating prepared using high-velocity air fuel (Apr), Surf. Coat. Technol. 481 (2024) 130629, https://doi.org/10.1016/J.SURFCOAT.2024.130629.

[90] Z.Y. Soon, J.H. Jung, A. Loh, C. Yoon, D. Shin, M. Kim, Seawater contamination associated with in-water cleaning of ship hulls and the potential risk to the marine environment (Oct), Mar. Pollut. Bull. 171 (2021) 112694, https://doi.org/10.1016/J.MARPOLBUL.2021.112694.

[91] I. Kalantzi, et al., Assessment of the use of copper alloy aquaculture nets: Potential impacts on the marine environment and on the farmed fish (Dec), Aquaculture 465 (2016) 209–222, https://doi.org/10.1016/J.AQUACULTURE.2016.09.016.

[92] L.S. Herbeck, D. Unger, Y. Wu, T.C. Jennerjahn, Effluent, nutrient and organic matter export from shrimp and fish ponds causing eutrophication in coastal and back-reef waters of NE Hainan, tropical China, Cont. Shelf Res. 57 (2013) 92–104, https://doi.org/10.1016/J.CSR.2012.05.006.

[93] S. Ur Rahman, et al., Pb uptake, accumulation, and translocation in plants: Plant physiological, biochemical, and molecular response: a review, Heliyon 10 (6) (2024) e27724, https://doi.org/10.1016/J.HELIYON.2024.E27724.

[94] G. Yu, et al., The mechanism of plant resistance to heavy metal, IOP Conf. Ser. Earth Environ. Sci. 310 (5) (2019) 1–6, doi: 10.1088/1755-1315/310/5/052004.

[95] Z. Shabbir, et al., Copper uptake, essentiality, toxicity, detoxification and risk assessment in soil-plant environment, Chemosphere 259 (2020) 127436, https://doi.org/10.1016/J.CHEMOSPHERE.2020.127436.

[96] E. Xu, et al., Molecular mechanisms of plant responses to copper: from deficiency to excess, Int. J. Mol. Sci. 25 (13) (2024) 6993, https://doi.org/10.3390/IJMS25136993.

[97] V. Kumar, et al., Copper bioavailability, uptake, toxicity and tolerance in plants: a comprehensive review, Chemosphere 262 (2021) 127810, https://doi.org/10.1016/j.chemosphere.2020.127810.

[98] S. Collin, et al., Bioaccumulation of lead (Pb) and its effects in plants: a review, J. Hazard. Mater. Lett. 3 (2022) 100064, https://doi.org/10.1016/j.hazl.2022.100064.

[99] S. Mitra, et al., Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity, J. King Saud. Univ. - Sci. 34 (3) (2022) 101865, https://doi.org/10.1016/J.JKSUS.2022.101865.

[100] A.B. Fulke, S. Ratanpal, S. Sonker, Understanding heavy metal toxicity: implications on human health, marine ecosystems and bioremediation strategies, Mar. Pollut. Bull. 206 (2024) 116707, https://doi.org/10.1016/j.marpolbul.2024.116707.

[101] K. Analuddin, et al., The carrying capacity of estuarine mangroves in maintaining the coastal urban environmental health of Southeast Sulawesi, Indonesia, Egypt. J. Aquat. Res. 49 (3) (2023) 327–338, https://doi.org/10.1016/J.EJAR.2023.03.002.

[102] T. Crespo-Toledo, F. Avelar-González, A. Guerrero-Barrera, K. Mitchell, L. Yamamoto-Flores, O. Flores-Amaro, Integrative assessment of heavy metal risks in mining polluted sediments and soils of Aguascalientes, Mexico, Case Stud. Chem. Environ. Eng. 11 (2025) 101130, https://doi.org/10.1016/J.CSCEE.2025.101130.

[103] P.B. Angon, et al., Sources, effects and present perspectives of heavy metals contamination: soil, plants and human food chain, Heliyon 10 (7) (2024) e28357, https://doi.org/10.1016/J.HELIYON.2024.E28357.

[104] M.R. Hasan, et al., Vertical distribution, contamination status and ecological risk assessment of heavy metals in core sediments from a mangrove-dominated tropical river, Mar. Pollut. Bull. 189 (2023) 114804, https://doi.org/10.1016/J.MARPOLBUL.2023.114804.

[105] P.B. Angon, et al., Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain, Heliyon 10 (7) (2024) e28357, https://doi.org/10.1016/j.heliyon.2024.e28357.

[106] S. Hoffmann, Challenges and opportunities of area-based conservation in reaching biodiversity and sustainability goals, Biodivers. Conserv 31 (2) (2022) 325–352, https://doi.org/10.1007/s10531-021-02340-2.

[107] G. Li, et al., Mixed effectiveness of global protected areas in resisting habitat loss, Nat. Commun. 15 (1) (2024) 8389, https://doi.org/10.1038/s41467-024-52693-9.

[108] J. Briffa, E. Sinagra, R. Blundell, Heavy metal pollution in the environment and their toxicological effects on humans, Heliyon 6 (9) (2020) e04691, https://doi.org/10.1016/J.HELIYON.2020.E04691.

[109] Ismarti Ramses, F. Amelia, Rozirwan, Suheryanto, Diversity and abundance of polychaetes in the west coast waters of batam island, Kepulauan Riau province-indonesia, AACL Bioflux 13 (1) (2020) 381–391.

[110] L.S. Miranda, B. Wijesiri, G.A. Ayoko, P. Egodawatta, A. Goonetilleke, Water-sediment interactions and mobility of heavy metals in aquatic environments, Water Res 202 (2021) 117386, https://doi.org/10.1016/j.watres.2021.117386.

[111] F. Brugnone, et al., Atmospheric deposition around the industrial areas of Milazzo and Priolo Gargallo (Sicily–Italy)—Part B: trace elements, Atmosphere (Basel) 14 (4) (2023), https://doi.org/10.3390/atmos14040737.

[112] S. Karmakar, et al., Effectiveness of artificially planted mangroves on remediation of metals released from ship-breaking activities, Mar. Pollut. Bull. 212 (2025) 117587, https://doi.org/10.1016/J.MARPOLBUL.2025.117587.

[113] S. Mitra, N. Naskar, P. Chaudhuri, A review on potential bioactive phytochemicals for novel therapeutic applications with special emphasis on mangrove species, Phytomedicine 1 (4) (2021) 100107, https://doi.org/10.1016/j.phyplu.2021.100107.

[114] N.P.E. Hikmawanti, S. Fatmawati, A.W. Asri, The effect of ethanol concentrations as the extraction solvent on antioxidant activity of Katuk (Sauropus androgynus (L.) Merr.) leaves extracts, IOP Conf. Ser. Earth Environ. Sci. 755 (1) (2021), https://doi.org/10.1088/1755-1315/755/1/012060.

[115] A. Altemimi, N. Lakhssassi, A. Baharlouei, D.G. Watson, D.A. Lightfoot, Phytochemicals: extraction, isolation, and identification of bioactive compounds from plant extracts (Dec), Plants 6 (4) (2017), https://doi.org/10.3390/PLANTS6040042.

[116] Rozirwan, R.Y. Nugroho, M. Hendri, Fauziyah, W.A.E. Putri, A. Agussalim, Phytochemical profile and toxicity of extracts from the leaf of Avicennia marina (Forssk.) Vierh. collected in mangrove areas affected by port activities, South Afr. J. Bot. 150 (2022) 903–919, https://doi.org/10.1016/J.SAJB.2022.08.037.

[117] K.A. Audah, et al., Indonesian mangrove sonneratia caseolaris leaves ethanol extract is a potential super antioxidant and anti methicillin-resistant staphylococcus aureus drug, Molecules 27 (23) (2022) 8369, https://doi.org/10.3390/MOLECULES27238369/S1.

[118] K.A.S. Kodikara, et al., Oxidative stress, leaf photosynthetic capacity and dry matter content in young mangrove plant Rhizophora mucronata Lam. under prolonged submergence and soil water stress, Physiol. Mol. Biol. Plants 26 (8) (2020) 1609, https://doi.org/10.1007/S12298-020-00843-W.

[119] F.P. Sabdanawaty, Purnomo, B.S. Daryono, Species diversity and phenetic relationship among accessions of api-api (Avicennia spp.) in java based on morphological characters and issr markers, Biodiversitas 22 (1) (2021) 193–198, https://doi.org/10.13057/biodiv/d220125.

[120] B. Nath, G. Birch, P. Chaudhuri, Assessment of sediment quality in Avicennia marina-dominated embayments of Sydney Estuary: The potential use of pneumatophores (aerial roots) as a bio-indicator of trace metal contamination, Sci. Total Environ. 472 (2014) 1010–1022, https://doi.org/10.1016/J.SCITOTENV.2013.11.096.

[121] S. Hao, W. Su, Q.Q. Li, Adaptive roots of mangrove Avicennia marina: structure and gene expressions analyses of pneumatophores, Sci. Total Environ. 757 (2021) 143994, https://doi.org/10.1016/J.SCITOTENV.2020.143994.

[122] R. Wilda, A.M. Hamdan, R. Rahmi, A review: the use of mangrove for biomonitoring on aquatic environment, IOP Conf. Ser. Mater. Sci. Eng. 980 (1) (2020), https://doi.org/10.1088/1757-899X/980/1/012083.

[123] S.J. Hossain, et al., Antibacterial, Anti-Diarrhoeal, Analgesic, Cytotoxic Activities, and GC-MS Profiling of Sonneratia apetala (Buch.-Ham.) Seed (Sep), Prev. Nutr. Food Sci. 22 (3) (2017) 157–165, https://doi.org/10.3746/pnf.2017.22.3.157.

[124] M.R. Bomfim, et al., Morphology, physical and chemical characteristics of mangrove soil under riverine and marine influence: a case study on Subaé River Basin, Bahia, Brazil, Mangrove Ecosyst. Ecol. Funct. (2018), https://doi.org/10.5772/INTECHOPEN.79142.

[125] I. Dewiyanti, D. Darmawi, Z.A. Muchlisin, T.Z. Helmi, I. Imelda, C.N. Defira, Physical and chemical characteristics of soil in mangrove ecosystem based on differences habitat in Banda Aceh and Aceh Besar, IOP Conf. Ser. Earth Environ. Sci. 674 (1) (2021) 012092, https://doi.org/10.1088/1755-1315/674/1/012092.

[126] M. Kumar, et al., Biomarkers as indicators of sedimentary organic matter sources and early diagenetic transformation of pentacyclic triterpenoids in a tropical mangrove ecosystem, Estuar. Coast. Shelf Sci. 229 (2019) 106403, https://doi.org/10.1016/j.ecss.2019.106403.

[127] M.F. Misrah, et al., Evaluation of antioxidant activity and total phenolics of selected mangrove plants in Sabah ([Online]. Available), Borneo Int. J. Biotechnol. 2 (December) (2022) 14–21, https://doi.org/10.51200/bijb.v2i.3330.

[128] Y.S. Wang, J.D. Gu, Ecological responses, adaptation and mechanisms of mangrove wetland ecosystem to global climate change and anthropogenic activities (Aug), Int. Biodeterior. Biodegrad. 162 (2021) 105248, https://doi.org/10.1016/J.IBIOD.2021.105248.

[129] S. Sudhir, A. Arunprasath, V. Sankara Vel, A critical review on adaptations, and biological activities of the mangroves, J. Nat. Pestic. Res. 1 (2022) 100006, https://doi.org/10.1016/J.NAPERE.2022.100006.

[130] M. Xu, C. Sun, Y. Zhan, Y. Liu, Impact and prediction of pollutant on mangrove and carbon stocks: a machine learning study based on urban remote sensing data, Geosci. Front (2023) 101665, https://doi.org/10.1016/J.GSF.2023.101665.

[131] J. Laoué, C. Fernandez, E. Ormeño, Plant flavonoids in mediterranean species: a focus on flavonols as protective metabolites under climate stress, Plants 11 (2) (2022), https://doi.org/10.3390/PLANTS11020172.

[132] O.M. Ighodaro, O.A. Akinloye, First line defence antioxidants-superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPX): their fundamental role in the entire antioxidant defence grid, Alex. J. Med. 54 (4) (2018) 287–293, https://doi.org/10.1016/J.AJME.2017.09.001.

[133] L. Valgimigli, Lipid peroxidation and antioxidant protection, Biomolecules 13 (9) (2023), https://doi.org/10.3390/biom13091291.

[134] B. Yang, H. Liu, J. Yang, V.K. Gupta, Y. Jiang, New insights on bioactivities and biosynthesis of flavonoid glycosides, Trends Food Sci. Technol. 79 (2018) 116–124, https://doi.org/10.1016/J.TIFS.2018.07.006.

[135] A.M.M. Youssef, D.A.M. Maaty, Y.M. Al-Saraireh, Phytochemistry and Anticancer Effects of Mangrove (Rhizophora mucronata Lam.) leaves and stems extract against different cancer cell lines, Pharmaceuticals 16 (1) (2023), https://doi.org/10.3390/ph16010004.

[136] A. Elaiyaraja, G. Chandramohan, Comparative phytochemical profile of crinum defixum Ker-Gawler leaves using GC-MS (Aug), J. Drug Deliv. Ther. 8 (4) (2018) 365–380, https://doi.org/10.22270/JDDT.V8I4.1758.

[137] R. Borgohain, A.K. Guha, S. Pratihar, J.G. Handique, Antioxidant activity of some phenolic aldehydes and their diimine derivatives: a DFT study, Comput. Theor. Chem. 1060 (2015) 17–23, https://doi.org/10.1016/J.COMPTC.2015.02.014.

[138] J. Ge, et al., Natural terpenoids with anti-inflammatory activities: Potential leads for anti-inflammatory drug discovery, Bioorg. Chem. 124 (2022) 105817, https://doi.org/10.1016/J.BIOORG.2022.105817.

[139] R. Rozirwan, et al., Anti-inflammatory activity and phytochemical profile from the leaves of the Mangrove Sonneratia caseolaris (L.) Engl. for future drug discovery, Sci. Technol. Indones. 9 (2) (2024) 502–516, https://doi.org/10.26554/STI.2024.9.2.502-516.

[140] I. Gutiérrez-Del-río, et al., Terpenoids and polyphenols as natural antioxidant agents in food preservation, Antioxidants 10 (8) (2021), https://doi.org/10.3390/ANTIOX10081264.

[141] V. Venepally, R.C. Reddy Jala, An insight into the biological activities of heterocyclic–fatty acid hybrid molecules, Eur. J. Med. Chem. 141 (2017) 113–137, https://doi.org/10.1016/J.EJMECH.2017.09.069.

[142] A. Cherkas, S. Holota, T. Mdzinarashvili, R. Gabbianelli, N. Zarkovic, Glucose as a major antioxidant: when, what for and why it fails? Antioxid. (Basel, Switz.) 9 (2) (2020) https://doi.org/10.3390/antiox9020140.

[143] N. Shen, T. Wang, Q. Gan, S. Liu, L. Wang, B. Jin, Plant flavonoids: classification, distribution, biosynthesis, and antioxidant activity (Jul), Food Chem. 383 (2022) 132531, https://doi.org/10.1016/J.FOODCHEM.2022.132531.

[144] I. Makuch-Pietraś, D. Grabek-Lejko, A. Górka, I. Kasprzyk, Antioxidant activities in relation to the transport of heavy metals from the soil to different parts of Betula pendula (Roth.), J. Biol. Eng. 17 (1) (2023) 1–25, https://doi.org/10.1186/s13036-022-00322-8.

[145] E.C. Georgiadou, et al., Influence of heavy metals (Ni, Cu, and Zn) on nitro-oxidative stress responses, proteome regulation and allergen production in basil (Ocimum basilicum L.) plants, *Front*, Plant Sci. 9 (2018) 374129, https://doi.org/10.3389/FPLS.2018.00862/BIBTEX.

[146] D.M. Kasote, S.S. Katyare, M.V. Hegde, H. Bae, Significance of antioxidant potential of plants and its relevance to therapeutic applications, Int. J. Biol. Sci. 11 (8) (2015) 982, https://doi.org/10.7150/IJBS.12096.

[147] Z. Cai, A. Kastell, C. Speiser, I. Smetanska, Enhanced resveratrol production in Vitis vinifera cell suspension cultures by heavy metals without loss of cell viability, Appl. Biochem. Biotechnol. 171 (2) (2013) 330–340, https://doi.org/10.1007/s12010-013-0354-4.

[148] M.O. Aljahdali, A.B. Alhassan, Z. Zhang, Environmental factors causing stress in avicennia marina mangrove in rabigh lagoon along the Red Sea: based on a multi-approach study (May), Front. Mar. Sci. 8 (2021) 328, https://doi.org/10.3389/FMARS.2021.646993/BIBTEX.

[149] S. Ghosh, M. Bakshi, S. Mahanty, P. Chaudhuri, Understanding potentially toxic metal (PTM) induced biotic response in two riparian mangrove species Sonneratia caseolaris and Avicennia officinalis along river Hooghly, India: Implications for sustainable sediment quality management, Mar. Environ. Res. 172 (June) (2021) 105486, https://doi.org/10.1016/j.marenvres.2021.105486.

[150] S. Ur Rahman, et al., Adaptation and remediation strategies of mangroves against heavy metal contamination in global coastal ecosystems: a review, J. Clean. Prod. 441 (2024) 140868, https://doi.org/10.1016/J.JCLEPRO.2024.140868.

[151] Z. Yan, X. Sun, Y. Xu, Q. Zhang, X. Li, Accumulation and tolerance of mangroves to heavy metals: a review, *2017 34*, Curr. Pollut. Rep. 3 (4) (2017) 302–317, https://doi.org/10.1007/S40726-017-0066-4.

[152] K. Kulbat-Warycha, E.C. Georgiadou, D. Mańkowska, B. Smolińska, V. Fotopoulos, J. Leszczyńska, Response to stress and allergen production caused by metal ions (Ni, Cu and Zn) in oregano (Origanum vulgare L.) plants (Dec), J. Biotechnol. 324 (2020) 171–182, https://doi.org/10.1016/J.JBIOTEC.2020.10.025.

[153] S. Mansoor, et al., Heavy Metal Induced Oxidative Stress Mitigation and ROS Scavenging in Plants, Plants 12 (16) (2023), https://doi.org/10.3390/PLANTS12163003.

[154] H.N. Thatoi, J.K. Patra, S.K. Das, Free radical scavenging and antioxidant potential of mangrove plants: a review, Acta Physiol. Plant 36 (3) (2014) 561–579, https://doi.org/10.1007/s11738-013-1438-z.

[155] J. Liu, T. Myat, Contaminants and heavy metals along the mangrove area of Dongzhai Harbor, China: distribution and assessment, SN Appl. Sci. 3 (10) (2021) 1–12, https://doi.org/10.1007/S42452-021-04802-2/FIGURES/6.