# Science of the Total Environment


## A critical review on pineapple (Ananas comosus) wastes for water treatment, challenges and future prospects towards circular economy

--Manuscript Draft--

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| **Abstract:** | Each year, nearly 30 million tons of pineapple fruit are harvested for food and drinking industries, along with the release of a huge amount of pineapple wastes. Without the proper treatment, pineapple wastes can cause adverse impacts on the environment, calling for new technologies to convert them into valuable products. Here, we review the production and application of adsorbents derived from pineapple wastes. The thermal processing or chemical modification improved the surface chemistry and porosity of these adsorbents. The specific surface areas of the pineapple wastes-based adsorbents were in range from 4.2 to at 522.9 m2·g–1. Almost adsorption systems followed the pseudo second order kinetic model, and Langmuir isotherm model. The adsorption mechanism was found with the major role of electrostatic attraction, complexation, chelation, and ion exchange. The pineapple wastes based adsorbents could be easily regenerated. We suggest the potential of the pineapple wastes towards circular economy. |
| **Response to Reviewers:** | Dear Editor and Reviewers,<br><br>Thank you very much for your critical and constructive comments. We are sending the requested files: “Response to Referees” and the version of the revised manuscript. Please find our highlighted changes in the revision. We hope the revised version of this manuscript can satisfy your requirements as well as the high standards of the journal.<br><br>Best,<br><br>Thuan Tran<br><br>Corresponding author |

***August 25th, 2022***

***Professor HUU HAO NGO***

***Associate Editor***

***Science of the Total Environment***

**Dear Editor,**

We are sending you the revised manuscript entitled

***"A critical review on pineapple (Ananas comosus) wastes for water treatment, challenges and future prospects towards circular economy"***

*by Thuan Van Tran, Duyen Thi Cam Nguyen, Thuy Thi Thanh Nguyen, Dai Hai Nguyen, Mansur Alhassan, A.A. Jalil, Walid Nabgan, Taeyoon Lee.*

We addressed the remarks suggested by the reviewers in the revised manuscript. We are sending the requested files: "Response to Referees" file and the version of the revised manuscript.

Additionally, we kindly request your approval on an authorship addition to our manuscript. All authors agreed to add two **new co-authors**, who had important contributions to our revised manuscript:

- **A.A. Jalil:** contributed to writing – review and editing, and validation for Section 10. "Potential of pineapple wastes towards circular economy", and Section 4.2. "Main findings of adsorption performance".
- **Walid Nabgan:** contributed to writing – review and editing, and validation for Section 3.2. "The characteristics of pineapple wastes", and Section 8.3. "Fixed bed column".

Thank you very much for your approval!

We hope that the revised manuscript may be suitable for the publication on *Science of the Total Environment.* We look forward to hearing from you at your earliest convenience.

Sincerely,

Thuan Van Tran

Corresponding author

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Title Page

# A critical review on pineapple (*Ananas comosus*) wastes for water treatment, challenges and future prospects towards circular economy

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**Acknowledgment**

This paper is respectfully dedicated to researchers all over the world in the fight against the COVID-19 pandemic. We also acknowledge Mina Rees Library, The Graduate Center of the City University of New York (CUNY) for granting access to databases, Freepik company projects at www.freepik.com, and Canva® graphic design platforms at www.canva.com for many graphic resources reproduced in this work.

**Professor HUU HAO NGO**

**Associate Editor**

**Science of the Total Environment**

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|---|---|
| **Re:** | *Revision requested for STOTEN-D-22-15981* |
| **Manuscript ID:** | *STOTEN-D-22-15981R1* |
| **Title of Paper:** | ***A critical review on pineapple (Ananas comosus) wastes for water treatment, challenges and future prospects towards circular economy*** |
| **Author(s):** | Thuan Van Tran, Duyen Thi Cam Nguyen, Thuy Thi Thanh Nguyen, Dai Hai Nguyen, Mansur Alhassan, A.A. Jalil, Walid Nabgan, Taeyoon Lee |
| **Journal:** | *Science of the Total Environment* |

**Dear Professor HUU HAO NGO,**

We would like to express our gratitude for the Editor and Reviewer's efforts to improve the quality of our manuscript. We believe that our manuscript as a qualified paper in *Science of the Total Environment.* We have tried our best to respond to all issues indicated in the review report fully. In the revised version, we have highlighted the changes to our manuscript using various colors. Here, we would like to address the reviewer's concerns as follows:

**Reviewer #1:**

**In the present manuscript, the authors reviewed pineapple (Ananas comosus) wastes as potential adsorbents for wastewater treatment for pollutants removal to safeguard public health. The authors presented a good overview of the topic even if a lot has been already reported in previous articles, which must be included in this manuscript. By citing previous articles, the authors can define how the present review differs from others and what is the need to still review wastewater treatment and specific applications, while many articles are already published. It'll improve the quality of the present manuscript. Although the topic is good it is still worthy of looking at from many other angles which will be worthy to the researchers and professionals working in this field albeit there are several issues, which must be addressed before further consideration. After carefully reviewing the manuscript, the manuscript recommends a significant revision of this work. The comments are given below.**

**Our response:**

The authors sincerely thank your instructive comments!

Moreover, to help you easy to follow the possible changes in this revision, all corrections and/or modifications have been highlighted with bright green color. We hope our response below will satisfy your requirements as well as standards of the journal. Thank you so much!

**1) The language of the manuscript is very pity, due to which several times it is hard to understand what the authors exactly want to tell. Hence, the language must be improved by a professional service.**

**Our response:**

The authors sincerely thank your instructive comments!

We are sorry that the previous version of this manuscript is not good in English. We insightfully proofread by native English speakers to improve the quality of this manuscript. All errors have been revised based on your suggestions.

Thank you so much!

**2. The abstract need to be revised. Please further organize your views and look to the future.**

**Our response:**

The authors sincerely thank your instructive comments!

Your statement is very reasonable! As your suggestion, we revised the abstract section more concise and further organized our views and look to the future as your suggestion.

"Each year, nearly 30 million tons of pineapple fruit are harvested for food and drinking industries, along with the release of a huge amount of pineapple wastes. Without the proper treatment, pineapple wastes can cause adverse impacts on the environment, calling for new technologies to convert them into valuable products. Here, we review the production and application of adsorbents derived from pineapple wastes. The thermal processing or chemical modification improved the surface chemistry and porosity of these adsorbents. The specific surface areas of the pineapple wastes-based adsorbents were in range from 4.2 to at 522.9 $m^2 \cdot g^{-1}$. Almost adsorption systems followed the pseudo second order kinetic model, and Langmuir isotherm model. The adsorption mechanism was found with the major role of electrostatic attraction, complexation, chelation, and ion exchange. The pineapple wastes based adsorbents could be easily regenerated. We suggest the potential of the pineapple wastes towards circular economy."

*Keywords section was also revised as follows.*

"Pineapple wastes; adsorbent production; heavy metal ions; toxic dyes; environmental treatment; circular economy."

**3. Please add some Figures, especially those drawn by the author. Mechanism Figures, morphology Figures, preparation Figures, and so on.**

**Our response:**

The authors sincerely thank your instructive comments!

Your statement is very reasonable! As your suggestion, we added more 10 figures for our manuscript.

In detail, we are pleased to show added figured here.

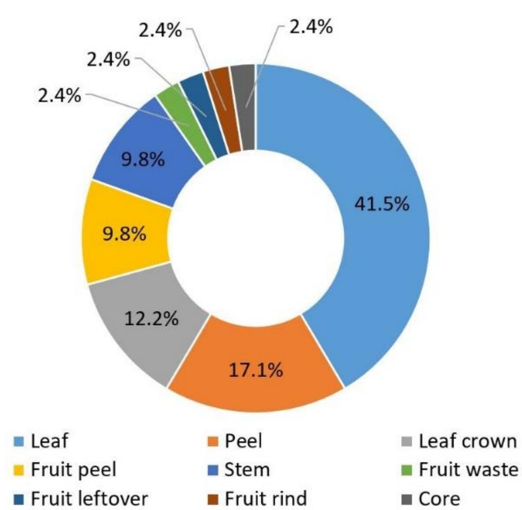


**Fig. 4.** Statistic data of popularity of various pineapple wastes studied in the past literatures.

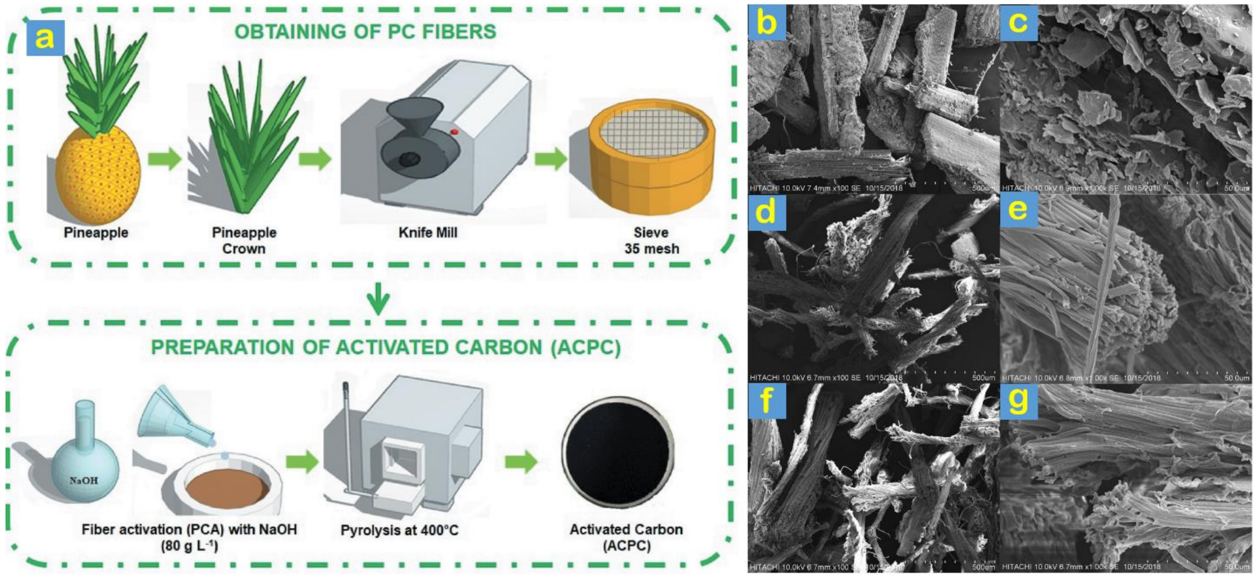


**Fig. 5.** Synthesis procedure for pineapple fibers and NaOH-activated carbon (a). Reproduced from the reference [1]. The SEM microphotograph of pineapple leaf powder (b, c), NaOH modified pineapple leaf powder (d, e), iminodiacetic acid modified pineapple leaf powder (f, g). Reproduced from the reference [2].

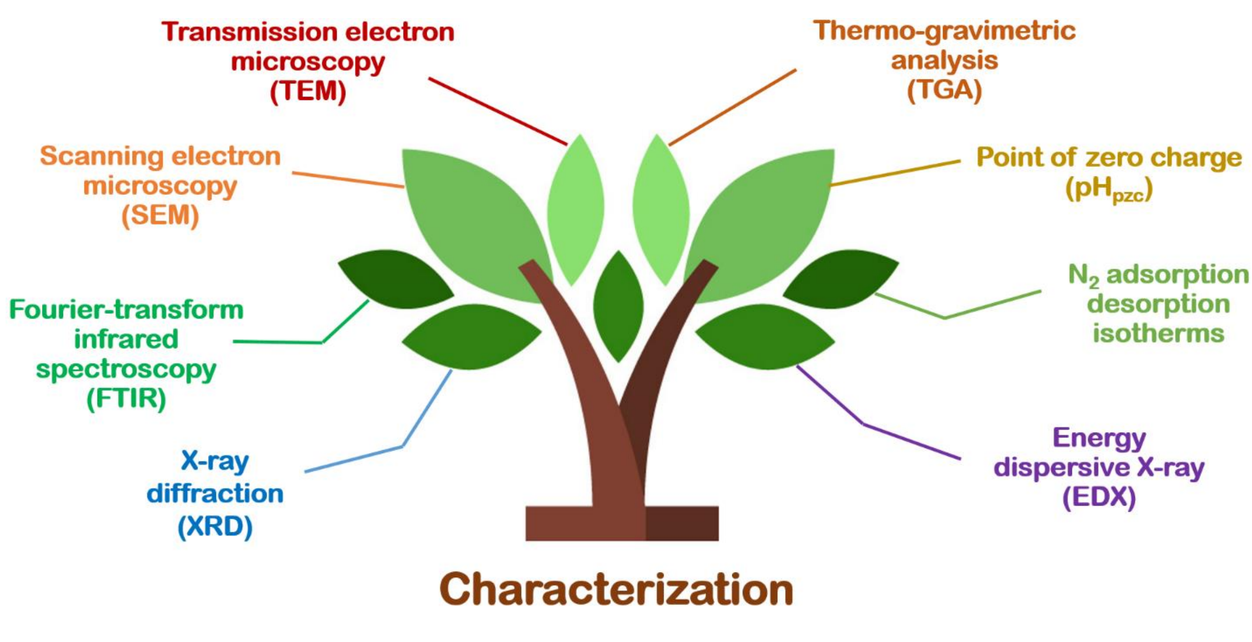


**Fig. 6.** Several common characterizations for analyses of the pineapple wastes-derived adsorbents.

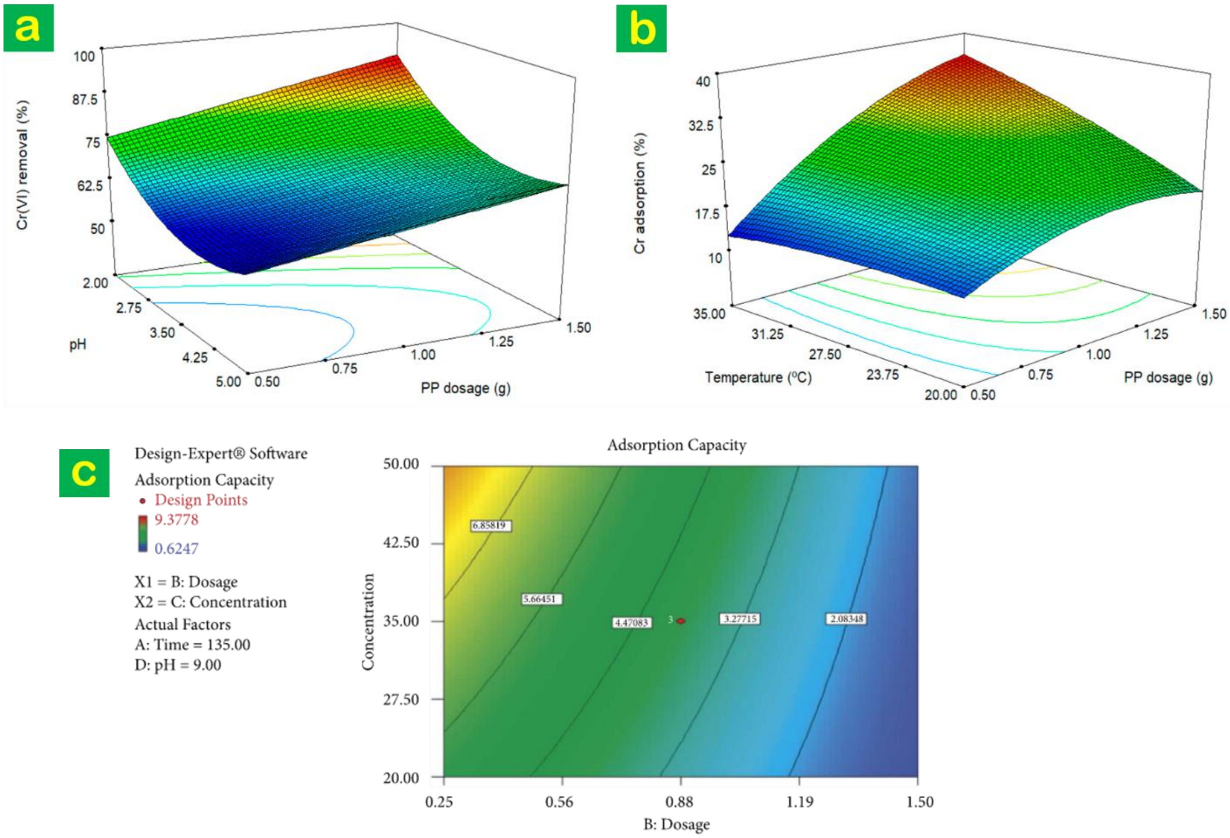


**Fig. 8.** Three dimensional surface plots for Cr(VI) removal by pineapple core (PP) adsorbent with two variables including pH and adsorbent dose, temperature was set at central level (a); effect of two variables including temperature and adsorbent dose on Cr(VI) removal by pineapple core, pH was set at central level (b). Reproduced from the reference [3] under an open access Creative Common CC BY license. A contour plot for the interaction between dose and concentration for removal of methylene blue (c). Reproduced from the reference [4] under an open access Creative Common CC BY license.

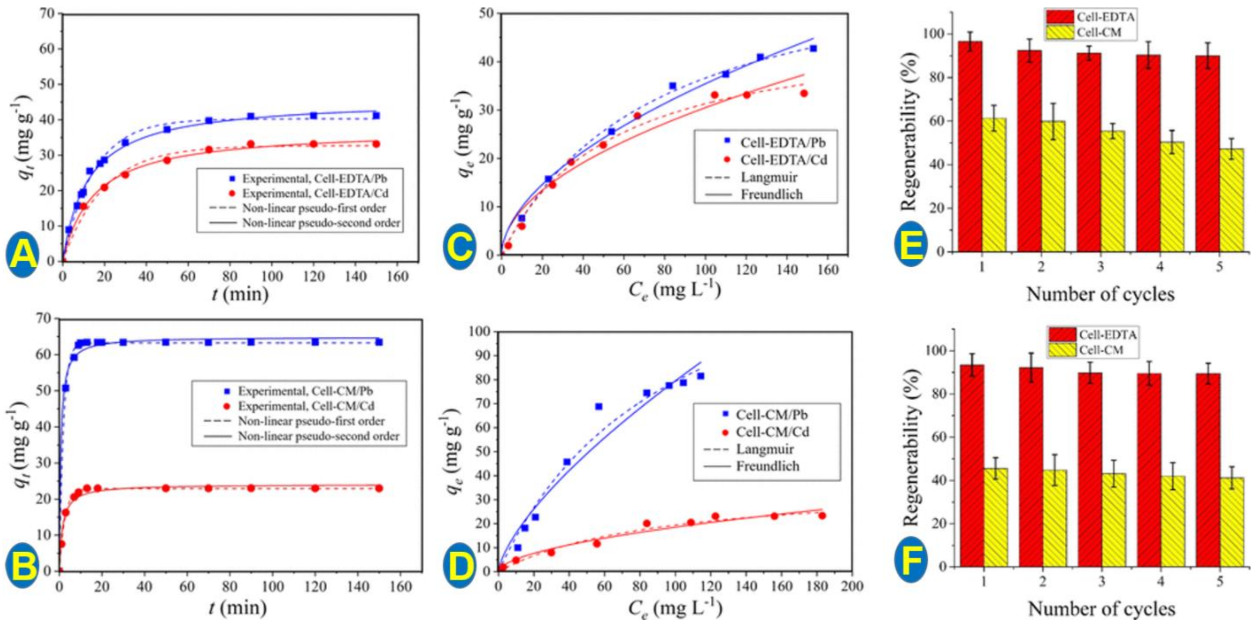


**Fig. 9.** The nonlinear fitting of pseudo first-order, pseudo second-order, Langmuir, and Freundlich (C) models for the kinetic (A, B) and isotherm (C, D) adsorption of Pb(II) and Cd(II) onto pineapple leaves modified with ethylenediaminetetraacetic acid, and carboxymethyl groups. The regeneration of these adsorbents (E, F). Reproduced from the reference [5] under an open access Creative Common CC BY license.

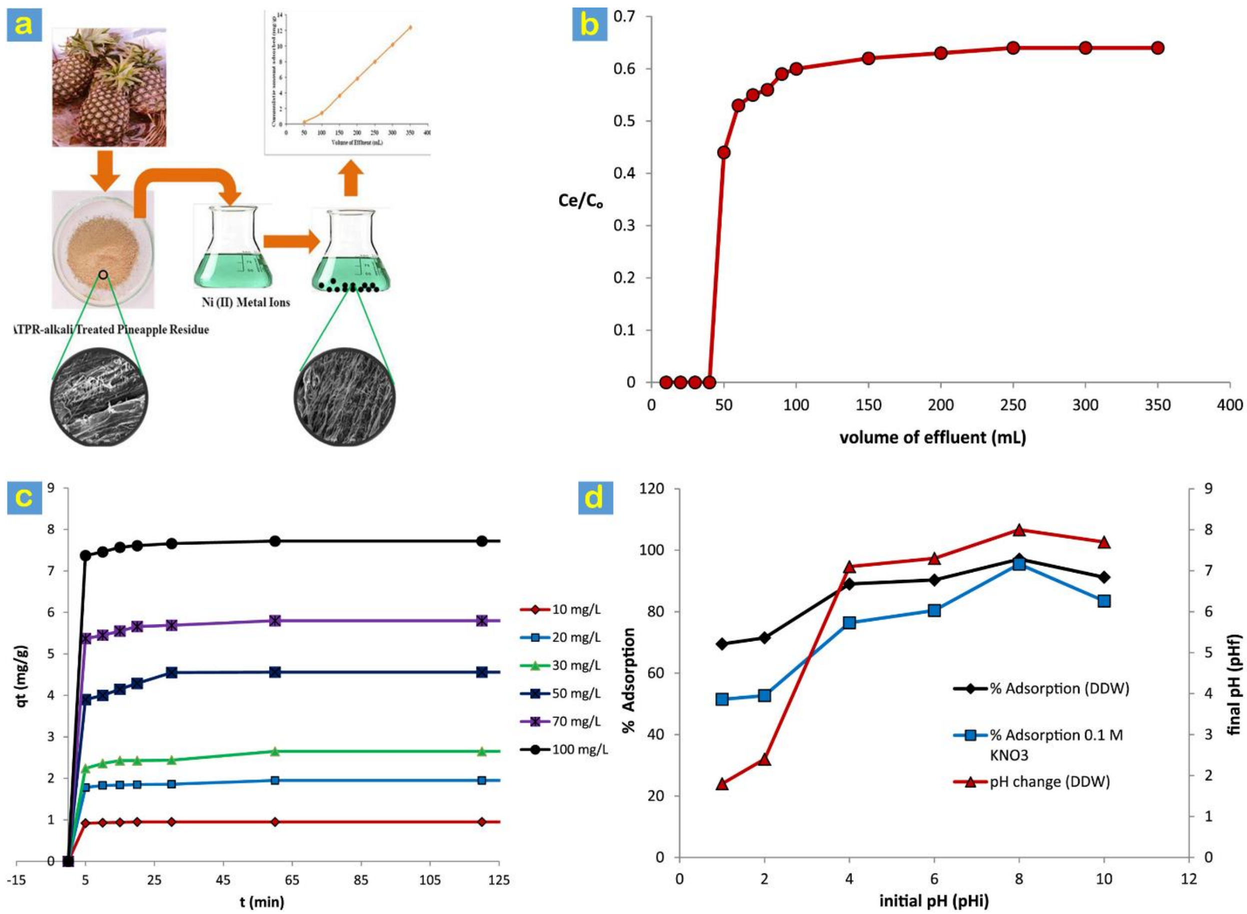


**Fig. 10.** Schematic illustration of synthesis and application of NaOH-treated pineapple residue adsorbent (ATPR) for removal of nickel ions from water (a); breakthrough curve for fixed bed column adsorption (b); effect of contact time (c); effect of pH and electrolyte on adsorption of nickel ions (d). Reproduced with permission of Elsevier from the reference [6].

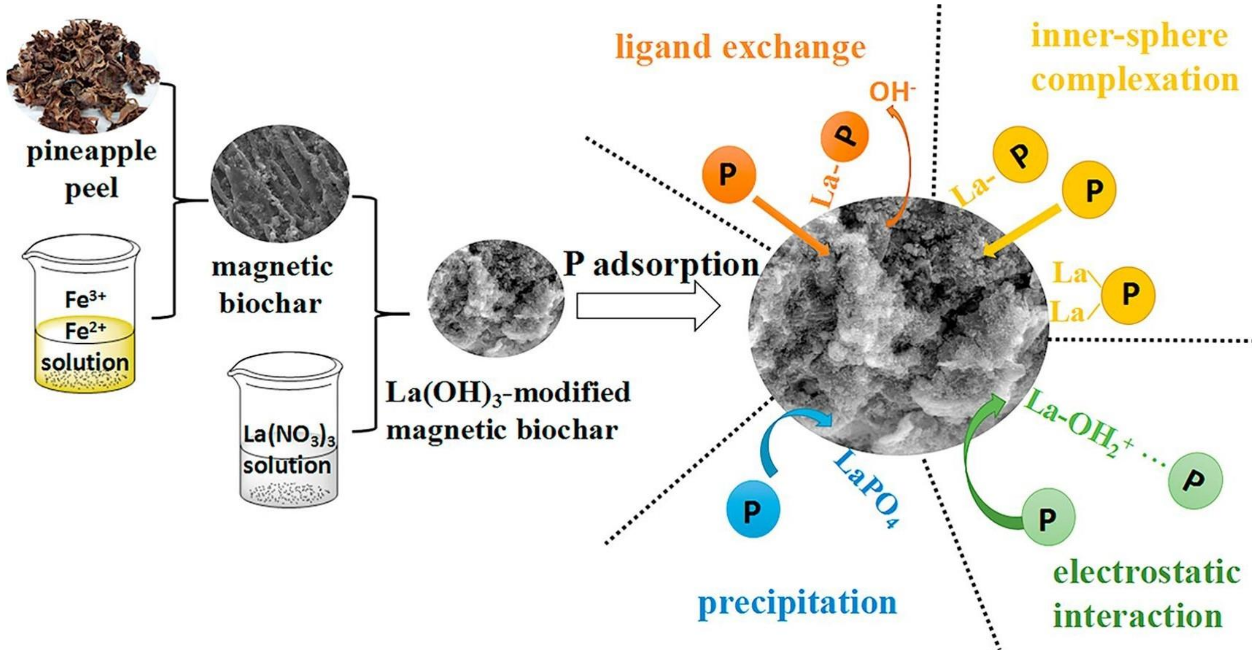


**Fig. 11.** Synthesis route of $La(OH)_3$-modified magnetic pineapple biochars and their applications for the removal of $[PO_4]^{3-}$ anions. Several possible adsorption mechanisms were suggested, including ligand exchange, inner-sphere complexation, electrostatic interaction and precipitation. Reproduced with the permission of Elsevier from the reference [7].

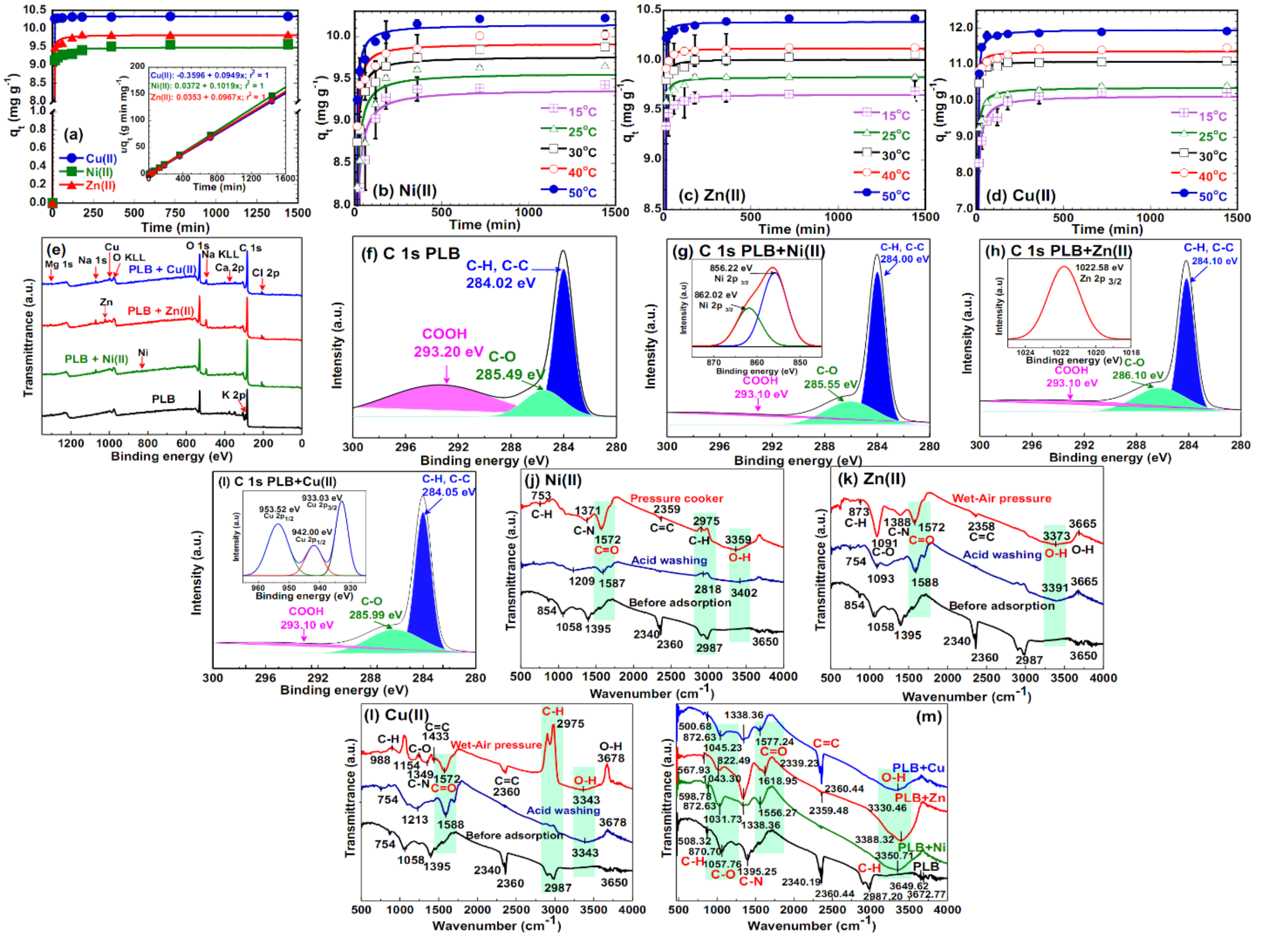


**Fig. 12.** Comparative kinetics of adsorption of heavy metal $Ni^{2+}$, $Zn^{2+}$, and $Cu^{2+}$ (a); effect of temperature on the kinetic adsorption of $Ni^{2+}$ (b), $Zn^{2+}$ (c), and $Cu^{2+}$ (d); (e) XPS survey spectra of pineapple leaf biochar before and after adsorption; XPS C 1s spectra of pineapple leaf biochar (f), pineapple leaf biochar + $Ni^{2+}$ (g), pineapple leaf biochar + $Zn^{2+}$ (h), and pineapple leaf biochar + $Cu^{2+}$ (i); FT-IR spectra of pineapple leaf biochar after regeneration using a pressure cooker and acid washing of $Ni^{2+}$ (j), $Zn^{2+}$ (k), and $Cu^{2+}$ (II) (l); chemical bond analysis by FT-IR spectra before and after regeneration (m). Reproduced from the reference [8] under an open access Creative Common CC BY license.

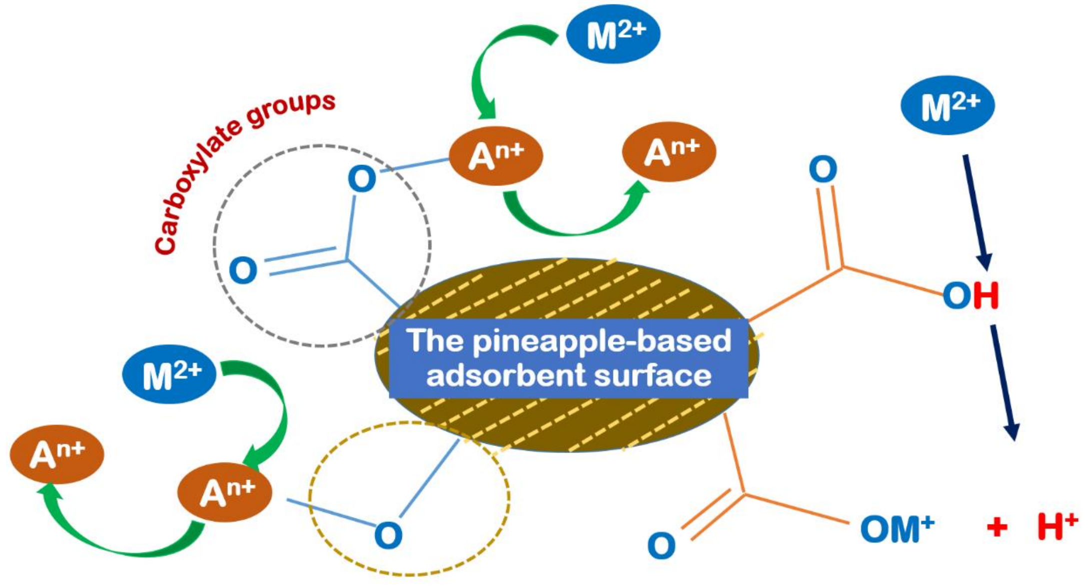


**Fig. 13.** Heavy metal adsorption onto the pineapple waste-based adsorbent via proposed ion exchange mechanism.

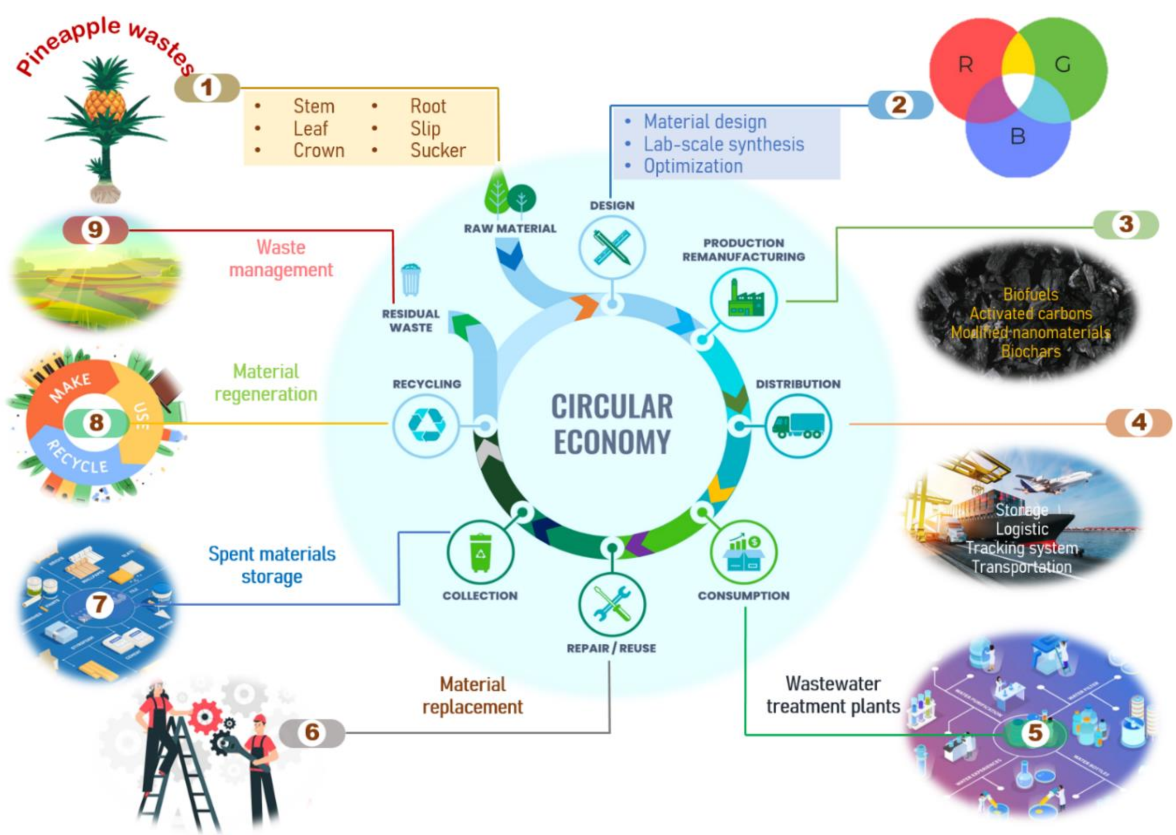


**Fig. 15.** Waste management and substantial contribution of the pineapple wastes to the circular economy.

**4. Please introduce the related work of the author's research group in detail.**

**Our response:**

The authors sincerely thank your instructive comments!

I believe that your comments are high reasonable, but we have no related works of the author's research group to introduce in this work. Therefore, we cited works from the other researchers.

Thank you so much!

**5. The abstract is too vague and should be focused on the theme of the manuscript and for what the manuscript stands.**

**Our response:**

The authors sincerely thank your instructive comments!

Your statement is very reasonable! As your suggestion, we revised the abstract section more concise and further organized our views and look to the future as your suggestion.

"Each year, nearly 30 million tons of pineapple fruit are harvested for food and drinking industries, along with the release of a huge amount of pineapple wastes. Without the proper treatment, pineapple wastes can cause adverse impacts on the environment, calling for new technologies to convert them into valuable products. Here, we review the production and application of adsorbents derived from pineapple wastes. The thermal processing or chemical modification improved the surface chemistry and porosity of these adsorbents. The specific surface areas of the pineapple wastes-based adsorbents were in range from 4.2 to at 522.9 $m^2 \cdot g^{-1}$. Almost adsorption systems followed the pseudo second order kinetic model, and Langmuir isotherm model. The adsorption mechanism was found with the major role of electrostatic attraction, complexation, chelation, and ion exchange. The pineapple wastes based adsorbents could be easily regenerated. We suggest the potential of the pineapple wastes towards circular economy."

*Keywords section was also revised as follows.*

"Pineapple wastes; adsorbent production; heavy metal ions; toxic dyes; environmental treatment; circular economy."

Thank you so much!

**6. In the section on Future prospective research, authors need to propose future research along with the current achievements or problems so that readers can better understand the proposals and their motivations**.

**Our response:**

The authors sincerely thank your instructive comments!

We stated some future research along with the current achievements or problems in the future prospects as follows:

"Over the past decades, the amount of agricultural wastes has continuously increased as a result of agricultural expansion to satisfy the demand for food and drinking. In the current context of serious environmental pollution caused by the agricultural by-products, the pineapple wastes need to be converted into more valuable products. In the future, the pineapple waste derived adsorbents may be still developed to contribute significantly to the environmental remediation."

Thank you so much!

**7. There are many studies reported in the literature regarding several wastewater treatments using potential materials and technology. Based on this, do the authors think that the selected pineapple (Ananas comosus) wastes as potential adsorbents are an improvement when compared to other functional-based nanomaterials and methods? The authors need to clarify the advantages and disadvantages based on the diverse waste treatment such as Chemical Engineering Journal, 307 (2017) 456-465; Journal of Environmental Chemical Engineering, 8 (2020) 103591; Chemical Engineering Journal, 300 (2016) 264-272; Journal of Cleaner Production, 228 (2019) 778-785; Chemical Engineering Journal, 289 (2016) 65-73; Journal of Cleaner Production, 224 (2019) 920-929; Journal of Environmental Chemical Engineering, 7 (2019) 103378; Composites Part B: Engineering, 171 (2019) 294-301; Chemical Engineering Journal, 303 (2016) 539-546; Journal of Molecular Liquids, 294 (2019) 111679; Journal of Environmental Chemical Engineering, 7 (2019) 103305. The authors need to take note of the above references in the revised manuscript.**

**<u>Our response:</u>**

The authors sincerely thank your instructive comments!

We cited references as suggested to state that the selected pineapple (Ananas comosus) wastes as potential adsorbents are an improvement when compared to other functional-based nanomaterials and methods in the introduction:

*In page 4, we added some statements plus relevant references as follows:*

“Complex composites and nanomaterials many disadvantages, e.g., having high cost production, enduring multiple synthesis steps, using toxic chemical for material fabrication, exhibiting less eco-friendly treatment methods [9,10,18,11–15,15–17]. Meanwhile, the agriculture derived adsorbents can alleviate above barriers, as a result, the biomass-derived adsorbents can be favourable to the environmental remediation."

References cited were also highlighted in the list reference.

Thank you so much!

**8. Similar to the abstract, the conclusion is too vague. It must be focused on the theme of the manuscript and talk about the concluding remarks based on the reviewed workout**.

**Our response:**

The authors sincerely thank your instructive comments!

Your statement is very reasonable! As your suggestion, we revised the conclusion section more concise and focused on the theme of the manuscript and the concluding remarks based on the reviewed workout.

"In the present work, the highlighted experimental results of the production and application of the pineapple waste derived adsorbents for the environmental treatment applications were systematically overviewed. The synthesis of the pineapple derived biosorbents, modified biochars, and activated carbons and composites was discussed. Almost adsorption systems followed the pseudo second order kinetic model, and Langmuir isotherm model. The adsorption by the pineapple based adsorbents was majorly due to the contribution of electrostatic attraction, complexation, chelation, and ion exchange. The research works reported that the adsorption processes were thermodynamically spontaneous. The pineapple waste based adsorbents could be reused at 3–5 times using

HCl or NaOH as eluents. For future prospects, the pineapple wastes may not only have potential for synthesis of materials such as nanoparticles, hydrogels, aerogels, and nanocomposites but also contribute proactively to circular economy."

**9. Introduction and discussion section need to be revised and written. There are many technologies invented for different problem solving with different treatment methods. Please explain the reasons in detail. The new references on the similar interest should be introduced and cited such as Journal of Cleaner Production, 244 (2020) 118805; Journal of Molecular Liquids, 336 (2021) 116325; Journal of Molecular Liquids, 319 (2020) 114356; Journal of Environmental Chemical Engineering, 8 (2020) 103515; New Journal of Chemistry, 43 (2019) 4620-4632; Journal of Molecular Liquids, 323 (2021) 114587.**

**<u>Our response:</u>**

The authors sincerely thank your instructive comments!

We cited references as suggested to state that many technologies invented for different problem solving with different treatment methods.

*In page 4, we added some statements plus relevant references as follows:*

"Nowadays, new technologies have been developed and widely used to detect, quantify and treat the pollutants from the wastewaters [19–23]."

References cited were also highlighted in the list reference. Thank you so much!

**10. Please note: The text, figures, and references need further modification. The details will be reviewed after revision. I would like to see the revised manuscript.**

**<u>Our response:</u>**

The authors sincerely thank your instructive comments! we made effort to revised this manuscript based on your suggestion. We hope that our response can satisfy your requirements.

Thank you so much!

**Reviewer #2: The paper is on the review of pine-apple waste for environmental applications as an adsorbent. These of studies have been well reported and this reviewer does not feel any novelty from the review work, even though the paper was nicely written. There are several problems in this paper.**

**Our response:**

The authors sincerely thank your instructive comments! The authors are very thankful for giving us the opportunity to revise this manuscript and answer your insightful questions.

We really regret that the previous version was not good to show the novelty of this work as well as important findings.

Here, we will seriously work to present a highly modified revision with our highest effort with many additions and changes. We also hope that our revision can satisfy your requirements as well as high standards of the journal.

To help you easy to follow the possible changes in this revision, all corrections and/or modifications have been highlighted with bright green color.

Thank you so much!

**1. What happens to the water after the treatment? Any TOC? How to deal with the spent adsorbents?**

**Our response:**

The authors sincerely thank your instructive comments!

We believe that your comments are very reasonable! As your suggestion, we revised our manuscript with some explanations as follows:

Yes! It is true that total organic carbon (TOC) is one of the most indicative to measure how the treated water qualify. We found some references that related to TOC or other biochemical indicatives to examine the water quality after the treatment:

*In page 21, we added some statements:*

"Some indexes such as total organic carbon (TOC), biochemical oxygen demand (COD), chemical oxygen demand (COD), total dissolved oxygen (TDS) are key indicatives to measure the quality of water after treatment. As an example, Oni et al. (2020) compared BOD and TDS values before and after the treatment of kitchen wastewater using activated carbons. Researchers used pineapple peel and crown as precursors to synthesize activated carbons. Accordingly, two chemical agents including $H_3PO_4$ and $ZnCl_2$ have been used to activate the pineapple waste derived adsorbents under carbonization at 270 °C. They found that $ZnCl_2$-activated carbon gave better performance of BOD and TDS results than those of $H_3PO_4$-activated carbon. It was suggested that the kitchen wastewater after treatment by $ZnCl_2$-activated carbon could obtain a safety threshold for further usage."

**How to deal with the spent adsorbents?**

Spent adsorbents should be treated after treatment of pollutants. There are many methods such as incineration and sedimentation. However, we think that they can be still used for many applications such as precursor for designing new catalysts, or biofertilizers in the context of circular economy.

*In page 46, we added some statements to suggest the possible ways for dealing with the spent adsorbents:*

"Residual wastes need to be managed through post-treatment technologies such as impregnation, geopolymerisation, or modification, etc. Post-treatment materials can still be modified to be used as catalysts for biomass conversion into bioenergy, biofertilizers for soil amendment in agriculture, or any applications to prolong the life cycle of the pineapple waste-based products.

Thank you so much!

**2. How to make the adsorbents for industrial applications? Any reactor can be used? Or it is only limited to a few types of reactors? CSTR? Fixed bed?**

**<u>Our response:</u>**

The authors sincerely thank your instructive comments!

We believe that your comments are very reasonable! As your suggestion, we added new section to expand the application of the pineapple wastes for industrial applications. In this section, we introduced new concept as "circular economy" because the pineapple wastes have great potential for industrial applications.

*In Page 44 – 46, we added "Section 10. Potential of pineapple wastes towards circular economy":*

According to Food and Agriculture Organization (FAO), nearly 30 million tons of pineapple fruit are harvested for food and drinking industries each year, along with the release of a huge amount of the pineapple wastes. The proper conversion methods of the pineapple wastes into more valuable products such as biofuels, biochars, activated carbons, modified nanomaterials, magnetic nanocomposites, etc. have contributed proactively to strengthening a low-carbon economy as well as mitigating the environmental pollution and climate change. However, almost studies on the production of the pineapple waste-based adsorbents are just lab-scaled, or burgeoning, and it would be too early to claim that these bio-based products (biofuels and materials) are very attractive in the future bioenergy and wastewater treatment technologies. To pave the way for commercializing the pineapple wastes-derived products and other real applications, in this section, we propose a systematic expansion from lab-scale production to consumption and waste management in the context of circular economy.

Circular economy is an emerging model of how to extend the life cycle of products through the core processes of material design, production, distribution, consumption, repair, material collection, recycling and residual waste management. Although there is still a debatable topic of definition and scope of circular economy, it is generally believed that effective management of the agro-industrial by-products, especially for the pineapple wastes in the principles of circular economy may be environmentally beneficial. It is evitable that incorporation of many sectors such as research and development (R&D), logistic systems, treatment plants, maintenance services, etc. in the usage and pineapple wastes management should be encouraged in circular economy. With the emphasis on nanotechnology and green chemistry, the potential of the pineapple wastes based products can be insightfully elucidated in the approaches of sustainable development.

Nine core processes are briefly described in Fig. 15. Initially, some pineapple by-products such as crown, leaf, and stem after harvesting juices are collected and treated to be ready for bioenergy and material production. To enhance the pineapple waste-based high-quality products, the material design process needs to be involved in lab-scale research, modification, and optimization. This process may be complicated and depended majorly on the purpose and availability of manufacturers. There are three types of main products derived from the pineapple wastes, including *(i)* value-added products, *(ii)* bioenergies, and *(iii)* materials. Natural compounds such as polyphenols, xylitol, antioxidants, enzymes, and organic acids can be extracted from the pineapple wastes through extraction processing technologies [25]. They are used to synthesize value-added products for food and cosmetic, medicine applications [26]. Pineapple waste-based biofuels such as biogas, biohydrogen, bioethanol, bio-oil, and biomethane can be produced through anaerobic digestion technologies, biorefinery systems, and other bioconversion/catalytic processes. These biofuels are an integral part of low-carbon economy towards circular bioeconomy. Consequently, production of biofuels from the pineapple wastes minimize the energy loss and greenhouse gas emission. For the purpose of zero waste, this process should be integrated with the production of materials as a result of carbon residuals. Accordingly, residuals after bioenergy production can be converted into valuable materials such as biochars, activated carbons, modified nanomaterials, magnetic nanocomposites, and functionalized porous carbon for water treatment. The fourth process are storage and transportation of bioenergies and material for consumption. For example, the materials can be delivered to wastewater treatment plants or sewage treatment plants while bioenergies can be distributed to power stations through logistic and storage systems. A repairing or optimization process is required to improve the performance of these plants. The next process includes material replacement, and addition. The spent materials can be collected from the treatment systems and stored for regeneration or recycling. Finally, residual wastes need to be managed through post-treatment technologies such as impregnation, geopolymerisation, or modification, etc. Post-treatment materials can still be modified to be used as catalysts for biomass conversion into bioenergy, biofertilizers for soil amendment in agriculture, or any applications to prolong the life cycle of the pineapple waste-based products.

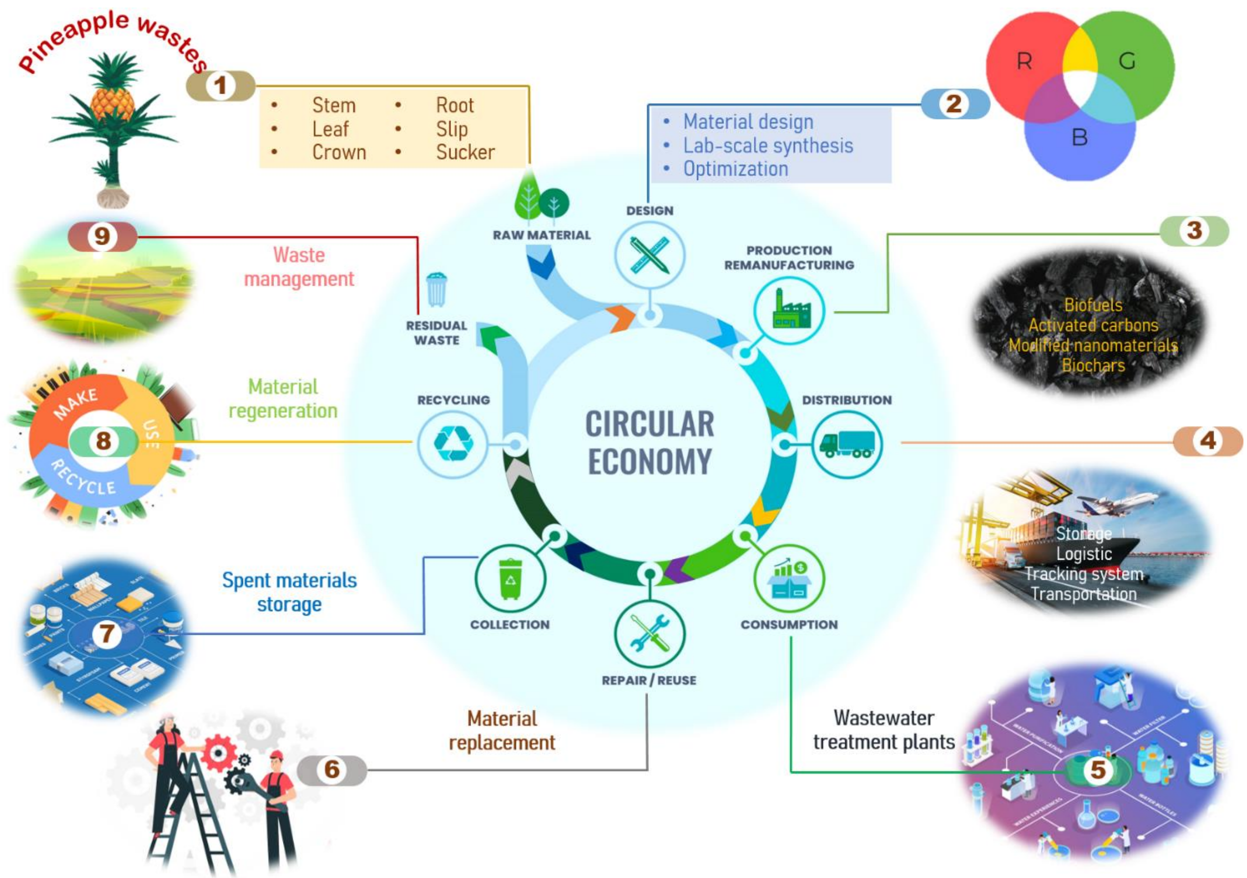


**Fig. 15.** Waste management and substantial contribution of the pineapple wastes to the circular economy.

**Any reactor can be used? Or it is only limited to a few types of reactors? CSTR?**

We think that reactor such as continuous stirred tank reactor (CSTR) is used for biohythane (a gaseous fuel) production rather than treatment.

Actually, it is a batch reactor equipped with an impeller or other mixing device to provide efficient mixing. In chemical engineering the name CSTR is often used to refer to an idealised agitated tank reactor used to model operation variables required to attain a specified output.

In usage, reagents, reactants and often solvents flow into the reactor while the product(s) of the reaction concurrently exit(s) the vessel. In this manner, the tank reactor is considered to be a valuable tool for continuous chemical processing. This process shows that the two-stage co-digestion process enhanced hydrogen production rate, with high-quality biogas production reducing fermentation time.

**Fixed bed?**

Fixed bed column is one of the efficient and practical mode for the treatment of pollutants. Depart from adsorption batch mode, up-flow/down-flow fixed bed column is another type of adsorption between adsorbate and adsorbent in a continuous liquid system. It is believed that adsorption beyond fixed bed column mode is highly adaptable for industrial scale treatment of different pollutants including organic and inorganic compounds.

Based on your suggestion, therefore we added new section to introduce the application of the pineapple waste based adsorbents in the fixed bed column adsorption mode.

*In pages 35-37, we added section 8.3. Fixed bed column:*

Depart from adsorption batch mode, up-flow/down-flow fixed bed column is another type of adsorption between adsorbate and adsorbent in a continuous liquid system [27]. It is believed that adsorption beyond fixed bed column mode is highly adaptable for industrial scale treatment of different pollutants including organic and inorganic compounds. As a result, many works made effort in the design and development of fixed bed columns [28]. The characteristic of fixed bed column adsorption study is breakthrough curves which show the relationship between concentration of the contaminant and time profile. Breakthrough curves are expressed through mass transfer zone or primary sorption zone [27]. Accordingly, wastewater is injected into the column and treated by the adsorbate. The adsorption is initially rapid due to availability of adsorption sites. The process continues until mass transfer zone reaches at the end of the column, or equilibrium is established. Breakthrough curves show S-shape in most cases of fixed bed column adsorption.

Some works used the pineapple waste-derived adsorbents to remove pollutants (e.g., heavy metal, and organic dye) in fixed bed column adsorption mode. Indeed, Rao and Khan (2017) successfully fabricated the pineapple residue adsorbent treated by NaOH solution (ATPR) and investigated its adsorption of nickel ions in water (Fig. 10). The authors initially optimized several batch adsorption conditions such as Ni(II) concentration (50 mg $L^{-1}$), pH (8), and contact time (60 min), and found $Q_m$ value of 17.56 mg $g^{-1}$. Afterwards, they designed a glass column (d = 0.6 cm, h = 3.7 cm) loaded with 0.2 g of the adsorbent. 500 mL of $Ni^{2+}$ solution was passed through this bed column (V = 1.04 $cm^3$). As a result, a breakthrough capacity was determined at 20 mg $g^{-1}$.

In another work, Azman and Subki (2022) conducted the removal of methylene blue and malachite green dyes through fixed bed column adsorption using pineapple crown $H_3PO_4$-activated carbon. The fixed bed column was designed with internal diameter (d = 3 cm) and height (h = 10 cm). 50 mL of each of the methylene blue and malachite green solution was filtered by this column. However, breakthrough and exhaustive capacities were not reported. In general, there were very few studies focusing on the adsorption of pollutants by fixed bed column using the pineapple waste-derived adsorbents. Therefore, more investigations of fixed bed column adsorption should be carried out.

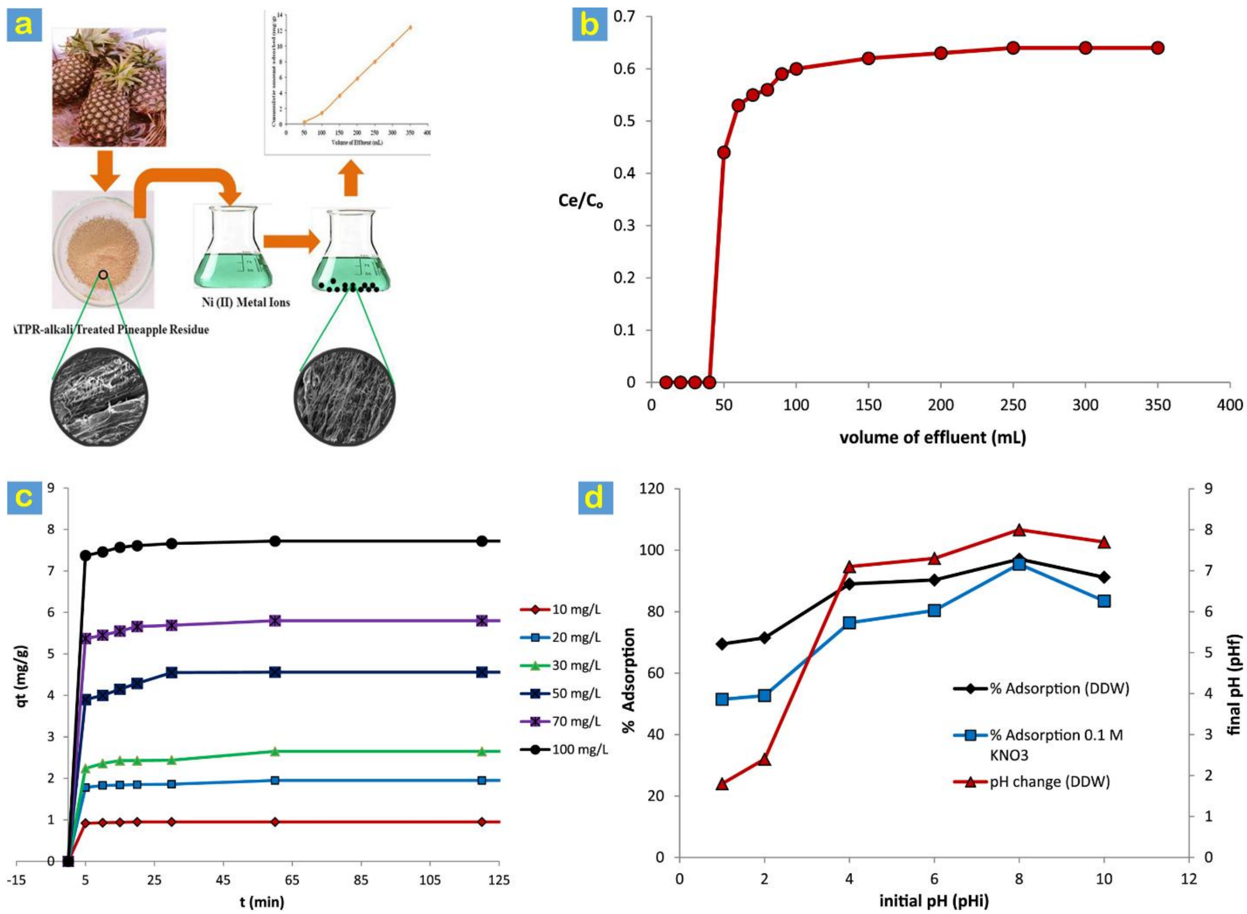


**Fig. 10.** Schematic illustration of synthesis and application of NaOH-treated pineapple residue adsorbent (ATPR) for removal of nickel ions from water (a); breakthrough curve for fixed bed column adsorption (b); effect of contact time (c); effect of pH and electrolyte on adsorption of nickel ions (d). Reproduced with permission of Elsevier from the reference [6].

**3. The mechanisms on the adsorption can be different when we have different types of adsorbates, like heavy metals, anionic substances and organic matters.**

**<u>Our response:</u>**

The authors sincerely thank your instructive comments!

Your question is highly reasonable! We totally agree with you that mechanisms on the adsorption can be different when we have different types of adsorbates, like heavy metals, anionic substances and organic matters. Because we have a numerous kind of pollutants, it is hard to mention all of them in this work. This study introduced the mutual mechanisms based on the references. These mechanisms can be responsible for adsorption of one or some pollutants. To do that, we arranged each of main mechanism in a sections.

*In addition, we added new section (section 9.3) to talk about the role of ion exchange in page 42 as follows:*

This mechanism may be helpful for explaining the adsorption of heavy metal over the adsorbent. Some exchangeable metal ions such as $K^+$, $Na^+$, $Ca^{2+}$ are available on the surface of the adsorbents. As a result, the replacement of these ions by heavy metal ions entail their sequestration according to Fig. 13. Even, proton $H^+$ or acidic groups can exchange with heavy metal ions.

As an example, Vivian Loh Zing et al. (2019) suggested that chemical reaction like ion exchange was anticipated through replacement of –COOH groups on oxalic acid-activated pineapple stem and stem powder. Apart from mechanisms mentioned, other mechanisms such as precipitation and cation–π interaction may contribute to adsorption of heavy metals. However, such investigations have been still very limited, suggesting a better elucidation of adsorption mechanisms.

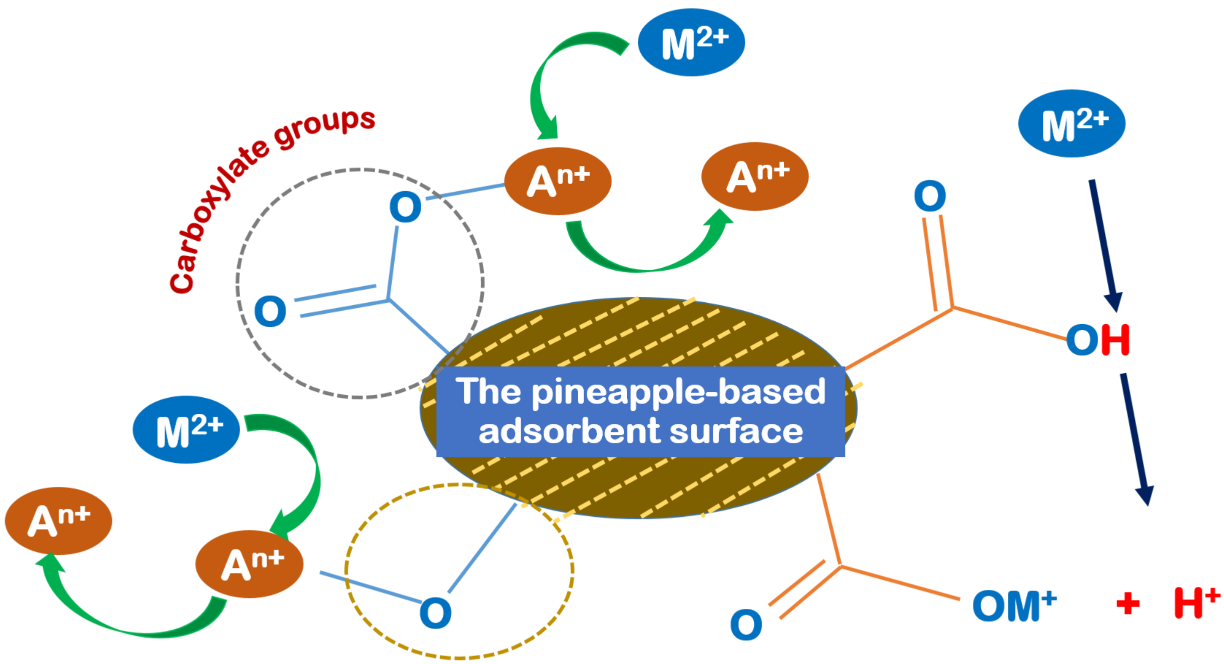


Fig. 13. Heavy metal adsorption onto the pineapple waste-based adsorbent via proposed ion exchange mechanism.

Thank you so much!

**Reviewer #3:**

**Manuscript Number: STOTEN-D-22-15981**

**Title: A review on the pineapple (Ananas comosus) wastes as potential adsorbents for water treatment**

**Article Type: Review Article**

**Reviewer#3**

**This article is a review on the pineapple (Ananas comosus) wastes as potential adsorbents for water treatment. The article is very important and well organized; however, it needs a major revision to be considered for the publication in Journal of Science of the Total Environment.**

**Our response:**

The authors sincerely thank your instructive comments! The authors are very thankful for giving us the opportunity to revise this manuscript and answer your insightful questions.

We really regret that the previous version might be not enough good to show the important findings.

Here, we will seriously work to present a highly modified revision with our highest effort with many additions and changes. We also hope that our revision can satisfy your requirements as well as high standards of the journal.

To help you easy to follow the possible changes in this revision, all corrections and/or modifications have been highlighted with bright green color.

Thank you so much!

**1. Page 4, section 1, although there is no comprehensive review on the production and application of pineapple wastes- based adsorbents in wastewater treatment, some reviews need to be cited because they included the utilization of pineapple wastes as adsorbents for dyes and heavy metals such as:**

**Aili Hamzah A.F., Hamzah M.H., Che Man H., Jamali N.S., Siajam S.I., Ismail M.H., Recent Updates on the Conversion of Pineapple Waste (Ananas comosus) to Value-Added Products, Future Perspectives and Challenges. Agronomy 2021, 11, 2221.** https://doi.org/10.3390/agronomy11112221.

**Our response:**

The authors sincerely thank your instructive comments!

This reference is very important to our work to have insight into updated knowledge. Thus, we cited this reference in the introduction in page 8 as follows.

"Recently, Aili Hamzah et al. (2021) overviewed the conversion of pineapple wastes as potential precursors for production of value-added products such as biofuels, biogasses, cellulose nanocrystals, biodegradable packaging and bio-sorbent."

Thank you so much!

**2. Page 8, section 2, other pineapple waste-based adsorbents in terms of modified or composite form are also important and need to be included in this section if available.**

**Our response:**

The authors sincerely thank your instructive comments!

Your comments are very reasonable! We just found the form of other pineapple waste-based adsorbent are biochars, activated carbons, and modified porous carbon. We really regret that there was no research article of composite for us to review.

*For modified adsorbents we showed in section* ***2.3. Modified carbons:***

*2.3.1. Physical activation*

In fact, both biosorbents and biochars derived from pineapple wastes can be immediately ready for using in the adsorption systems without any further processes. To improve their surface chemistry as well as structural characteristic, however, the modification stage should be undergone. Thereby, the adsorbents are more likely to reach better adsorption performance. The studies reported that the pineapple-derived activated carbon products can be prepared through either the physical or chemical method. The physical activation of pineapple wastes is often surveyed under the atmosphere of $CO_2$, steam, or steam/$CO_2$ [31]. However, this activation method was not still applied to produce activated carbons from the apple wastes.

*2.3.2. Chemical activation*

Meanwhile, the chemical activation uses strongly dehydrated/oxidative agents such as $H_2SO_4$, $KMnO_4$ [32], $ZnCl_2$ [33], NaOH [34], oxalic acid [30], NaOH/ethylenediaminetetraacetic acid [5], and iminodiacetic acid [2]. Fig. 5 illustrates the synthesis procedure for pineapple fibers and NaOH-activated pineapple fiber derived carbon. The introduction of chemical reagents is to develop new pores and/or increase surface area of obtained activated carbons. Therefore, their adsorption performance can be improved considerably. However, the important points in this strategy may be the selection of chemicals, optimization of chemical/precursor ratio, temperature and duration of carbonization. Moreover, the residual chemicals after activation should be wholly treated to avoid the negative impacts on the environment. Some considerations of properties of chemically modified pineapple-derived adsorbents should be taken.

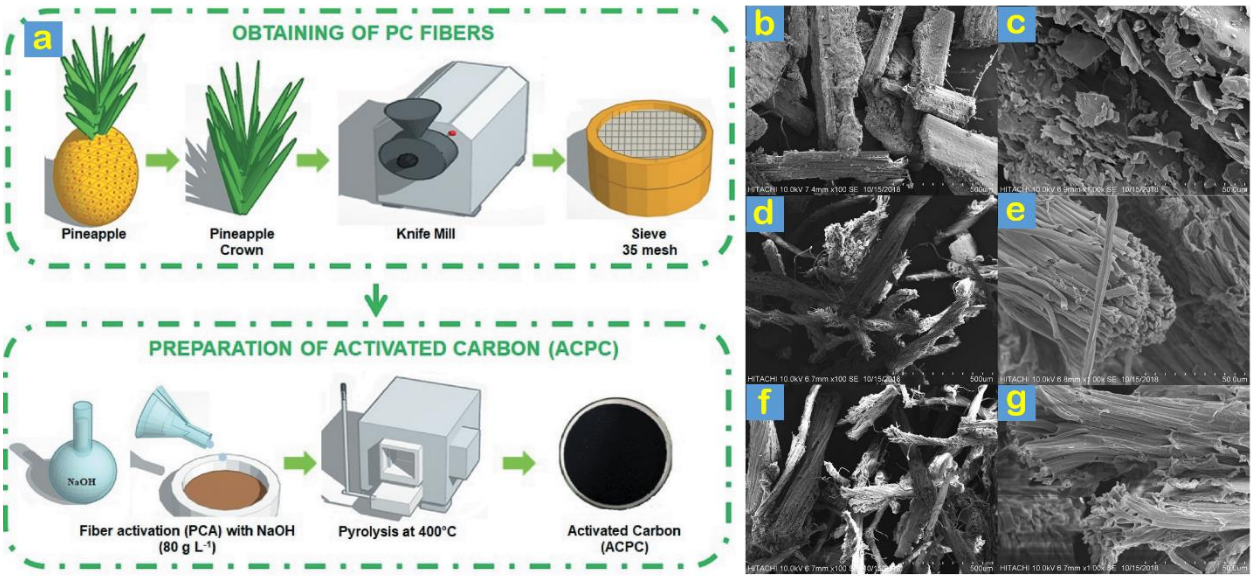


**Fig. 5.** Synthesis procedure for pineapple fibers and NaOH-activated carbon (a). Reproduced from the reference [1]. The SEM microphotograph of pineapple leaf powder (b, c), NaOH modified pineapple leaf powder (d, e), iminodiacetic acid modified pineapple leaf powder (f, g). Reproduced from the reference [2].

Thank you so much!

**3. Page 8, section 2.1, the most adopted and efficient parts of pineapple wastes (peel, leaf, core, fruit rind, stem, etc.) also need to be mentioned**.

**Our response:**

The authors sincerely thank your instructive comments!

Your comments are very reasonable! As your suggestion, we added some statements and proper references.

Thank you so much!

*In page 10, we showed:*

According to Fig. 4, the most adopted and efficient part of pineapple wastes is leaf (41.5%), followed by pineapple peel (17.1%) and leaf crown (12.2%). It can be understandable that leaf is the major and available component of the pineapple. Therefore, the majority of works studied the pineapple leaf due to its popularity. Next, the precursors are pretreated to remove the dirties or residuals by washing with $H_2O$ many times [35]. After pretreatment, they are dried at 80-120 °C in oven or under solar energy source [3,36].

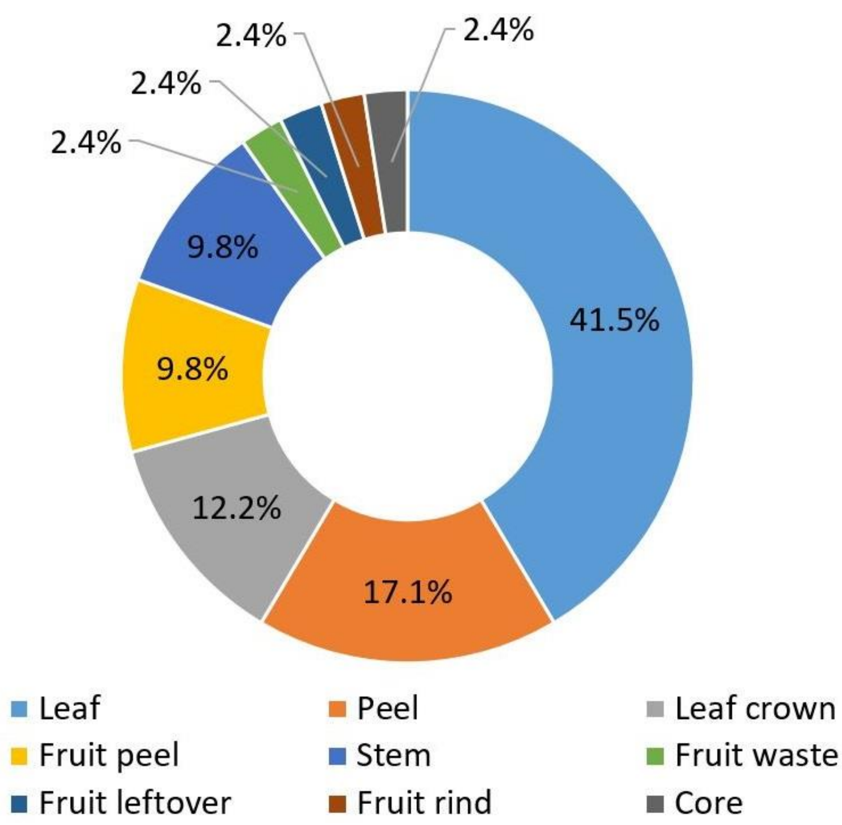


**Fig. 4.** Statistic data of popularity of various pineapple wastes studied in the past literatures.

**4. Page 10, section 3, the characteristics of pineapple wastes such as lignocellulosic composition, ultimate and approximate analyses need to be summarized in a table and include in the discussion**.

**Our response:**

The authors sincerely thank your instructive comments!

Your comments are very reasonable! As your suggestion, we added a new table with as lignocellulosic composition, ultimate and approximate analyses. We added a new section (3.2. The characteristics of pineapple wastes) to discuss these results.

*In pages 14 – 15, we added:*

3.2. The characteristics of pineapple wastes

The characteristics of pineapple wastes relies majorly on the parts (e.g., leaf, stem, peel, crown, and root) and geographical origin of the pineapple plants cultivated in various regions. Table 2 summaries the lignocellulosic composition, proximate analysis, and ultimate analysis to better understand their characteristics. The lignocellulosic composition of pineapple wastes includes cellulose, hemicellulose, lignin. Crown leaf has a low content of cellulose (12.93–17.4%), but high content of lignin (24.3–26.4%). Meanwhile, the pineapple leaf, root, and stem contain a high percentage of cellulose (30–73%) and relatively low lignin (5–20%). For example, lignin content in leaves of the pineapple cultivated in Johor Malaysia was reported to be very low, at 4.76% [37]. Hemicellulose was the highest content (31.8%) found in pineapple peel [38].

Proximate analysis includes moisture, ash, volatile matter, and fixed carbon. The content of moisture and ash content can be based on ASTM D1762-84 standard method, while volatile matter content can be determined by thermogravimetric analyzer (TGA) [39]. Fixed carbon can be calculated after known content of moisture, ash and volatile matter, or [100% – (moisture content + ash content + volatile content)]. According to Table 2, the moisture of the pineapple waste residues is lower than 10%. By contrast, the percentage of volatile matter is the highest between 41.56% and 94.4%. Ash content was determined on the dry basis, between 0.59% and 7.7%. The highest ash content (30.07%) belongs to pineapple root cultivated in Johor, Malaysia [40,41]. Fixed carbon of pineapple crown leaf was found about 7% [42,43]. In the same geographic location, fixed carbon of pineapple leaf was so far different between two studies. For example, Mansor et al. (2018) found a fixed carbon content of 34.16%, compared with 11.2% reported by Mathew et al. (2015). These results may be due to the difference between determination methods used in proximate analysis.

Ultimate analysis can be conducted using elemental analyzer to determine the percentage of chemical elements in pineapple parts. According to Table 2, the chemical composition includes carbon, oxygen, hydrogen, nitrogen, and sulfur. Carbon and oxygen distributed significantly (>90%) to the chemical composition of pineapple waste residues. A high nitrogen content in ultimate analysis suggests the presence of protein and acid amine in pineapple leaf. More importantly, (O + N)/C ratio is used predict the polarity of the sample, which correlated with the pyrolysis for the production of biochars and activated carbons [39].

*Below is the table used to summarize the results of lignocellulosic composition, proximate, and ultimate analysis of the pineapple species.*

**Table 2.** Lignocellulosic composition, proximate, and ultimate analysis of the pineapple species

| Location | Part | Lignocellulosic composition | Proximate analysis | Ultimate analysis | Ref. |
|---|---|---|---|---|---|
| Cruz das Almas, Brazil | Leaf | Cellulose: 49–63%, Hemicellulose: | Ash: 1.2–3.3% | Not reported | [45] |

| | | | | | |
|---|---|---|---|---|---|
| | | 6–13%, Lignin: 20–36% | | | |
| Johor, Malaysia | Leaf | Cellulose: 72.76%, Hemicellulose: 17.15%, Lignin: 4.76% | Ash: 0.59% | Not reported | [37] |
| São Paulo, Brazil | Crown leaf | Cellulose: 17.4%, Hemicellulose: 19.1%, Lignin: 24.3% | Ash: 5.2% | Not reported | [46] |
| Araçagi, Brazil | Crown leaf | Cellulose: 12.93%, Hemicellulose: 35.49%, Lignin: 26.4% | Moisture: 8.96%, volatile matter: 78.84%, ash: 5.22%, fixed carbon: 6.98% | C: 44.05%, H: 5.81%, O: 49.27%, N: 0.87% | [42] |
| Johor, Malaysia | Leaf | Cellulose: 30%, Hemicellulose: 37%, Lignin: 22% | Moisture: 6.75%, volatile matter: 51.74%, ash: 7.35%, fixed carbon: 34.16% | C: 43.4%, H: 6.7%, O: 59.2%, N: 1.7%, S: 0.4% | [40,41] |
| Johor, Malaysia | Stem | Cellulose: 37%, Hemicellulose: 34%, Lignin: 20% | Moisture: 9.1%, volatile matter: 58.25%, ash: 7.68%, fixed carbon: 25.18% | C: 41.1%, H: 6.7%, O: 57.3%, N: 1.45%, S: 0.56% | [40,41] |
| Johor, Malaysia | Root | Cellulose: 42%, Hemicellulose: | Moisture: 4.55%, volatile matter: 41.56%, ash: | C: 38.7%, H: 5.4%, O: 75.4%, N: 1.0%, S: 0.23% | [40,41] |

| | | | | | |
|---|---|---|---|---|---|
| | | 32%, Lignin: 19% | 30.07%, fixed carbon: 28.82% | | |
| Araçagi, Brazil | Crown leaf | Cellulose: 13.3%, Hemicellulose: 35.4%, Lignin: 26.4% | Moisture: 8.9%, volatile matter: 78.8%, ash: 5.2%, fixed carbon: 7.1% | C: 44.1%, H: 5.8%, O: 49.3%, N: 0.8% | [43] |
| Mumbai, India | Peel | Cellulose: 20.9%, Hemicellulose: 31.8%, Lignin: 10.4% | Volatile matter: 94.04%, ash: 5.9% | C: 43.9%, H: 5.7%, N: 0.6% | [38] |
| Johor, Malaysia | Leaf | Cellulose: 31.2%, Hemicellulose: 13.6%, Lignin: 17.6% | Moisture: 4.56%, volatile matter: 80.4%, ash: 3.57%, fixed carbon: 11.2% | C: 40.5%, H: 6.91%, O: 50.3%, N: 1.78%, S: 0.36% | [44] |
| Johor, Malaysia | Stem | Cellulose: 49.2%, Hemicellulose: 8.26%, Lignin: 5.42% | Moisture: 7.92%, volatile matter: 78.9%, ash: 4.87%, fixed carbon: 8.24% | C: 37.6%, H: 6.69%, O: 52.7%, N: 1.89%, S: 0.97% | [44] |
| Haryana, India | Peel | Not reported | Moisture: 6.87%, volatile matter: 68.96%, ash: 4.75%, fixed carbon: 19.52% | C: 47.39%, H: 6.13%, O: 40.64%, N: 1.08% | [39] |
| Guangdong, China | Crown and peel residue | Cellulose: 27.35%, Hemicellulose: 21.15%, | Moisture: 2.15%, volatile matter: 72.12%, ash: 6.24%, fixed carbon: 19.5% | C: 44.95%, H: 5.5%, O: 47.65%, N: 1.68%, S: 0.22% | [47] |

| | |
|---|---|
| | Lignin: 10.25% |

**5. Page 10, section 3, the most important findings need to be mentioned at the end of this section**.

**<u>Our response:</u>**

The authors sincerely thank your instructive comments!

Your comments are very reasonable! As your suggestion, we added above statement plus your reference.

*We added some statements as follows:*

"To analyze the characterization of the pineapple wastes-derived adsorbents, some techniques such as scanning electron microscopy (SEM), Brunauer–Emmett–Teller (BET), energy-dispersive X-ray spectroscopy (EDX), point of zero charge ($pH_{pzc}$), Fourier transform infrared spectroscopy (FT-IR), X-ray diffraction (XRD) pattern profile, distribution of pore sizes, and thermo-gravimetric analysis (TGA) as shown in Fig. 6. Moreover, the surface area and pore volume for the pineapple-based sorbents as functions of activating chemicals, activation temperature, time and ramping rate are involved for comparison."

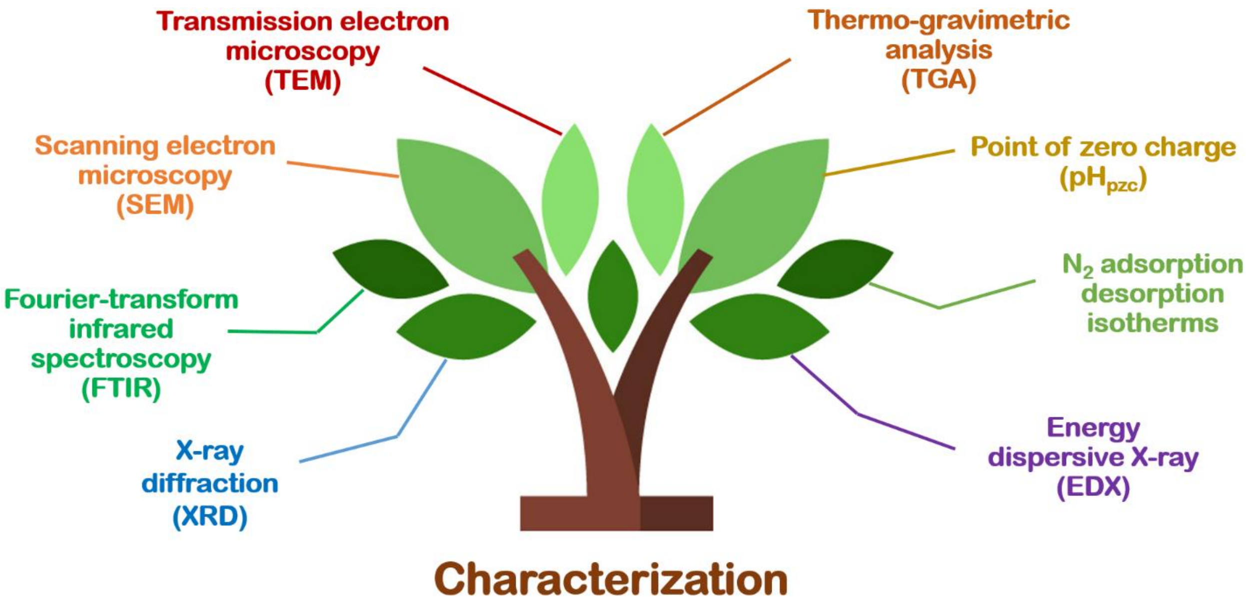


**Fig. 6.** Several common characterizations for analyses of the pineapple wastes-derived adsorbents.

*We added a summarized statement for this section:*

"To sum up, with high surface area, many surface functional groups, the pineapple waste derived adsorbents can have potential for water treatment."

Thank you so much!

**6. Page 15, section 4.2, the most utilized and efficient type of pineapple wastes-based adsorbents needs to be mentioned in this section**.

**Our response:**

The authors sincerely thank your instructive comments!

Your comments are very reasonable! Your comment is very important to our work. As your suggestion, we added new statements for section 4.2., and added proper references.

*In page 19–21, we added:*

4.2. Main findings of adsorption performance

According to Table 4, almost works reported very high removal efficiencies (>80%) of heavy metals, e.g., $Cd^{2+}$, $Pb^{2+}$, $Cu^{2+}$, $Zn^{2+}$, $Cr^{3+}$, and $CrO_4^{2-}$, except for several low efficiency results (23.0–30.5%), which were obtained by using pineapple fruit peel powder or $ZnCl_2$-activated fruit rind for removal of $Zn^{2+}$ in water [48,49]. In general, the monolayer adsorption capacities for heavy metals was acceptable between 0.45 and 42.1 $mg{\cdot}g^{-1}$. Few works reported extremely high heavy metal adsorption capacities, i.e., 102.92– 111.41 $mg{\cdot}g^{-1}$ ($Cd^{2+}$, $Pb^{2+}$) using the modified pineapple peel powder, 155.06 $mg{\cdot}g^{-1}$ ($Pb^{2+}$) using the pineapple leaf-derived cellulose [5], and 165–273 $mg{\cdot}g^{-1}$ ($Pb^{2+}$, $Cu^{2+}$, $CrO_4^{2-}$) using polyethyleneimine-carbamate (PEI)-cross-linked leaf fiber [50,51]. Moreover, the effect of pyrolysis temperature on structure and heavy metal adsorption capacity of the pineapple peel biochars was investigated by [39]. Accordingly, the biochar synthesized at higher temperature (350–650 °C) obtained lower $CrO_4^{2-}$ capacity (41.67–23.81 $mg{\cdot}g^{-1}$) and removal efficiency (99.19–40.78%).

The pineapple waste derived adsorbents were applied to treat other toxic inorganic compounds such as phosphate and fluoride. For example, Liao et al. (2018) fabricated $La(OH)_3$-modified magnetic pineapple biochar-based composites, giving an improved surface area of 84.89 $m^2$ $g^{-1}$ compared with 36.22 $m^2$ $g^{-1}$ of the origin pineapple biochar and 1.18 $m^2$ $g^{-1}$ of the pineapple-derived magnetic biochar. More importantly, a promising uptake capacity was obtained at 101.16 mg phosphate per gram of the pineapple-based magnetic composite and this composite showed a high selectivity (> 96%) in the presence of co-existing inorganic ions. In another work, Reza and Ahmaruzzaman (2022) developed an adsorbent based on the pineapple juice-extracted residue (74.92 $m^2$ $g^{-1}$) for removal of flouride from wastewater. They found a equilibrium duration of 120 min and an optimized dose of 0.9 g $L^{-1}$. As expected, a monolayer uptake capacity was found at 7.06 mg $g^{-1}$. The pineapple wasted based adsorbent could be easily recovered by 0.05 M NaOH solution.

For removal of organic dyes, more than 92% of dyes can be eliminated by the pineapple leaf powder according to Table 4. The maximum adsorption capacities towards organic dyes are higher than those towards heavy metals, between 58.80 and 288.34 $mg \cdot g^{-1}$. This result may reflect higher affinity of organic dyes than heavy metals to pineapple wastes-derived adsorbents. Weng et al. (2009) reported a very high adsorption capacity (284.03 $mg \cdot g^{-1}$) of methylene blue using the pineapple leaf powder. This result was nearly equivalent to adsorption capacity obtained by $ZnCl_2$-activated carbon [54] or NaOH-activated crown-derived carbon [1]. Microwave-assisted synthesis is expected to enhance the adsorption performance of activated carbon compared to the conventional carbonization. However, Astuti et al. (2019) found there was no improvement of dye adsorption capacity for microwave-assisted KOH-activated crown leaf-derived carbon. Some cationic surfactants have been aslo used to modify the surface of the pineapple waste adsorbents. For instance, Kamaru et al. (2016) used a cationic surfactant, namely, hexadecyltrimethylammonium bromide for the synthesis of the pineapple leaf powder. Adsorption capacity for ethylene blue and methyl orange was found, at 52.6 and 47.6 $mg \cdot g^{-1}$, respectively.

Antibiotics have played a key role in human and animal therapies as well as many aquacultural activities. However, the residue of antibiotics is causing many harmful effects, i.e., promoting antibiotic-resistant genes in bacteria. It is calling for removal of antibiotics using efficient methods such as adsorption. The pineapple waste derived adsorbents demonstrated their potential for antibiotic remediation. Indeed, Fu et al. (2016) synthesized a range of biochar at various temperatures between 350 and 650 °C to treat oxytetracycline antibiotic. As a result, the authors found the best adsorbent synthesized at 650 °C, but the adsorption capacity obtained was still very low (1.072 mg·g$^{-1}$). Zahoor et al. (2019) reported that 80% of enrofloxacin in water could be removed by $Fe_3O_4$/activated carbon. Moreover, this adsorbent had advantages such as easy separation by a magnet, simple regeneration by 3% NaOH and outstanding uptake capacity (46.3 mg·g$^{-1}$). Thus, it would be promising for the pineapple waste derived magnetic adsorbents.

Some indexes such as total organic carbon (TOC), biochemical oxygen demand (COD), chemical oxygen demand (COD), total dissolved oxygen (TDS) are key indicatives to measure the quality of water after treatment. As an example, Oni et al. (2020) compared BOD and TDS values before and after the treatment of kitchen wastewater using activated carbons. Researchers used pineapple peel and crown as precursors to synthesize activated carbons. Accordingly, two chemical agents including $H_3PO_4$ and $ZnCl_2$ have been used to activate the pineapple waste derived adsorbents under carbonization at 270 °C. They found that $ZnCl_2$-activated carbon gave better performance of BOD and TDS results than those of $H_3PO_4$-activated carbon. It was suggested that the kitchen wastewater after treatment by $ZnCl_2$-activated carbon could obtain a safety threshold for further usage.

Thank you so much!

**7. Page 15, section 5, the most important findings need to be mentioned at the end of this section.**

**<u>Our response:</u>**

The authors sincerely thank your instructive comments!

Your comments are very reasonable! As your suggestion, we added a new section (section 5.4 effect of coexisting ions) some summary on the response surface methodology (RSM)

### *5.4. Effect of coexisting ions*

In real wastewaters, strange ions can exist in the nature and they vitally affect the adsorption of adsorbate onto adsorbent. This phenomenon is due to adsorption competition and ionic forces. Liao et al. (2018) investigated the effect of ions such as $CO_3^{2-}$, $HCO_3^-$, $NO_3^-$, $SO_4^{2-}$ and $Cl^-$ on the adsorption of $[(PO_4)]^{3-}$ onto $La(OH)_3$-modified magnetic pineapple peel derived biochar. The findings indicated that there was no significant effect on phosphate removal efficiency in the presence of such anions. Therefore, the chemical affinity of adsorbent towards $[(PO_4)]^{3-}$ is strong to overcome the ionic forces during the adsorption.

*At the end of the section, we summarized some findings and gaps of the past studies as follows:*

Although the optimization using response surface methodology (RSM) has many advantages such as high reliability and rapid operation, there are very few studies reported this method to optimize the adsorption by the pineapple wastes derived adsorbents.

Thank you so much for your kind suggestion!

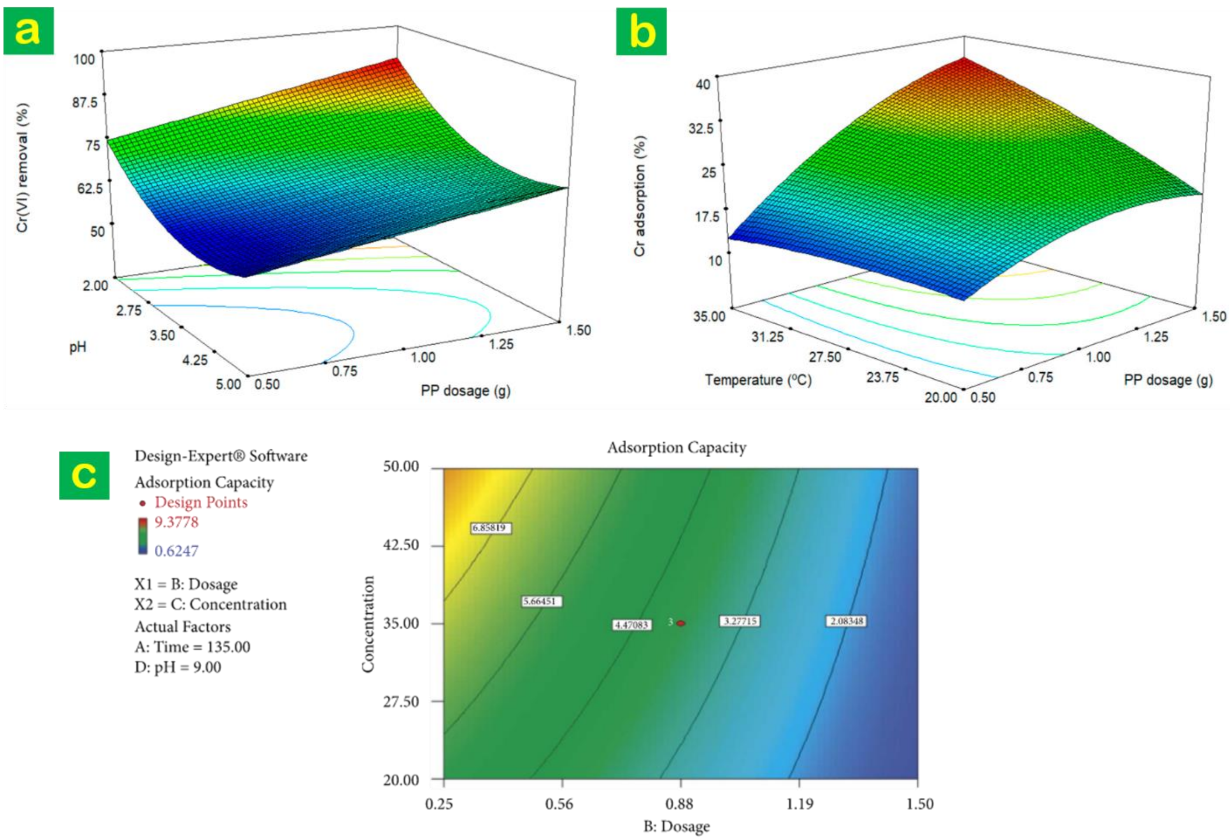


**Fig. 8.** Three dimensional surface plots for Cr(VI) removal by pineapple core (PP) adsorbent with two variables including pH and adsorbent dose, temperature was set at central level (a); effect of two variables including temperature and adsorbent dose on Cr(VI) removal by pineapple core, pH was set at central level (b). Reproduced from the reference [3] under an open access Creative Common CC BY license. A contour plot for the interaction between dose and concentration for removal of methylene blue (c). Reproduced from the reference [4] under an open access Creative Common CC BY license.

**8. Pages 27-28, sections 8 and 9, the most important findings need to be mentioned at the end of this section.**

**Our response:**

The authors sincerely thank your instructive comments!

Your comments are very reasonable! As your suggestion, we added new subsections as well as discussion to expand this section:

*In page 35 – 37, we added section 8.3. Fixed bed column:*

Depart from adsorption batch mode, up-flow/down-flow fixed bed column is another type of adsorption between adsorbate and adsorbent in a continuous liquid system [27]. It is believed that adsorption beyond fixed bed column mode is highly adaptable for industrial scale treatment of different pollutants including organic and inorganic compounds. As a result, many works made effort in the design and development of fixed bed columns [28]. The characteristic of fixed bed column adsorption study is breakthrough curves which show the relationship between concentration of the contaminant and time profile. Breakthrough curves are expressed through mass transfer zone or primary sorption zone [27]. Accordingly, wastewater is injected into the column and treated by the adsorbate. The adsorption is initially rapid due to availability of adsorption sites. The process continues until mass transfer zone reaches at the end of the column, or equilibrium is established. Breakthrough curves show S-shape in most cases of fixed bed column adsorption.

Some works used the pineapple waste-derived adsorbents to remove pollutants (e.g., heavy metal, and organic dye) in fixed bed column adsorption mode. Indeed, Rao and Khan (2017) successfully fabricated the pineapple residue adsorbent treated by NaOH solution (ATPR) and investigated its adsorption of nickel ions in water (Fig. 10). The authors initially optimized several batch adsorption conditions such as Ni(II) concentration (50 mg $L^{-1}$), pH (8), and contact time (60 min), and found $Q_m$ value of 17.56 mg $g^{-1}$. Afterwards, they designed a glass column (d = 0.6 cm, h = 3.7 cm) loaded with 0.2 g of the adsorbent. 500 mL of $Ni^{2+}$ solution was passed through this bed column (V = 1.04 $cm^3$). As a result, a breakthrough capacity was determined at 20 mg $g^{-1}$. In another work, Azman and Subki

(2022) conducted the removal of methylene blue and malachite green dyes through fixed bed column adsorption using pineapple crown $H_3PO_4$-activated carbon. The fixed bed column was designed with internal diameter (d = 3 cm) and height (h = 10 cm). 50 mL of each of the methylene blue and malachite green solution was filtered by this column. However, breakthrough and exhaustive capacities were not reported. In general, there were very few studies focusing on the adsorption of pollutants by fixed bed column using the pineapple waste-derived adsorbents. Therefore, more investigations of fixed bed column adsorption should be carried out.

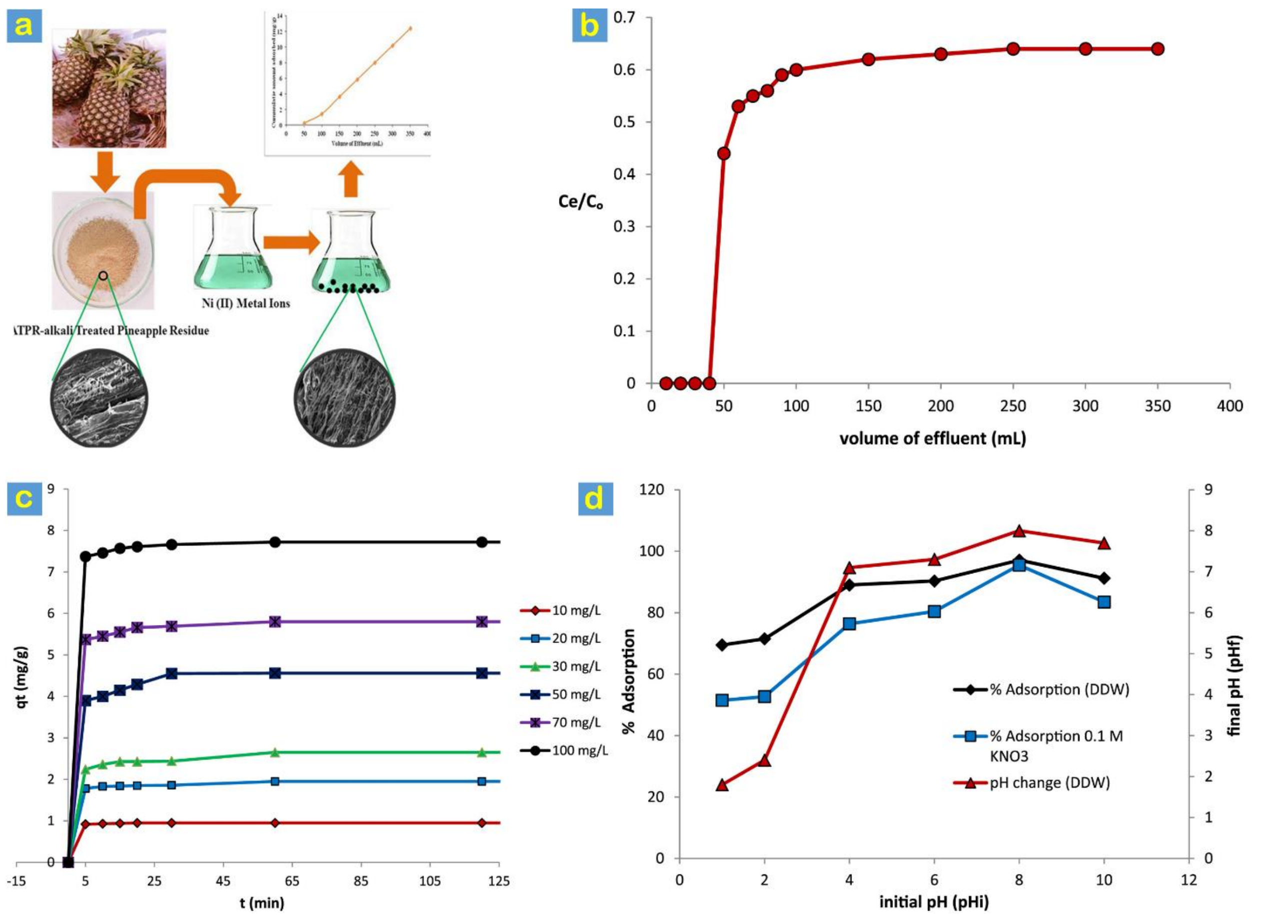


Fig. 10. Schematic illustration of synthesis and application of NaOH-treated pineapple residue adsorbent (ATPR) for removal of nickel ions from water (a); breakthrough curve for fixed bed column adsorption (b); effect of contact time (c); effect of pH and electrolyte on

adsorption of nickel ions (d). Reproduced with permission of Elsevier from the reference [6].

*In page 35 – 37, we added section 9.2 The role of complexation:*

***9.2. The role of complexation***

In general, the adsorption of heavy metals over the pineapple waste-based adsorbents can be well explained by complexation mechanisms. The surface of these modified adsorbents often contain functional groups (e.g., carboxylic acid) that can complex with heavy metal ions or transition metals (d- or f-block elements). Depending on the coordination number of metal elements, the number of functional groups is required to form a metal-functional groups complexation. By this mechanism, metal ions are captured on the surface of the pineapple-based adsorbents.

By using XPS, FTIR, and SEM-EDS spectra, the mechanism could be identified for the heavy metal adsorption on the surface of pineapple leaf biochar before and after adsorption [8]. Accordingly, it was possible that surface complexation and cation exchange involved in the adsorption mechanisms (Fig. 12).

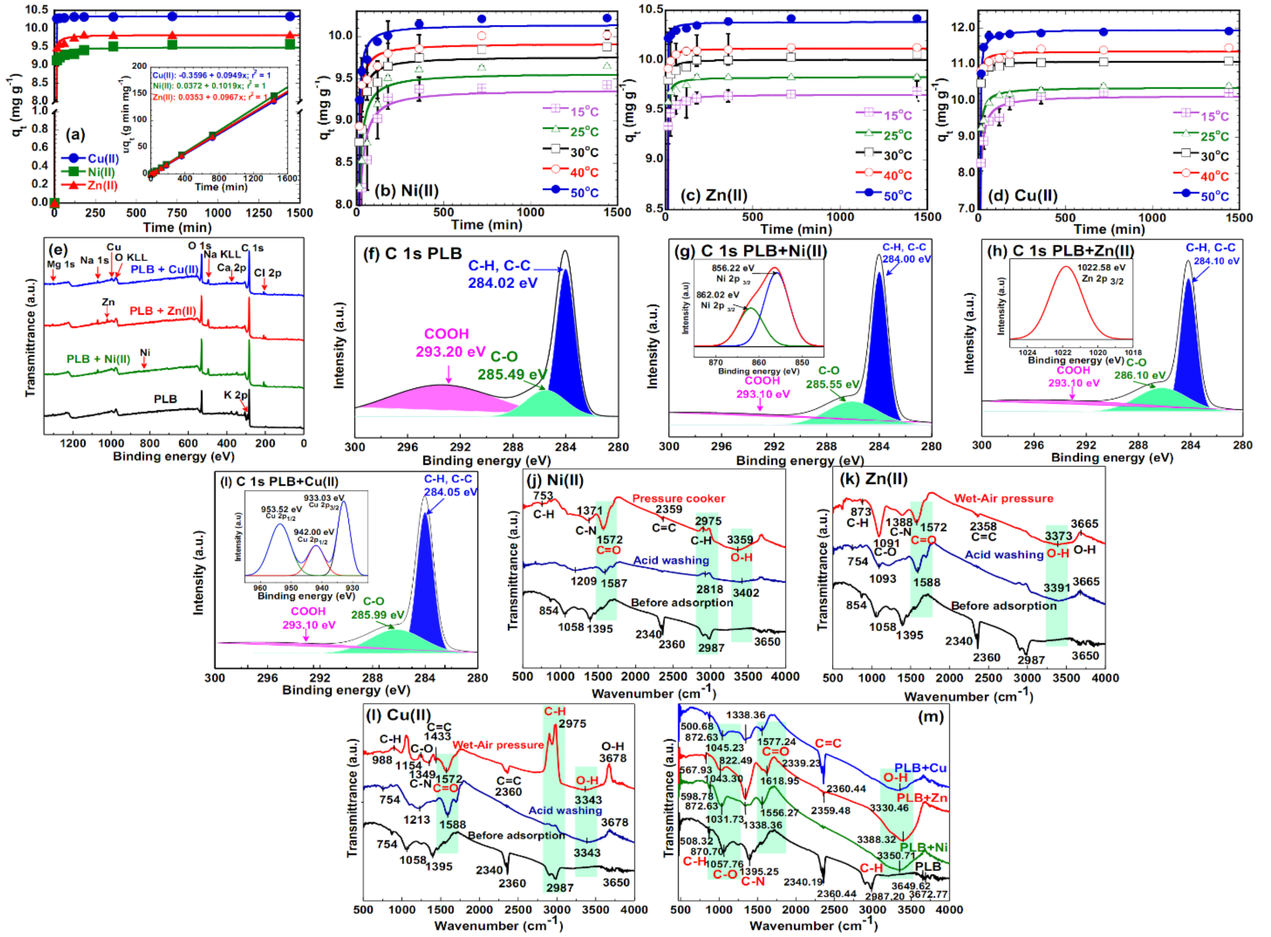

**Fig. 12.** Comparative kinetics of adsorption of heavy metal $Ni^{2+}$, $Zn^{2+}$, and $Cu^{2+}$ (a); effect of temperature on the kinetic adsorption of $Ni^{2+}$ (b), $Zn^{2+}$ (c), and $Cu^{2+}$ (d); (e) XPS survey spectra of pineapple leaf biochar before and after adsorption; XPS C 1s spectra of pineapple leaf biochar (f), pineapple leaf biochar + $Ni^{2+}$ (g), pineapple leaf biochar + $Zn^{2+}$ (h), and pineapple leaf biochar + $Cu^{2+}$ (i); FT-IR spectra of pineapple leaf biochar after regeneration using a pressure cooker and acid washing of $Ni^{2+}$ (j), $Zn^{2+}$ (k), and $Cu^{2+}$ (II) (l); chemical bond analysis by FT-IR spectra before and after regeneration (m). Reproduced from the reference [8] under an open access Creative Common CC BY license.

### *9.3. The role of ion exchange*

This mechanism may be helpful for explaining the adsorption of heavy metal over the adsorbent. Some exchangeable metal ions such as $K^+$, $Na^+$, $Ca^{2+}$ are available on the surface of the adsorbents. As a result, the replacement of these ions by heavy metal ions entail their sequestration according to Fig. 13. Even, proton $H^+$ or acidic groups can exchange with heavy metal ions. As an example, Vivian Loh Zing et al. (2019) suggested that chemical reaction like ion exchange was anticipated through replacement of –COOH groups on oxalic acid-activated pineapple stem and stem powder. Apart from mechanisms mentioned, other mechanisms such as precipitation and cation–π interaction may contribute to adsorption of heavy metals. However, such investigations have been still very limited, suggesting a better elucidation of adsorption mechanisms.

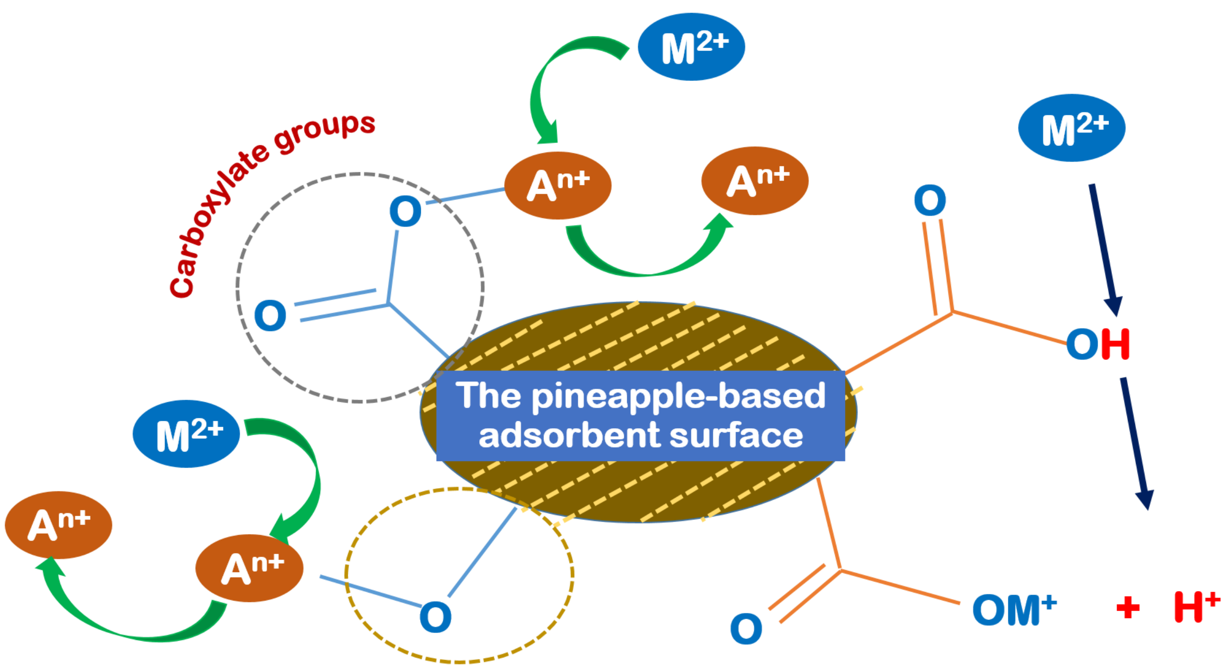


**Fig. 13.** Heavy metal adsorption onto the pineapple waste-based adsorbent via proposed ion exchange mechanism.

*At the end of the section, we summarized some findings and gaps of the past studies as follows:*

To sum up, plausible adsorption mechanisms such as electrostatic interaction, complexation, ion exchange, and chelation were included, but needed to be verified by physicochemical techniques such as FT-IR, and XPS.

Thank you so much for your kind suggestion!

**9. Page 32, section 11, conclusion needs to include other important points such as the most studied pineapple waste and the most utilized and efficient type of pineapple waste- based adsorbents.**

**Our response:**

The authors sincerely thank your instructive comments!

Your comments are very reasonable!

You comment are also very important to our work. As your suggestion, we carefully revised the conclusion section to include other important points such as the most studied pineapple waste and the most utilized and efficient type of pineapple waste- based adsorbents towards circular economy.

"In the present work, the highlighted experimental results of the production and application of the pineapple waste derived adsorbents for the environmental treatment applications were systematically overviewed. The synthesis of the pineapple derived biosorbents, modified biochars, and activated carbons and composites was discussed. Almost adsorption systems followed the pseudo second order kinetic model, and Langmuir isotherm model. The adsorption by the pineapple based adsorbents was majorly due to the contribution of electrostatic attraction, complexation, chelation, and ion exchange. The research works reported that the adsorption processes were thermodynamically spontaneous. The pineapple waste based adsorbents could be reused at 3–5 times using HCl or NaOH as eluents. For future prospects, the pineapple wastes may not only have potential for synthesis of materials such as nanoparticles, hydrogels, aerogels, and nanocomposites but also contribute proactively to circular economy.”

Thank you so much!

Below are references to support our response:


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Yours Sincerely,

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# Contents

## Abstract

Each year, nearly 30 million tons of pineapple fruit are harvested for food and drinking industries, along with the release of a huge amount of pineapple wastes. Without the proper treatment, pineapple wastes can cause adverse impacts on the environment, calling for new technologies to convert them into valuable products. Here, we review the production and application of adsorbents derived from pineapple wastes. The thermal processing or chemical modification improved the surface chemistry and porosity of these adsorbents. The specific surface areas of the pineapple wastes-based adsorbents were in range from 4.2 to at 522.9 $m^2 \cdot g^{-1}$. Almost adsorption systems followed the pseudo second order kinetic model, and Langmuir isotherm model. The adsorption mechanism was found with the major role of electrostatic attraction, complexation, chelation, and ion exchange. The pineapple wastes based adsorbents could be easily regenerated. We suggest the potential of the pineapple wastes towards circular economy.

**Keywords:** Pineapple wastes; adsorbent production; heavy metal ions; toxic dyes; environmental treatment; circular economy.

# 1. Introduction

Over the past decades, the release of pollutants such as heavy metal ions, pharmaceuticals, textile dyes from industrial effluents and influents have been becoming the hazardous sources and posed a great threat to the environment animal as well as human health (Bhavya et al., 2021). Nowadays, new technologies have been developed and widely used to detect, quantify and treat the pollutants from the wastewaters (Hasan et al., 2021; Islam et al., 2020; Kubra et al., 2021; Md. Munjur et al., 2020; Rahman et al., 2019). Adsorption method is considered as a feasible and efficient approach to solve these problems (Saheed et al., 2021). This technology offers many advantages such as high performance, good selectivity, cost-effectiveness, eco-friendliness, and easy operation (Liu et al., 2022). The biomass-derived adsorbents have been recently developed to combat the pollution of wastewater (Gopinath et al., 2021). Many works suggested that adsorbents can be easily produced by the agricultural waste with a very low cost or zero-cost (Kosheleva et al., 2019). Complex composites and nanomaterials many disadvantages, e.g., having high cost production, enduring multiple synthesis steps, using toxic chemical for material fabrication, exhibiting less eco-friendly treatment methods (Awual, 2019, 2019; Md. Rabiul Awual et al., 2019b; Awual, 2017, 2016b, 2016a, 2016c; Awual et al., 2020; Md Rabiul Awual et al., 2019; Md. Rabiul Awual et al., 2019a; Awual and Hasan, 2019). Meanwhile, the agriculture derived adsorbents can alleviate above barriers, as a result, the biomass-derived adsorbents can be favourable to the environmental remediation.

The pineapple, scientific name: *Ananas comosus* (L) Merr., belongs to Bromeliaceae family, is widely cultivated in some tropical countries in such as Brazil, Indonesia, Vietnam, Malaysia, Thailand, India, etc. Brazil is the top pineapple producer with an average production of

2.2 million tons, and Asia region accounts for 46.7% of the global pineapple production as shown in Fig. 1. According to Food and Agriculture Organization (FAO), the global production and expansion in harvested area of pineapple annually increase at 2%, and 1.8%, respectively. It is estimated that the pineapple will obtain a quantity of 37 million tons in 2030. According to Fig. 2, the worldwide production and harvested area of the pineapple have been increasing between 1994 and 2020, indicating their high demand for food and drinking industries.

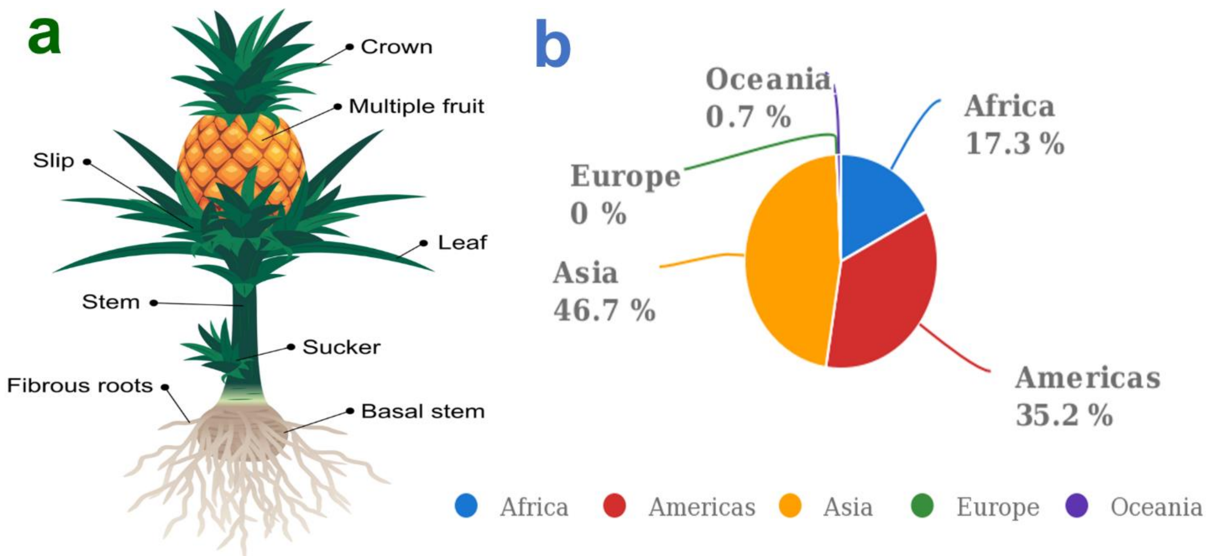


**Fig. 1.** Morphological structure of the pineapple plant with various parts including crown, fruit, leaf, sucker, basal stem, stem, root, and slip (a). Reproduced from the reference (Vieira et al., 2022). The average production shares of pineapples by region between 1994 and 2020 (b). Source: Food and Agriculture Organization, FAOSTAT (June 2022).

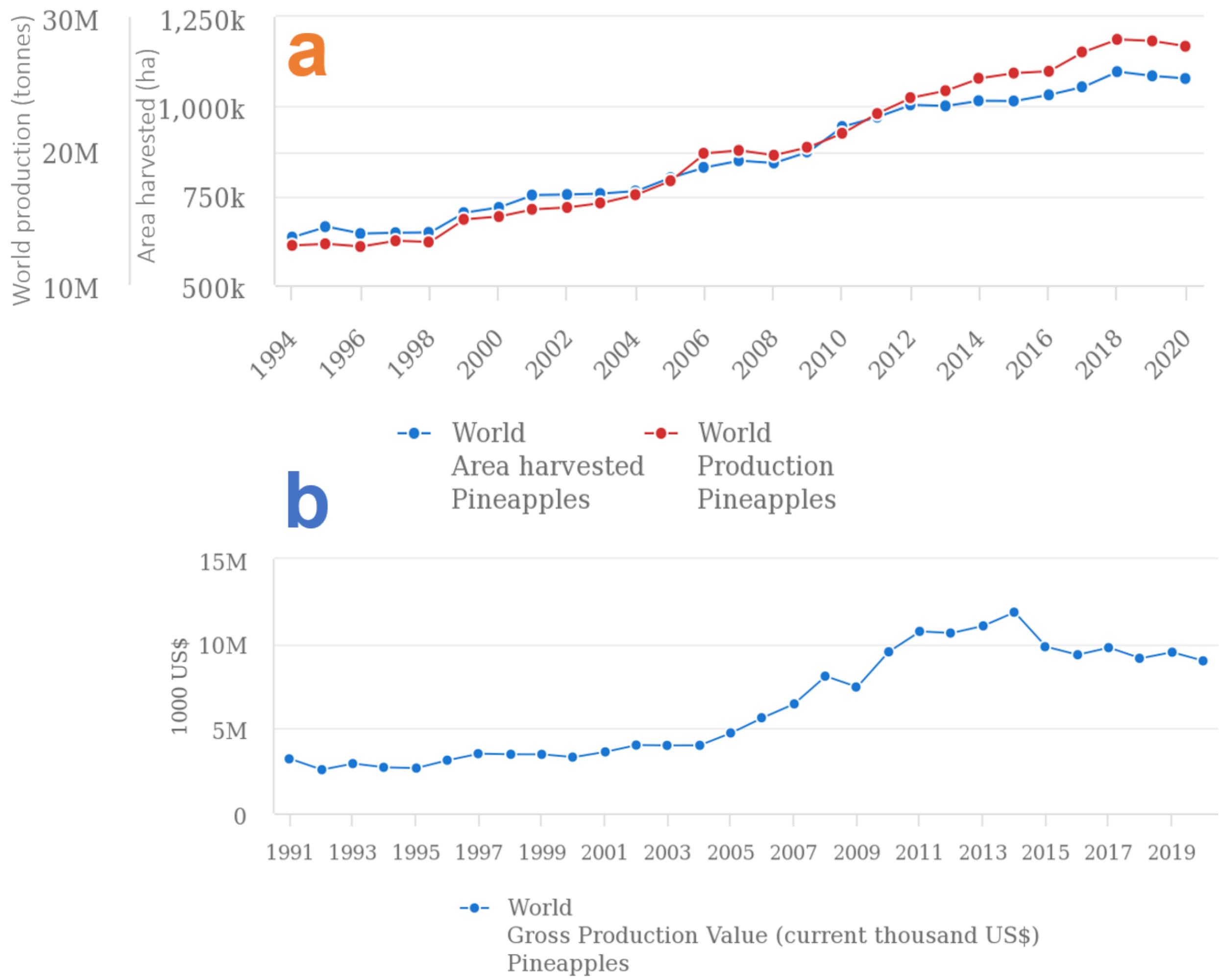


**Fig. 2.** The worldwide production and harvested area of the pineapple between 1994 and 2020 (a); the gross production value of the pineapples between 1991 and 2020 (b). Source: Food and Agriculture Organization, FAOSTAT (June 2022).

In terms of the gross production value, the pineapple has been becoming one of the economically important species (Casabar et al., 2019). Pineapple fruit obtain a good property with excellent quality, special flavor, and nutritional richness. Each pineapple fruit can provide many parts such as peel, core, crown, and pulp with various utilization (Fig. 3). For example, the nutrients of pineapple juice are important vitamins such as vitamin A, vitamin C, vitamin $B_3$, vitamin $B_6$, vitamin $B_{12}$, and many compounds useful to human health (Mohd Ali et al., 2020). As a result, pineapple juice is favored by consumers worldwide. Meanwhile, some by-products such as peel, core, and crown from the pineapple can be further processed to extract many useful compounds (e.g., phenolic, organic acid, and dietary fiber) (Meena et al., 2021). Their wastes can still contain many valuable chemical components such as celluloses (Vieira et al., 2022). It is, therefore, necessary to process such wastes to produce value-added products such as potential adsorbents for removal of pollutants in wastewater.

Many works investigated the use of the by-products such as peel, leaf or stem from the pineapple for processing of bioactive compounds, extraction, and utilization (Meena et al., 2021). The substances can be obtained with many components such as polysaccharides, antioxidants, and polyphenolic. Biosorbents and activated carbons can be directly produced from the pyrolysis of pineapple waste under nitrogen atmosphere or limited level of oxygen. These sorbents showed many good properties for the environmental mitigation. For example, Ahmad et al. (2016) demonstrated good performance of biomass-based adsorbents to remove heavy metals such as Cd(II) and Pb(II) in water. The leaf powder acted as good adsorbents to treat toxic dyes such as methylene blue and crystal violet (Chakraborty et al., 2012; Weng et al., 2009). Some researches assessed the possibility of recycling pineapple leaf powder up to 4-5 times for heavy metal removal (Daochalermwong et al., 2020; Heba et al., 2019). Therefore, conversion of pineapple wastes into useful adsorbent is very meaningful because this strategy can mitigate effectively the pollution caused by organic and inorganic compounds in different water sources such as surface waters, groundwater and drinking waters.

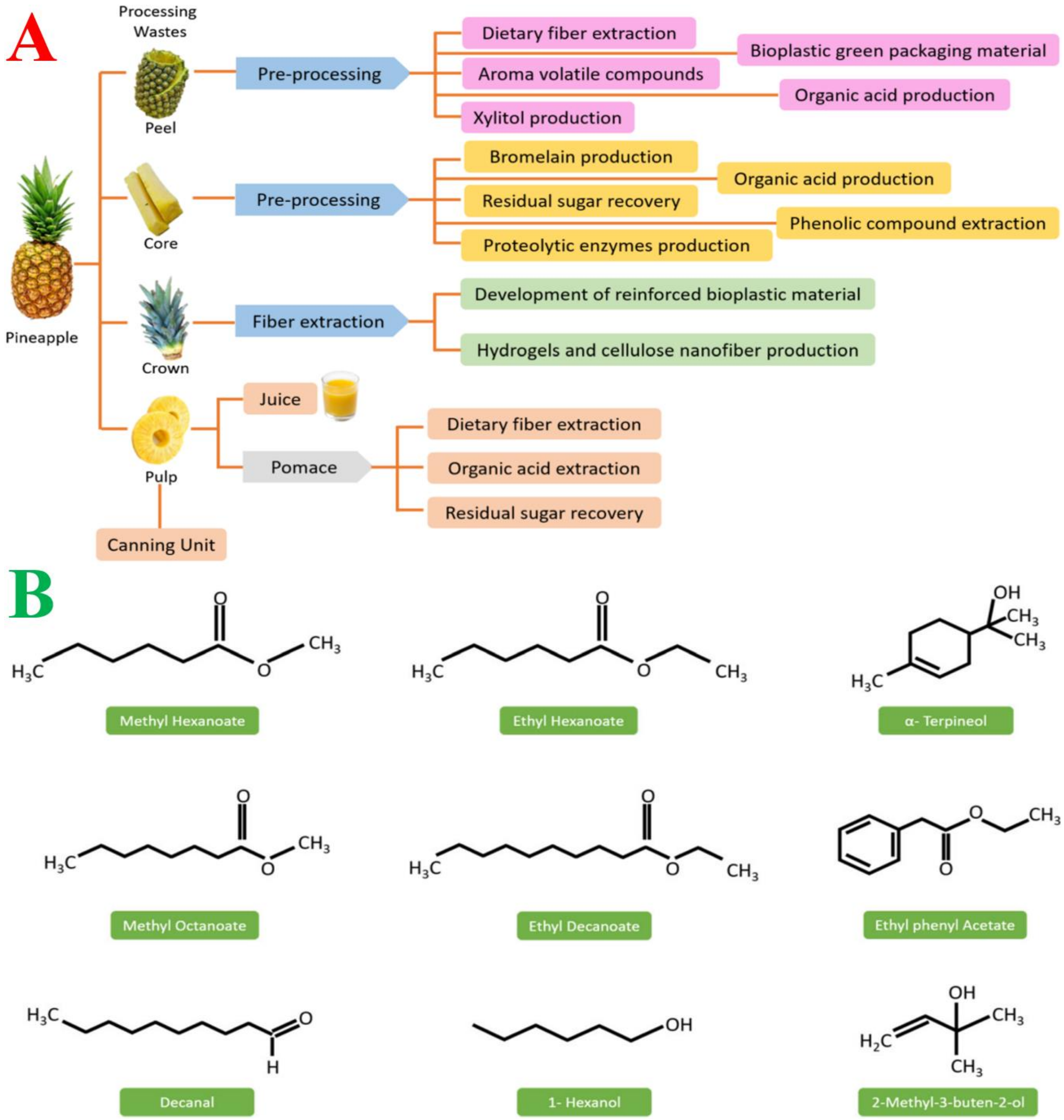


**Fig. 3.** Processing waste of pineapple to bring multiple applications (A), and major volatile compounds (B) found in pineapple wastes. Reproduced from the reference (Chakraborty et al., 2012) under an open access Creative Common CC BY license.

Recently, Aili Hamzah et al. (2021) overviewed the conversion of pineapple wastes as potential precursors for production of value-added products such as biofuels, biogasses, cellulose nanocrystals, biodegradable packaging and bio-sorbent. Similarly, several previous works have reviewed the synthesis and application of the adsorbents based on other biomass such as pistachio (*Pistacia vera*) waste (Igwegbe et al., 2021), sunflower family (Nguyen et al., 2021b), invasive plants (Nguyen et al., 2022c), water hyacinth (Li et al., 2021). However, there was no comprehensive review on pineapple wastes for the production and application of bio-based adsorbents in wastewater treatment. The authors of the current work observed a number of articles related to the use and adoption of pineapple wastes based adsorbents, but many aspects in synthesis method, empirical findings, adsorption performance, and recyclability study need to be systematically elucidated. Moreover, this review is expected to assess correctly the potential of the pineapple waste based adsorbents in the future works.

## 2. Production of the pineapple wastes-derived adsorbents

### *2.1. Pineapple waste sorbents*

Pineapple wastes can be transformed into sorbents through some proper techniques including chemical modification, thermal pyrolysis and activation. In this section, we elucidate the procedure of these techniques as well as highlight some findings obtained from the previous works. The chemical modification and carbonization to produce the pineapple wastes-based sorbents are displayed in Table 1. Initially, the source of pineapple wastes can come from various parts such as fruit peel, leaf, core, fruit rind, and stem. According to Fig. 4, the most adopted and efficient part of pineapple wastes is leaf (41.5%), followed by pineapple peel (17.1%) and leaf crown (12.2%). It can be understandable that leaf is the major and available component of the pineapple. Therefore, the majority of works studied the pineapple leaf due to its popularity. Next, the precursors are pretreated to remove the dirties or residuals by washing with $H_2O$ many times (Weng and Wu, 2012). After pretreatment, they are dried at 80-120 °C in oven or under solar energy source (Mishra and Tadepalli, 2015; Rosales et al., 2019). To form the adsorbents, the dried precursors need to be ground and sieved into small particles with the size between 75 and 3000 μm. This step aims to increase the surface area of the sorbents, which helps to enhance the treatment efficiency of pineapple-derived adsorbents.

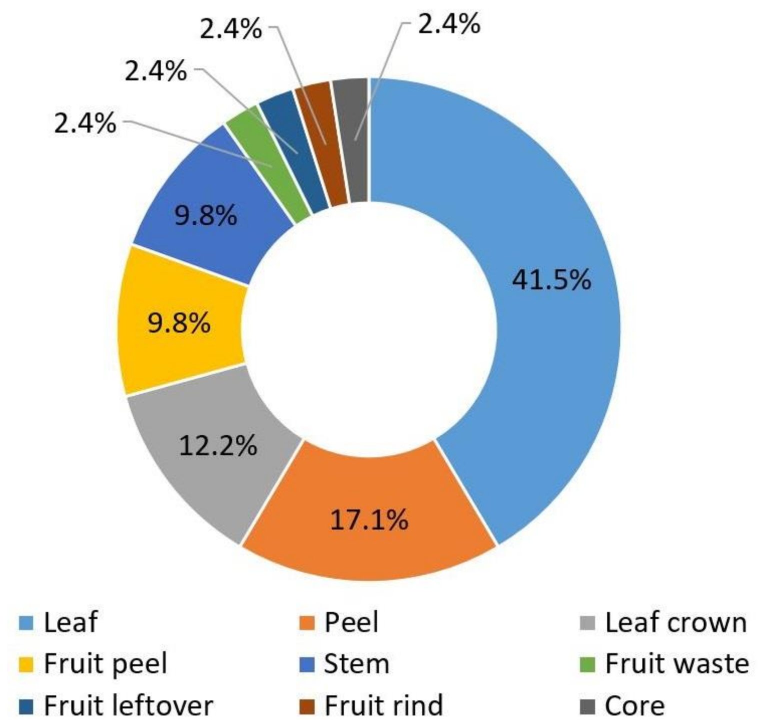


Fig. 4. Statistic data of popularity of various pineapple wastes studied in the past literatures.

### *2.2. Pineapple waste biochars*

In general, pineapple biomass wastes treated above 150 °C may significantly change many inherent properties of the products, not called 'bio-sorbents', but 'biochar'. In this case, the cellulose structure of pineapple precursor is broken under thermolysis condition, leading to the formation of amorphous carbon matrix. A majority of volatile components such as $H_2O$ in the biomass are swiftly released from the precursor. Some small molecules such as monosaccharide can be decomposed into $CO_2$, $H_2O$, and several decomposed products (Krishni et al., 2014).

Sometimes, the thermolysis of pineapple biomass wastes can be undertaken by using microwave irradiation (Turkmen et al., 2021). The most significant advantage of microwave pyrolysis is to accelerate the duration of process from seconds to minutes. However, it may be difficult to control the microwave heating and the quality of biochar obtained.

### *2.3. Modified carbons*

#### *2.3.1. Physical activation*

In fact, both biosorbents and biochars derived from pineapple wastes can be immediately ready for using in the adsorption systems without any further processes. To improve their surface chemistry as well as structural characteristic, however, the modification stage should be undergone. Thereby, the adsorbents are more likely to reach better adsorption performance. The studies reported that the pineapple-derived activated carbon products can be prepared through either the physical or chemical method. The physical activation of pineapple wastes is often surveyed under the atmosphere of $CO_2$, steam, or steam/$CO_2$ (Nguyen et al., 2021a). However, this activation method was not still applied to produce activated carbons from the apple wastes.

#### *2.3.2. Chemical activation*

Meanwhile, the chemical activation uses strongly dehydrated/oxidative agents such as $H_2SO_4$, $KMnO_4$ (Ahmad et al., 2016), $ZnCl_2$ (Turkmen et al., 2021), NaOH (Gogoi et al., 2018), oxalic acid (Vivian Loh Zing et al., 2019), NaOH/ethylenediaminetetraacetic acid (Daochalermwong et al., 2020), and iminodiacetic acid (Heba et al., 2019). Fig. 5 illustrates the synthesis procedure for pineapple fibers and NaOH-activated pineapple fiber derived carbon. The introduction of chemical reagents is to develop new pores and/or increase surface area of obtained activated carbons. Therefore, their adsorption performance can be improved considerably. However, the important points in this strategy may be the selection of chemicals, optimization of chemical/precursor ratio, temperature and duration of carbonization. Moreover, the residual chemicals after activation should be wholly treated to avoid the negative impacts on the environment. Some considerations of properties of chemically modified pineapple-derived adsorbents should be taken.

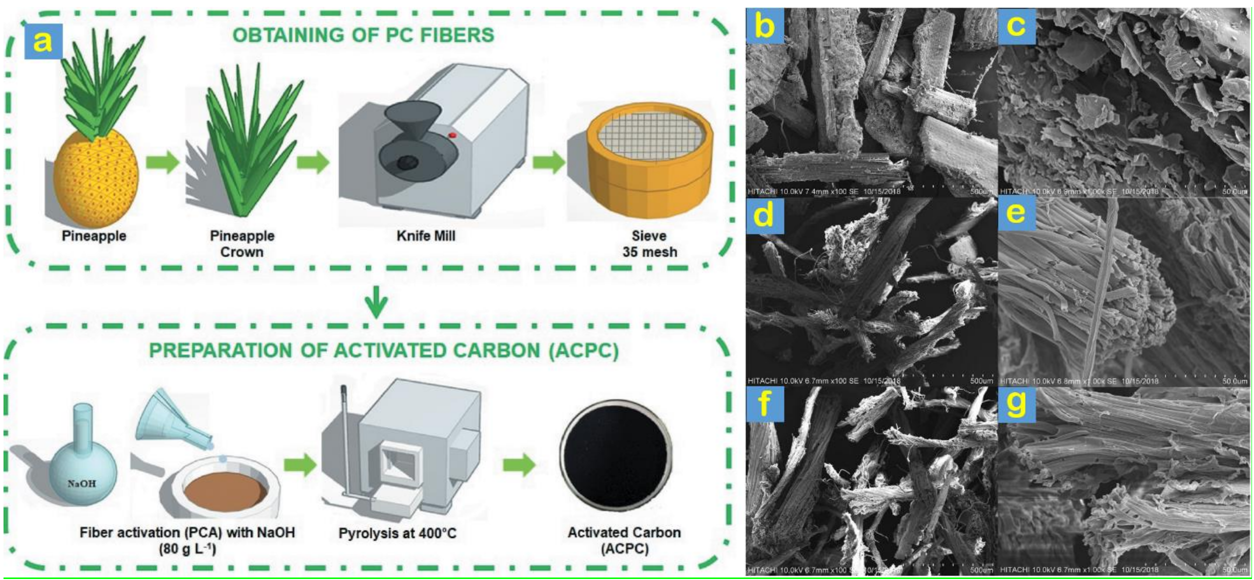


Fig. 5. Synthesis procedure for pineapple fibers and NaOH-activated carbon (a). Reproduced from the reference (da Silva et al., 2021). The SEM microphotograph of pineapple leaf powder (b, c), NaOH modified pineapple leaf powder (d, e), iminodiacetic acid modified pineapple leaf powder (f, g). Reproduced from the reference (Heba et al., 2019).

# 3. Characterization of pineapple wastes-derived adsorbents

## *3.1. Background*

Because the adsorption process relies on the surface area, surface functional groups and porosity of the adsorbents, the structural investigation should be a key task. To analyze the characterization of the pineapple wastes-derived adsorbents, some techniques such as scanning electron microscopy (SEM), Brunauer–Emmett–Teller (BET), energy-dispersive X-ray spectroscopy (EDX), point of zero charge ($pH_{pzc}$), Fourier transform infrared spectroscopy (FT-IR), X-ray diffraction (XRD) pattern profile, distribution of pore sizes, and thermo-gravimetric analysis (TGA) as shown in Fig. 6. Moreover, the surface area and pore volume for the pineapple-based sorbents as functions of activating chemicals, activation temperature, time and ramping rate are involved for comparison. This section will discuss the effect of fabrication conditions on the structure and characterization of for pineapple wastes-derived adsorbents.

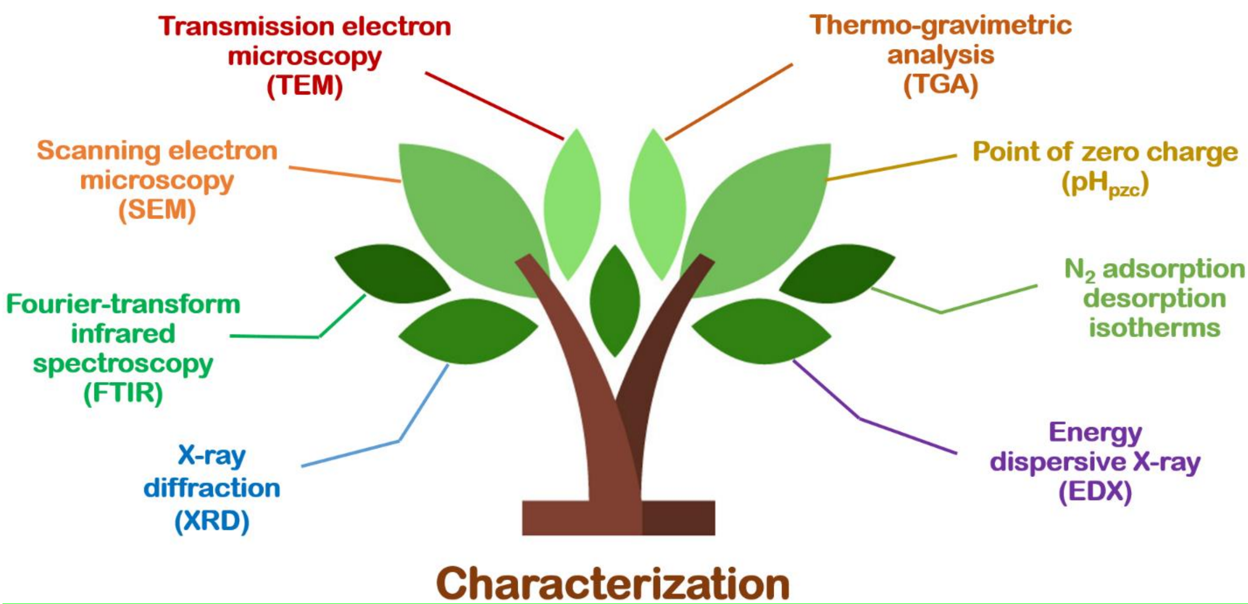


Fig. 6. Several common characterizations for analyses of the pineapple wastes-derived adsorbents.

### *3.2. The characteristics of pineapple wastes*

The characteristics of pineapple wastes relies majorly on the parts (e.g., leaf, stem, peel, crown, and root) and geographical origin of the pineapple plants cultivated in various regions. Table 2 summaries the lignocellulosic composition, proximate analysis, and ultimate analysis to better understand their characteristics. The lignocellulosic composition of pineapple wastes includes cellulose, hemicellulose, lignin. Crown leaf has a low content of cellulose (12.93–17.4%), but high content of lignin (24.3–26.4%). Meanwhile, the pineapple leaf, root, and stem contain a high percentage of cellulose (30–73%) and relatively low lignin (5–20%). For example, lignin content in leaves of the pineapple cultivated in Johor Malaysia was reported to be very low, at 4.76% (Nashiruddin et al., 2020). Hemicellulose was the highest content (31.8%) found in pineapple peel (Banerjee et al., 2019).

Proximate analysis includes moisture, ash, volatile matter, and fixed carbon. The content of moisture and ash content can be based on ASTM D1762-84 standard method, while volatile matter content can be determined by thermogravimetric analyzer (TGA) (Shakya and Agarwal, 2019). Fixed carbon can be calculated after known content of moisture, ash and volatile matter, or [100% – (moisture content + ash content + volatile content)]. According to Table 2, the moisture of the pineapple waste residues is lower than 10%. By contrast, the percentage of volatile matter is the highest between 41.56% and 94.4%. Ash content was determined on the dry basis, between 0.59% and 7.7%. The highest ash content (30.07%) belongs to pineapple root cultivated in Johor, Malaysia (Mansor et al., 2019, 2018). Fixed carbon of pineapple crown leaf was found about 7% (Braga et al., 2015; Calixto et al., 2022). In the same geographic location, fixed carbon of pineapple leaf was so far different between two studies. For example, Mansor et al. (2018) found a fixed carbon content of 34.16%, compared with 11.2% reported by Mathew et al. (2015). These results may be due to the difference between determination methods used in proximate analysis.

Ultimate analysis can be conducted using elemental analyzer to determine the percentage of chemical elements in pineapple parts. According to Table 2, the chemical composition includes carbon, oxygen, hydrogen, nitrogen, and sulfur. Carbon and oxygen distributed significantly (>90%) to the chemical composition of pineapple waste residues. A high nitrogen content in ultimate analysis suggests the presence of protein and acid amine in pineapple leaf. More importantly, (O + N)/C ratio is used predict the polarity of the sample, which correlated with the pyrolysis for the production of biochars and activated carbons (Shakya and Agarwal, 2019).

### *3.3. Specific surface area*

The specific surface areas of the pineapple wastes-derived adsorbents are initially mentioned (Table 3). For the unmodified pineapple wastes-derived adsorbents, the surface area and pore volume were found to be very low at 4.26 $m^2$ $g^{-1}$ and 0.033 $cm^3$ $g^{-1}$ (Weng and Wu, 2012). Similarly, Weng et al. (2009) reported a low surface area (5.24 $m^2$ $g^{-1}$) of the dried pineapple leaf powder. Low porosity of the adsorbent is attributable to the undeveloped nanofiber structure of pineapple biomass. As modified by 0.1 M NaOH for 2 h, Gogoi et al. (2018) reported an improved porosity (32.9 $m^2$ $g^{-1}$) of pineapple crown leaf-derived activated carbon. Some pineapple biochars synthesized by pyrolysis of dried leaves at 500 °C for 2 min gave a moderate surface area (44.775 $m^2$ $g^{-1}$) (Herlinawati et al., 2022). However, the $H_2SO_4$-activated carbon possessed a lower surface area (25.68 $m^2$ $g^{-1}$). The temperature of pyrolysis of pineapple biomass waste can affect the structure of biochars. Indeed, Ponou et al. (2011) elucidated the effect calcination temperature (350 and 450 °C) on the surface area. The authors found that the pineapple leaf powder with a very low surface area (6.84 $m^2$ $g^{-1}$) gave a value surface area (374.9 $m^2$ $g^{-1}$) as activated at 450 °C higher than that (44.08 $m^2$ $g^{-1}$) at 350 °C.

### *3.4. The point of zero charge*

The point of zero charge ($pH_{pzc}$) is an important indicator to determine whether the surface of pineapple wastes-derived adsorbents is positively charged or negatively charged at a certain pH. The $pH_{pzc}$ can be used to better understand the role of electrostatic interaction between adsorbent and adsorbate. In Table 3, the $pH_{pzc}$ values of the adsorbents are from 2.1 to 4.0, indicating that the surface of pineapple wastes-derived adsorbents can be positively charged at pH 4 or less than 4. The presence of oxygenated groups such as carboxylic acids or polyphenols is mainly responsible for the low $pH_{pzc}$ value. However, the modification by acid or base reagents can differ the point of zero charge. For example, the modification by NaOH can increase the $pH_{pzc}$ of pineapple wastes-derived adsorbents (Gogoi et al., 2018). Meanwhile, the acid-modified adsorbents reduce this indicator due to the insertion of many acid groups into their structure.

### *3.5. Morphology*

Apart from the characteristics of surface area, pore volume, and point of zero charge, other analyses such as scanning electron microscopy and surface chemistry also play a vital role. Firstly, the scanning electron microscopy can be used to examine the morphology of pineapple-derived adsorbents. In general, pineapple biomass has a smooth surface with the original fibrous structure. Meanwhile, the activated carbons or biochars from pineapple waste can offer many defective degree and high porosity due to the deconstruction of cellulose chains (Das et al., 2016). One of the typical morphologies is honeycomb or a hierarchical order (Fig. 7). Not only the precursor, but a treatment method by various chemical agents can also lead to the considerable difference in the morphology. As shown Fig. 7, the preparation procedure of the pineapple peels into various hydrogels by a modification by NaOH or bleaching treatment for lignin and hemicellulose removal can obtain the morphological diversity. Moreover, Mahamad et al. (2015) reported the difference of morphology of $ZnCl_2$-activated carbons derived from a variety of pineapple parts including crown, stem or leaf.

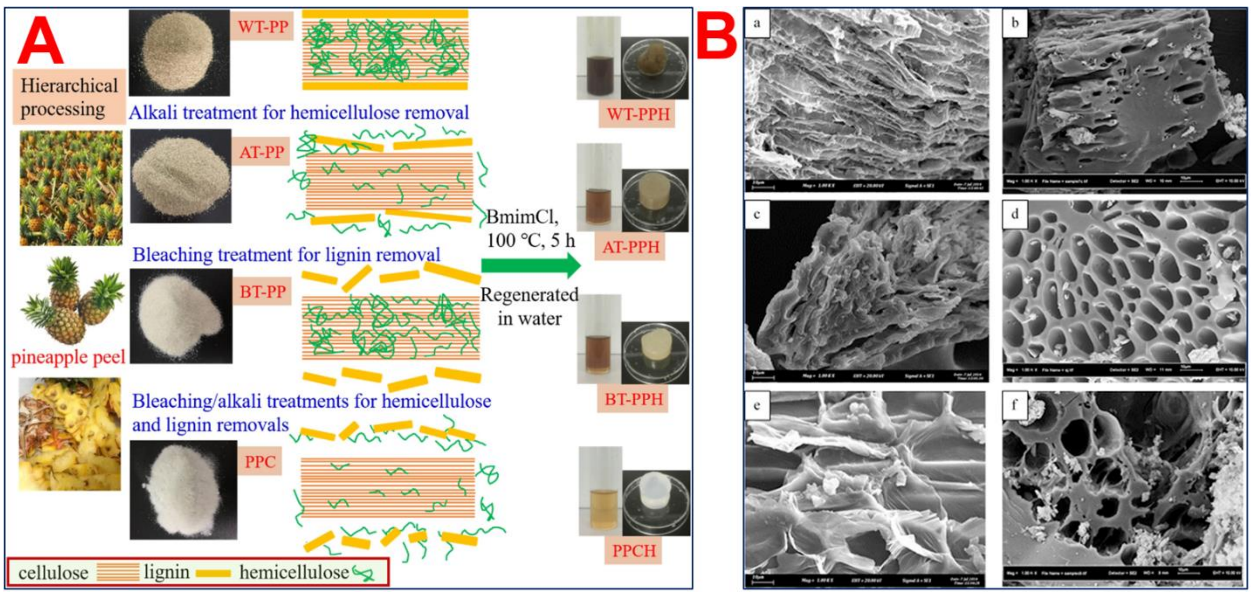


**Fig. 7.** (A) The preparation procedure of the pineapple peels into various hydrogels by modification by NaOH or bleaching treatment for lignin and hemicellulose removal. Reproduced from the reference (Das et al., 2016); (B) the scanning electron micrographs of pineapple stem (a), $ZnCl_2$-activated carbon derived from pineapple leaf (b), pineapple crown (c), $ZnCl_2$-activated carbon derived from pineapple stem (d), pineapple leaf (e), and $ZnCl_2$-activated carbon from pineapple crown (f). Reproduced with the permission of Elsevier B.V. from the reference (Mahamad et al., 2015).

### *3.6. Surface chemistry*

Surface chemistry of pineapple-derived adsorbents explore the functional groups, which can be determined by FT-IR analysis. Overall, the alternation of typical summits in FT-IR before and after adsorption suggest a relevant mechanism with the contribution of respective functional groups to the adsorption performance of pineapple wastes derived adsorbents. For pineapple wastes based biosorbents, there is frequently included with bending vibrations of the $-CH_2-$ bond, which belongs to the cellulose backbone (Daochalermwong et al., 2020). In terms of biochars or activated carbons, C–O/C=O (1660–1720 $cm^{-1}$) can be found due to the existence of aldehydes or ketones, e.g., lactones, or carboxylates or esters, which can be formed under pyrolysis of monosaccharide or proteins in pineapple biomass (Yılmaz and Tugrul, 2022). Almost pineapple-derived adsorbents contain O–H bonds (~3400 $cm^{-1}$) from hydroxyl compounds such as phenols, carboxylic acids or alcohols. Moreover, C=C bonds (1515–1518 $cm^{-1}$) offers many electrons in aromatic rings, which can interact with the adsorbate through π–π interaction (Krishni et al., 2014). Sometimes, the presence of heteroatom such as N (C–N/C=N), P (P–O–C), S (S–C) in the structure of benzene rings are found (Krishni et al., 2014). To sum up, with high surface area, many surface functional groups, the pineapple waste derived adsorbents can have potential for water treatment.

## 4. Adsorption performance of pineapple wastes-derived adsorbents

### *4.1. Scope of studies*

The performance of pineapple wastes-derived adsorbents can be assessed by maximum adsorption capacity and removal efficiency. The maximum adsorption capacity is calculated by using Langmuir isotherm fitting. The removal efficiency can be determined experimentally. According to Table 4, the maximum adsorption capacity values are listed in above 30 articles, which is more widely than the removal efficiency found in about 20 articles. There are two main kinds of pollutants including heavy metals and organic dyes treated by pineapple wastes derived adsorbents. The heavy metals used for surveys include $Cd^{2+}$, $Pb^{2+}$, $Cu^{2+}$, $Cr^{6+}$, and $Zn^{2+}$. The organic dyes were selected as adsorbate, such as methylene blue, crystal violet, basic green 4, rose Bengal, and Congo red organic dyes.

***4.2. Main findings of adsorption performance***

According to Table 4, almost works reported very high removal efficiencies (>80%) of heavy metals, e.g., $Cd^{2+}$, $Pb^{2+}$, $Cu^{2+}$, $Zn^{2+}$, $Cr^{3+}$, and $CrO_4^{2-}$, except for several low efficiency results (23.0–30.5%), which were obtained by using pineapple fruit peel powder or $ZnCl_2$-activated fruit rind for removal of $Zn^{2+}$ in water (Mishra et al., 2010; Yılmaz and Tugrul, 2022). In general, the monolayer adsorption capacities for heavy metals was acceptable between 0.45 and 42.1 $mg \cdot g^{-1}$. Few works reported extremely high heavy metal adsorption capacities, i.e., 102.92–111.41 $mg \cdot g^{-1}$ ($Cd^{2+}$, $Pb^{2+}$) using the modified pineapple peel powder, 155.06 $mg \cdot g^{-1}$ ($Pb^{2+}$) using the pineapple leaf-derived cellulose (Daochalermwong et al., 2020), and 165–273 $mg \cdot g^{-1}$ ($Pb^{2+}$, $Cu^{2+}$, $CrO_4^{2-}$) using polyethyleneimine-carbamate (PEI)-cross-linked leaf fiber (Tangtubtim and Saikrasun, 2019a, 2019b). Moreover, the effect of pyrolysis temperature on structure and heavy metal adsorption capacity of the pineapple peel biochars was investigated by (Shakya and Agarwal, 2019). Accordingly, the biochar synthesized at higher temperature (350–650 °C) obtained lower $CrO_4^{2-}$ capacity (41.67–23.81 $mg \cdot g^{-1}$) and removal efficiency (99.19–40.78%).

The pineapple waste derived adsorbents were applied to treat other toxic inorganic compounds such as phosphate and fluoride. For example, Liao et al. (2018) fabricated $La(OH)_3$-modified magnetic pineapple biochar-based composites, giving an improved surface area of 84.89

$m^2\ g^{-1}$ compared with 36.22 $m^2\ g^{-1}$ of the origin pineapple biochar and 1.18 $m^2\ g^{-1}$ of the pineapple-derived magnetic biochar. More importantly, a promising uptake capacity was obtained at 101.16 mg phosphate per gram of the pineapple-based magnetic composite and this composite showed a high selectivity (> 96%) in the presence of co-existing inorganic ions. In another work, Reza and Ahmaruzzaman (2022) developed an adsorbent based on the pineapple juice-extracted residue (74.92 $m^2\ g^{-1}$) for removal of flouride from wastewater. They found a equilibrium duration of 120 min and an optimized dose of 0.9 g $L^{-1}$. As expected, a monolayer uptake capacity was found at 7.06 mg $g^{-1}$. The pineapple wasted based adsorbent could be easily recovered by 0.05 M NaOH solution.

For removal of organic dyes, more than 92% of dyes can be eliminated by the pineapple leaf powder according to Table 4. The maximum adsorption capacities towards organic dyes are higher than those towards heavy metals, between 58.80 and 288.34 mg·$g^{-1}$. This result may reflect higher affinity of organic dyes than heavy metals to pineapple wastes-derived adsorbents. Weng et al. (2009) reported a very high adsorption capacity (284.03 mg·$g^{-1}$) of methylene blue using the pineapple leaf powder. This result was nearly equivalent to adsorption capacity obtained by $ZnCl_2$-activated carbon (Mahamad et al., 2015) or NaOH-activated crown-derived carbon (da Silva et al., 2021). Microwave-assisted synthesis is expected to enhance the adsorption performance of activated carbon compared to the conventional carbonization. However, Astuti et al. (2019) found there was no improvement of dye adsorption capacity for microwave-assisted KOH-activated crown leaf-derived carbon. Some cationic surfactants have been aslo used to modify the surface of the pineapple waste adsorbents. For instance, Kamaru et al. (2016) used a cationic surfactant, namely, hexadecyltrimethylammonium bromide for the synthesis of the pineapple leaf powder.

Adsorption capacity for ethylene blue and methyl orange was found, at 52.6 and 47.6 mg·g$^{-1}$, respectively.

Antibiotics have played a key role in human and animal therapies as well as many aquacultural activities. However, the residue of antibiotics is causing many harmful effects, i.e., promoting antibiotic-resistant genes in bacteria. It is calling for removal of antibiotics using efficient methods such as adsorption. The pineapple waste derived adsorbents demonstrated their potential for antibiotic remediation. Indeed, Fu et al. (2016) synthesized a range of biochar at various temperatures between 350 and 650 °C to treat oxytetracycline antibiotic. As a result, the authors found the best adsorbent synthesized at 650 °C, but the adsorption capacity obtained was still very low (1.072 mg·g$^{-1}$). Zahoor et al. (2019) reported that 80% of enrofloxacin in water could be removed by $Fe_3O_4$/activated carbon. Moreover, this adsorbent had advantages such as easy separation by a magnet, simple regeneration by 3% NaOH and outstanding uptake capacity (46.3 mg·g$^{-1}$). Thus, it would be promising for the pineapple waste derived magnetic adsorbents.

Some indexes such as total organic carbon (TOC), biochemical oxygen demand (COD), chemical oxygen demand (COD), total dissolved oxygen (TDS) are key indicatives to measure the quality of water after treatment. As an example, Oni et al. (2020) compared BOD and TDS values before and after the treatment of kitchen wastewater using activated carbons. Researchers used pineapple peel and crown as precursors to synthesize activated carbons. Accordingly, two chemical agents including $H_3PO_4$ and $ZnCl_2$ have been used to activate the pineapple waste derived adsorbents under carbonization at 270 °C. They found that $ZnCl_2$-activated carbon gave better performance of BOD and TDS results than those of $H_3PO_4$-activated carbon. It was suggested that the kitchen wastewater after treatment by $ZnCl_2$-activated carbon could obtain a safety threshold for further usage.

## 5. Effect of factors on adsorption and treatment optimization

### *5.1. Effect of solution pH*

To undertake the optimization of treatment efficiency, the operation of parameters such as pH of the solution, adsorbent dosage, and contact time. It is understood that the pH of the solution profoundly affects the ionization and disassociation of adsorbate. As a result, the change in the pH solution may lead to the significant change in the removal efficiency and adsorption capacity.

As shown in Table 4, the optimized pH at 2–7 was found for the removal of heavy metal, except for a report on the use of fruit peel to remove Cd(II), Cr(VI), and Pb(II) ions (Yusoff et al., 2020). It can be understood that heavy metal ions compete with protons ($H^+$) in the acidic solution, resulting in the difficulty to remove them from water. However, in the alkaline solution (pH > 7), even neutral or slightly acidic solution, some heavy metal ions can be precipitated. As such, the adsorption performance of pineapple wastes derived adsorbents cannot be reflected exactly. To select the proper range of pH, the point of zero charge of these adsorbents should be examined to find the best adsorption conditions.

For the removal of organic dyes, the optimum conditions for pH is widely varied from 4 to 9 using different adsorbents. For example, pineapple peel hydrogels were used to remove Congo red dye from the solution at optimum pH 4, giving a high maximum adsorption capacity (114.94–138.89 mg $g^{-1}$) (Das et al., 2016). At neutral pH, Weng et al. (2009) used the pineapple leaf powder sorbent for the treatment of methylene blue. They reported that 95.0% of this dye could be treated from water, while the adsorption capacity was obtained to be very high, at 284.03 mg $g^{-1}$. Meanwhile, 99.36% of basic green 4 has been eliminated at pH 9 by the pineapple leaf powder as reported previously (Chowdhury et al., 2011).

### *5.2. Effect of adsorbent dose*

The adsorbent dose affects the removal efficiency as well as the treatment cost. As a result, the adsorbent dosage needs to be optimized before the adsorbent can be used in the real applications. Based on Table 4, the removal of heavy metals was conducted under doses of 0.2 – 120 g $L^{-1}$. Meanwhile, the optimum dose of pineapple wastes based adsorbents was acceptable from 0.67 to 5.0 g $L^{-1}$ for the removal of organic dyes. It showed a general trend that a large amount of pineapple biomass adsorbents with dosages of 4–60 g $L^{-1}$ was used to treat heavy metals, while a smaller dosage of chemically activated adsorbents is required. For example, the pineapple fruit peel carbon activated by $ZnCl_2$ with a dose of 0.25 g $L^{-1}$ could remove 92–94% of Zn(II) as reported by a recent work (Turkmen et al., 2021). Meanwhile, despite a higher dose of 1.0 g $L^{-1}$, the pineapple fruit peel powder (0.5 mm in particle size) only treated 23.0% of Zn(II) after 480 min (Mishra et al., 2010). These findings proposed a statement of better quality of activated adsorbents than normal ones that not activated.

### *5.3. Effect of contact time*

Adsorption process using pineapple-based adsorbents can reach equilibrium nature at a certain period. Therefore, the optimization of contact time is required. As shown in Table 4, there was no fixed optimum contact time to reach equilibrium for adsorption of heavy metals. A contact time of 20-240 min was important to reach adsorption equilibrium. As an example, Weng and Wu (2012) found a short equilibrium time of 20 min for adsorption of Cu(II) ions using the pineapple leaf powder. The same contact time was established for removal of methylene blue (95%) (Weng et al., 2009). It was suggested to prolong the time to obtain higher removal efficiency until equilibrium.

### *5.4. Effect of coexisting ions*

In real wastewaters, strange ions can exist in the nature and they vitally affect the adsorption of adsorbate onto adsorbent. This phenomenon is due to adsorption competition and ionic forces. Liao et al. (2018) investigated the effect of ions such as $CO_3^{2-}$, $HCO_3^-$, $NO_3^-$, $SO_4^{2-}$ and $Cl^-$ on the adsorption of $[(PO_4)]^{3-}$ onto $La(OH)_3$-modified magnetic pineapple peel derived biochar. The findings indicated that there was no significant effect on phosphate removal efficiency in the presence of such anions. Therefore, the chemical affinity of adsorbent towards $[(PO_4)]^{3-}$ is strong to overcome the ionic forces during the adsorption.

### *5.5. Response surface methodology as an optimization tool*

The adsorption of pollutants could be optimized with statistical analysis using response surface methodology. A quadratic equation can be established to show the relationship between predicted and experimental data. Some common experimental designs or design of experiments (DoE), e.g., Box–Behnken, Central composite design, Taguchi, Gradient-enhanced kriging, Plackett–Burman design, and Polynomial regression are widely used in accordance with response surface methodology.

In that case, Rosales et al. (2019) reported that total 17 runs were conducted duplicate with the mixed survey of factors involving initial pH, dosage, and temperature for removal of Cr(VI). Three dimensional surfaces were plotted to elucidate the interaction between two variables while the other was remained at central level (Fig. 8). Based on the Box–Behnken design, the researchers found the optimum conditions to remove Cr(VI) ions from water were initial solution pH 2.01, pineapple core wastes derived biosorbent dosage of 30 g $L^{-1}$, and temperature of 30.05 °C. Just a tiny absolute error of 0.18% was measured after the adoption of response surface methodology, indicating the reliability between experimental results with the predicted values. Although the optimization using response surface methodology (RSM) has many advantages such as high reliability and rapid operation, there are very few studies reported this method to optimize the adsorption by the pineapple wastes derived adsorbents.

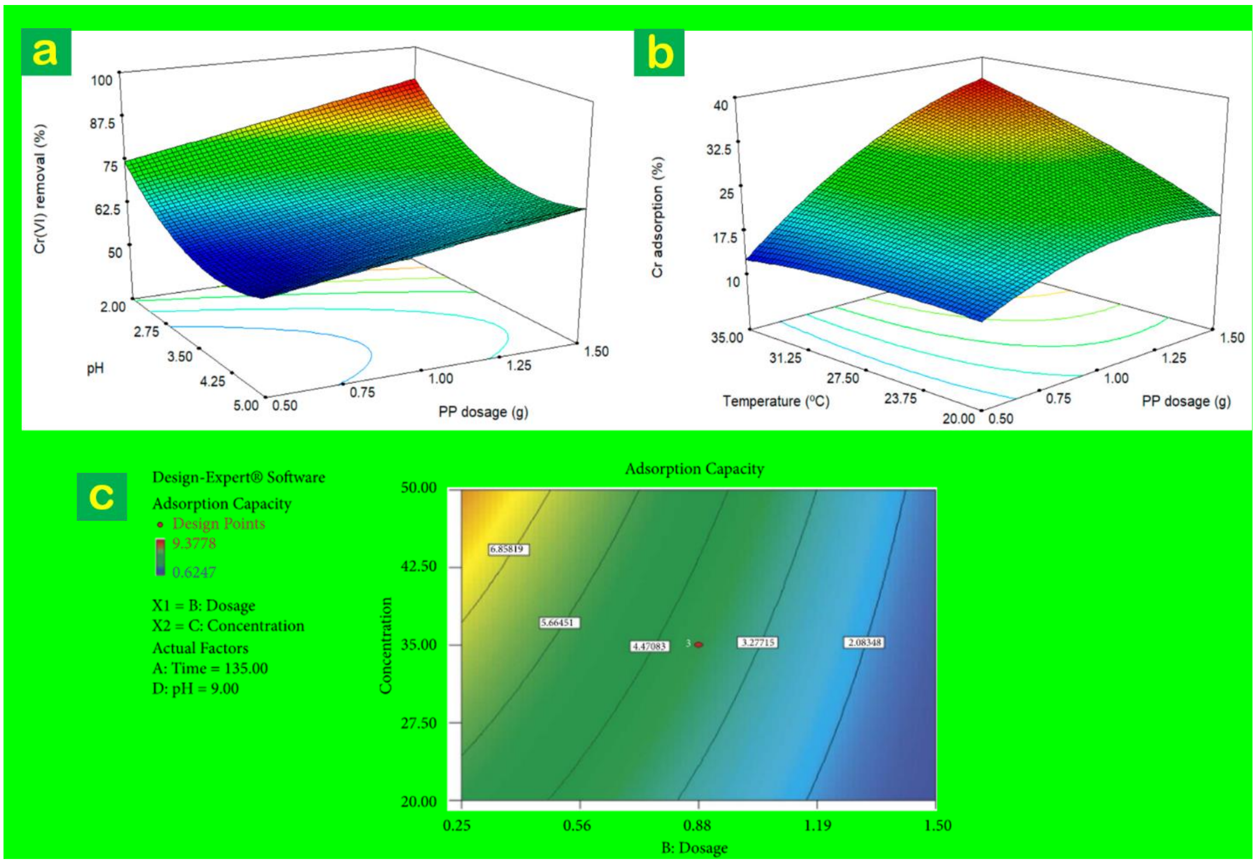


Fig. 8. Three dimensional surface plots for Cr(VI) removal by pineapple core (PP) adsorbent with two variables including pH and adsorbent dose, temperature was set at central level (a); effect of two variables including temperature and adsorbent dose on Cr(VI) removal by pineapple core, pH was set at central level (b). Reproduced from the reference (Rosales et al., 2019) under an open access Creative Common CC BY license. A contour plot for the interaction between dose and concentration for removal of methylene blue (c). Reproduced from the reference (Shukor et al., 2022) under an open access Creative Common CC BY license.

## 6. Kinetic and isotherm studies

### *6.1. Background*

The isotherm and kinetics studies are considered as core parts of adsorption investigations; hence, many authors mentioned these models in their works (Brião et al., 2020). Isotherm adsorption models assume the relationship between the equilibrium adsorbate concentration and the quantity that the adsorbate loaded on an adsorbent at a certain temperature (Van Tran et al., 2019). Meanwhile, the kinetic models assume the rate of adsorption process dependent on the contact time (Tran et al., 2020c). Both models suggest some possibilities of how the adsorbate can adsorb on the adsorbent. In general, nonlinear fitting of isotherm and kinetics models give better accuracy and reliability than linear fitting (Tran et al., 2020b). The fitted model plots of kinetic and isotherm are illustrated in Fig. 9.

In detail, the mathematic form (linear and nonlinear) of common kinetic and isotherm models used for the fitting in the previous works can be listed in Eqs.1–20.

### *6.2. Kinetic models*

- *Pseudo first-order equation in the nonlinear form (Eq. 1) and linear form (Eq. 2):* this model was firstly proposed by Lagergren (1898). It assumes the adsorption by localized sites without any interaction between adsorbed sites. The adsorption energy is unrelated to surface coverage (Largitte and Pasquier, 2016).

$$Q_t = Q_1\left[1 - \exp(-k_1 \times t)\right] \quad (1)$$

$$\log(Q_1 - Q_t) = \log Q_1 - \frac{k_1 \times t}{2.303} \quad (2)$$

where, $Q_1$ (mg g$^{-1}$) and $Q_t$ (mg g$^{-1}$) are the pseudo first-order kinetic adsorption capacities at the equilibrium moment and time t, $k_1$ (min$^{-1}$) is the pseudo first-order rate constant.

- *Pseudo second-order equation in the nonlinear form (Eq. 3) and linear form (Eq. 4):* This model was described by Ho and McKay (1999). It suggests that the adsorption rate is proportional to the number of available sites on the adsorbent. It also expresses the role of chemisorption in controlling the adsorption.

$$Q_t = \frac{k_2 Q_2^2 t}{1 + k_2 Q_2 t} \quad (3)$$

$$\frac{t}{Q_t} = \frac{1}{k_2 \times Q_2^2} + \frac{t}{Q_2} \quad (4)$$

where, $Q_2$ (mg g$^{-1}$) and $Q_t$ (mg g$^{-1}$) are the pseudo second-order kinetic adsorption capacities at the equilibrium moment and time t, $k_2$ (min$^{-1}$) is the pseudo second-order rate constant.

- *Elovich model equation in the nonlinear form (Eq. 5) and linear form (Eq. 6):* This model was described by Elovich and Larinov (1962).

$$Q_t = \frac{1}{\beta} \ln(1 + \alpha\beta t) \quad (5)$$

$$Q_t = \frac{1}{\beta} \ln(\alpha\,\beta) + \frac{1}{\beta} \ln(t) \quad (6)$$

where, $Q_t$ (mg g$^{-1}$) is the pseudo second-order kinetic adsorption capacity at the time t, $\alpha$ (mg g$^{-1}$ min$^{-1}$) and $\beta$ (g mg$^{-1}$) are the adsorption rate and desorption rate constants.

- *Bangham equation in the nonlinear form (Eq. 7) and linear form (Eq. 8):* This model is based on the assumption that pore diffusion was the only rate controlling step during adsorption (Yokogawa et al., 2017).

$$Q_t = k_B \times t^{a_B} \tag{7}$$

$$\log\log\left(\frac{C_o}{C_o - Q_t \frac{m}{V}}\right) = \log\left(\frac{k_B}{2.303V}\right) + \alpha_B \log(t) \tag{8}$$

where, $Q_t$ (mg g$^{-1}$) is the pseudo second-order kinetic adsorption capacity value at the time t, $k_B$, and $\alpha_B$ are the constants of Bangham kinetic equation.

### *6.3. Isotherm models*

- *Langmuir equation in the nonlinear form (Eq. 9) and linear form (Eq. 10):* this model assumes an equilibrium between adsorbate and adsorbent system and can be used for a description of chemisorption phenomenon caused by the formation of chemical bonds between the adsorbent and the adsorbate (Langmuir, 1916).

$$Q_e = \frac{Q_m K_L C_e}{1 + K_L C_e} \tag{9}$$

$$\frac{C_e}{Q_e} = \frac{1}{Q_m K_L} + \frac{C_e}{Q_m} \tag{10}$$

where, $Q_e$ (mg g$^{-1}$) and $Q_m$ (mg g$^{-1}$) are the equilibrium and monolayer adsorption capacities, $C_e$ (mg L$^{-1}$) is the equilibrium concentration of adsorbate, and $K_L$ (L mg$^{-1}$) is a constant of the Langmuir isotherm.

- *Freundlich equation in the nonlinear form (Eq. 11) and linear form (Eq. 12):* this equation describes empirical results of a consistency with the thermodynamics of heterogeneous adsorption (Freundlich, 1906).

$$Q_e = K_F C_e^{1/n} \tag{11}$$

$$\log Q_e = \log K_F + \frac{1}{n} \log C_e \tag{12}$$

where, $Q_e$ (mg $g^{-1}$) is the equilibrium adsorption capacity, $C_e$ (mg $L^{-1}$) is the equilibrium concentration of adsorbate, and $K_F$ (L $mg^{-1}$) is a constant indicative of Freundlich equation, which is related to the relative adsorption capacity of an adsorbent.

- *Temkin equation in the nonlinear form (Eq. 13) and linear form (Eq. 14):* this model is a two-parameter equation, which assumes that the heat of adsorption process caused by all molecules reduces linearly with the increase in the coverage of the adsorbent surface (Temkin and Pyzhev, 1940).

$$Q_e = B_T \ln\left(K_T C_e\right) \tag{13}$$

$$Q_e = B_T \ln K_T + B_T \ln C_e \tag{14}$$

where, $Q_e$ (mg $g^{-1}$) is the equilibrium adsorption capacity, $C_e$ (mg $L^{-1}$) is the equilibrium concentration of adsorbate, $k_T$ (L $g^{-1}$) is the constant of Temkin isotherm, $B_T$ (mg $g^{-1}$) is related to the heat of adsorption process.

- *Dubinin-Radushkevich (D–R) equation in the nonlinear form (Eq. 13) and linear form (Eq. 14):* this model is a three-parameter equation, which describes empirical results, and it is compiled to confirm whether the adsorption process is chemisorption or physical adsorption (Nguyen and Do, 2001).

$$Q_e = Q_m \, e^{-K_D \varepsilon^2} \quad (15)$$

$$\ln Q_e = \ln Q_m - K_D \varepsilon^2 \quad (16)$$

where, $Q_e$ (mg $g^{-1}$) is the equilibrium adsorption capacity, $C_e$ (mg $L^{-1}$) is the equilibrium concentration of adsorbate, $K_D$ (L $mg^{-1}$) is a constant of the D–R isotherm, $\varepsilon$ (kJ $mol^{-1}$) is the polanyi potential of the D–R model.

- *Redlich–Peterson (R–P) equation in the nonlinear form (Eq. 13) and linear form (Eq. 14):* this model is a three-parameter equation as a result of combining Freundlich and Langmuir isotherms, which it assumes the formation of the monolayer with multisite interaction (Redlich and Peterson, 1959).

$$Q_e = \frac{K_R C_e}{1 + a_R C_e^{\alpha}} \quad (17)$$

$$\frac{C_e}{Q_e} = \frac{1}{K_R} + \frac{a_R}{K_R}(C_e)^{\alpha} \quad (18)$$

where, $Q_e$ (mg $g^{-1}$) is the equilibrium adsorption capacity, $C_e$ (mg $L^{-1}$) is the equilibrium concentration of adsorbate, $K_R$ (L $mg^{-1}$) and $a_R$ (L $g^{-1}$) are the constants of the R–P isotherm.

- *Sips equation in the nonlinear form (Eq. 13) and linear form (Eq. 14):* this model is a three-parameter equation, which is as a combined form of Langmuir and Freundlich equations (Sips, 1948).

$$Q_e = \frac{K_S C_e^{\beta}}{1 + a_S C_e^{\beta}} \quad (19)$$

$$\ln\left(\frac{Q_e}{K_S - a_S Q_e}\right) = \beta \ln C_e \quad (20)$$

where, $Q_e$ (mg $g^{-1}$) is the equilibrium adsorption capacity, $C_e$ (mg $L^{-1}$) is the equilibrium concentration of adsorbate, $K_S$ (L $mg^{-1}$) and $a_S$ (L $g^{-1}$) are the constants of the Sips isotherm, β is an exponent of the Sips isotherm.

### *6.4. Main findings of kinetic and isotherm studies*

According to Table 5, the adherence and correlation coefficients of kinetic and isotherm models for adsorption of various pollutants including heavy metals and organic compounds by the pineapple-based adsorbents are summarized. Data collected from the previous works indicated that almost kinetic models obeyed the pseudo-second order equation with very high coefficients of determination ($R^2 > 0.99$). According to Fig. 9, the trend was excepted for the adsorption of Pb(II) and Cd(II) onto the pineapple leaf derived cellulose adsorbent since the pseudo-first order model ($R^2 > 0.99$) fitted best with the experimental data (Daochalermwong et al., 2020). The adherence of the pseudo second order equation gives information about the role of chemisorption during the adsorption of heavy metals and organic compounds by the pineapple-derived adsorbents (Nguyen et al., 2022d). For isotherm models, the best-fitting model was found to be Langmuir with $R^2$ values of 0.94–1.00 for almost studies. The adsorption of pollutants over the pineapple wastes derived adsorbents was suggested a monolayer behavior (Tran et al., 2020a). However, some works revealed the adherence of other isotherm models such as Freundlich (Rosales et al., 2019), and Liu (Gogoi et al., 2018). Specifically, Rosales et al. (2019) concluded that the adsorption of

Cr(VI) by the pineapple core powder reflected multilayer behavior. Meanwhile, Gogoi et al. (2018) found that the adsorption of Cr(III) and Cr(VI) species followed Liu isotherm, which attributed to the surface active sites of the pineapple crown leaf adsorbent.

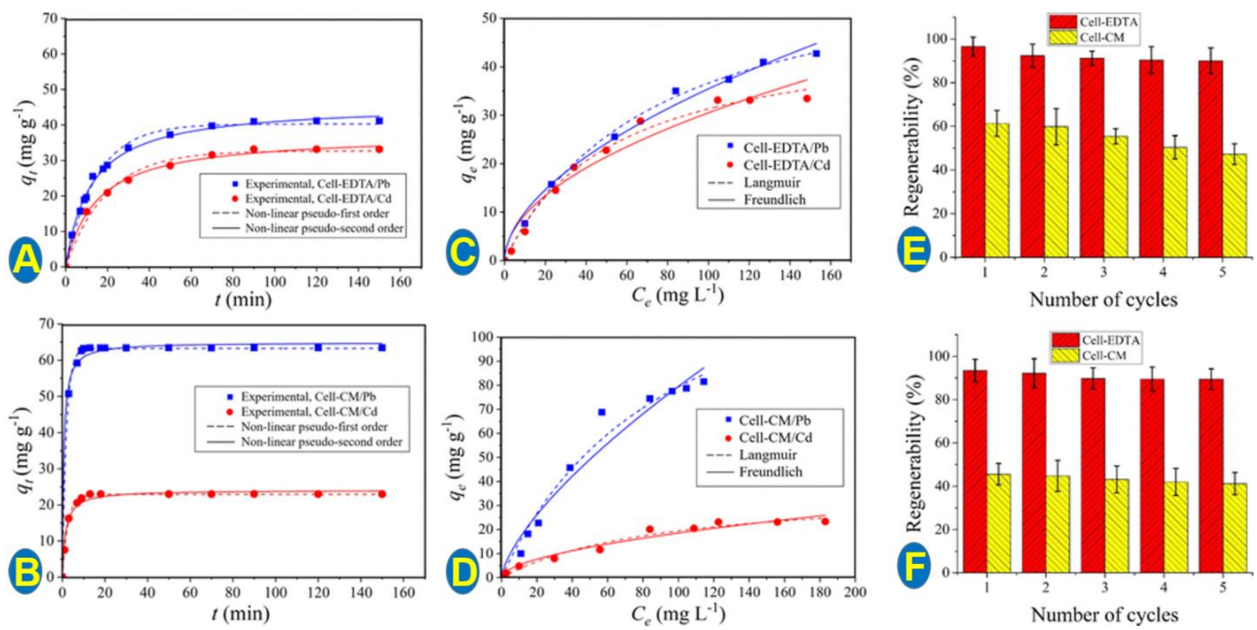


**Fig. 9.** The nonlinear fitting of pseudo first-order, pseudo second-order, Langmuir, and Freundlich (C) models for the kinetic (A, B) and isotherm (C, D) adsorption of Pb(II) and Cd(II) onto pineapple leaves modified with ethylenediaminetetraacetic acid, and carboxymethyl groups. The regeneration of these adsorbents (E, F). Reproduced from the reference (Daochalermwong et al., 2020) under an open access Creative Common CC BY license.

## 7. Thermodynamic studies

### *7.1. The van't Hoff equation*

The thermodynamic investigation supplies information about the change of standard Gibbs free energy (ΔG°), enthalpy (ΔH°), and entropy (ΔS°). To conduct the thermodynamic study, the adsorption as a function of temperature using the van't Hoff equation is established. The van't Hof equation with a differential form can be described by Eqs. 21–23.

$$\frac{\partial}{\partial T}(\ln K_c) = \frac{\Delta H^o}{RT^2} \quad (21)$$

$$\ln K_c = -\left(\frac{\Delta H^o}{R}\right)\frac{1}{T} + \left(\frac{\Delta S^o}{R}\right) \quad (22)$$

$$K_c = \frac{Q_e}{C_e} \quad (23)$$

where, $K_c$ is the thermodynamic equilibrium constant calculated from the ratio between equilibrium $Q_e$ ( mg·g$^{-1}$), and $C_e$ (mg L$^{-1}$). T (K) is the absolute temperature, R is the gas constant (8.314 J mol$^{-1}$ K$^{-1}$). In this section, the thermodynamic study of the adsorption of heavy metals and organic dyes by the pineapple-derived adsorbents will be discussed.

### *7.2. Main findings of thermodynamic studies*

According to Table 6, the thermodynamic parameters for adsorption of various pollutants by the pineapple wastes based adsorbents are summarized. The temperature of the investigations was in range from 298K to 343K. All works reported that the Gibbs free energy received negative values between −32.874 and −0.857 kJ mol$^{-1}$. Therefore, the adsorption of heavy metals and organic dyes over the pineapple wastes derived adsorbents such as biosorbents, biochars, activated carbons were thermodynamically spontaneous, which matched with the results of kinetic and isotherm adsorption. For the heat of adsorption process, ΔH° calculated in the works had both positive and negative values. For example, Ahmad et al. (2016) used chemically oxidized fruit peel as an adsorbent to treat Cd(II) and Pb(II). The heat energy of the adsorption was large between −26.089 and −63.530 kJ mol$^{-1}$. As a result, the pollutant uptake of two metals was an exothermic process. By contrast, the adsorption of chromium species onto leaf powder and activated carbons from the pineapple had an endothermic nature with ΔH° of 21.358−77.89 kJ $mol^{-1}$ (Gogoi et al., 2018; Ponou et al., 2011). The entropy of adsorption system was varied dependent on the difference of pollutants and adsorbents. For instance, ΔS° of the adsorption of methylene blue by the pineapple leaf powder was 76.4 J $mol^{-1}\cdot K^{-1}$ (Weng et al., 2009), while a previous work reported a negative ΔS° (−101.40 J $mol^{-1}\cdot K^{-1}$) for the uptake of basic green 4 by the pineapple leaf powder (Chowdhury et al., 2011). The positive entropy measures a system's thermal energy, indicating the increasing disorder, or randomness, uncertainty of molecules (Alabbad, 2021).

## 8. Desorption, regeneration and fixed bed column

### *8.1. Desorption*

The purpose of recyclability study of an adsorbent is to decrease the total cost of the treatment process. If the adsorbents can be easily generated through a desorption procedure, and reused multiple cycles, then they can be upgraded for commercial values. The eluents or solvents using for desorption of pollutants from the adsorption should be less toxic and low cost. Therefore, the regeneration of that adsorbent is a critically green process. According to Table 7, however, there are very few studies (about 13 articles) reported the desorption and regeneration of the pineapple-based adsorbents. The green eluents were often used as HCl solution for the desorption of $Cd^{2+}$, and $Pb^{2+}$ (Ahmad et al., 2016; Daochalermwong et al., 2020), or NaOH solution for the desorption of $Cr_2O_7^{2-}$ (Gogoi et al., 2018). The major explanation relies on the strongly competition between metal cations and $H^+$ as well as the competition between anions and $OH^-$ ions. This force allows to push metals out the structure of the adsorbents.

### *8.2. Regeneration*

If the desorption of adsorbent to remove the adsorbate is successful, the regeneration study is to count the number of recycle that the adsorbent can obtain. Daochalermwong et al. (2020) reported the number of recycle up to 5 times by using 1 M HCl as an eluent to desorb $Cd^{2+}$, and $Pb^{2+}$ from the pineapple leaf-derived cellulose adsorbent. The removal efficiency still obtained 43–41% for $Cd^{2+}$ and 62–44% for $Pb^{2+}$ for the final cycle (Fig. 9). For the procedure to desorb organic compounds from the pineapple leaf adsorbents, Neupane et al. (2015) used 1 N acetic acid as an efficient solvent for desorption of crystal violet. However, the number of cycles has not been reported in their work. Congo red was well desorbed from the pineapple wastes based peel hydrogel as reported by Das et al. (2016). With four cycles, this adsorbent could be a good recyclability, which was expected to extend the actual applications. Despite such advantages, the cost for each reuse of adsorbent was still questionable. It is, therefore, suggested with a better analysis of regeneration cost in the future works.

### *8.3. Fixed bed column*

Depart from adsorption batch mode, up-flow/down-flow fixed bed column is another type of adsorption between adsorbate and adsorbent in a continuous liquid system (Patel, 2019). It is believed that adsorption beyond fixed bed column mode is highly adaptable for industrial scale treatment of different pollutants including organic and inorganic compounds. As a result, many works made effort in the design and development of fixed bed columns (Ahmed and Hameed, 2018). The characteristic of fixed bed column adsorption study is breakthrough curves which show the relationship between concentration of the contaminant and time profile. Breakthrough curves are expressed through mass transfer zone or primary sorption zone (Patel, 2019). Accordingly, wastewater is injected into the column and treated by the adsorbate. The adsorption is initially rapid due to availability of adsorption sites. The process continues until mass transfer zone reaches at the end of the column, or equilibrium is established. Breakthrough curves show S-shape in most cases of fixed bed column adsorption.

Some works used the pineapple waste-derived adsorbents to remove pollutants (e.g., heavy metal, and organic dye) in fixed bed column adsorption mode. Indeed, Rao and Khan (2017) successfully fabricated the pineapple residue adsorbent treated by NaOH solution (ATPR) and investigated its adsorption of nickel ions in water (Fig. 10). The authors initially optimized several batch adsorption conditions such as Ni(II) concentration (50 mg $L^{-1}$), pH (8), and contact time (60 min), and found $Q_m$ value of 17.56 mg $g^{-1}$. Afterwards, they designed a glass column (d = 0.6 cm, h = 3.7 cm) loaded with 0.2 g of the adsorbent. 500 mL of $Ni^{2+}$ solution was passed through this bed column (V = 1.04 $cm^3$). As a result, a breakthrough capacity was determined at 20 mg $g^{-1}$. In another work, Azman and Subki (2022) conducted the removal of methylene blue and malachite green dyes through fixed bed column adsorption using pineapple crown $H_3PO_4$-activated carbon. The fixed bed column was designed with internal diameter (d = 3 cm) and height (h = 10 cm). 50 mL of each of the methylene blue and malachite green solution was filtered by this column. However, breakthrough and exhaustive capacities were not reported. In general, there were very few studies focusing on the adsorption of pollutants by fixed bed column using the pineapple waste-derived adsorbents. Therefore, more investigations of fixed bed column adsorption should be carried out.

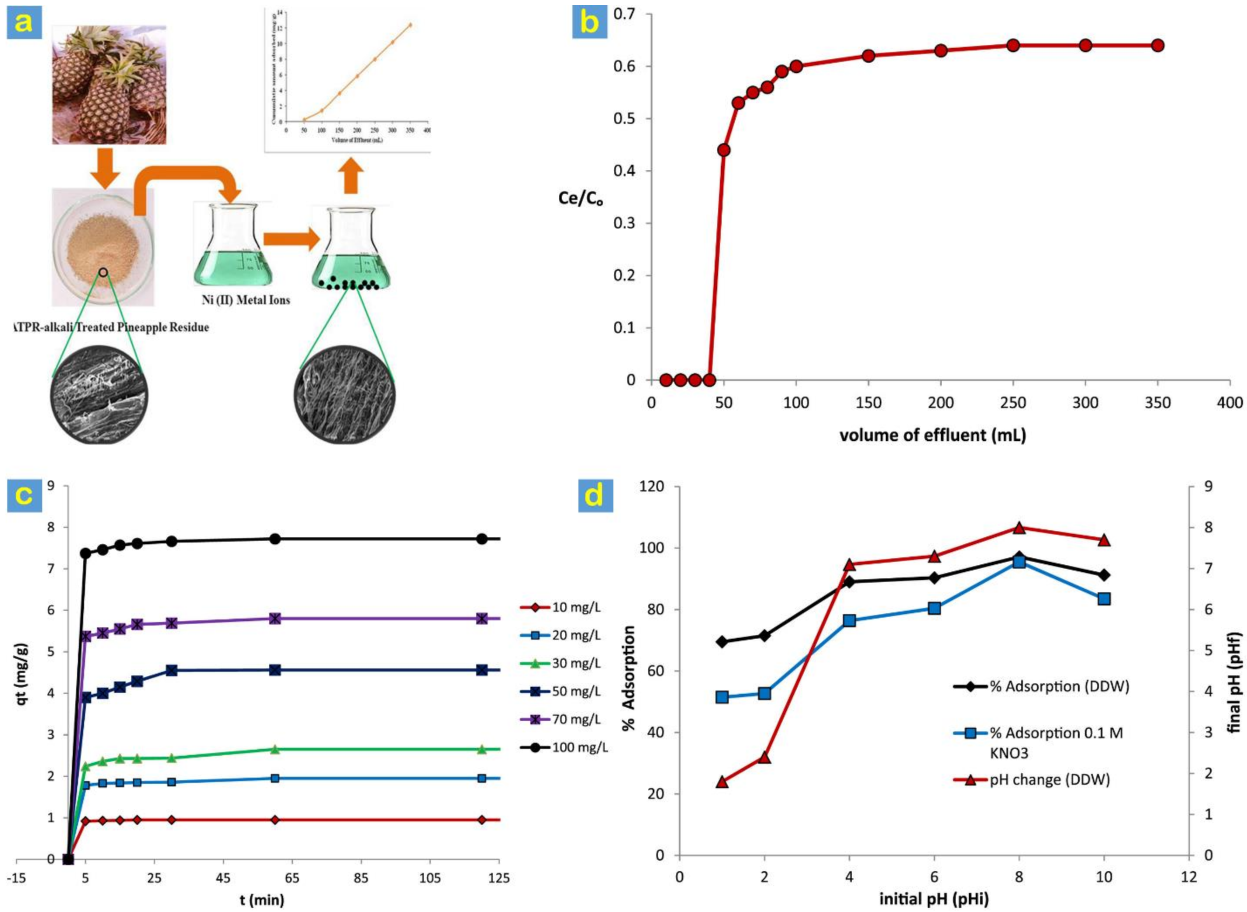


Fig. 10. Schematic illustration of synthesis and application of NaOH-treated pineapple residue adsorbent (ATPR) for removal of nickel ions from water (a); breakthrough curve for fixed bed column adsorption (b); effect of contact time (c); effect of pH and electrolyte on adsorption of nickel ions (d). Reproduced with permission of Elsevier from the reference (Rao and Khan, 2017).

# 9. Adsorption mechanism

## *9.1. The role of electrostatic interactions*

Adsorption mechanism is of great importance for better understanding how the adsorbate can be captured by the adsorbent. In this section, we discuss some adsorption mechanisms proposed by the previous works. Basically, the adsorption of heavy metal ions by the pineapple-based adsorbents was majorly due to the contribution of electrostatic attraction as summarized in Table 8. This mechanism reflects the interaction between reversely charged sites of adsorbent and adsorbate. To elucidate the role of this interaction, the point of zero charge of the adsorbent needs to be determined. As an example, Gogoi et al. (2018) found that the point of zero charge of pretreated and modified pineapple crown leaves were 3.5 and 4, respectively. At optimum pH at 2.5, the surface of the pineapple crown leaves-based adsorbents was positively charged. This condition facilitates the electrostatic attraction between positively charged adsorbent surface and $CrO_4^{2-}$ ions. The authors also explained the effect of photoreduction mechanism as a result of −OH groups present on the surface. At very low pH, −OH groups of cellulose were oxidized into aldehyde/ketone by Cr(VI) ions. This finding was one of the reasons why the concentration of Cr(VI) was decreased, and Cr(VI) increased. In the presence of the adsorbent, Cr(III) can be easily removed at optimum pH 5 due to the electrostatic interaction. Apart from electrostatic interactions, the mechanism for adsorption, e.g., inorganic compounds such as $[PO_4]^{3-}$ anions can be controlled by many ways such as ligand exchange, inner-sphere complexation, and precipitation (Fig. 11). The next section will mention about these mechanisms.

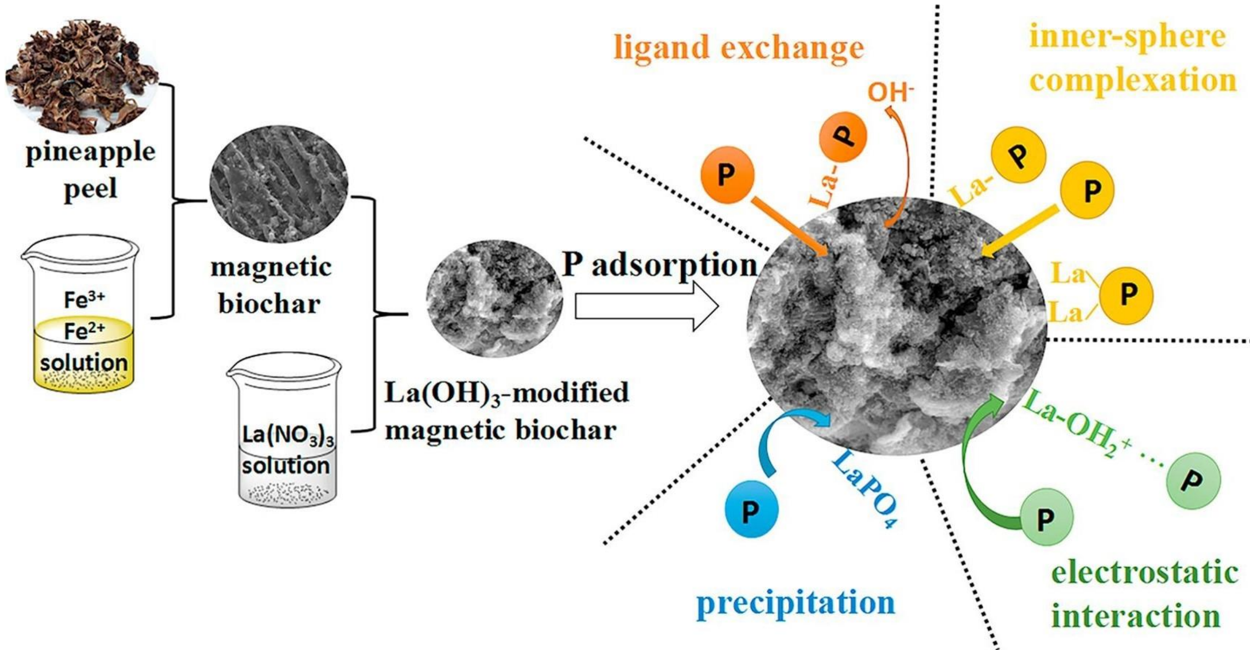


Fig. 11. Synthesis route of $La(OH)_3$-modified magnetic pineapple biochars and their applications for the removal of $[PO_4]^{3-}$ anions. Several possible adsorption mechanisms were suggested, including ligand exchange, inner-sphere complexation, electrostatic interaction and precipitation. Reproduced with the permission of Elsevier from the reference (Liao et al., 2018).

### *9.2. The role of complexation*

In general, the adsorption of heavy metals over the pineapple waste-based adsorbents can be well explained by complexation mechanisms. The surface of these modified adsorbents often contain functional groups (e.g., carboxylic acid) that can complex with heavy metal ions or transition metals (d- or f-block elements). Depending on the coordination number of metal elements, the number of functional groups is required to form a metal-functional groups complexation. By this mechanism, metal ions are captured on the surface of the pineapple-based adsorbents. Weng and Wu (2012) suggested the vital role of complexation in removing $Cu^{2+}$ by the pineapple leaf powder. The point of zero charge of this adsorbent was found, at 2.3. In this case, optimum pH higher than 2.3 was the best condition to obtain a negatively charged surface. In other words, the surface functional groups containing oxygen and nitrogen were deprotonated to enhance the density of lone pair electrons. As a result, $Cu^{2+}$ complexed with lone pair electrons of the surface functional groups on the adsorbent, improving the copper removal efficiency. Apart from the complexation mechanism, ion-exchange might contribute significantly to the lead adsorption efficiency. Indeed, a recent research assumed that the carboxylic acid groups present on the surface of the oxalic acid modified pineapple plant stem could exchange $H^{+}$ with $Pb^{2+}$ ions (Vivian Loh Zing et al., 2019). However, the increase in $H^{+}$ concentration after adsorption has not been evidenced yet. By using XPS, FTIR, and SEM-EDS spectra, the mechanism could be identified for the heavy metal adsorption on the surface of pineapple leaf biochar before and after adsorption (Iamsaard et al., 2022). Accordingly, it was possible that surface complexation and cation exchange involved in the adsorption mechanisms (Fig. 12).

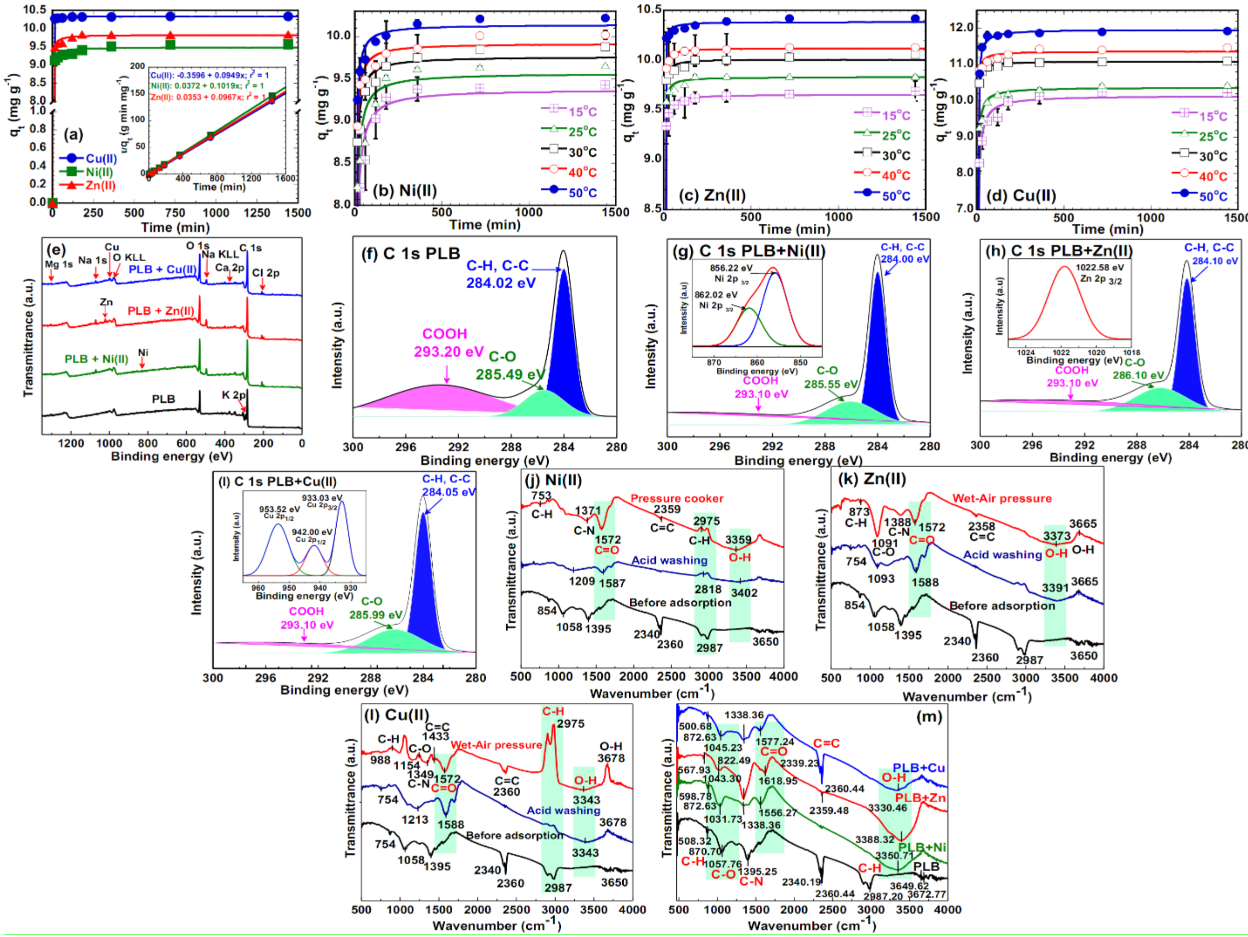


Fig. 12. Comparative kinetics of adsorption of heavy metal $Ni^{2+}$, $Zn^{2+}$, and $Cu^{2+}$ (a); effect of temperature on the kinetic adsorption of $Ni^{2+}$ (b), $Zn^{2+}$ (c), and $Cu^{2+}$ (d); (e) XPS survey spectra of pineapple leaf biochar before and after adsorption; XPS C 1s spectra of pineapple leaf biochar (f), pineapple leaf biochar + $Ni^{2+}$ (g), pineapple leaf biochar + $Zn^{2+}$ (h), and pineapple leaf biochar + $Cu^{2+}$ (i); FT-IR spectra of pineapple leaf biochar after regeneration using a pressure cooker and acid washing of $Ni^{2+}$ (j), $Zn^{2+}$ (k), and $Cu^{2+}$ (II) (l); chemical bond analysis by FT-IR spectra before and after regeneration (m). Reproduced from the reference (Iamsaard et al., 2022) under an open access Creative Common CC BY license.

### *9.3. The role of ion exchange*

This mechanism may be helpful for explaining the adsorption of heavy metal over the adsorbent. Some exchangeable metal ions such as $K^+$, $Na^+$, $Ca^{2+}$ are available on the surface of the adsorbents. As a result, the replacement of these ions by heavy metal ions entail their sequestration according to Fig. 13. Even, proton $H^+$ or acidic groups can exchange with heavy metal ions. As an example, Vivian Loh Zing et al. (2019) suggested that chemical reaction like ion exchange was anticipated through replacement of –COOH groups on oxalic acid-activated pineapple stem and stem powder. Apart from mechanisms mentioned, other mechanisms such as precipitation and cation–π interaction may contribute to adsorption of heavy metals. However, such investigations have been still very limited, suggesting a better elucidation of adsorption mechanisms.

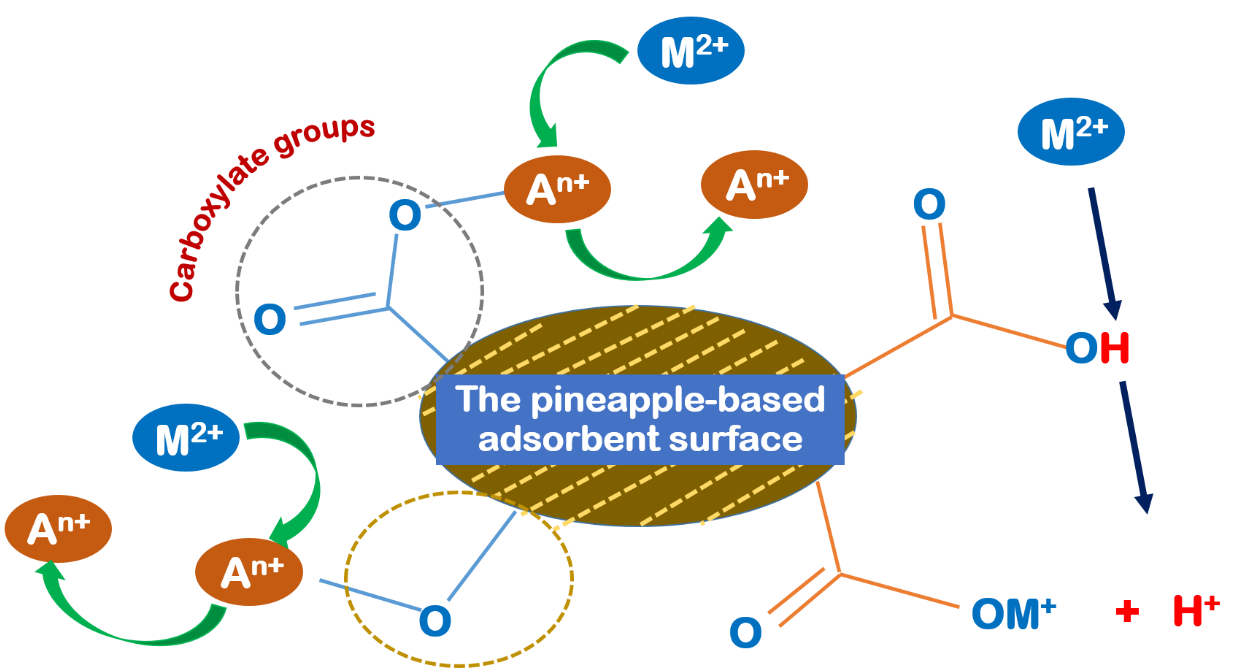


Fig. 13. Heavy metal adsorption onto the pineapple waste-based adsorbent via proposed ion exchange mechanism.

### *9.4. The role of chelation*

On the other hand, Ahmad et al. explained the adsorption of $Cd^{2+}$ and $Pb^{2+}$ using $H_2SO_4/KMnO_4$ oxidized pineapple fruit peel by the electrostatic attraction, and chelation mechanism (Ahmad et al., 2016). As illustrated in Fig. 14, the surface of the adsorbent possesses many carboxylic acid and hydroxyl groups, which can be deprotonated at pH > 3. As a result, $Cd^{2+}$ and $Pb^{2+}$ interacted with these negatively charged groups at optimum pH 4. Moreover, the coordination bond between empty d-orbitals of $Cd^{2+}/Pb^{2+}$ metals with lone pair electrons of oxygen from functional groups. This event may lead to the chelation between $Cd^{2+}/Pb^{2+}$ and functional groups on the surface of the adsorbent. By examining FT-IR spectra before and after adsorption of chromium anions on carbonized pineapple leaves, Ponou et al. (2011) suggested that both covalent bonding and electrostatic attraction strongly affected the adsorption of Cr(VI) over the pineapple leaf derived porous carbon. To sum up, plausible adsorption mechanisms such as electrostatic interaction, complexation, ion exchange, and chelation were included, but needed to be verified by physicochemical techniques such as FT-IR, and XPS.

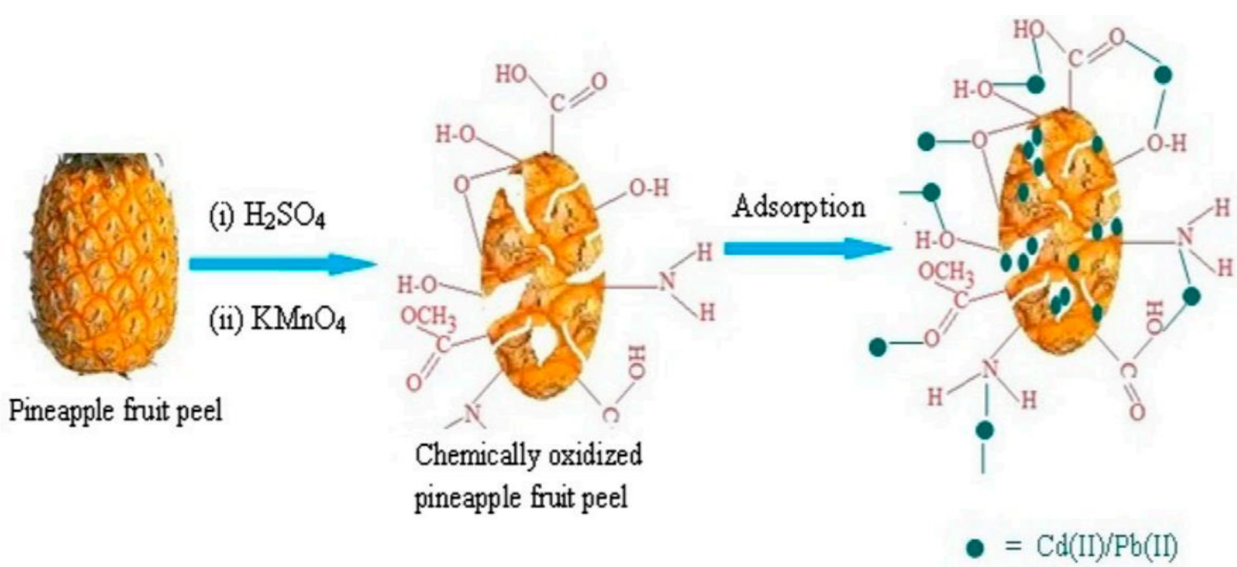

**Fig. 14.** Plausible mechanism of Cd(II) and Pb(II) adsorption using $H_2SO_4$/$KMnO_4$ oxidized pineapple fruit peel. Reproduced from the reference (Ahmad et al., 2016).

## 10. Potential of pineapple wastes towards circular economy

According to Food and Agriculture Organization (FAO), nearly 30 million tons of pineapple fruit are harvested for food and drinking industries each year, along with the release of a huge amount of the pineapple wastes. The proper conversion methods of the pineapple wastes into more valuable products such as biofuels, biochars, activated carbons, modified nanomaterials, magnetic nanocomposites, etc. have contributed proactively to strengthening a low-carbon economy as well as mitigating the environmental pollution and climate change. However, almost studies on the production of the pineapple waste-based adsorbents are just lab-scaled, or burgeoning, and it would be too early to claim that these bio-based products (biofuels and materials) are very attractive in the future bioenergy and wastewater treatment technologies. To pave the way for commercializing the pineapple wastes-derived products and other real applications, in this section, we propose a systematic expansion from lab-scale production to consumption and waste management in the context of circular economy.

Circular economy is an emerging model of how to extend the life cycle of products through the core processes of material design, production, distribution, consumption, repair, material collection, recycling and residual waste management. Although there is still a debatable topic of definition and scope of circular economy, it is generally believed that effective management of the agro-industrial by-products, especially for the pineapple wastes in the principles of circular economy may be environmentally beneficial. It is evitable that incorporation of many sectors such as research and development (R&D), logistic systems, treatment plants, maintenance services, etc.

in the usage and pineapple wastes management should be encouraged in circular economy. With the emphasis on nanotechnology and green chemistry, the potential of the pineapple wastes based products can be insightfully elucidated in the approaches of sustainable development.

Nine core processes are briefly described in Fig. 15. Initially, some pineapple by-products such as crown, leaf, and stem after harvesting juices are collected and treated to be ready for bioenergy and material production. To enhance the pineapple waste-based high-quality products, the material design process needs to be involved in lab-scale research, modification, and optimization. This process may be complicated and depended majorly on the purpose and availability of manufacturers. There are three types of main products derived from the pineapple wastes, including *(i)* value-added products, *(ii)* bioenergies, and *(iii)* materials. Natural compounds such as polyphenols, xylitol, antioxidants, enzymes, and organic acids can be extracted from the pineapple wastes through extraction processing technologies (Meena et al., 2021). They are used to synthesize value-added products for food and cosmetic, medicine applications (Aili Hamzah et al., 2021). Pineapple waste-based biofuels such as biogas, biohydrogen, bioethanol, bio-oil, and biomethane can be produced through anaerobic digestion technologies, biorefinery systems, and other bioconversion/catalytic processes. These biofuels are an integral part of low-carbon economy towards circular bioeconomy. Consequently, production of biofuels from the pineapple wastes minimize the energy loss and greenhouse gas emission. For the purpose of zero waste, this process should be integrated with the production of materials as a result of carbon residuals. Accordingly, residuals after bioenergy production can be converted into valuable materials such as biochars, activated carbons, modified nanomaterials, magnetic nanocomposites, and functionalized porous carbon for water treatment. The fourth process are storage and transportation of bioenergies and material for consumption. For example, the materials can be delivered to wastewater treatment plants or sewage treatment plants while bioenergies can be distributed to power stations through logistic and storage systems. A repairing or optimization process is required to improve the performance of these plants. The next process includes material replacement, and addition. The spent materials can be collected from the treatment systems and stored for regeneration or recycling. Finally, residual wastes need to be managed through post-treatment technologies such as impregnation, geopolymerisation, or modification, etc. Post-treatment materials can still be modified to be used as catalysts for biomass conversion into bioenergy, biofertilizers for soil amendment in agriculture, or any applications to prolong the life cycle of the pineapple waste-based products.

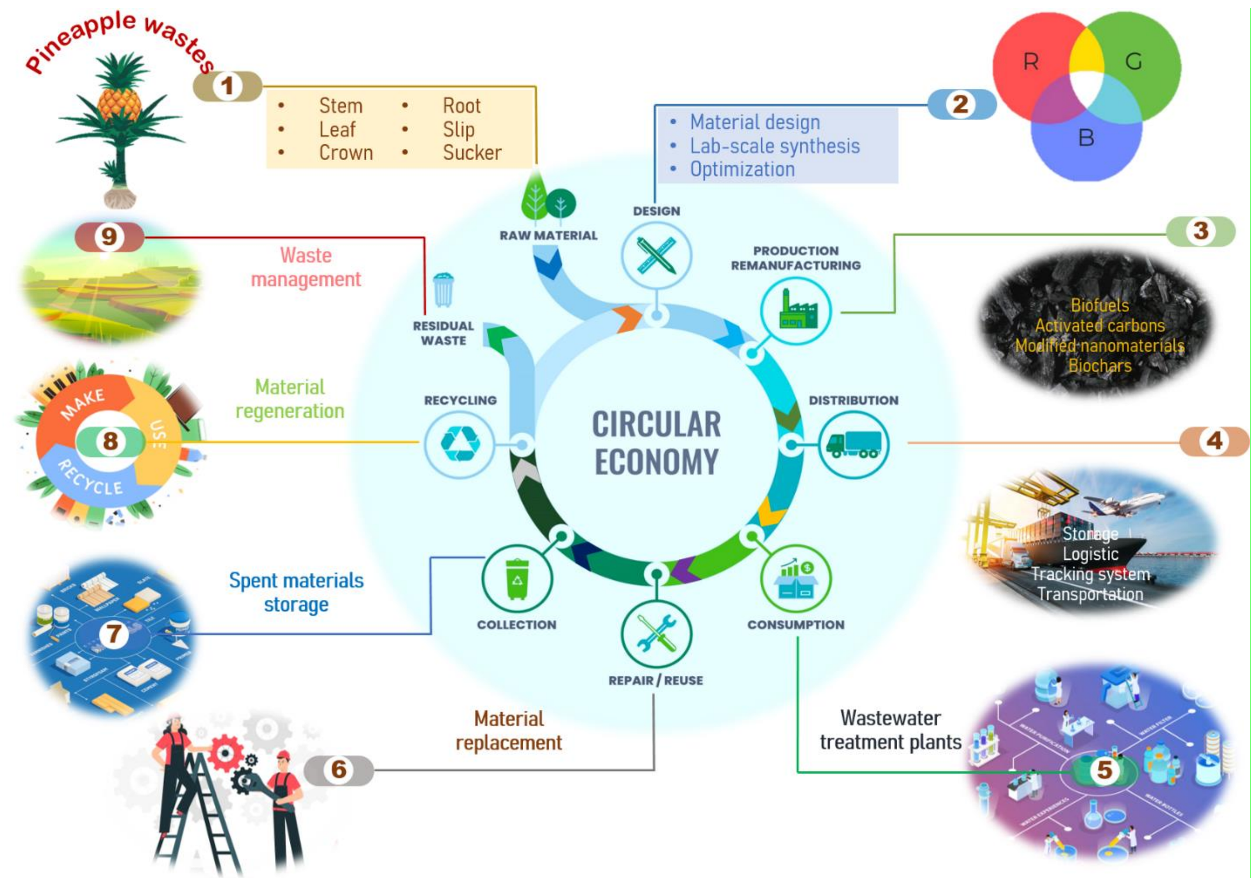


Fig. 15. Waste management and substantial contribution of the pineapple wastes to the circular economy.

# 11. Literature gaps and future prospects

## *11.1. Literature gaps*

The researchers demonstrated the great potential of the pineapple wastes derived adsorbents including biosorbents, biochars, modified sorbents, and activated carbon for the environmental remediation. However, there are still some unreported areas which may be very important to better illuminate. The first point is to extend the scope of the pollutants as the previous works only investigated the use of the pineapple derived adsorbents for the treatment of heavy metals and organic dyes. Many emerging contaminants such as persistent organic pollutants, polychlorinated biphenyls, pharmaceuticals and personal care products are highly harmful to the environment and human health, but not tested for treatment by such adsorbents. Secondly, one of the key activation of the pineapple wastes is the physical activation, but not still applied to produce low cost biochar or activated carbon. It may be also interesting to investigate several physical parameters such as activators (e.g., $CO_2$, steam), pyrolysis temperature, or heating power by microwave energy. Thirdly, the chemical activations of the pineapple wastes put many unanswered questions since the residuals of chemical reagents such as $H_2SO_4$, $KMnO_4$, NaOH, and $ZnCl_2$ after the activation can cause the secondary pollutions. The future works should focus on how to treat such residuals completely. Moreover, this review observed that the pineapple derived adsorbents could be desorbed for regeneration, but the selection of eluents has not been insightfully investigated. There are very few studies reported the desorption and regeneration of the pineapple wastes based adsorbents. The researchers should also improve the desorption efficiency to increase the number of reuse because the final cycle has drastically fallen.

### *11.2. Future prospects*

Over the past decades, the amount of agricultural wastes has continuously increased as a result of agricultural expansion to satisfy the demand for food and drinking. In the current context of serious environmental pollution caused by the agricultural by-products, the pineapple wastes need to be converted into more valuable products. In the future, the pineapple waste derived adsorbents may be still developed to contribute significantly to the environmental remediation. To realize this aspiration, the researchers should improve the adsorption efficiency of the pineapple waste derived adsorbents by new modification methods. Moreover, the green synthesis of nanoparticles using the pineapple wastes as precursors may be an interesting area since their applications are widely used in the nanotechnology, nano-scaled fertilizers, and nano-scaled sensors for the agricultural fields (N. T. T. Nguyen et al., 2022). Many new materials such as hydrogels, aerogels, and nanocomposites can be synthesized from the pineapple wastes, bringing great potential in the environmental remediation, material science, and electrical engineering.

## 12. Conclusion

In the present work, the highlighted experimental results of the production and application of the pineapple waste derived adsorbents for the environmental treatment applications were systematically overviewed. The synthesis of the pineapple derived biosorbents, modified biochars, and activated carbons and composites was discussed. Almost adsorption systems followed the pseudo second order kinetic model, and Langmuir isotherm model. The adsorption by the pineapple based adsorbents was majorly due to the contribution of electrostatic attraction, complexation, chelation, and ion exchange. The research works reported that the adsorption processes were thermodynamically spontaneous. The pineapple waste based adsorbents could be reused at 3–5 times using HCl or NaOH as eluents. For future prospects, the pineapple wastes may not only have potential for synthesis of materials such as nanoparticles, hydrogels, aerogels, and nanocomposites but also contribute proactively to circular economy.

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**Table 1.** Chemical modification and carbonization for the pineapple wastes based adsorbents

| Location | Part of pineapple | Particle size (µm) | Modification (chemicals, activation) | Activation (Tem, time, ramping rate) | Carbonization (Tem, time) | Characterization | Ref. |
|---|---|---|---|---|---|---|---|
| Local market, Johor, Malaysia | Fruit peel | 150–200 | 0.1 M $H_2SO_4$ and 0.1 M $KMnO_4$ | 60 ºC for 24 h | - | SEM, FT-IR, $pH_{pzc}$ | (Ahmad et al., 2016) |
| Kaohsiung, Taiwan | Leaf | - | - | 100 ºC for 20 min at 70 kPa | - | SEM, FT-IR, BET, $pH_{pzc}$ | (Weng and Wu, 2012) |
| Vigo, Pontevedra, Spain | Core | - | - | 80 °C for 48 h | - | SEM, FT-IR, $pH_{pzc}$ | (Rosales et al., 2019) |
| Istanbul, Turkey | Fruit peel | 841 | $ZnCl_2$ (3:1 by wt.%) and $H_2SO_4$ (3:1 by vol.) | 75 °C for 2 h, then treated by 0.1 M HCl for 1 h | - | FT-IR, TGA, SEM | (Turkmen et al., 2021) |
| Istanbul, Turkey | Fruit peel | 841 | - | - | Microwave 800 W, 4 min | FT-IR, TGA, SEM | (Turkmen et al., 2021) |
| Roorkee, India | Fruit peel | 500–3000 | - | - | - | FT-IR, SEM | (Mishra et al., 2010) |
| Assam, India | Crown leaf | 100 | 0.1 M NaOH for 2 h | 50 °C for overnight | - | Distribution of pore sizes, SEM, | (Gogoi et al., 2018) |
| Bangsaphan, Thailand | Leaf | - | 10% NaOH, EDTA | 100 °C for 1 h | - | SEM, EDX, FT-IR | (Daochalermwong et al., 2020) |

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|---|---|---|---|---|---|---|---|
| Dehradun, India | Leaf | 500 | - | 121°C for 15 min at 103.42 kPa | - | BET | (Mishra and Tadepalli, 2015) |
| Pontian, Johor, Malaysia | Fruit peel | - | 0.1 M $H_2SO_4$ and 0.1 M $KMnO_4$ | 60 °C for 24 h | - | - | (Yusoff et al., 2020) |
| Selangor, Malaysia | Leaf | 125–500 | 20% NaOH | 18 h | - | SEM, FT-IR, EDX | (Heba et al., 2019) |
| Selangor, Malaysia | Leaf | 180 | Iminodiacetic acid | 95 °C for 8 h | - | SEM, FT-IR, EDX | (Heba et al., 2019) |
| Istanbul, Turkey | Fruit rind | 180 | $ZnCl_2$ (3:1 by wt.%) | 75 °C for 2 h or 4 h | Microwave 800 W for 4 min | FT-IR | (Yılmaz and Tugrul, 2022) |
| Selangor, Malaysia | Stem | 105–250 | 0.5 M oxalic acid | Room temperature for 30 min | 120 °C for 90 min | $pH_{pzc}$ | (Vivian Loh Zing et al., 2019) |
| Tokyo, Japan | Leaf | 600 | - | - | 350 °C or 450 °C for 60 min | TGA, FT-IR, SEM, BET, Boehm titration | (Ponou et al., 2011) |
| Kaohsiung, Taiwan | Leaf | 75 | - | 80 °C for 48 h | - | BET-$N_2$, $pH_{pzc}$, SEM, FT-IR | (Weng et al., 2009) |
| Durgapur, India | Leaf | 100–125 | | 90 °C for 24 h | - | - | (Chakraborty et al., 2012) |
| Nibong Tebal, Malaysia | Leaf | 355–500 | - | 70 °C for 48 h | - | FT-IR, SEM, | (Krishni et al., 2014) |
| Tamil Nadu, India | Leaf | 150 | - | 100 °C for 48 h | - | $pH_{pzc}$, FT-IR | (Neupane et al., 2015) |
| Sepang, Malaysia | Stem | 106–250 | - | 90 ± 2 °C | - | SEM, FT-IR, BET, $pH_{pzc}$ | (Chan et al., 2016) |

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|---|---|---|---|---|---|---|---|
| West Bengal, India | Leaf | 100–125 µm | - | 90 °C for 24 h | - | SEM, FT-IR, BET | (Chowdhury et al., 2011) |
| Guangzhou, China | Peel | 150–200 µm | 1.25 M NaOH or 1.25 M $NaClO_2$ for 10 h, | 100 °C for 24 h | - | SEM, FT-IR, BET, XRD, TGA | (Das et al., 2016) |
| Johor, Malaysia | Crown, leaf, stem | 2000 µm | $ZnCl_2$ (1:1 by wt.%) for 24 h | 110 °C for 24 h | 500 °C, 1 h | SEM, FT-IR, BET, TGA | (Mahamad et al., 2015) |
| Johor, Malaysia | Leaf | - | CTAB (1.0–4.0 mM) | 90 °C for 24 h | - | SEM, FT-IR, | (Kamaru et al., 2016) |
| Assam, India | Stem | 300 µm | - | 70 °C for 24 h | - | SEM, FT-IR, BET, $pH_{pzc}$ | (Rajesh et al., 2014) |
| Guangzhou, China | Peel | 100 µm | Isopropyl alcohol (20%), 0.1 M NaOH | 50 °C for 24 h | - | XRD, FT-IR | (Hu et al., 2010) |
| Nasugbu Public Market, Philippines | Crown leaf | 149 µm | - | 90 °C | - | SEM, FT-IR, XRF | (Nieva et al., 2020) |
| Penang, Malaysia | Stem | 355–500 µm | - | 70 °C for 24 h | - | SEM, FT-IR | (Hameed et al., 2009) |
| Buriram, Thailand | Leaf | 3–80 µm | Treated with 5 wt.% NaOH, TEA, and cross-linked with PEI | 80 °C for 24 h | - | SEM, FT-IR, TGA/DTG, XPS | (Tangtubtim and Saikrasun, 2019a) |

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|---|---|---|---|---|---|---|---|
| Buriram, Thailand | Leaf | 3–80 µm | Treated with 5 wt.% NaOH, TEA, and cross-linked with PEI | Stirring for 12 h | - | SEM, FT-IR, TGA, XPS | (Tangtubtim and Saikrasun, 2019b) |
| Pahang, Malaysia | Peel | Not reported | 1.0 M of $ZnCl_2$ | Room temperature for 24 h | 800 °C for 1 h | SEM, FT-IR | (Abd Ghapar et al., 2020) |
| Hainan, China | Peel | Not reported | Limited oxygen | 200 °C for 2 h | 350–650 °C, 10 °C/min, 3 h | SEM, FT-IR, EDX | (Fu et al., 2016) |
| Nantou City, Taiwan | Leaf | 2000 µm | - | 60 °C for 24 h | 600 °C, 10 °C/min, 2 h | $pH_{pzc}$, BET, SEM, EDX, FT-IR, XPS | (Iamsaard et al., 2022) |
| Guangzhou, China | Peel | 177 µm | - | 80 °C overnight | 300 °C for 1 h | Zeta potential, VSM, BET, FE-SEM, EDX, FT-IR, ICP, XPS | (Liao et al., 2018) |
| Guangzhou, China | Peel | 177 µm | $FeCl_2/FeCl_3$ (1:1), then NaOH | 60 °C for 0.5 h | 80 °C overnight | Zeta potential, VSM, BET, FE-SEM, EDX, FT-IR, ICP, XPS | (Liao et al., 2018) |
| Guangzhou, China | Peel | 177 µm | $La(OH)_3$ | Room temperature for 24 h | 80 °C overnight | Zeta potential, VSM, BET, FE-SEM, EDX, FT-IR, ICP, XPS | (Liao et al., 2018) |

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|---|---|---|---|---|---|---|---|
| Semarang, Indonesia | Crown leaf | <150 µm | KOH | Microwave 800 W for 4 min | 500 °C for 90 min in limited air | VSM, BET, FE-SEM, EDX, FT-IR, XRD | (Astuti et al., 2019) |
| Guangzhou, China | Peel | 100–200 µm | Succinic anhydride (3:1 by wt.) | Room temperature for 24 h | - | FT-IR | (Hu et al., 2011) |
| Aligarh, India | Fruit leftover | - | 0.1 M NaOH | Room temperature for 2 h | 80 °C for 2 h | BET, SEM, EDX, FT-IR, AAS, $pH_{pzc}$ | (Veeramalai et al., 2022) |
| Paraná, Brazil | Leaf | - | $H_3PO_4$ (1:1 by vol./wt.) | 65 °C for 24 h | 500 °C, 5 °C/min, $N_2$ flow (100 mL/min) | BET, SEM, FT-IR, TGA, Raman, $pH_{pzc}$ | (Beltrame et al., 2018) |
| Delhi, India | Peel | - | - | - | 350–650 °C for 60 min, 5 °C/min | BET, EDX, SEM, FT-IR, TGA, $pH_{pzc}$ | (Shakya and Agarwal, 2019) |
| Resende-RJ, Brazil | Crown | 500 µm | NaOH (1:1 by wt.) | Room temperature for 24 h | 400 °C for 180 min | XRD, SEM, FT-IR, TGA | (da Silva et al., 2021) |
| Johor, Malaysia | Leaf | 300 µm | NaOH (2.18:1 by wt.) for 2h | 110 °C overnight | 464 °C for 180 min | - | (Abd Latif et al., 2021) |
| Chakdara, Pakistan | Fruit waste | - | $FeCl_3/FeSO_4$ (2:1), then 5 M NaOH | Room temperature for 50 min | - | XRD, SEM, FT-IR, TGA, BET, EDX | (Zahoor et al., 2019) |

**Note:** SEM, scanning electron microscopy; FT-IR, Fourier transform infrared spectroscopy; XRD, X-Ray diffraction pattern analysis; TGA, thermogravimetric analysis; BET, Brunauer-Emmett-Teller; BJH, Barrett-Joyner-Halenda; $pH_{pzc}$, point of zero charge; EDX, Energy dispersive X-ray analysis; XRF, X-ray fluorescence; CTAB, Hexadecyltrimethylammoniumbromide; TEA, trimethylamine; PEI, polyethyleneimine-carbamate.

1218 **Table 2.** Lignocellulosic composition, proximate, and ultimate analysis of the pineapple species

| Location | Part | Lignocellulosic composition | Proximate analysis | Ultimate analysis | Ref. |
|---|---|---|---|---|---|
| Cruz das Almas, Brazil | Leaf | Cellulose: 49–63%, Hemicellulose: 6–13%, Lignin: 20–36% | Ash: 1.2–3.3% | Not reported | (Sena Neto et al., 2015) |
| Johor, Malaysia | Leaf | Cellulose: 72.76%, Hemicellulose: 17.15%, Lignin: 4.76% | Ash: 0.59% | Not reported | (Nashiruddin et al., 2020) |
| São Paulo, Brazil | Crown leaf | Cellulose: 17.4%, Hemicellulose: 19.1%, Lignin: 24.3% | Ash: 5.2% | Not reported | (Pereira et al., 2021) |
| Araçagi, Brazil | Crown leaf | Cellulose: 12.93%, Hemicellulose: 35.49%, Lignin: 26.4% | Moisture: 8.96%, volatile matter: 78.84%, ash: 5.22%, fixed carbon: 6.98% | C: 44.05%, H: 5.81%, O: 49.27%, N: 0.87% | (Braga et al., 2015) |
| Johor, Malaysia | Leaf | Cellulose: 30%, Hemicellulose: 37%, Lignin: 22% | Moisture: 6.75%, volatile matter: 51.74%, ash: 7.35%, fixed carbon: 34.16% | C: 43.4%, H: 6.7%, O: 59.2%, N: 1.7%, S: 0.4% | (Mansor et al., 2019, 2018) |

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|---|---|---|---|---|---|
| Johor, Malaysia | Stem | Cellulose: 37%, Hemicellulose: 34%, Lignin: 20% | Moisture: 9.1%, volatile matter: 58.25%, ash: 7.68%, fixed carbon: 25.18% | C: 41.1%, H: 6.7%, O: 57.3%, N: 1.45%, S: 0.56% | (Mansor et al., 2019, 2018) |
| Johor, Malaysia | Root | Cellulose: 42%, Hemicellulose: 32%, Lignin: 19% | Moisture: 4.55%, volatile matter: 41.56%, ash: 30.07%, fixed carbon: 28.82% | C: 38.7%, H: 5.4%, O: 75.4%, N: 1.0%, S: 0.23% | (Mansor et al., 2019, 2018) |
| Araçagi, Brazil | Crown leaf | Cellulose: 13.3%, Hemicellulose: 35.4%, Lignin: 26.4% | Moisture: 8.9%, volatile matter: 78.8%, ash: 5.2%, fixed carbon: 7.1% | C: 44.1%, H: 5.8%, O: 49.3%, N: 0.8% | (Calixto et al., 2022) |
| Mumbai, India | Peel | Cellulose: 20.9%, Hemicellulose: 31.8%, Lignin: 10.4% | Volatile matter: 94.04%, ash: 5.9% | C: 43.9%, H: 5.7%, N: 0.6% | (Banerjee et al., 2019) |
| Johor, Malaysia | Leaf | Cellulose: 31.2%, Hemicellulose: 13.6%, Lignin: 17.6% | Moisture: 4.56%, volatile matter: 80.4%, ash: 3.57%, fixed carbon: 11.2% | C: 40.5%, H: 6.91%, O: 50.3%, N: 1.78%, S: 0.36% | (Mathew et al., 2015) |
| Johor, Malaysia | Stem | Cellulose: 49.2%, Hemicellulose: 8.26%, Lignin: 5.42% | Moisture: 7.92%, volatile matter: 78.9%, ash: 4.87%, fixed carbon: 8.24% | C: 37.6%, H: 6.69%, O: 52.7%, N: 1.89%, S: 0.97% | (Mathew et al., 2015) |

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|---|---|---|---|---|---|
| Haryana, India | Peel | Not reported | Moisture: 6.87%, volatile matter: 68.96%, ash: 4.75%, fixed carbon: 19.52% | C: 47.39%, H: 6.13%, O: 40.64%, N: 1.08% | (Shakya and Agarwal, 2019) |
| Guangdong, China | Crown and peel residue | Cellulose: 27.35%, Hemicellulose: 21.15%, Lignin: 10.25% | Moisture: 2.15%, volatile matter: 72.12%, ash: 6.24%, fixed carbon: 19.5% | C: 44.95%, H: 5.5%, O: 47.65%, N: 1.68%, S: 0.22% | (Wang et al., 2022) |

**Table 3.** The effect of activating agents, and activation conditions on the point of zero charge, surface area and pore volume for the pineapple wastes based adsorbents

| Part of pineapple | Activating chemical | Activation (tem, time, ramping rate) | $pH_{pzc}$ or zeta potential (mV) | Method | Surface area ($m^2\ g^{-1}$) | Pore volume ($cm^3\ g^{-1}$) | Ref. |
|---|---|---|---|---|---|---|---|
| Leaf | - | - | 2.3 | BET | 4.26 | 0.033 | (Weng and Wu, 2012) |
| Crown leaf | 0.1 M NaOH for 2 h | - | 4.0 | BET | 32.9 | - | (Gogoi et al., 2018) |
| Leaf powder | - | - | - | BET | 14.55 | - | (Mishra and Tadepalli, 2015) |
| Leaf | - | 500 °C for 2 min | - | BJH | 44.775 | 8.183 | (Herlinawati et al., 2022) |
| Leaf | 1 M $H_2SO_4$ for 24 h | 500 °C for 2 min | - | BJH | 25.68 | 5.133 | (Herlinawati et al., 2022) |
| Leaf powder | - | - | 2.8 | BET | 6.84 | 0.29 | (Ponou et al., 2011) |
| Leaf-derived carbon | - | 350 °C for 60 min | 2.2 | BET | 44.08 | 0.93 | (Ponou et al., 2011) |
| Leaf-derived carbon | - | 450 °C for 60 min | 2.1 | BET | 374.9 | 3.66 | (Ponou et al., 2011) |
| Leaf powder | - | 80 °C for 48 h | 2.3 | BET | 5.24 | 1.53 | (Weng et al., 2009) |
| Leaf powder | - | 90 °C for 24 h | - | BET | 4.2 | 0.024 | (Chowdhury et al., 2011) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $ZnCl_2$-activated carbon | $ZnCl_2$ (0.5, 1.0, 1.5 by wt.%) for 24 h | 500 °C, 1 h | - | BET | 22.99–521.88 | 0.02–0.30 | (Mahamad et al., 2015) |
| Stem powder | - | - | 4.08 | BET | 11.47 | - | (Rajesh et al., 2014) |
| Peel powder | Limited oxygen | 200 °C for 2 h | - | BET | 0.352 | 0.001 | (Fu et al., 2016) |
| Peel biochar | Limited oxygen | 350 °C for 3 h | - | BET | 0.815 | 0.0015 | (Fu et al., 2016) |
| Peel biochar | Limited oxygen | 500 °C for 3 h | - | BET | 2.729 | 0.0022 | (Fu et al., 2016) |
| Peel biochar | Limited oxygen | 650 °C for 3 h | - | BET | 6.643 | 0.0031 | (Fu et al., 2016) |
| Leaf biochar | - | 600 °C for 2 h, $N_2$ atmosphere | <2.0 | BET | 7.3 | 0.0106 | (Iamsaard et al., 2022) |
| Peel biochar | - | 300 °C for 1 h | −4.49 mV | BET | 36.22 | - | (Liao et al., 2018) |
| Peel biochar | $FeCl_2/FeCl_3$ (1:1) | 80 °C overnight | −16.87 mV | BET | 1.18 | - | (Liao et al., 2018) |
| Peel biochar | $La(OH)_3$ | 80 °C overnight | 7.03 mV | BET | 84.89 | - | (Liao et al., 2018) |
| Crown leaf biochar | - | 500 °C for 90 min | - | BET | 17.03 | 0.0242 | (Astuti et al., 2019) |
| Crown leaf KOH-activated carbon | KOH | 105 °C for 24 h | - | BET | 71.75–383.17 | 0.027–0.1193 | (Astuti et al., 2019) |
| Crown leaf microwave | KOH | Microwave 800 W for 4 min | - | BET | 95.11–314.08 | 0.1056–0.1098 | (Astuti et al., 2019) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| KOH-activated carbon | | | | | | | |
| Leaf activated carbon | $H_3PO_4$ | 65 °C for 24 h | 2.8 | BET | 1031 | 1.27 | (Beltrame et al., 2018) |
| Peel biochar at 350 °C | - | - | 7.7 | BET | 5.548 | 0.004 | (Shakya and Agarwal, 2019) |
| Peel biochar at 450 °C | - | - | 7.9 | BET | 3.372 | 0.005 | (Shakya and Agarwal, 2019) |
| Peel biochar at 550 °C | - | - | 8.2 | BET | 11.112 | 0.017 | (Shakya and Agarwal, 2019) |
| Peel biochar at 650 °C | - | - | 8.2 | BET | 6.391 | 0.010 | (Shakya and Agarwal, 2019) |
| $Fe_3O_4$/activated carbon | $FeCl_3$/$FeSO_4$ (2:1), then 5 M NaOH | Room temperature for 50 min | 7.2 | BET | 39.0 | 0.2 | (Zahoor et al., 2019) |

**Note:** BET, Brunauer-Emmett-Teller; BJH, Barrett-Joyner-Halenda.

**Table 4.** Optimum adsorption conditions and adsorption performance (removal efficiency and maximum adsorption capacity) of the pineapple wastes based adsorbents for removal of various pollutants.

| Adsorbent | Pollutant | Optimized pH | Dose ($g L^{-1}$) | Time (min) | Removal (%) | Maximum capacity ($mg g^{-1}$) | Ref. |
|---|---|---|---|---|---|---|---|
| Chemically oxidized fruit peel | Cd(II) | 4 | 4.0 | 30 | 90.0 | 42.1 | (Ahmad et al., 2016) |
| Chemically oxidized fruit peel | Pb(II) | 4 | 4.0 | 30 | 87.0 | 28.55 | (Ahmad et al., 2016) |
| Leaf powder | Cu(II) | 5 | 0.2 | 20 | 90.0 | 9.28 | (Weng and Wu, 2012) |
| Core powder | Cr(VI) [a] | 2 | 30 | 1440 | 92.39 | 8.8 | (Rosales et al., 2019) |
| Fruit peel activated by $ZnCl_2$ | Zn(II) | - | 0.25 | 240 | 92 | 37.23 | (Turkmen et al., 2021) |
| Fruit peel activated by $H_2SO_4$ | Zn(II) | - | 0.25 | 240 | 94 | 36.99 | (Turkmen et al., 2021) |
| Fruit peel powder (0.5 mm) | Zn(II) | 5 | 1.0 | 480 | 23.0 | 0.45 | (Mishra et al., 2010) |
| Crown leaf | Cr(VI) | 2.5 | 60 | 120 | - | 2.503 | (Gogoi et al., 2018) |
| Crown leaf | Cr(III) | 5 | 60 | 120 | - | 4.42 | (Gogoi et al., 2018) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Leaf-derived cellulose | Pb(II) | 6.0 | 10 | 90 | 95 | 155.06 | (Daochalermwong et al., 2020) |
| Leaf-derived cellulose | Cd(II) | 6.0 | 10 | 90 | 93 | 37.26 | (Daochalermwong et al., 2020) |
| Leaf powder | Pb(II) | 7.0 | 15 | 450 | 92.67 | 2.16 | (Mishra and Tadepalli, 2015) |
| Leaf powder | Zn(II) | 7.0 | 15 | 450 | 85.77 | 1.33 | (Mishra and Tadepalli, 2015) |
| Leaf powder | Cr(III) | 7.0 | 15 | 450 | 92.67 | 0.86 | (Mishra and Tadepalli, 2015) |
| Fruit peel | Cd(II) | 9.0 | 120 | 90 | 98.44 | 1.91 | (Yusoff et al., 2020) |
| Fruit peel | Cr(VI) | 9.0 | 120 | 90 | 88.35 | - | (Yusoff et al., 2020) |
| Fruit peel | Pb(II) | 9.0 | 120 | 90 | 93.65 | - | (Yusoff et al., 2020) |
| Leaf powder | Pb(II) | 5.5 | 4.0 | 240 | 80.8 | 32.55 | (Heba et al., 2019) |
| Fruit rind activated by $ZnCl_2$ | Zn(II) | - | 5.0 | 240 | 30.50 | 12.2 | (Yılmaz and Tugrul, 2022) |
| Oxalic acid-activated stem | Pb(II) | 4.0 | 2.0 | 60 | - | 27.53 | (Vivian Loh Zing et al., 2019) |
| Stem powder | Pb(II) | 5.0 | 2.0 | 60 | - | 12.13 | (Vivian Loh Zing et al., 2019) |
| Leaf-derived carbon at 450 °C | Cr(VI) | 2.0 | 10 | 60 | 90.1 | 18.77 | (Ponou et al., 2011) |
| Succinic anhydride- | Cu(II) | 5.4 | 1.0 | 30 | 36.0 [b] | 31.78 | (Hu et al., 2011) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| modified peel fiber | | | | | | | |
| Succinic anhydride-modified peel fiber | Cd(II) | 7.5 | 1.0 | 30 | 42.0 [b] | 39.93 | (Hu et al., 2011) |
| Succinic anhydride-modified peel fiber | Pd(II) | 5.6 | 1.0 | 30 | 56.0 [b] | 75.58 | (Hu et al., 2011) |
| Modified peel powder | Cu(II) | 5.5 | 1.0 | 30 | 50 [b] | 65.98 | (Hu et al., 2010) |
| Modified peel powder | Cd(II) | 7.5 | 1.0 | 30 | 80 [b] | 102.92 | (Hu et al., 2010) |
| Modified peel powder | Pd(II) | 5.5 | 1.0 | 30 | 74 [b] | 111.41 | (Hu et al., 2010) |
| $KMnO_4$-modified pineapple cellulose | Cu(II) | 7.0 | 1.0 | 80 | 96.0 | 28.99 | (Zhuang et al., 2020) |
| Stem powder | Ni(II) | 5.0 | 0.1 | 300 | 85.24 | 2.4 | (Rajesh et al., 2014) |
| NaOH-treated leaf fiber | Cr(VI) | 3.0 | 0.1 | 60 | - | 133 | (Tangtubtim and Saikrasun, 2019a) |
| PEI-cross-linked leaf fiber | Cr(VI) | 3.0 | 0.1 | 60 | - | 222 | (Tangtubtim and Saikrasun, 2019a) |
| PEI-cross-linked leaf fiber | Cu(II) | 5.0 | 0.1 | 60 | - | 273 | (Tangtubtim and Saikrasun, 2019b) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| PEI-cross-linked leaf fiber | Pb(II) | 5.0 | 0.1 | 60 | - | 165 | (Tangtubtim and Saikrasun, 2019b) |
| $ZnCl_2$-activated carbon | Fe(III) | Not reported | 4.0 | 120 | 55.26 | - | (Abd Ghapar et al., 2020) |
| Leaf biochar at 600 °C | Ni(II) | 5.0 | 2.0 | 1440 | >94.0 | 44.88 | (Iamsaard et al., 2022) |
| Leaf biochar at 600 °C | Zn(II) | 5.0 | 2.0 | 1440 | >92.0 | 46.0 | (Iamsaard et al., 2022) |
| Leaf biochar at 600 °C | Cu(II) | 5.0 | 2.0 | 1440 | >96.0 | 53.14 | (Iamsaard et al., 2022) |
| NaOH-treated fruit leftover | Ni(II) | 4–6 | 10.0 | 60 | 97.60 | 8.98 | (Veeramalai et al., 2022) |
| Peel biochar at 350 °C | Cr(VI) | 2.0 | 5.0 | 480 | 99.19 | 41.67 | (Shakya and Agarwal, 2019) |
| Peel biochar at 450 °C | Cr(VI) | 2.0 | 5.0 | 480 | 82.63 | 33.33 | (Shakya and Agarwal, 2019) |
| Peel biochar at 550 °C | Cr(VI) | 2.0 | 5.0 | 480 | 58.22 | 32.26 | (Shakya and Agarwal, 2019) |
| Peel biochar at 650 °C | Cr(VI) | 2.0 | 5.0 | 480 | 40.78 | 23.81 | (Shakya and Agarwal, 2019) |
| $La(OH)_3$-modified magnetic biochar | $[PO_4]^{3-}$ | 2.0 | 1.0 | 1440 | 100.0 | 101.16 | (Liao et al., 2018) |
| Modified pineapple juice extracted residue | $F^-$ | 6.0 | 0.9 | 120 | 79.6 | 7.06 | (Reza and Ahmaruzzaman, 2022) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Leaf powder | Methylene blue | 7.5 | 3.0 | 20 | 95.0 | 284.03 | (Weng et al., 2009) |
| Leaf powder | Crystal violet | 8.0 | 3.0 | 180 | 96.0 | 78.22 | (Chakraborty et al., 2012) |
| Leaf powder | Methylene blue | 6.0 | 1.5 | 280 | - | 97.09 | (Krishni et al., 2014) |
| Leaf powder | Crystal violet | 8.0 | 1.0 | 120 | - | 158.73 | (Neupane et al., 2015) |
| Leaf powder | Basic green 4 | 9.0 | 5.0 | 150 | 99.36 | 54.64 | (Chowdhury et al., 2011) |
| Leaf powder | Rose Bengal | 5.0 | 1.0 | 180 | 92.53 | 58.80 | (Hassan et al., 2020) |
| Peel hydrogels | Congo red | 4.0 | 0.67 | 60 | - | 114.94 | (Das et al., 2016) |
| Peel hydrogels | Congo red | 4.0 | 0.67 | 60 | - | 138.89 | (Das et al., 2016) |
| $ZnCl_2$-activated carbon | Methylene blue | - | 2.0 | 240 | - | 288.34 | (Mahamad et al., 2015) |
| Stem powder | Methylene blue | 4.0 | 1.5 | 60 | 96.70 | 119.05 | (Hameed et al., 2009) |
| Leaf powder | Remazol Brilliant Blue R | - | 50 | 1440 | 96.2 | 42.02 | (Rahmat et al., 2016) |
| KOH-activated crown leaf-derived carbon | Methyl violet | 5.0 | 6.0 | 180 | 97.0 [b] | 31.24 | (Astuti et al., 2019) |
| Microwave-assisted KOH-activated crown leaf-derived carbon | Methyl violet | 5.0 | 6.0 | 180 | 93.0 [b] | 16.76 | (Astuti et al., 2019) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| NaOH-activated crown-derived carbon | Methylene blue | 6.0 | 0.3 | 60 | - | 292 | (da Silva et al., 2021) |
| NaOH-activated leaf-derived carbon | Reactive black 5 | - | 1.0 | 60 | 98.25 | 50 | (Abd Latif et al., 2021) |
| Bark powder | Dye mixture [a] (methylene blue, brilliant green, and Congo red) | 6.0 | 2.0 | 60 | 97.93 | 14.6 | (Fegousse et al., 2019) |
| Crown leaf powder | Crystal violet | 8.0 | 8.0 | 180 | 98 [b] | 6.49 | (Nieva et al., 2020) |
| Surfactant-modified leaf powder | Methylene blue | 11.0 | 10.0 | 120 | - | 52.63 | (Kamaru et al., 2016) |
| Surfactant-modified leaf powder | Methyl orange | 3.0 | 10.0 | 120 | - | 47.62 | (Kamaru et al., 2016) |
| Poly(acrylic acid)-grafted pineapple leaf | Methylene blue | 5.6 | 1.33 | 180 | 98 | - | (Pomicpic et al., 2020) |
| $HNO_3$-activated carbon | Methylene blue | 4.0 | 5.0 | 120 | 92.99 | 5.136 | (Veeramalai et al., 2022) |
| Peel biochar at 350 °C | Oxytetracycline | - | 10.0 | 1440 | 80 | 0.781 | (Fu et al., 2016) |
| Peel biochar at 500 °C | Oxytetracycline | - | 10.0 | 1440 | 80 | 0.897 | (Fu et al., 2016) |

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|---|---|---|---|---|---|---|---|
| Peel biochar at 650 °C | Oxytetracycline | - | 10.0 | 1440 | 80 | 1.072 | (Fu et al., 2016) |
| $Fe_3O_4$/activated carbon | Enrofloxacin | 6–8 | 0.8 | 80 | 80 [b] | 46.3 | (Zahoor et al., 2019) |
| $H_3PO_4$-activated biochar | Caffeine | 5.8 | 1.0 | 360 | - | 155.5 | (Beltrame et al., 2018) |

**Note:** [a] adsorption tests were optimized by response surface methodology, [b] data was estimated from figure of the reference.

**Table 5.** Adherence and correlation coefficients of kinetic and isotherm models for adsorption of various pollutants by the pineapple wastes based adsorbents

| Adsorbent | Pollutant(s) | Kinetic model | $R^2$ | Isotherm model | $R^2$ | Ref. |
|---|---|---|---|---|---|---|
| Chemically oxidized fruit peel | Cd(II) | PSO | 0.995 | Langmuir | 0.9839 | (Ahmad et al., 2016) |
| Chemically oxidized fruit peel | Pb(II) | PSO | 0.993 | Langmuir | 0.9916 | (Ahmad et al., 2016) |
| Leaf powder | Cu(II) | PSO | 0.99 | Langmuir | 0.99 | (Weng and Wu, 2012) |
| Core powder | Cr(VI) | - | - | Freundlich | 0.97 | (Rosales et al., 2019) |
| Crown leaf | Cr(VI) | PSO | 0.9963 | Liu | 0.9938 | (Gogoi et al., 2018) |
| Crown leaf | Cr(III) | PSO | 0.9934 | Liu | 0.9963 | (Gogoi et al., 2018) |
| Leaf-derived cellulose | Pb(II) | PFO | 0.9982 | Langmuir | 0.9775 | (Daochalermwong et al., 2020) |
| Leaf-derived cellulose | Cd(II) | PFO | 0.9982 | Langmuir | 0.9746 | (Daochalermwong et al., 2020) |
| Leaf powder | Pb(II) | - | - | Langmuir | 0.96 | (Mishra and Tadepalli, 2015) |
| Leaf powder | Zn(II) | - | - | Langmuir | 0.95 | (Mishra and Tadepalli, 2015) |
| Leaf powder | Cr(III) | - | - | Langmuir | 0.97 | (Mishra and Tadepalli, 2015) |
| Leaf powder | Pb(II) | PSO | 0.998 | Langmuir | 0.94 | (Heba et al., 2019) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Oxalic acid-activated stem | Pb(II) | PSO | 0.9997 | Langmuir | 0.9997 | (Vivian Loh Zing et al., 2019) |
| Stem powder | Pb(II) | PSO | 0.9994 | Langmuir | 0.9992 | (Vivian Loh Zing et al., 2019) |
| Leaf-derived carbon at 450 °C | Cr(VI) | PSO | 0.99 | Langmuir | - | (Ponou et al., 2011) |
| $KMnO_4$-modified pineapple cellulose | Cu(II) | Lagergren | >0.999 | Freundlich | 0.9999 | (Zhuang et al., 2020) |
| Stem powder | Ni(II) | PSO | >0.99 | Freundlich | 0.9964 | (Rajesh et al., 2014) |
| Modified peel powder | Cu(II) | PSO | 0.99 | Langmuir | 0.999 | (Hu et al., 2010) |
| Modified peel powder | Cd(II) | PSO | 0.99 | Langmuir | 0.999 | (Hu et al., 2010) |
| Modified peel powder | Pd(II) | PSO | 0.99 | Langmuir | 0.999 | (Hu et al., 2010) |
| NaOH-treated leaf fiber | Cr(VI) | PSO | >0.98 | Langmuir | 0.998 | (Tangtubtim and Saikrasun, 2019a) |
| PEI-cross-linked leaf fiber | Cr(VI) | PSO | >0.98 | Langmuir | 0.991 | (Tangtubtim and Saikrasun, 2019a) |
| NaOH-treated leaf fiber | Cu(II) | PSO | >0.96 | Langmuir | 0.9998 | (Tangtubtim and Saikrasun, 2019b) |
| NaOH-treated leaf fiber | Pb(II) | PSO | >0.98 | Langmuir | 0.9906 | (Tangtubtim and Saikrasun, 2019b) |
| PEI-cross-linked leaf fiber | Cu(II) | PSO | >0.99 | Langmuir | 0.9825 | (Tangtubtim and Saikrasun, 2019b) |
| PEI-cross-linked leaf fiber | Pb(II) | PSO | >0.98 | Langmuir | 0.9752 | (Tangtubtim and Saikrasun, 2019b) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Leaf biochar at 600 °C | Ni(II) | PFO | 0.998 | Langmuir | >0.99 | (Iamsaard et al., 2022) |
| Leaf biochar at 600 °C | Zn(II) | PFO | 0.999 | Langmuir | >0.99 | (Iamsaard et al., 2022) |
| Leaf biochar at 600 °C | Cu(II) | PFO | 1.000 | Langmuir | >0.99 | (Iamsaard et al., 2022) |
| NaOH-treated fruit leftover | Ni(II) | PSO | 0.99 | Langmuir | ≥0.96 | (Veeramalai et al., 2022) |
| Peel biochar at 350 °C | Cr(VI) | PSO | 0.986 | Freundlich | 0.972 | (Shakya and Agarwal, 2019) |
| Peel biochar at 450 °C | Cr(VI) | PSO | 0.981 | Freundlich | 0.968 | (Shakya and Agarwal, 2019) |
| Peel biochar at 550 °C | Cr(VI) | PSO | 0.993 | Freundlich | 0.967 | (Shakya and Agarwal, 2019) |
| Peel biochar at 650 °C | Cr(VI) | PSO | 0.994 | Freundlich | 0.957 | (Shakya and Agarwal, 2019) |
| $La(OH)_3$-modified magnetic biochar | $[PO_4]^{3-}$ | PSO | 0.98 | Langmuir | 0.99 | (Liao et al., 2018) |
| Leaf powder | Methylene blue | PSO | 0.999 | Langmuir | 0.993 | (Weng et al., 2009) |
| Leaf powder | Crystal violet | PSO | 0.992 | Langmuir | 0.999 | (Chakraborty et al., 2012) |
| Leaf powder | Methylene blue | PSO | >0.99 | Langmuir | 0.9952 | (Krishni et al., 2014) |
| Leaf powder | Crystal violet | PSO | 0.99 | Langmuir | 0.98 | (Neupane et al., 2015) |
| Leaf powder | Basic Green 4 | PSO | 0.999 | Langmuir | 1.000 | (Chowdhury et al., 2011) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Surfactant-modified leaf powder | Methylene blue | PSO | - | Langmuir | >0.97 | (Kamaru et al., 2016) |
| Surfactant-modified leaf powder | Methyl orange | PSO | - | Langmuir | >0.99 | (Kamaru et al., 2016) |
| Crown leaf powder | Crystal violet | - | - | Langmuir | 0.99 | (Nieva et al., 2020) |
| Stem powder | Methylene blue | PSO | >0.99 | Langmuir | 0.998 | (Hameed et al., 2009) |
| Leaf powder | Remazol Brilliant Blue R | PSO | 1.0000 | Langmuir | 0.9945 | (Rahmat et al., 2016) |
| KOH-activated crown leaf-derived carbon | Methyl violet | - | - | Redlich-Peterson | 0.995 | (Astuti et al., 2019) |
| Microwave-assisted KOH-activated crown leaf-derived carbon | Methyl violet | - | - | Redlich-Peterson | 0.991 | (Astuti et al., 2019) |
| $HNO_3$-activated carbon | Methylene blue | PFO | 1.00 | Langmuir | >0.85 | (Veeramalai et al., 2022) |
| Peel biochar at 350 °C | Oxytetracycline | PSO | 0.999 | Langmuir | >0.999 | (Fu et al., 2016) |
| Peel biochar at 500 °C | Oxytetracycline | PSO | 0.999 | Langmuir | >0.95 | (Fu et al., 2016) |
| Peel biochar at 650 °C | Oxytetracycline | PSO | 0.999 | Langmuir | >0.81 | (Fu et al., 2016) |
| $Fe_3O_4$/activated carbon | Enrofloxacin | PSO | 0.999 | Langmuir | 0.99 | (Zahoor et al., 2019) |

**Note:** PFO, pseudo first-order model; PSO, pseudo second-order model; $R^2$, coefficient of determination.

**Table 6.** A summary on the parameters for the thermodynamic model of the adsorption of various pollutants by the pineapple wastes based adsorbents

| Adsorbent | Pollutant(s) | Tem (K) | ΔG° (kJ mol$^{-1}$) | ΔH° (kJ mol$^{-1}$) | ΔS° (J mol$^{-1}$ K$^{-1}$) | Ref. |
|---|---|---|---|---|---|---|
| Chemically oxidized fruit peel | Cd(II) | 298–323 | −3.499 | −26.089 | −75.017 | (Ahmad et al., 2016) |
| Chemically oxidized fruit peel | Pb(II) | 298–323 | −0.857 | −63.530 | −217.66 | (Ahmad et al., 2016) |
| Crown leaf | Cr(VI) | 303–328 | −32.77 | 25.449 | 192.210 | (Gogoi et al., 2018) |
| Crown leaf | Cr(III) | 303–328 | −32.874 | 21.358 | 179.00 | (Gogoi et al., 2018) |
| Leaf-derived carbon at 450 °C | Cr(VI) | 323–343 | −1.14 | 77.89 | 28.93 | (Ponou et al., 2011) |
| Leaf-derived carbon at 350 °C | Cr(VI) | 323–343 | −2.72 | 77.89 | 9.48 | (Ponou et al., 2011) |
| Leaf powder | Cr(VI) | 323–343 | −1.52 | 77.89 | 23.23 | (Ponou et al., 2011) |
| $KMnO_4$-modified pineapple cellulose | Cu(II) | 298–333 | −2.42 | 9.49 | 39.84 | (Zhuang et al., 2020) |
| Leaf biochar at 600 °C | Ni(II) | 298–323 | −17.59 | 24.26 | 59.11 | (Iamsaard et al., 2022) |
| Leaf biochar at 600 °C | Zn(II) | 298–323 | −5.83 | 7.62 | 19.61 | (Iamsaard et al., 2022) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Leaf biochar at 600 °C | Cu(II) | 298–323 | −10.40 | 14.78 | 34.94 | (Iamsaard et al., 2022) |
| NaOH-treated fruit leftover | Ni(II) | 303–323 | −7.61 | 32.55 | 132 | (Veeramalai et al., 2022) |
| Leaf powder | Methylene blue | 277–327 | −26.12 | −5.93 | 76.4 | (Weng et al., 2009) |
| Leaf powder | Crystal violet | 293–303 | −18.25 | −68.47 | −171.29 | (Chakraborty et al., 2012) |
| Leaf powder | Basic green 4 | 298–318 | −17.96 | −101.40 | −280.0 | (Chowdhury et al., 2011) |
| Surfactant-modified leaf powder | Methylene blue | 308–333 | −4.3 | −2.79 | 4.0 | (Kamaru et al., 2016) |
| Surfactant-modified leaf powder | Methyl orange | 308–333 | −3.7 | −8.75 | 16.0 | (Kamaru et al., 2016) |
| Bark powder | Dye mixture (methylene blue, brilliant green, and Congo red) | 293–323 | −38.1 | −22.44 | −51.68 | (Fegousse et al., 2019) |
| Peel biochar at 350 °C | Oxytetracycline | 298–303 | −13.47 | 11.49 | 84 | (Fu et al., 2016) |
| Peel biochar at 500 °C | Oxytetracycline | 298–303 | −13.88 | 19.37 | 113 | (Fu et al., 2016) |
| Peel biochar at 650 °C | Oxytetracycline | 298–303 | −15.42 | 23.12 | 130 | (Fu et al., 2016) |
| $Fe_3O_4$/activated carbon | Enrofloxacin | 298–333 | −0.27 | - | - | (Zahoor et al., 2019) |

**Note:** ΔG° (kJ $mol^{-1}$) at 298K, standard free energy change; ΔH° (kJ $mol^{-1}$), standard enthalpy change; ΔS° (J $mol^{-1}$ $K^{-1}$), standard entropy change.

**Table 7.** A summary on the desorption eluent and recyclability study for adsorption of various pollutants by the pineapple wastes based adsorbents

| Adsorbent | Pollutant(s) | Eluent | Number of cycle | Ref. |
|---|---|---|---|---|
| Chemically oxidized fruit peel | Cd(II), Pb(II) | 0.1 M HCl | - | (Ahmad et al., 2016) |
| Crown leaf | Cr(III), Cr(VI) | 0.2–2 M NaOH | - | (Gogoi et al., 2018) |
| Leaf-derived cellulose | Cd(II) | 1 M HCl | 5 (90% for the final run) [a] | (Daochalermwong et al., 2020) |
| Leaf-derived cellulose | Pb(II) | 1 M HCl | 5 (90% for the final run) [a] | (Daochalermwong et al., 2020) |
| Leaf powder | Pb(II) | - | 4 (87% for the final run) [a] | (Heba et al., 2019) |
| NaOH-treated leaf fiber | Cr(VI) | 0.1 M NaOH | 5 (30 mg/g for the final run) [a] | (Tangtubtim and Saikrasun, 2019a) |
| PEI-cross-linked leaf fiber | Cr(VI) | 0.1 M NaOH | 5 (110 mg/g for the final run) [a] | (Tangtubtim and Saikrasun, 2019a) |
| NaOH-treated leaf fiber | Cu(II) | 0.1 M HCl | 5 (50 mg/g for the final run) [a] | (Tangtubtim and Saikrasun, 2019b) |
| NaOH-treated leaf fiber | Pb(II) | 0.1 M HCl | 5 (39 mg/g for the final run) [a] | (Tangtubtim and Saikrasun, 2019b) |
| PEI-cross-linked leaf fiber | Cu(II) | 0.1 M HCl | 5 (160 mg/g for the final run) [a] | (Tangtubtim and Saikrasun, 2019b) |
| PEI-cross-linked leaf fiber | Pb(II) | 0.1 M HCl | 5 (67 mg/g for the final run) [a] | (Tangtubtim and Saikrasun, 2019b) |

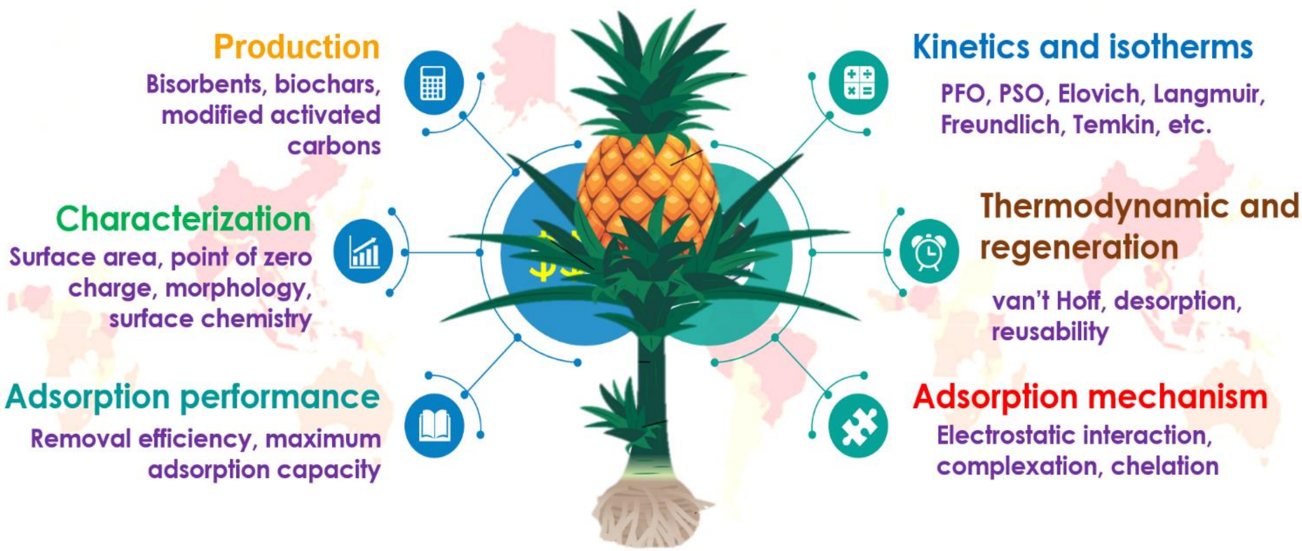
| | | | | |
|---|---|---|---|---|
| Leaf biochar at 600 °C | Ni(II), Zn(II), Cu(II) | Acid washing | 6 (72% for the final run) | (Iamsaard et al., 2022) |
| Leaf biochar at 600 °C | Ni(II), Zn(II), Cu(II) | Wet air oxidation | 6 (11% for the final run) | (Iamsaard et al., 2022) |
| $La(OH)_3$-modified magnetic biochar | $[PO_4]^{3-}$ | 3.0 M NaOH | 3 (92.93% for the final run) | (Liao et al., 2018) |
| Peel biochar at 350 °C | Cr(VI) | 1 M HCl | 5 (32% for the final run) [a] | (Shakya and Agarwal, 2019) |
| Peel biochar at 450 °C | Cr(VI) | 1 M HCl | 5 (11% for the final run) [a] | (Shakya and Agarwal, 2019) |
| Peel biochar at 550 °C | Cr(VI) | 1 M HCl | 5 (14% for the final run) [a] | (Shakya and Agarwal, 2019) |
| Peel biochar at 650 °C | Cr(VI) | 1 M HCl | 5 (6% for the final run) [a] | (Shakya and Agarwal, 2019) |
| Leaf powder | Crystal violet | 1 N acetic acid | - | (Neupane et al., 2015) |
| Peel hydrogel | Congo red | - | 4 | (Das et al., 2016) |
| Surfactant-modified leaf powder | Methylene blue, methyl orange | Acid solution at pH 3 | - | (Kamaru et al., 2016) |
| $Fe_3O_4$/activated carbon | Enrofloxacin | 3% NaOH | 6 (40% for the final run) [a] | (Zahoor et al., 2019) |

1238 **Note:** [a] data was estimated from figure of the reference.

**Table 8.** Plausible mechanism of adsorption of various pollutants by the pineapple-based adsorbents.

| Adsorbent | Pollutant(s) | Plausible mechanism | Ref. |
|---|---|---|---|
| Chemically oxidized fruit peel | Cd(II), Pb(II) | Electrostatic attraction, chelation | (Ahmad et al., 2016) |
| Leaf powder | Cu(II) | Complexation, electrostatic interaction | (Weng and Wu, 2012) |
| Crown leaf | Cr(III), Cr(VI) | Electrostatic interaction | (Gogoi et al., 2018) |
| Oxalic acid-activated stem, stem powder | Pb(II) | Ion-exchange, electrostatic attraction, monolayer chemisorption | (Vivian Loh Zing et al., 2019) |
| Leaf-derived carbon | Cr(VI) | Covalent bonding, electrostatic attraction | (Ponou et al., 2011) |
| $La(OH)_3$-modified magnetic biochar | $[PO_4]^{3-}$ | Precipitation, electrostatic interaction, ligand exchange and inner-sphere complexation. | (Liao et al., 2018) |
| Leaf biochar at 600 °C | Ni(II), Zn(II), Cu(II) | Cation exchange, surface complexation | (Iamsaard et al., 2022) |
| Leaf powder | Methylene blue | Chemical interaction, electrostatic interaction | (Weng et al., 2009) |

Graphical Abstract



Highlights

- The conversion of pineapple wastes into adsorbents was presented.
- Chemical modification and thermal processing of pineapple wastes were discussed.
- Surface areas of the pineapple waste derived adsorbents were found, 4.2–522.9 $m^2/g$.
- Electrostatic attraction, complexation, chelation, ion exchange were main mechanisms.
- Pineapple wastes could contribute proactively to circular economy.

## Contents

# Abstract

Each year, nearly 30 million tons of pineapple fruit are harvested for food and drinking industries, along with the release of a huge amount of pineapple wastes. Without the proper treatment, pineapple wastes can cause adverse impacts on the environment, calling for new technologies to convert them into valuable products. Here, we review the production and application of adsorbents derived from pineapple wastes. The thermal processing or chemical modification improved the surface chemistry and porosity of these adsorbents. The specific surface areas of the pineapple wastes-based adsorbents were in range from 4.2 to at 522.9 $m^2 \cdot g^{-1}$. Almost adsorption systems followed the pseudo second order kinetic model, and Langmuir isotherm model. The adsorption mechanism was found with the major role of electrostatic attraction, complexation, chelation, and ion exchange. The pineapple wastes based adsorbents could be easily regenerated. We suggest the potential of the pineapple wastes towards circular economy.

**Keywords:** Pineapple wastes; adsorbent production; heavy metal ions; toxic dyes; environmental treatment; circular economy.

## 1. Introduction

Over the past decades, the release of pollutants such as heavy metal ions, pharmaceuticals, textile dyes from industrial effluents and influents have been becoming the hazardous sources and posed a great threat to the environment animal as well as human health (Bhavya et al., 2021). Nowadays, new technologies have been developed and widely used to detect, quantify and treat the pollutants from the wastewaters (Hasan et al., 2021; Islam et al., 2020; Kubra et al., 2021; Md. Munjur et al., 2020; Rahman et al., 2019). Adsorption method is considered as a feasible and efficient approach to solve these problems (Saheed et al., 2021). This technology offers many advantages such as high performance, good selectivity, cost-effectiveness, eco-friendliness, and easy operation (Liu et al., 2022). The biomass-derived adsorbents have been recently developed to combat the pollution of wastewater (Gopinath et al., 2021). Many works suggested that adsorbents can be easily produced by the agricultural waste with a very low cost or zero-cost (Kosheleva et al., 2019). Complex composites and nanomaterials many disadvantages, e.g., having high cost production, enduring multiple synthesis steps, using toxic chemical for material fabrication, exhibiting less eco-friendly treatment methods (Awual, 2019, 2019; Md. Rabiul Awual et al., 2019b; Awual, 2017, 2016b, 2016a, 2016c; Awual et al., 2020; Md Rabiul Awual et al., 2019; Md. Rabiul Awual et al., 2019a; Awual and Hasan, 2019). Meanwhile, the agriculture derived adsorbents can alleviate above barriers, as a result, the biomass-derived adsorbents can be favourable to the environmental remediation.

The pineapple, scientific name: *Ananas comosus* (L) Merr., belongs to Bromeliaceae family, is widely cultivated in some tropical countries in such as Brazil, Indonesia, Vietnam, Malaysia, Thailand, India, etc. Brazil is the top pineapple producer with an average production of

2.2 million tons, and Asia region accounts for 46.7% of the global pineapple production as shown in Fig. 1. According to Food and Agriculture Organization (FAO), the global production and expansion in harvested area of pineapple annually increase at 2%, and 1.8%, respectively. It is estimated that the pineapple will obtain a quantity of 37 million tons in 2030. According to Fig. 2, the worldwide production and harvested area of the pineapple have been increasing between 1994 and 2020, indicating their high demand for food and drinking industries.

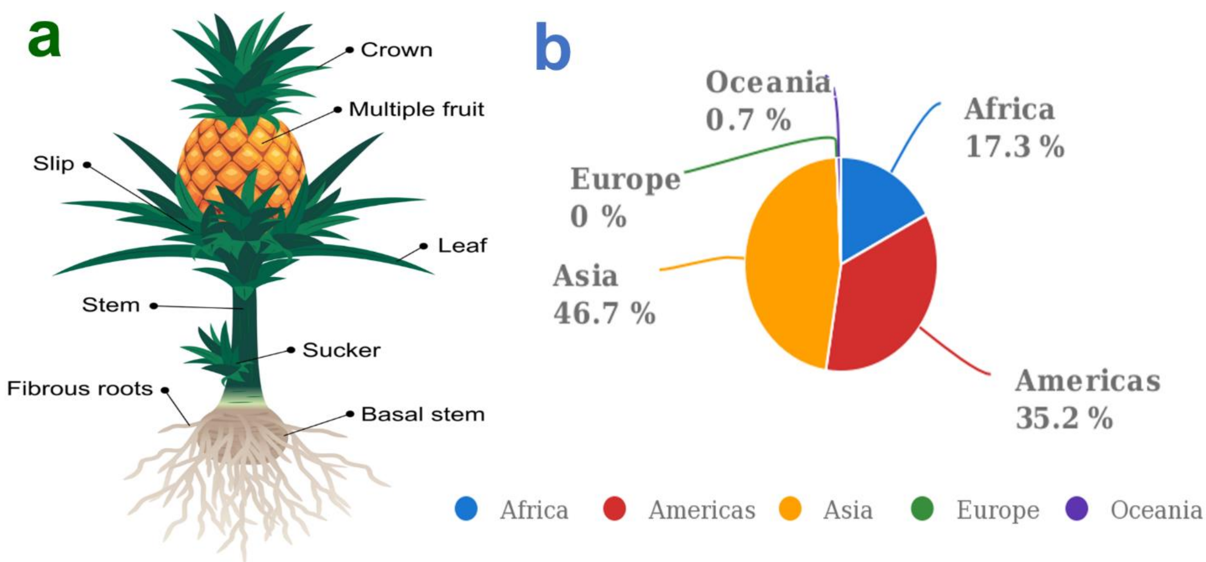



**Fig. 1.** Morphological structure of the pineapple plant with various parts including crown, fruit, leaf, sucker, basal stem, stem, root, and slip (a). Reproduced from the reference (Vieira et al., 2022). The average production shares of pineapples by region between 1994 and 2020 (b). Source: Food and Agriculture Organization, FAOSTAT (June 2022).

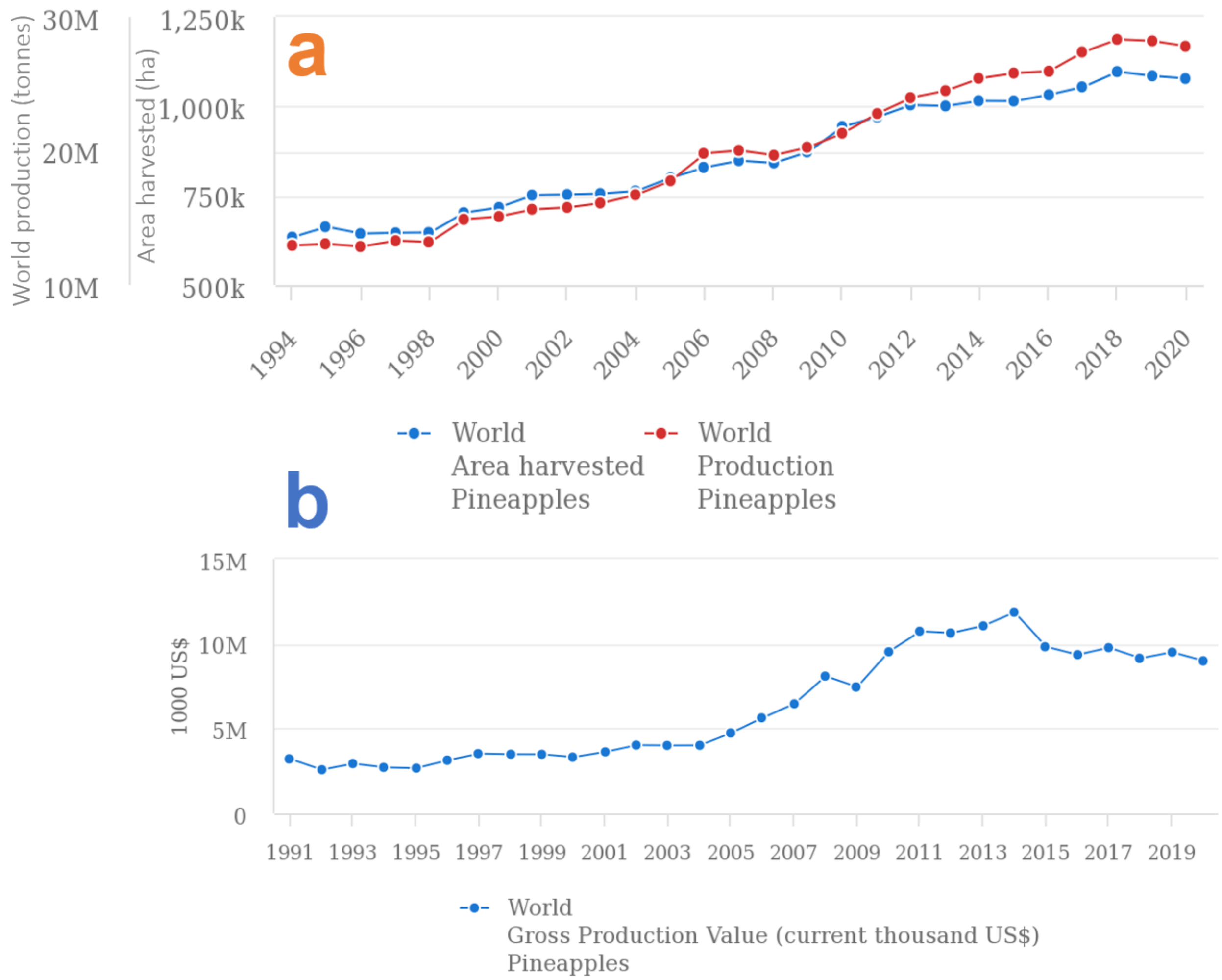



**Fig. 2.** The worldwide production and harvested area of the pineapple between 1994 and 2020 (a); the gross production value of the pineapples between 1991 and 2020 (b). Source: Food and Agriculture Organization, FAOSTAT (June 2022).

In terms of the gross production value, the pineapple has been becoming one of the economically important species (Casabar et al., 2019). Pineapple fruit obtain a good property with excellent quality, special flavor, and nutritional richness. Each pineapple fruit can provide many parts such as peel, core, crown, and pulp with various utilization (Fig. 3). For example, the nutrients of pineapple juice are important vitamins such as vitamin A, vitamin C, vitamin $B_3$, vitamin $B_6$, vitamin $B_{12}$, and many compounds useful to human health (Mohd Ali et al., 2020). As a result, pineapple juice is favored by consumers worldwide. Meanwhile, some by-products such as peel, core, and crown from the pineapple can be further processed to extract many useful compounds (e.g., phenolic, organic acid, and dietary fiber) (Meena et al., 2021). Their wastes can still contain many valuable chemical components such as celluloses (Vieira et al., 2022). It is, therefore, necessary to process such wastes to produce value-added products such as potential adsorbents for removal of pollutants in wastewater.

Many works investigated the use of the by-products such as peel, leaf or stem from the pineapple for processing of bioactive compounds, extraction, and utilization (Meena et al., 2021). The substances can be obtained with many components such as polysaccharides, antioxidants, and polyphenolic. Biosorbents and activated carbons can be directly produced from the pyrolysis of pineapple waste under nitrogen atmosphere or limited level of oxygen. These sorbents showed many good properties for the environmental mitigation. For example, Ahmad et al. (2016) demonstrated good performance of biomass-based adsorbents to remove heavy metals such as Cd(II) and Pb(II) in water. The leaf powder acted as good adsorbents to treat toxic dyes such as methylene blue and crystal violet (Chakraborty et al., 2012; Weng et al., 2009). Some researches assessed the possibility of recycling pineapple leaf powder up to 4-5 times for heavy metal removal (Daochalermwong et al., 2020; Heba et al., 2019). Therefore, conversion of pineapple wastes into useful adsorbent is very meaningful because this strategy can mitigate effectively the pollution caused by organic and inorganic compounds in different water sources such as surface waters, groundwater and drinking waters.

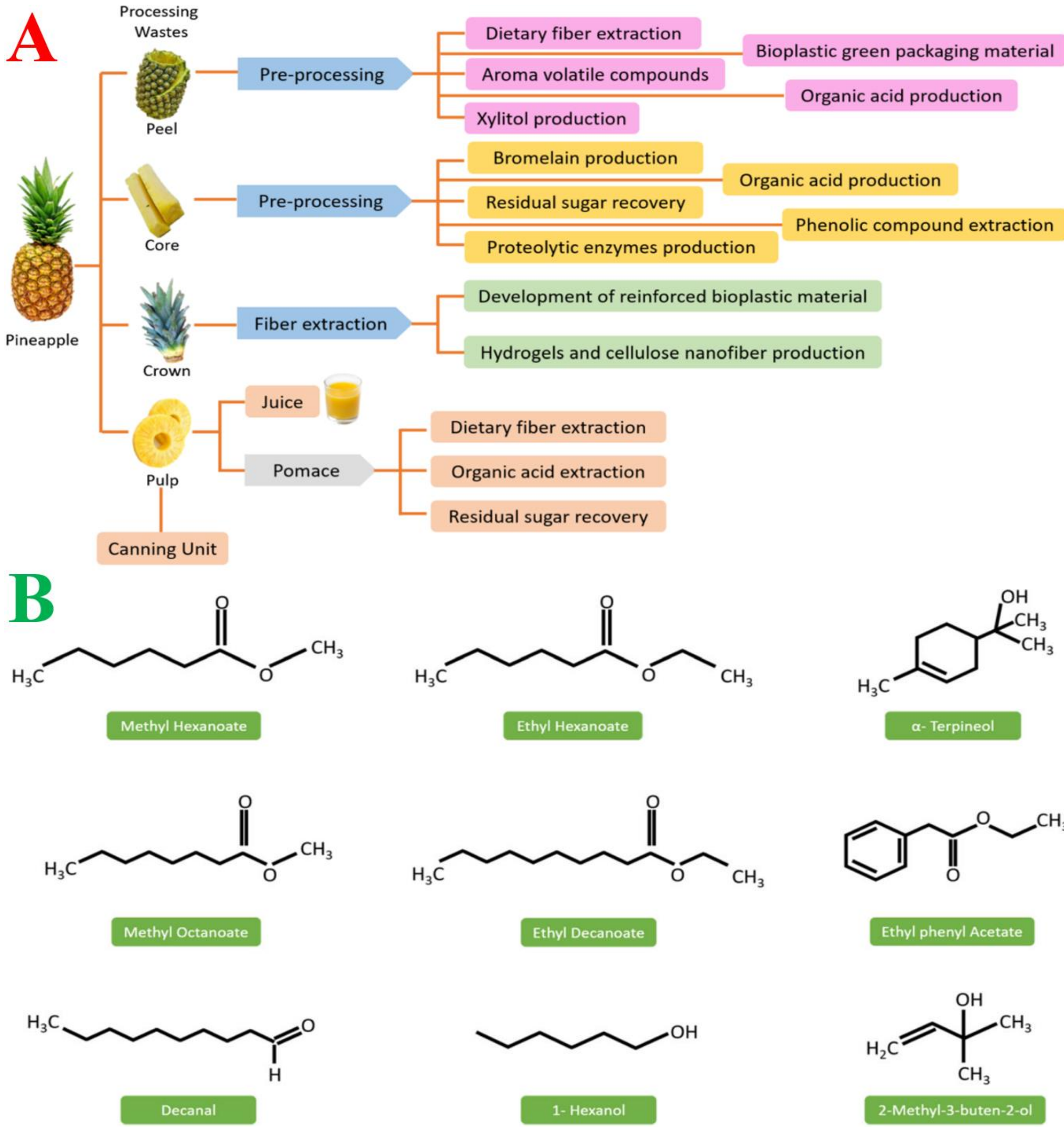



**Fig. 3.** Processing waste of pineapple to bring multiple applications (A), and major volatile compounds (B) found in pineapple wastes. Reproduced from the reference (Chakraborty et al., 2012) under an open access Creative Common CC BY license.

Recently, Aili Hamzah et al. (2021) overviewed the conversion of pineapple wastes as potential precursors for production of value-added products such as biofuels, biogasses, cellulose nanocrystals, biodegradable packaging and bio-sorbent. Similarly, several previous works have reviewed the synthesis and application of the adsorbents based on other biomass such as pistachio (*Pistacia vera*) waste (Igwegbe et al., 2021), sunflower family (Nguyen et al., 2021b), invasive plants (Nguyen et al., 2022c), water hyacinth (Li et al., 2021), However, there was no comprehensive review on pineapple wastes for the production and application of bio-based adsorbents in wastewater treatment. The authors of the current work observed a number of articles related to the use and adoption of pineapple wastes based adsorbents, but many aspects in synthesis method, empirical findings, adsorption performance, and recyclability study need to be systematically elucidated. Moreover, this review is expected to assess correctly the potential of the pineapple waste based adsorbents in the future works.

## 2. Production of the pineapple wastes-derived adsorbents

### *2.1. Pineapple waste sorbents*

Pineapple wastes can be transformed into sorbents through some proper techniques including chemical modification, thermal pyrolysis and activation. In this section, we elucidate the procedure of these techniques as well as highlight some findings obtained from the previous works. The chemical modification and carbonization to produce the pineapple wastes-based sorbents are displayed in Table 1. Initially, the source of pineapple wastes can come from various parts such as fruit peel, leaf, core, fruit rind, and stem. According to Fig. 4, the most adopted and efficient part of pineapple wastes is leaf (41.5%), followed by pineapple peel (17.1%) and leaf crown (12.2%). It can be understandable that leaf is the major and available component of the pineapple. Therefore, the majority of works studied the pineapple leaf due to its popularity. Next, the precursors are pretreated to remove the dirties or residuals by washing with $H_2O$ many times (Weng and Wu, 2012). After pretreatment, they are dried at 80-120 °C in oven or under solar energy source (Mishra and Tadepalli, 2015; Rosales et al., 2019). To form the adsorbents, the dried precursors need to be ground and sieved into small particles with the size between 75 and 3000 µm. This step aims to increase the surface area of the sorbents, which helps to enhance the treatment efficiency of pineapple-derived adsorbents.

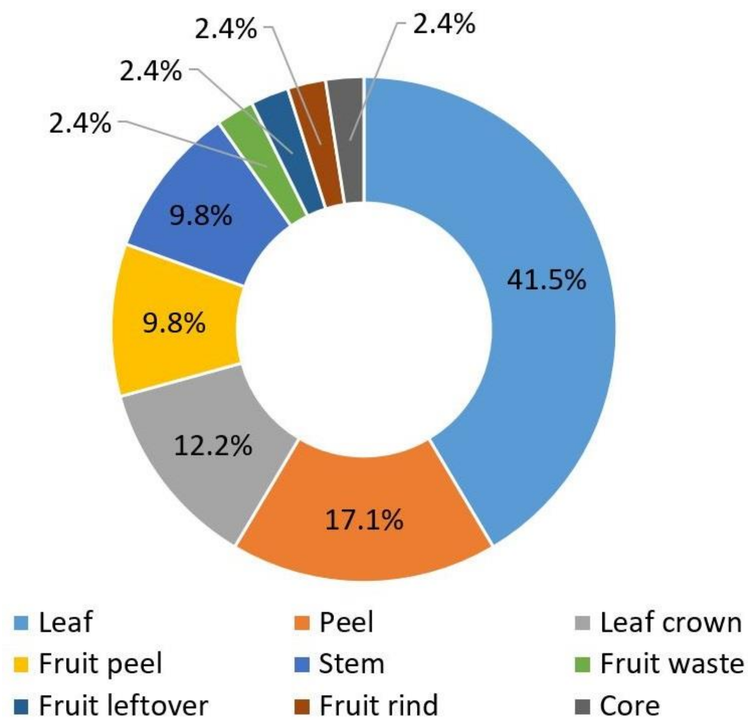



**Fig. 4.** Statistic data of popularity of various pineapple wastes studied in the past literatures.

### *2.2. Pineapple waste biochars*

In general, pineapple biomass wastes treated above 150 °C may significantly change many inherent properties of the products, not called 'bio-sorbents', but 'biochar'. In this case, the cellulose structure of pineapple precursor is broken under thermolysis condition, leading to the formation of amorphous carbon matrix. A majority of volatile components such as $H_2O$ in the biomass are swiftly released from the precursor. Some small molecules such as monosaccharide can be decomposed into $CO_2$, $H_2O$, and several decomposed products (Krishni et al., 2014).

Sometimes, the thermolysis of pineapple biomass wastes can be undertaken by using microwave irradiation (Turkmen et al., 2021). The most significant advantage of microwave pyrolysis is to accelerate the duration of process from seconds to minutes. However, it may be difficult to control the microwave heating and the quality of biochar obtained.

### ***2.3. Modified carbons***

#### *2.3.1. Physical activation*

In fact, both biosorbents and biochars derived from pineapple wastes can be immediately ready for using in the adsorption systems without any further processes. To improve their surface chemistry as well as structural characteristic, however, the modification stage should be undergone. Thereby, the adsorbents are more likely to reach better adsorption performance. The studies reported that the pineapple-derived activated carbon products can be prepared through either the physical or chemical method. The physical activation of pineapple wastes is often surveyed under the atmosphere of $CO_2$, steam, or steam/$CO_2$ (Nguyen et al., 2021a). However, this activation method was not still applied to produce activated carbons from the apple wastes.

#### *2.3.2. Chemical activation*

Meanwhile, the chemical activation uses strongly dehydrated/oxidative agents such as $H_2SO_4$, $KMnO_4$ (Ahmad et al., 2016), $ZnCl_2$ (Turkmen et al., 2021), NaOH (Gogoi et al., 2018), oxalic acid (Vivian Loh Zing et al., 2019), NaOH/ethylenediaminetetraacetic acid (Daochalermwong et al., 2020), and iminodiacetic acid (Heba et al., 2019). Fig. 5 illustrates the synthesis procedure for pineapple fibers and NaOH-activated pineapple fiber derived carbon. The introduction of chemical reagents is to develop new pores and/or increase surface area of obtained activated carbons. Therefore, their adsorption performance can be improved considerably. However, the important points in this strategy may be the selection of chemicals, optimization of chemical/precursor ratio, temperature and duration of carbonization. Moreover, the residual chemicals after activation should be wholly treated to avoid the negative impacts on the environment. Some considerations of properties of chemically modified pineapple-derived adsorbents should be taken.

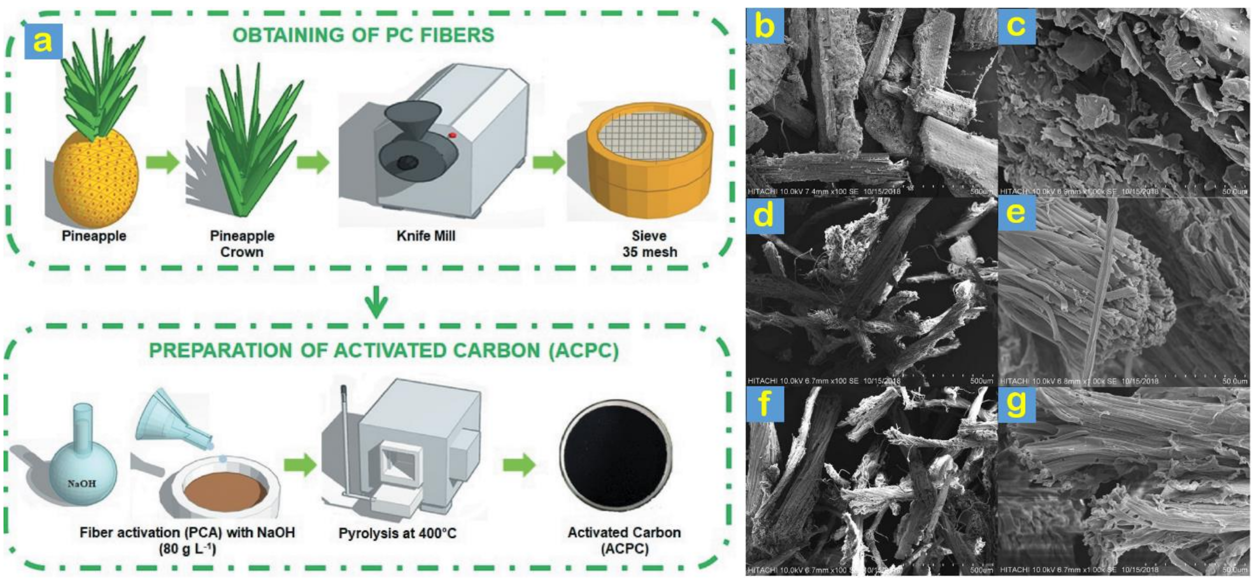



**Fig. 5.** Synthesis procedure for pineapple fibers and NaOH-activated carbon (a). Reproduced from the reference (da Silva et al., 2021). The SEM microphotograph of pineapple leaf powder (b, c), NaOH modified pineapple leaf powder (d, e), iminodiacetic acid modified pineapple leaf powder (f, g). Reproduced from the reference (Heba et al., 2019).

## 3. Characterization of pineapple wastes-derived adsorbents

### *3.1. Background*

Because the adsorption process relies on the surface area, surface functional groups and porosity of the adsorbents, the structural investigation should be a key task. To analyze the characterization of the pineapple wastes-derived adsorbents, some techniques such as scanning electron microscopy (SEM), Brunauer–Emmett–Teller (BET), energy-dispersive X-ray spectroscopy (EDX), point of zero charge ($pH_{pzc}$), Fourier transform infrared spectroscopy (FT-IR), X-ray diffraction (XRD) pattern profile, distribution of pore sizes, and thermo-gravimetric analysis (TGA) as shown in Fig. 6. Moreover, the surface area and pore volume for the pineapple-based sorbents as functions of activating chemicals, activation temperature, time and ramping rate are involved for comparison. This section will discuss the effect of fabrication conditions on the structure and characterization of for pineapple wastes-derived adsorbents.

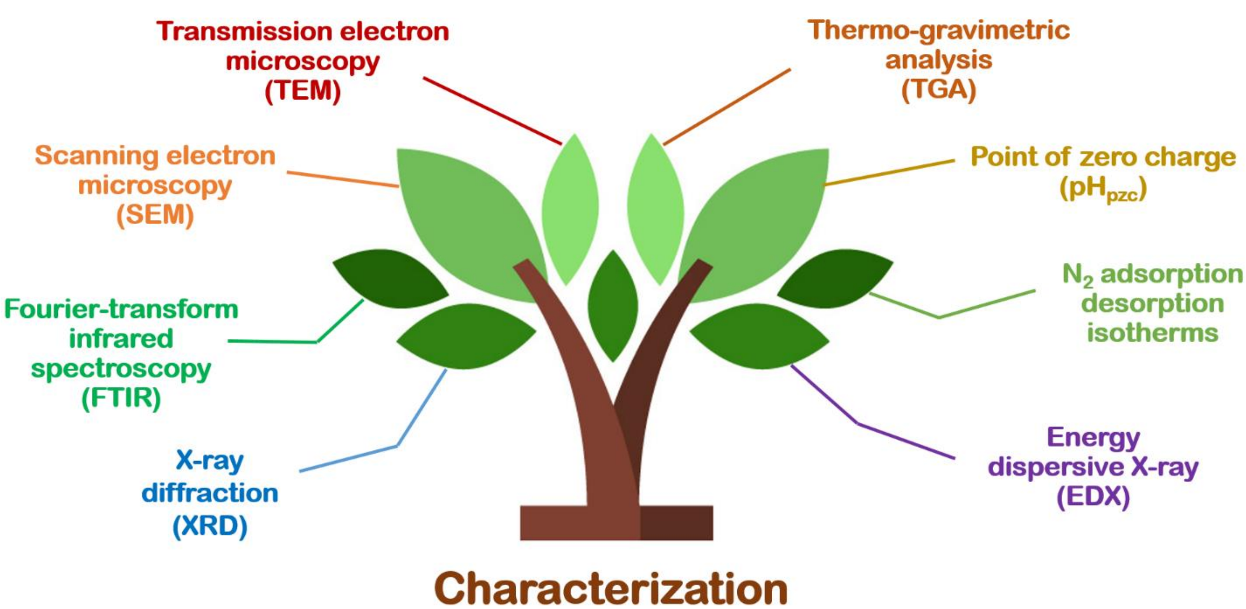



**Fig. 6.** Several common characterizations for analyses of the pineapple wastes-derived adsorbents.

### *3.2. The characteristics of pineapple wastes*

The characteristics of pineapple wastes relies majorly on the parts (e.g., leaf, stem, peel, crown, and root) and geographical origin of the pineapple plants cultivated in various regions. Table 2 summaries the lignocellulosic composition, proximate analysis, and ultimate analysis to better understand their characteristics. The lignocellulosic composition of pineapple wastes includes cellulose, hemicellulose, lignin. Crown leaf has a low content of cellulose (12.93–17.4%), but high content of lignin (24.3–26.4%). Meanwhile, the pineapple leaf, root, and stem contain a high percentage of cellulose (30–73%) and relatively low lignin (5–20%). For example, lignin content in leaves of the pineapple cultivated in Johor Malaysia was reported to be very low, at 4.76% (Nashiruddin et al., 2020). Hemicellulose was the highest content (31.8%) found in pineapple peel (Banerjee et al., 2019).

Proximate analysis includes moisture, ash, volatile matter, and fixed carbon. The content of moisture and ash content can be based on ASTM D1762-84 standard method, while volatile matter content can be determined by thermogravimetric analyzer (TGA) (Shakya and Agarwal, 2019). Fixed carbon can be calculated after known content of moisture, ash and volatile matter, or [100% – (moisture content + ash content + volatile content)]. According to Table 2, the moisture of the pineapple waste residues is lower than 10%. By contrast, the percentage of volatile matter is the highest between 41.56% and 94.4%. Ash content was determined on the dry basis, between 0.59% and 7.7%. The highest ash content (30.07%) belongs to pineapple root cultivated in Johor, Malaysia (Mansor et al., 2019, 2018). Fixed carbon of pineapple crown leaf was found about 7% (Braga et al., 2015; Calixto et al., 2022). In the same geographic location, fixed carbon of pineapple leaf was so far different between two studies. For example, Mansor et al. (2018) found a fixed carbon content of 34.16%, compared with 11.2% reported by Mathew et al. (2015). These results may be due to the difference between determination methods used in proximate analysis.

Ultimate analysis can be conducted using elemental analyzer to determine the percentage of chemical elements in pineapple parts. According to Table 2, the chemical composition includes carbon, oxygen, hydrogen, nitrogen, and sulfur. Carbon and oxygen distributed significantly (>90%) to the chemical composition of pineapple waste residues. A high nitrogen content in ultimate analysis suggests the presence of protein and acid amine in pineapple leaf. More importantly, (O + N)/C ratio is used predict the polarity of the sample, which correlated with the pyrolysis for the production of biochars and activated carbons (Shakya and Agarwal, 2019).

### *3.3. Specific surface area*

The specific surface areas of the pineapple wastes-derived adsorbents are initially mentioned (Table 3). For the unmodified pineapple wastes-derived adsorbents, the surface area and pore volume were found to be very low at 4.26 $m^2 \cdot g^{-1}$ and 0.033 $cm^3 \cdot g^{-1}$ (Weng and Wu, 2012). Similarly, Weng et al. (2009) reported a low surface area (5.24 $m^2 \cdot g^{-1}$) of the dried pineapple leaf powder. Low porosity of the adsorbent is attributable to the undeveloped nanofiber structure of pineapple biomass. As modified by 0.1 M NaOH for 2 h, Gogoi et al. (2018) reported an improved porosity (32.9 $m^2 \cdot g^{-1}$) of pineapple crown leaf-derived activated carbon. Some pineapple biochars synthesized by pyrolysis of dried leaves at 500 °C for 2 min gave a moderate surface area (44.775 $m^2 \cdot g^{-1}$) (Herlinawati et al., 2022). However, the $H_2SO_4$-activated carbon possessed a lower surface area (25.68 $m^2 \cdot g^{-1}$). The temperature of pyrolysis of pineapple biomass waste can affect the structure of biochars. Indeed, Ponou et al. (2011) elucidated the effect calcination temperature (350 and 450 °C) on the surface area. The authors found that the pineapple leaf powder with a very low surface area (6.84 $m^2 \cdot g^{-1}$) gave a value surface area (374.9 $m^2 \cdot g^{-1}$) as activated at 450 °C higher than that (44.08 $m^2 \cdot g^{-1}$) at 350 °C.

### *3.4. The point of zero charge*

The point of zero charge ($pH_{pzc}$) is an important indicator to determine whether the surface of pineapple wastes-derived adsorbents is positively charged or negatively charged at a certain pH. The $pH_{pzc}$ can be used to better understand the role of electrostatic interaction between adsorbent and adsorbate. In Table 3, the $pH_{pzc}$ values of the adsorbents are from 2.1 to 4.0, indicating that the surface of pineapple wastes-derived adsorbents can be positively charged at pH 4 or less than 4. The presence of oxygenated groups such as carboxylic acids or polyphenols is mainly responsible for the low $pH_{pzc}$ value. However, the modification by acid or base reagents can differ the point of zero charge. For example, the modification by NaOH can increase the $pH_{pzc}$ of pineapple wastes-derived adsorbents (Gogoi et al., 2018). Meanwhile, the acid-modified adsorbents reduce this indicator due to the insertion of many acid groups into their structure.

### *3.5. Morphology*

Apart from the characteristics of surface area, pore volume, and point of zero charge, other analyses such as scanning electron microscopy and surface chemistry also play a vital role. Firstly, the scanning electron microscopy can be used to examine the morphology of pineapple-derived adsorbents. In general, pineapple biomass has a smooth surface with the original fibrous structure. Meanwhile, the activated carbons or biochars from pineapple waste can offer many defective degree and high porosity due to the deconstruction of cellulose chains (Das et al., 2016). One of the typical morphologies is honeycomb or a hierarchical order (Fig. 7). Not only the precursor, but a treatment method by various chemical agents can also lead to the considerable difference in the morphology. As shown Fig. 7, the preparation procedure of the pineapple peels into various hydrogels by a modification by NaOH or bleaching treatment for lignin and hemicellulose removal can obtain the morphological diversity. Moreover, Mahamad et al. (2015) reported the difference of morphology of $ZnCl_2$-activated carbons derived from a variety of pineapple parts including crown, stem or leaf.

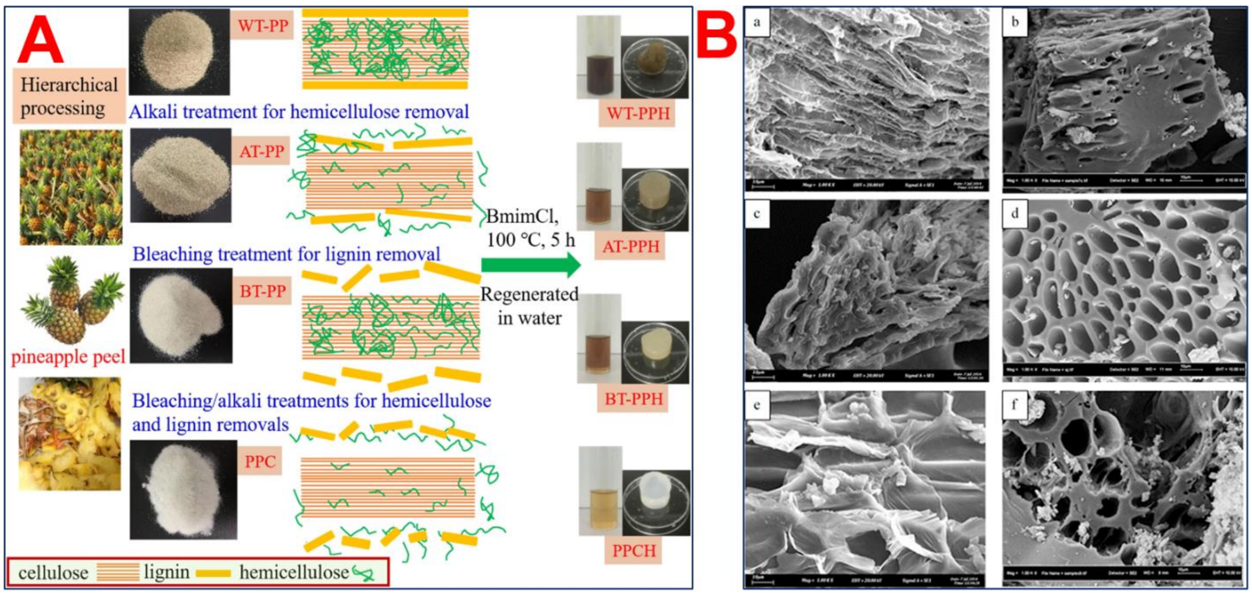



**Fig. 7.** (A) The preparation procedure of the pineapple peels into various hydrogels by modification by NaOH or bleaching treatment for lignin and hemicellulose removal. Reproduced from the reference (Das et al., 2016). (B) the scanning electron micrographs of pineapple stem (a), $ZnCl_2$-activated carbon derived from pineapple leaf (b), pineapple crown (c), $ZnCl_2$-activated carbon derived from pineapple stem (d), pineapple leaf (e), and $ZnCl_2$-activated carbon from pineapple crown (f). Reproduced with the permission of Elsevier B.V. from the reference (Mahamad et al., 2015).

### *3.6. Surface chemistry*

Surface chemistry of pineapple-derived adsorbents explore the functional groups, which can be determined by FT-IR analysis. Overall, the alternation of typical summits in FT-IR before and after adsorption suggest a relevant mechanism with the contribution of respective functional groups to the adsorption performance of pineapple wastes derived adsorbents. For pineapple wastes based biosorbents, there is frequently included with bending vibrations of the $-CH_2-$ bond, which belongs to the cellulose backbone (Daochalermwong et al., 2020). In terms of biochars or activated carbons, C–O/C=O (1660–1720 $cm^{-1}$) can be found due to the existence of aldehydes or ketones, e.g., lactones, or carboxylates or esters, which can be formed under pyrolysis of monosaccharide or proteins in pineapple biomass (Yılmaz and Tugrul, 2022). Almost pineapple-derived adsorbents contain O–H bonds (~3400 $cm^{-1}$) from hydroxyl compounds such as phenols, carboxylic acids or alcohols. Moreover, C=C bonds (1515–1518 $cm^{-1}$) offers many electrons in aromatic rings, which can interact with the adsorbate through $\pi$–$\pi$ interaction (Krishni et al., 2014). Sometimes, the presence of heteroatom such as N (C–N/C=N), P (P–O–C), S (S–C) in the structure of benzene rings are found (Krishni et al., 2014). To sum up, with high surface area, many surface functional groups, the pineapple waste derived adsorbents can have potential for water treatment.

## 4. Adsorption performance of pineapple wastes-derived adsorbents

### *4.1. Scope of studies*

The performance of pineapple wastes-derived adsorbents can be assessed by maximum adsorption capacity and removal efficiency. The maximum adsorption capacity is calculated by using Langmuir isotherm fitting. The removal efficiency can be determined experimentally. According to Table 4, the maximum adsorption capacity values are listed in above 30 articles, which is more widely than the removal efficiency found in about 20 articles. There are two main kinds of pollutants including heavy metals and organic dyes treated by pineapple wastes derived adsorbents. The heavy metals used for surveys include $Cd^{2+}$, $Pb^{2+}$, $Cu^{2+}$, $Cr^{6+}$, and $Zn^{2+}$. The organic dyes were selected as adsorbate, such as methylene blue, crystal violet, basic green 4, rose Bengal, and Congo red organic dyes.

### *4.2. Main findings of adsorption performance*

According to Table 4, almost works reported very high removal efficiencies (>80%) of heavy metals, e.g., $Cd^{2+}$, $Pb^{2+}$, $Cu^{2+}$, $Zn^{2+}$, $Cr^{3+}$, and $CrO_4^{2-}$, except for several low efficiency results (23.0–30.5%), which were obtained by using pineapple fruit peel powder or $ZnCl_2$-activated fruit rind for removal of $Zn^{2+}$ in water (Mishra et al., 2010; Yılmaz and Tugrul, 2022). In general, the monolayer adsorption capacities for heavy metals was acceptable between 0.45 and 42.1 $mg \cdot g^{-1}$. Few works reported extremely high heavy metal adsorption capacities, i.e., 102.92–111.41 $mg \cdot g^{-1}$ ($Cd^{2+}$, $Pb^{2+}$) using the modified pineapple peel powder, 155.06 $mg \cdot g^{-1}$ ($Pb^{2+}$) using the pineapple leaf-derived cellulose (Daochalermwong et al., 2020), and 165–273 $mg \cdot g^{-1}$ ($Pb^{2+}$, $Cu^{2+}$, $CrO_4^{2-}$) using polyethyleneimine-carbamate (PEI)-cross-linked leaf fiber (Tangtubtim and Saikrasun, 2019a, 2019b). Moreover, the effect of pyrolysis temperature on structure and heavy metal adsorption capacity of the pineapple peel biochars was investigated by (Shakya and Agarwal, 2019). Accordingly, the biochar synthesized at higher temperature (350–650 °C) obtained lower $CrO_4^{2-}$ capacity (41.67–23.81 $mg \cdot g^{-1}$) and removal efficiency (99.19–40.78%).

The pineapple waste derived adsorbents were applied to treat other toxic inorganic compounds such as phosphate and fluoride. For example, Liao et al. (2018) fabricated $La(OH)_3$-modified magnetic pineapple biochar-based composites, giving an improved surface area of 84.89

$m^2\ g^{-1}$ compared with 36.22 $m^2\ g^{-1}$ of the origin pineapple biochar and 1.18 $m^2\ g^{-1}$ of the pineapple-derived magnetic biochar. More importantly, a promising uptake capacity was obtained at 101.16 mg phosphate per gram of the pineapple-based magnetic composite and this composite showed a high selectivity (> 96%) in the presence of co-existing inorganic ions. In another work, Reza and Ahmaruzzaman (2022) developed an adsorbent based on the pineapple juice-extracted residue (74.92 $m^2\ g^{-1}$) for removal of flouride from wastewater. They found a equilibrium duration of 120 min and an optimized dose of 0.9 g $L^{-1}$. As expected, a monolayer uptake capacity was found at 7.06 mg $g^{-1}$. The pineapple wasted based adsorbent could be easily recovered by 0.05 M NaOH solution.

For removal of organic dyes, more than 92% of dyes can be eliminated by the pineapple leaf powder according to Table 4. The maximum adsorption capacities towards organic dyes are higher than those towards heavy metals, between 58.80 and 288.34 $mg\cdot g^{-1}$. This result may reflect higher affinity of organic dyes than heavy metals to pineapple wastes-derived adsorbents. Weng et al. (2009) reported a very high adsorption capacity (284.03 $mg\cdot g^{-1}$) of methylene blue using the pineapple leaf powder. This result was nearly equivalent to adsorption capacity obtained by $ZnCl_2$-activated carbon (Mahamad et al., 2015) or NaOH-activated crown-derived carbon (da Silva et al., 2021). Microwave-assisted synthesis is expected to enhance the adsorption performance of activated carbon compared to the conventional carbonization. However, Astuti et al. (2019) found there was no improvement of dye adsorption capacity for microwave-assisted KOH-activated crown leaf-derived carbon. Some cationic surfactants have been aslo used to modify the surface of the pineapple waste adsorbents. For instance, Kamaru et al. (2016) used a cationic surfactant, namely, hexadecyltrimethylammonium bromide for the synthesis of the pineapple leaf powder.

Adsorption capacity for ethylene blue and methyl orange was found, at 52.6 and 47.6 mg·g$^{-1}$, respectively.

Antibiotics have played a key role in human and animal therapies as well as many aquacultural activities. However, the residue of antibiotics is causing many harmful effects, i.e., promoting antibiotic-resistant genes in bacteria. It is calling for removal of antibiotics using efficient methods such as adsorption. The pineapple waste derived adsorbents demonstrated their potential for antibiotic remediation. Indeed, Fu et al. (2016) synthesized a range of biochar at various temperatures between 350 and 650 °C to treat oxytetracycline antibiotic. As a result, the authors found the best adsorbent synthesized at 650 °C, but the adsorption capacity obtained was still very low (1.072 mg·g$^{-1}$). Zahoor et al. (2019) reported that 80% of enrofloxacin in water could be removed by $Fe_3O_4$/activated carbon. Moreover, this adsorbent had advantages such as easy separation by a magnet, simple regeneration by 3% NaOH and outstanding uptake capacity (46.3 mg·g$^{-1}$). Thus, it would be promising for the pineapple waste derived magnetic adsorbents.

Some indexes such as total organic carbon (TOC), biochemical oxygen demand (COD), chemical oxygen demand (COD), total dissolved oxygen (TDS) are key indicatives to measure the quality of water after treatment. As an example, Oni et al. (2020) compared BOD and TDS values before and after the treatment of kitchen wastewater using activated carbons. Researchers used pineapple peel and crown as precursors to synthesize activated carbons. Accordingly, two chemical agents including $H_3PO_4$ and $ZnCl_2$ have been used to activate the pineapple waste derived adsorbents under carbonization at 270 °C. They found that $ZnCl_2$-activated carbon gave better performance of BOD and TDS results than those of $H_3PO_4$-activated carbon. It was suggested that the kitchen wastewater after treatment by $ZnCl_2$-activated carbon could obtain a safety threshold for further usage.

## 5. Effect of factors on adsorption and treatment optimization

### *5.1. Effect of solution pH*

To undertake the optimization of treatment efficiency, the operation of parameters such as pH of the solution, adsorbent dosage, and contact time. It is understood that the pH of the solution profoundly affects the ionization and disassociation of adsorbate. As a result, the change in the pH solution may lead to the significant change in the removal efficiency and adsorption capacity.

As shown in Table 4, the optimized pH at 2–7 was found for the removal of heavy metal, except for a report on the use of fruit peel to remove Cd(II), Cr(VI), and Pb(II) ions (Yusoff et al., 2020). It can be understood that heavy metal ions compete with protons ($H^+$) in the acidic solution, resulting in the difficulty to remove them from water. However, in the alkaline solution (pH > 7), even neutral or slightly acidic solution, some heavy metal ions can be precipitated. As such, the adsorption performance of pineapple wastes derived adsorbents cannot be reflected exactly. To select the proper range of pH, the point of zero charge of these adsorbents should be examined to find the best adsorption conditions.

For the removal of organic dyes, the optimum conditions for pH is widely varied from 4 to 9 using different adsorbents. For example, pineapple peel hydrogels were used to remove Congo red dye from the solution at optimum pH 4, giving a high maximum adsorption capacity (114.94–138.89 $mg \cdot g^{-1}$) (Das et al., 2016). At neutral pH, Weng et al. (2009) used the pineapple leaf powder sorbent for the treatment of methylene blue. They reported that 95.0% of this dye could be treated from water, while the adsorption capacity was obtained to be very high, at 284.03 $mg \cdot g^{-1}$. Meanwhile, 99.36% of basic green 4 has been eliminated at pH 9 by the pineapple leaf powder as reported previously (Chowdhury et al., 2011).

### *5.2. Effect of adsorbent dose*

The adsorbent dose affects the removal efficiency as well as the treatment cost. As a result, the adsorbent dosage needs to be optimized before the adsorbent can be used in the real applications. Based on Table 4, the removal of heavy metals was conducted under doses of 0.2 – 120 g·L$^{-1}$. Meanwhile, the optimum dose of pineapple wastes based adsorbents was acceptable from 0.67 to 5.0 g·L$^{-1}$ for the removal of organic dyes. It showed a general trend that a large amount of pineapple biomass adsorbents with dosages of 4–60 g·L$^{-1}$ was used to treat heavy metals, while a smaller dosage of chemically activated adsorbents is required. For example, the pineapple fruit peel carbon activated by $ZnCl_2$ with a dose of 0.25 g·L$^{-1}$ could remove 92–94% of Zn(II) as reported by a recent work (Turkmen et al., 2021). Meanwhile, despite a higher dose of 1.0 g·L$^{-1}$, the pineapple fruit peel powder (0.5 mm in particle size) only treated 23.0% of Zn(II) after 480 min (Mishra et al., 2010). These findings proposed a statement of better quality of activated adsorbents than normal ones that not activated.

### *5.3. Effect of contact time*

Adsorption process using pineapple-based adsorbents can reach equilibrium nature at a certain period. Therefore, the optimization of contact time is required. As shown in Table 4, there was no fixed optimum contact time to reach equilibrium for adsorption of heavy metals. A contact time of 20-240 min was important to reach adsorption equilibrium. As an example, Weng and Wu (2012) found a short equilibrium time of 20 min for adsorption of Cu(II) ions using the pineapple leaf powder. The same contact time was established for removal of methylene blue (95%) (Weng et al., 2009). It was suggested to prolong the time to obtain higher removal efficiency until equilibrium.

### *5.4. Effect of coexisting ions*

In real wastewaters, strange ions can exist in the nature and they vitally affect the adsorption of adsorbate onto adsorbent. This phenomenon is due to adsorption competition and ionic forces. Liao et al. (2018) investigated the effect of ions such as $CO_3^{2-}$, $HCO_3^{-}$, $NO_3^{-}$, $SO_4^{2-}$ and $Cl^{-}$ on the adsorption of $[(PO_4)]^{3-}$ onto $La(OH)_3$-modified magnetic pineapple peel derived biochar. The findings indicated that there was no significant effect on phosphate removal efficiency in the presence of such anions. Therefore, the chemical affinity of adsorbent towards $[(PO_4)]^{3-}$ is strong to overcome the ionic forces during the adsorption.

### *5.5. Response surface methodology as an optimization tool*

The adsorption of pollutants could be optimized with statistical analysis using response surface methodology. A quadratic equation can be established to show the relationship between predicted and experimental data. Some common experimental designs or design of experiments (DoE), e.g., Box–Behnken, Central composite design, Taguchi, Gradient-enhanced kriging, Plackett–Burman design, and Polynomial regression are widely used in accordance with response surface methodology.

In that case, Rosales et al. (2019) reported that total 17 runs were conducted duplicate with the mixed survey of factors involving initial pH, dosage, and temperature for removal of Cr(VI). Three dimensional surfaces were plotted to elucidate the interaction between two variables while the other was remained at central level (Fig. 8). Based on the Box–Behnken design, the researchers found the optimum conditions to remove Cr(VI) ions from water were initial solution pH 2.01, pineapple core wastes derived biosorbent dosage of 30 $g \cdot L^{-1}$, and temperature of 30.05 °C. Just a tiny absolute error of 0.18% was measured after the adoption of response surface methodology, indicating the reliability between experimental results with the predicted values. Although the optimization using response surface methodology (RSM) has many advantages such as high reliability and rapid operation, there are very few studies reported this method to optimize the adsorption by the pineapple wastes derived adsorbents.

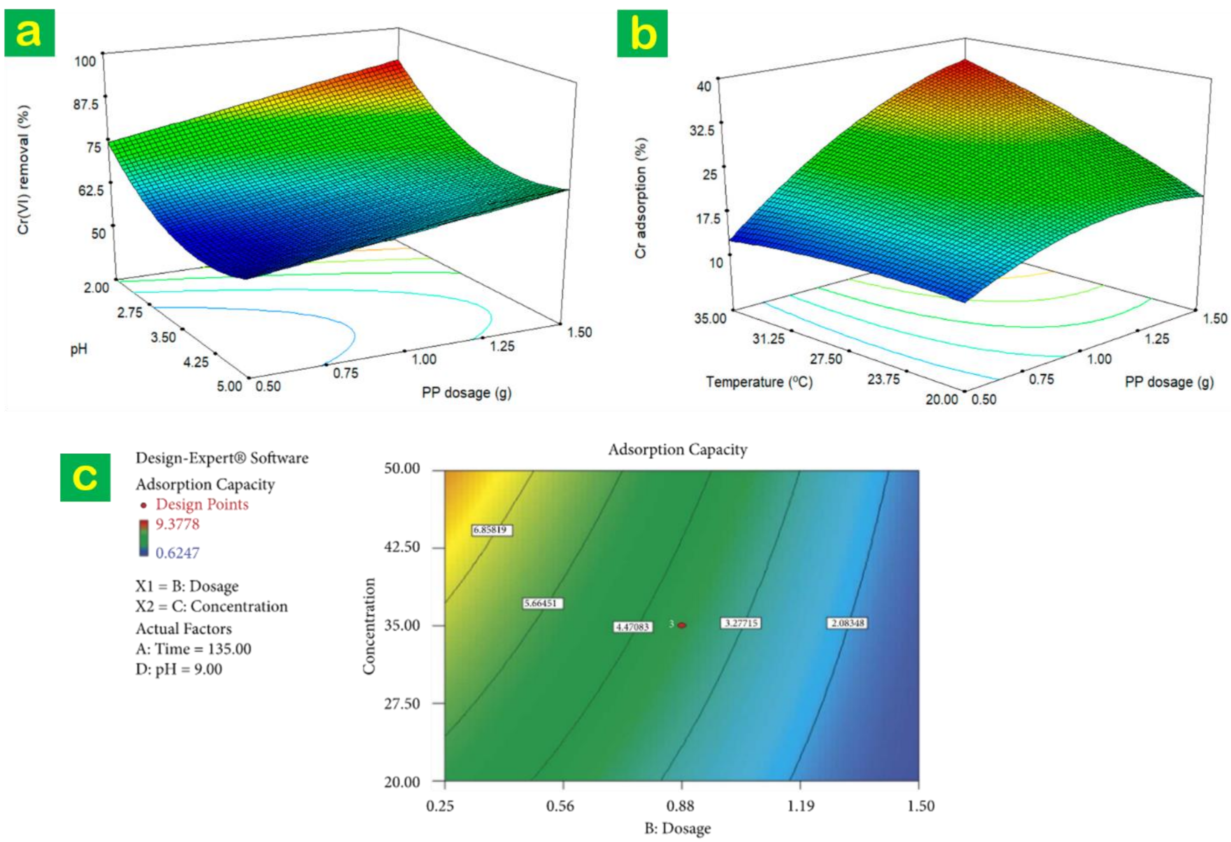



**Fig. 8.** Three dimensional surface plots for Cr(VI) removal by pineapple core (PP) adsorbent with two variables including pH and adsorbent dose, temperature was set at central level (a); effect of two variables including temperature and adsorbent dose on Cr(VI) removal by pineapple core, pH was set at central level (b). Reproduced from the reference (Rosales et al., 2019) under an open access Creative Common CC BY license. A contour plot for the interaction between dose and concentration for removal of methylene blue (c). Reproduced from the reference (Shukor et al., 2022) under an open access Creative Common CC BY license.

# 6. Kinetic and isotherm studies

## *6.1. Background*

The isotherm and kinetics studies are considered as core parts of adsorption investigations; hence, many authors mentioned these models in their works (Brião et al., 2020). Isotherm adsorption models assume the relationship between the equilibrium adsorbate concentration and the quantity that the adsorbate loaded on an adsorbent at a certain temperature (Van Tran et al., 2019). Meanwhile, the kinetic models assume the rate of adsorption process dependent on the contact time (Tran et al., 2020c). Both models suggest some possibilities of how the adsorbate can adsorb on the adsorbent. In general, nonlinear fitting of isotherm and kinetics models give better accuracy and reliability than linear fitting (Tran et al., 2020b). The fitted model plots of kinetic and isotherm are illustrated in Fig. 9.

In detail, the mathematic form (linear and nonlinear) of common kinetic and isotherm models used for the fitting in the previous works can be listed in Eqs.1–20.

## *6.2. Kinetic models*

- *Pseudo first-order equation in the nonlinear form (Eq. 1) and linear form (Eq. 2):* this model was firstly proposed by Lagergren (1898). It assumes the adsorption by localized sites without any interaction between adsorbed sites. The adsorption energy is unrelated to surface coverage (Largitte and Pasquier, 2016).

$$Q_t = Q_1\left[1 - \exp(-k_1 \times t)\right] \qquad (1)$$

$$\log(Q_1 - Q_t) = \log Q_1 - \frac{k_1 \times t}{2.303} \qquad (2)$$

where, $Q_1$ (mg g$^{-1}$) and $Q_t$ (mg g$^{-1}$) are the pseudo first-order kinetic adsorption capacities at the equilibrium moment and time t, $k_1$ (min$^{-1}$) is the pseudo first-order rate constant.

- *Pseudo second-order equation in the nonlinear form (Eq. 3) and linear form (Eq. 4):* This model was described by Ho and McKay (1999). It suggests that the adsorption rate is proportional to the number of available sites on the adsorbent. It also expresses the role of chemisorption in controlling the adsorption.

$$Q_t = \frac{k_2 Q_2^2 t}{1 + k_2 Q_2 t} \quad (3)$$

$$\frac{t}{Q_t} = \frac{1}{k_2 \times Q_2^2} + \frac{t}{Q_2} \quad (4)$$

where, $Q_2$ (mg g$^{-1}$) and $Q_t$ (mg g$^{-1}$) are the pseudo second-order kinetic adsorption capacities at the equilibrium moment and time t, $k_2$ (min$^{-1}$) is the pseudo second-order rate constant.

- *Elovich model equation in the nonlinear form (Eq. 5) and linear form (Eq. 6):* This model was described by Elovich and Larinov (1962).

$$Q_t = \frac{1}{\beta}\ln(1 + \alpha\beta t) \quad (5)$$

$$Q_t = \frac{1}{\beta}\ln(\alpha\,\beta) + \frac{1}{\beta}\ln(t) \quad (6)$$

where, $Q_t$ (mg g$^{-1}$) is the pseudo second-order kinetic adsorption capacity at the time t, $\alpha$ (mg g$^{-1}$ min$^{-1}$) and $\beta$ (g mg$^{-1}$) are the adsorption rate and desorption rate constants.

- *Bangham equation in the nonlinear form (Eq. 7) and linear form (Eq. 8):* This model is based on the assumption that pore diffusion was the only rate controlling step during adsorption (Yokogawa et al., 2017).

$$Q_t = k_B \times t^{a_B} \qquad (7)$$

$$\log\log\left(\frac{C_o}{C_o - Q_t \frac{m}{V}}\right) = \log\left(\frac{k_B}{2.303V}\right) + \alpha_B \log(t) \qquad (8)$$

where, $Q_t$ (mg g$^{-1}$) is the pseudo second-order kinetic adsorption capacity value at the time t, $k_B$, and $\alpha_B$ are the constants of Bangham kinetic equation.

### ***6.3. Isotherm models***

- *Langmuir equation in the nonlinear form (Eq. 9) and linear form (Eq. 10):* this model assumes an equilibrium between adsorbate and adsorbent system and can be used for a description of chemisorption phenomenon caused by the formation of chemical bonds between the adsorbent and the adsorbate (Langmuir, 1916).

$$Q_e = \frac{Q_m K_L C_e}{1 + K_L C_e} \qquad (9)$$

$$\frac{C_e}{Q_e} = \frac{1}{Q_m K_L} + \frac{C_e}{Q_m} \qquad (10)$$

where, $Q_e$ (mg g$^{-1}$) and $Q_m$ (mg g$^{-1}$) are the equilibrium and monolayer adsorption capacities, $C_e$ (mg L$^{-1}$) is the equilibrium concentration of adsorbate, and $K_L$ (L mg$^{-1}$) is a constant of the Langmuir isotherm.

- *Freundlich equation in the nonlinear form (Eq. 11) and linear form (Eq. 12):* this equation describes empirical results of a consistency with the thermodynamics of heterogeneous adsorption (Freundlich, 1906).

$$Q_e = K_F C_e^{1/n} \quad (11)$$

$$\log Q_e = \log K_F + \frac{1}{n} \log C_e \quad (12)$$

where, $Q_e$ (mg g$^{-1}$) is the equilibrium adsorption capacity, $C_e$ (mg L$^{-1}$) is the equilibrium concentration of adsorbate, and $K_F$ (L mg$^{-1}$) is a constant indicative of Freundlich equation, which is related to the relative adsorption capacity of an adsorbent.

- *Temkin equation in the nonlinear form (Eq. 13) and linear form (Eq. 14):* this model is a two-parameter equation, which assumes that the heat of adsorption process caused by all molecules reduces linearly with the increase in the coverage of the adsorbent surface (Temkin and Pyzhev, 1940).

$$Q_e = B_T \ln\left(K_T C_e\right) \quad (13)$$

$$Q_e = B_T \ln K_T + B_T \ln C_e \quad (14)$$

where, $Q_e$ (mg g$^{-1}$) is the equilibrium adsorption capacity, $C_e$ (mg L$^{-1}$) is the equilibrium concentration of adsorbate, $k_T$ (L g$^{-1}$) is the constant of Temkin isotherm, $B_T$ (mg g$^{-1}$) is related to the heat of adsorption process.

- *Dubinin-Radushkevich (D–R) equation in the nonlinear form (Eq. 13) and linear form (Eq. 14):* this model is a three-parameter equation, which describes empirical results, and it is compiled to confirm whether the adsorption process is chemisorption or physical adsorption (Nguyen and Do, 2001).

$$Q_e = Q_m \, e^{-K_D \varepsilon^2} \qquad (15)$$

$$\ln Q_e = \ln Q_m - K_D \varepsilon^2 \qquad (16)$$

where, $Q_e$ (mg g$^{-1}$) is the equilibrium adsorption capacity, $C_e$ (mg L$^{-1}$) is the equilibrium concentration of adsorbate, $K_D$ (L mg$^{-1}$) is a constant of the D–R isotherm, $\varepsilon$ (kJ mol$^{-1}$) is the polanyi potential of the D–R model.

- *Redlich–Peterson (R–P) equation in the nonlinear form (Eq. 13) and linear form (Eq. 14):* this model is a three-parameter equation as a result of combining Freundlich and Langmuir isotherms, which it assumes the formation of the monolayer with multisite interaction (Redlich and Peterson, 1959).

$$Q_e = \frac{K_R C_e}{1 + a_R C_e^{\alpha}} \qquad (17)$$

$$\frac{C_e}{Q_e} = \frac{1}{K_R} + \frac{a_R}{K_R} (C_e)^{\alpha} \qquad (18)$$

where, $Q_e$ (mg g$^{-1}$) is the equilibrium adsorption capacity, $C_e$ (mg L$^{-1}$) is the equilibrium concentration of adsorbate, $K_R$ (L mg$^{-1}$) and $a_R$ (L g$^{-1}$) are the constants of the R–P isotherm.

- *Sips equation in the nonlinear form (Eq. 13) and linear form (Eq. 14):* this model is a three-parameter equation, which is as a combined form of Langmuir and Freundlich equations (Sips, 1948).

$$Q_e = \frac{K_S C_e^{\beta}}{1 + a_S C_e^{\beta}} \quad (19)$$

$$\ln\left(\frac{Q_e}{K_S - a_S Q_e}\right) = \beta \ln C_e \quad (20)$$

where, $Q_e$ (mg $g^{-1}$) is the equilibrium adsorption capacity, $C_e$ (mg $L^{-1}$) is the equilibrium concentration of adsorbate, $K_S$ (L $mg^{-1}$) and $a_S$ (L $g^{-1}$) are the constants of the Sips isotherm, β is an exponent of the Sips isotherm.

### *6.4. Main findings of kinetic and isotherm studies*

According to Table 5, the adherence and correlation coefficients of kinetic and isotherm models for adsorption of various pollutants including heavy metals and organic compounds by the pineapple-based adsorbents are summarized. Data collected from the previous works indicated that almost kinetic models obeyed the pseudo-second order equation with very high coefficients of determination ($R^2 > 0.99$). According to Fig. 9, the trend was excepted for the adsorption of Pb(II) and Cd(II) onto the pineapple leaf derived cellulose adsorbent since the pseudo-first order model ($R^2 > 0.99$) fitted best with the experimental data (Daochalermwong et al., 2020). The adherence of the pseudo second order equation gives information about the role of chemisorption during the adsorption of heavy metals and organic compounds by the pineapple-derived adsorbents (Nguyen et al., 2022d). For isotherm models, the best-fitting model was found to be Langmuir with $R^2$ values of 0.94–1.00 for almost studies. The adsorption of pollutants over the pineapple wastes derived adsorbents was suggested a monolayer behavior (Tran et al., 2020a). However, some works revealed the adherence of other isotherm models such as Freundlich (Rosales et al., 2019), and Liu (Gogoi et al., 2018). Specifically, Rosales et al. concluded that the adsorption of Cr(VI) by the pineapple core powder reflected multilayer behavior (Rosales et al., 2019). Meanwhile, Gogoi et al. (2018) found that the adsorption of Cr(III) and Cr(VI) species followed Liu isotherm, which attributed to the surface active sites of the pineapple crown leaf adsorbent.

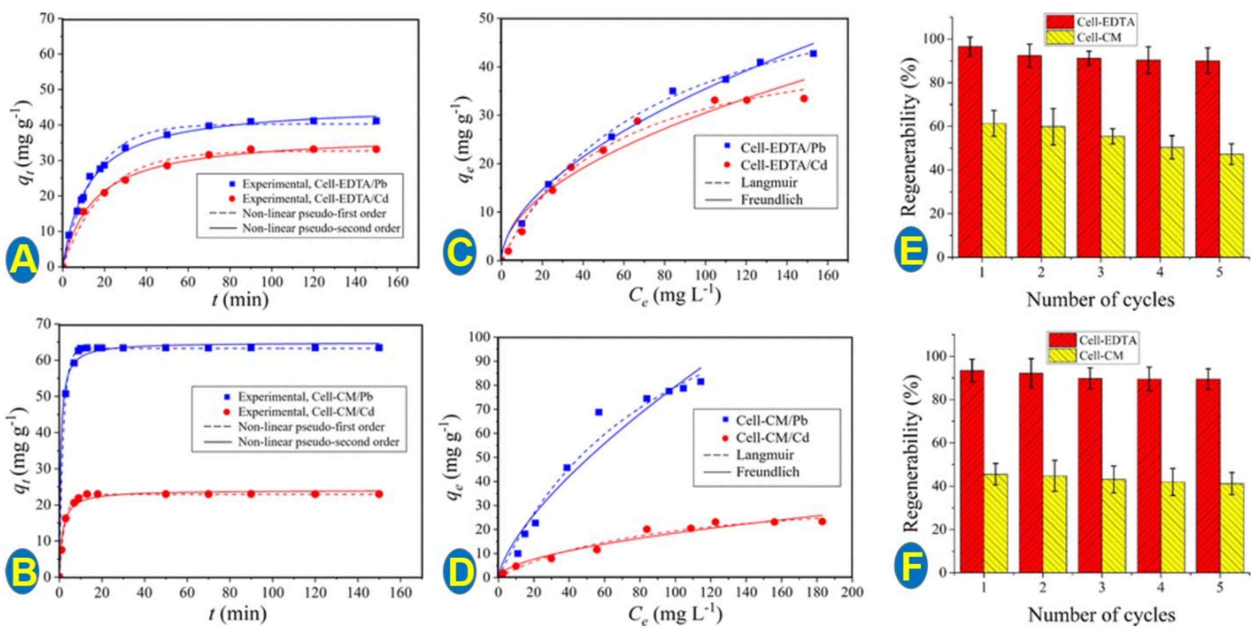



**Fig. 9.** The nonlinear fitting of pseudo first-order, pseudo second-order, Langmuir, and Freundlich (C) models for the kinetic (A, B) and isotherm (C, D) adsorption of Pb(II) and Cd(II) onto pineapple leaves modified with ethylenediaminetetraacetic acid, and carboxymethyl groups. The regeneration of these adsorbents (E, F). Reproduced from the reference (Daochalermwong et al., 2020) under an open access Creative Common CC BY license.

## 7. Thermodynamic studies

### *7.1. The van't Hoff equation*

The thermodynamic investigation supplies information about the change of standard Gibbs free energy (ΔG°), enthalpy (ΔH°), and entropy (ΔS°). To conduct the thermodynamic study, the adsorption as a function of temperature using the van't Hoff equation is established. The van't Hof equation with a differential form can be described by Eqs. 21–23.

$$\frac{\partial}{\partial T}(\ln K_c) = \frac{\Delta H^o}{RT^2} \quad (21)$$

$$\ln K_c = -\left(\frac{\Delta H^o}{R}\right)\frac{1}{T} + \left(\frac{\Delta S^o}{R}\right) \quad (22)$$

$$K_c = \frac{Q_e}{C_e} \quad (23)$$

where, $K_c$ is the thermodynamic equilibrium constant calculated from the ratio between equilibrium $Q_e$ ( mg·g$^{-1}$), and $C_e$ (mg L$^{-1}$). T (K) is the absolute temperature, R is the gas constant (8.314 J mol$^{-1}$ K$^{-1}$). In this section, the thermodynamic study of the adsorption of heavy metals and organic dyes by the pineapple-derived adsorbents will be discussed.

### *7.2. Main findings of thermodynamic studies*

According to Table 6, the thermodynamic parameters for adsorption of various pollutants by the pineapple wastes based adsorbents are summarized. The temperature of the investigations was in range from 298K to 343K. All works reported that the Gibbs free energy received negative values between −32.874 and −0.857 kJ mol$^{-1}$. Therefore, the adsorption of heavy metals and organic dyes over the pineapple wastes derived adsorbents such as biosorbents, biochars, activated carbons were thermodynamically spontaneous, which matched with the results of kinetic and isotherm adsorption. For the heat of adsorption process, ΔH° calculated in the works had both positive and negative values. For example, Ahmad et al. (2016) used chemically oxidized fruit peel as an adsorbent to treat Cd(II) and Pb(II). The heat energy of the adsorption was large between −26.089 and −63.530 kJ mol$^{-1}$. As a result, the pollutant uptake of two metals was an exothermic process. By contrast, the adsorption of chromium species onto leaf powder and activated carbons from the pineapple had an endothermic nature with ΔH° of 21.358−77.89 kJ $mol^{-1}$ (Gogoi et al., 2018; Ponou et al., 2011). The entropy of adsorption system was varied dependent on the difference of pollutants and adsorbents. For instance, ΔS° of the adsorption of methylene blue by the pineapple leaf powder was 76.4 J $mol^{-1}\cdot K^{-1}$ (Weng et al., 2009), while a previous work reported a negative ΔS° (−101.40 J $mol^{-1}\cdot K^{-1}$) for the uptake of basic green 4 by the pineapple leaf powder (Chowdhury et al., 2011). The positive entropy measures a system's thermal energy, indicating the increasing disorder, or randomness, uncertainty of molecules (Alabbad, 2021).

# 8. Desorption, regeneration and fixed bed column

## *8.1. Desorption*

The purpose of recyclability study of an adsorbent is to decrease the total cost of the treatment process. If the adsorbents can be easily generated through a desorption procedure, and reused multiple cycles, then they can be upgraded for commercial values. The eluents or solvents using for desorption of pollutants from the adsorption should be less toxic and low cost. Therefore, the regeneration of that adsorbent is a critically green process. According to Table 7, however, there are very few studies (about 13 articles) reported the desorption and regeneration of the pineapple-based adsorbents. The green eluents were often used as HCl solution for the desorption of $Cd^{2+}$, and $Pb^{2+}$ (Ahmad et al., 2016; Daochalermwong et al., 2020), or NaOH solution for the desorption of $Cr_2O_7^{2-}$ (Gogoi et al., 2018). The major explanation relies on the strongly competition between metal cations and $H^+$ as well as the competition between anions and $OH^-$ ions. This force allows to push metals out the structure of the adsorbents.

### *8.2. Regeneration*

If the desorption of adsorbent to remove the adsorbate is successful, the regeneration study is to count the number of recycle that the adsorbent can obtain. Daochalermwong et al. (2020) reported the number of recycle up to 5 times by using 1 M HCl as an eluent to desorb $Cd^{2+}$, and $Pb^{2+}$ from the pineapple leaf-derived cellulose adsorbent. The removal efficiency still obtained 43–41% for $Cd^{2+}$ and 62–44% for $Pb^{2+}$ for the final cycle (Fig. 9). For the procedure to desorb organic compounds from the pineapple leaf adsorbents, Neupane et al. (2015) used 1 N acetic acid as an efficient solvent for desorption of crystal violet. However, the number of cycles has not been reported in their work. Congo red was well desorbed from the pineapple wastes based peel hydrogel as reported by Das et al. (2016). With four cycles, this adsorbent could be a good recyclability, which was expected to extend the actual applications. Despite such advantages, the cost for each reuse of adsorbent was still questionable. It is, therefore, suggested with a better analysis of regeneration cost in the future works.

### *8.3. Fixed bed column*

Depart from adsorption batch mode, up-flow/down-flow fixed bed column is another type of adsorption between adsorbate and adsorbent in a continuous liquid system (Patel, 2019). It is believed that adsorption beyond fixed bed column mode is highly adaptable for industrial scale treatment of different pollutants including organic and inorganic compounds. As a result, many works made effort in the design and development of fixed bed columns (Ahmed and Hameed, 2018). The characteristic of fixed bed column adsorption study is breakthrough curves which show the relationship between concentration of the contaminant and time profile. Breakthrough curves are expressed through mass transfer zone or primary sorption zone (Patel, 2019). Accordingly, wastewater is injected into the column and treated by the adsorbate. The adsorption is initially rapid due to availability of adsorption sites. The process continues until mass transfer zone reaches at the end of the column, or equilibrium is established. Breakthrough curves show S-shape in most cases of fixed bed column adsorption.

Some works used the pineapple waste-derived adsorbents to remove pollutants (e.g., heavy metal, and organic dye) in fixed bed column adsorption mode. Indeed, Rao and Khan (2017) successfully fabricated the pineapple residue adsorbent treated by NaOH solution (ATPR) and investigated its adsorption of nickel ions in water (Fig. 10). The authors initially optimized several batch adsorption conditions such as Ni(II) concentration (50 mg $L^{-1}$), pH (8), and contact time (60 min), and found $Q_m$ value of 17.56 mg $g^{-1}$. Afterwards, they designed a glass column (d = 0.6 cm, h = 3.7 cm) loaded with 0.2 g of the adsorbent. 500 mL of $Ni^{2+}$ solution was passed through this bed column (V = 1.04 $cm^3$). As a result, a breakthrough capacity was determined at 20 mg $g^{-1}$. In another work, Azman and Subki (2022) conducted the removal of methylene blue and malachite green dyes through fixed bed column adsorption using pineapple crown $H_3PO_4$-activated carbon. The fixed bed column was designed with internal diameter (d = 3 cm) and height (h = 10 cm). 50 mL of each of the methylene blue and malachite green solution was filtered by this column. However, breakthrough and exhaustive capacities were not reported. In general, there were very few studies focusing on the adsorption of pollutants by fixed bed column using the pineapple waste-derived adsorbents. Therefore, more investigations of fixed bed column adsorption should be carried out.

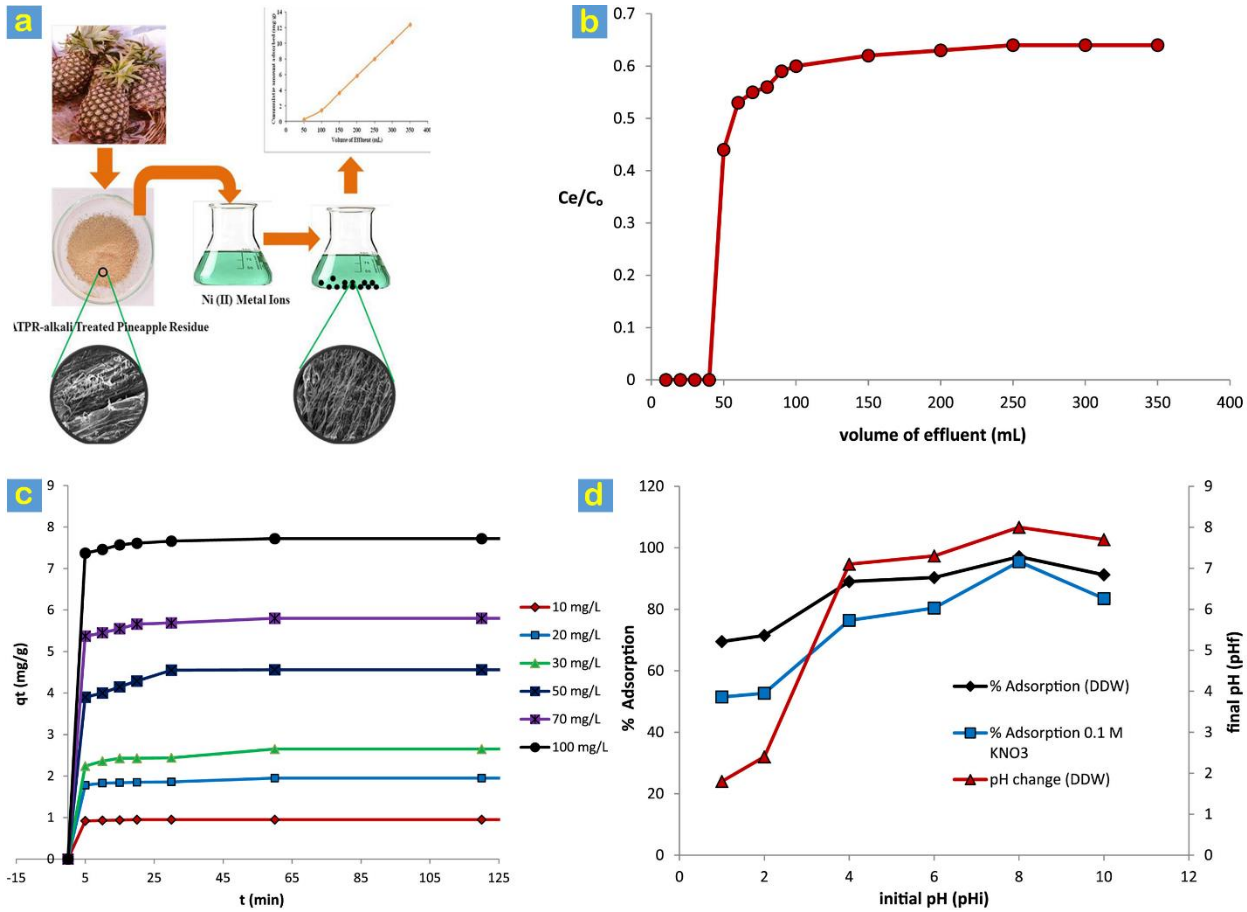



**Fig. 10.** Schematic illustration of synthesis and application of NaOH-treated pineapple residue adsorbent (ATPR) for removal of nickel ions from water (a); breakthrough curve for fixed bed column adsorption (b); effect of contact time (c); effect of pH and electrolyte on adsorption of nickel ions (d). Reproduced with permission of Elsevier from the reference (Rao and Khan, 2017).

# 9. Adsorption mechanism

## *9.1. The role of electrostatic interactions*

Adsorption mechanism is of great importance for better understanding how the adsorbate can be captured by the adsorbent. In this section, we discuss some adsorption mechanisms proposed by the previous works. Basically, the adsorption of heavy metal ions by the pineapple-based adsorbents was majorly due to the contribution of electrostatic attraction as summarized in Table 8. This mechanism reflects the interaction between reversely charged sites of adsorbent and adsorbate. To elucidate the role of this interaction, the point of zero charge of the adsorbent needs to be determined. As an example, Gogoi et al. (2018) found that the point of zero charge of pretreated and modified pineapple crown leaves were 3.5 and 4, respectively. At optimum pH at 2.5, the surface of the pineapple crown leaves-based adsorbents was positively charged. This condition facilitates the electrostatic attraction between positively charged adsorbent surface and $CrO_4^{2-}$ ions. The authors also explained the effect of photoreduction mechanism as a result of −OH groups present on the surface. At very low pH, −OH groups of cellulose were oxidized into aldehyde/ketone by Cr(VI) ions. This finding was one of the reasons why the concentration of Cr(VI) was decreased, and Cr(VI) increased. In the presence of the adsorbent, Cr(III) can be easily removed at optimum pH 5 due to the electrostatic interaction. Apart from electrostatic interactions, the mechanism for adsorption, e.g., inorganic compounds such as $[PO_4]^{3-}$ anions can be controlled by many ways such as ligand exchange, inner-sphere complexation, and precipitation (Fig. 11). The next section will mention about these mechanisms.

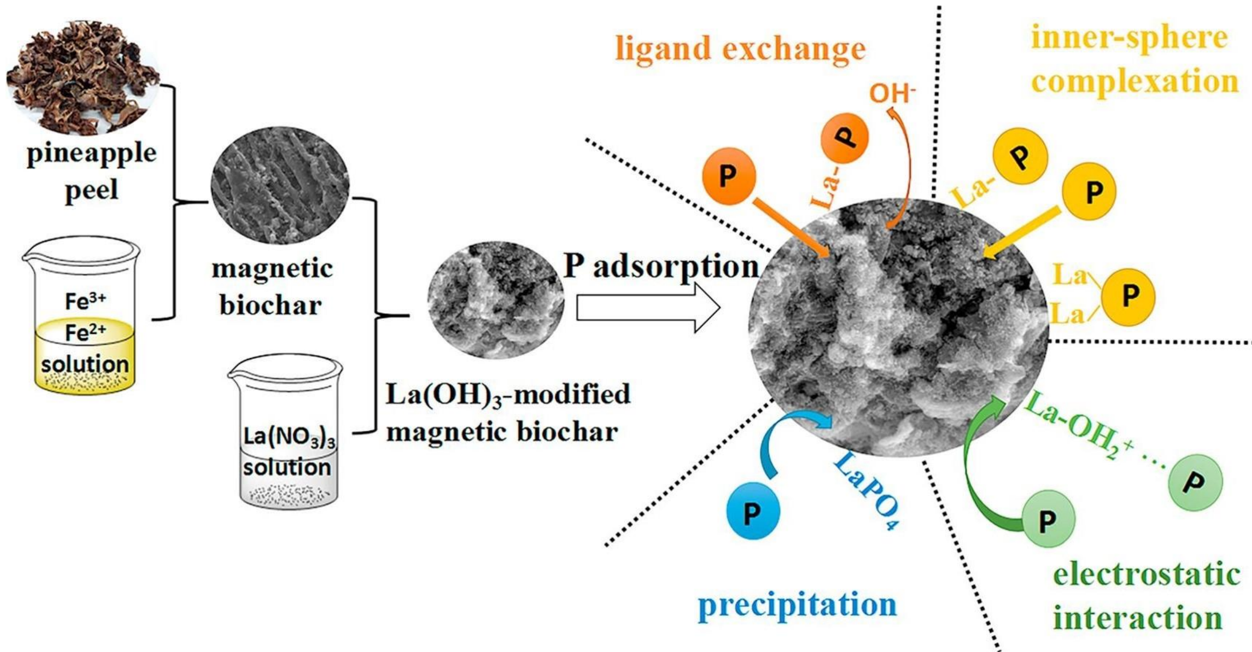



**Fig. 11.** Synthesis route of $La(OH)_3$-modified magnetic pineapple biochars and their applications for the removal of $[PO_4]^{3-}$ anions. Several possible adsorption mechanisms were suggested, including ligand exchange, inner-sphere complexation, electrostatic interaction and precipitation. Reproduced with the permission of Elsevier from the reference (Liao et al., 2018).

### *9.2. The role of complexation*

In general, the adsorption of heavy metals over the pineapple waste-based adsorbents can be well explained by complexation mechanisms. The surface of these modified adsorbents often contain functional groups (e.g., carboxylic acid) that can complex with heavy metal ions or transition metals (d- or f-block elements). Depending on the coordination number of metal elements, the number of functional groups is required to form a metal-functional groups complexation. By this mechanism, metal ions are captured on the surface of the pineapple-based adsorbents. Weng and Wu (2012) suggested the vital role of complexation in removing $Cu^{2+}$ by the pineapple leaf powder. The point of zero charge of this adsorbent was found, at 2.3. In this case, optimum pH higher than 2.3 was the best condition to obtain a negatively charged surface. In other words, the surface functional groups containing oxygen and nitrogen were deprotonated to enhance the density of lone pair electrons. As a result, $Cu^{2+}$ complexed with lone pair electrons of the surface functional groups on the adsorbent, improving the copper removal efficiency. Apart from the complexation mechanism, ion-exchange might contribute significantly to the lead adsorption efficiency. Indeed, a recent research assumed that the carboxylic acid groups present on the surface of the oxalic acid modified pineapple plant stem could exchange $H^+$ with $Pb^{2+}$ ions (Vivian Loh Zing et al., 2019). However, the increase in $H^+$ concentration after adsorption has not been evidenced yet. By using XPS, FTIR, and SEM-EDS spectra, the mechanism could be identified for the heavy metal adsorption on the surface of pineapple leaf biochar before and after adsorption (Iamsaard et al., 2022). Accordingly, it was possible that surface complexation and cation exchange involved in the adsorption mechanisms (Fig. 12).

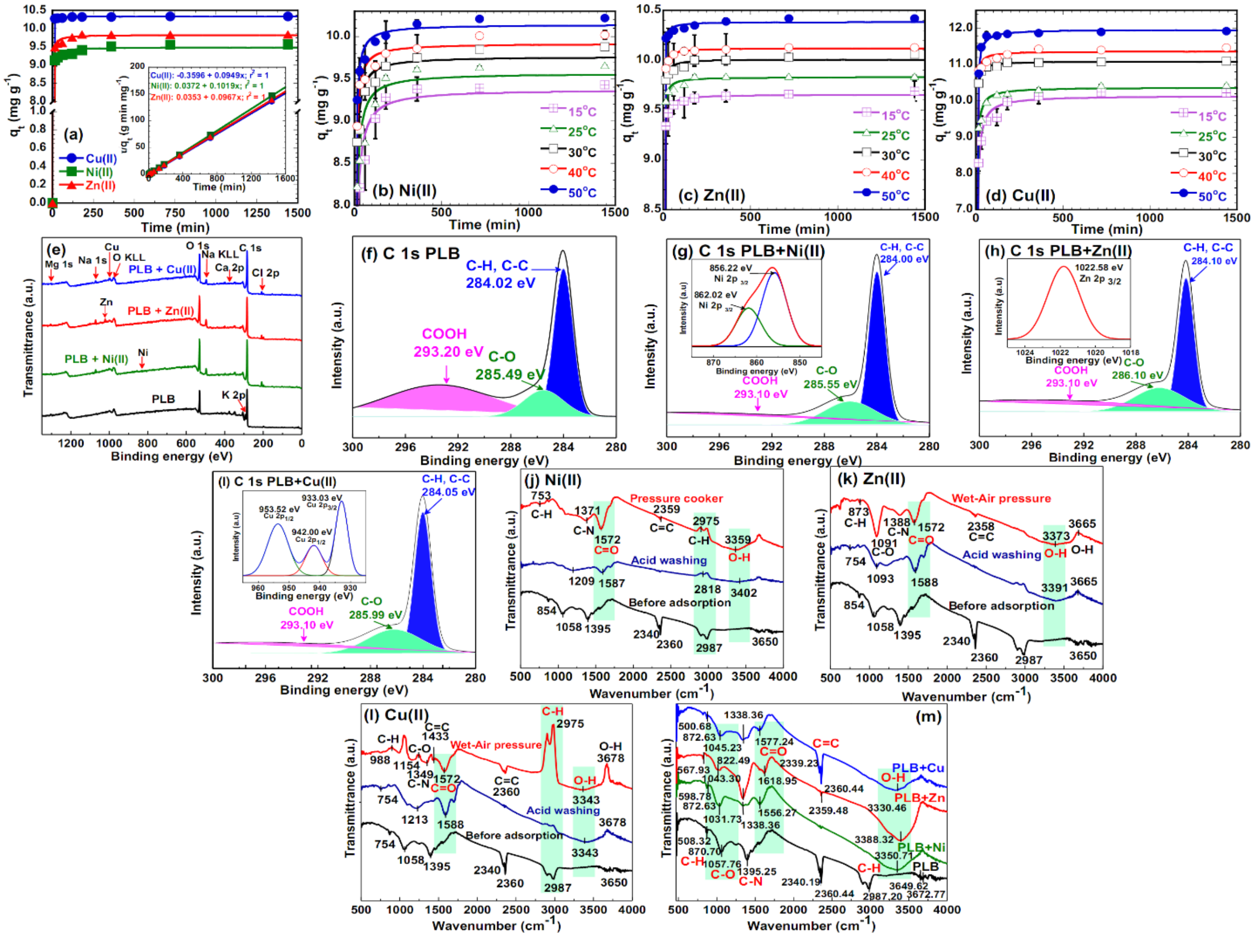



**Fig. 12.** Comparative kinetics of adsorption of heavy metal $Ni^{2+}$, $Zn^{2+}$, and $Cu^{2+}$ (a); effect of temperature on the kinetic adsorption of $Ni^{2+}$ (b), $Zn^{2+}$ (c), and $Cu^{2+}$ (d); (e) XPS survey spectra of pineapple leaf biochar before and after adsorption; XPS C 1s spectra of pineapple leaf biochar (f), pineapple leaf biochar + $Ni^{2+}$ (g), pineapple leaf biochar + $Zn^{2+}$ (h), and pineapple leaf biochar + $Cu^{2+}$ (i); FT-IR spectra of pineapple leaf biochar after regeneration using a pressure cooker and acid washing of $Ni^{2+}$ (j), $Zn^{2+}$ (k), and $Cu^{2+}$ (II) (l); chemical bond analysis by FT-IR spectra before and after regeneration (m). Reproduced from the reference (Iamsaard et al., 2022) under an open access Creative Common CC BY license.

### *9.3. The role of ion exchange*

This mechanism may be helpful for explaining the adsorption of heavy metal over the adsorbent. Some exchangeable metal ions such as $K^+$, $Na^+$, $Ca^{2+}$ are available on the surface of the adsorbents. As a result, the replacement of these ions by heavy metal ions entail their sequestration according to Fig. 13. Even, proton $H^+$ or acidic groups can exchange with heavy metal ions. As an example, Vivian Loh Zing et al. (2019) suggested that chemical reaction like ion exchange was anticipated through replacement of –COOH groups on oxalic acid-activated pineapple stem and stem powder. Apart from mechanisms mentioned, other mechanisms such as precipitation and cation–π interaction may contribute to adsorption of heavy metals. However, such investigations have been still very limited, suggesting a better elucidation of adsorption mechanisms.

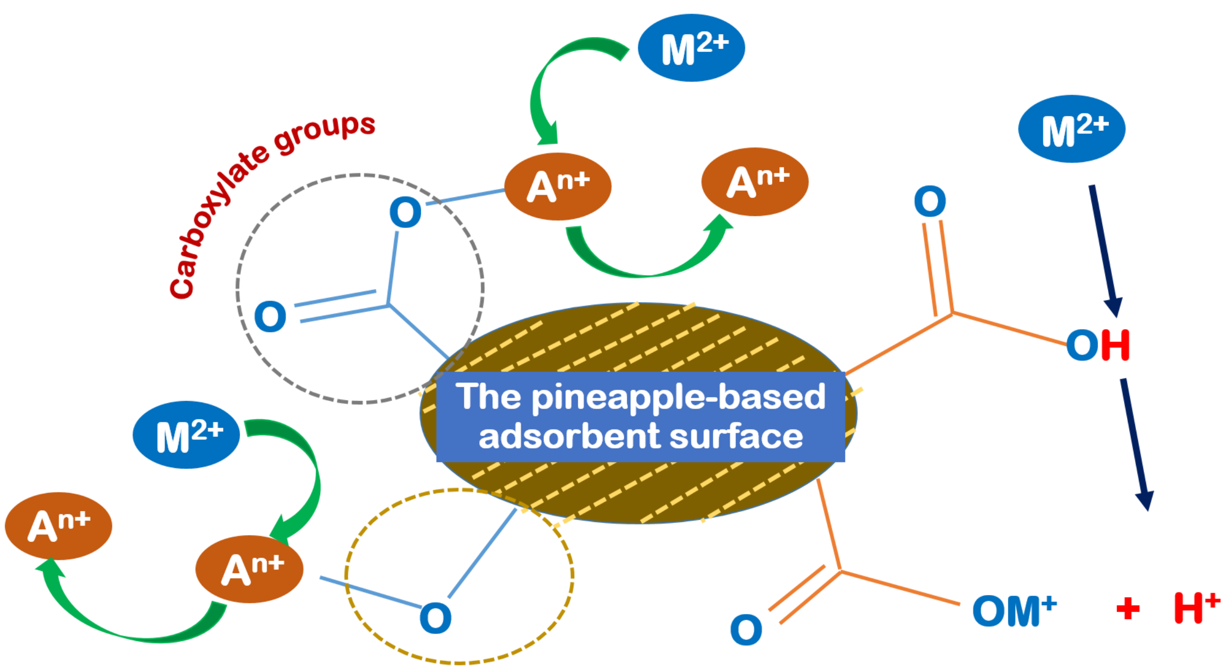



**Fig. 13.** Heavy metal adsorption onto the pineapple waste-based adsorbent via proposed ion exchange mechanism.

### *9.4. The role of chelation*

On the other hand, Ahmad et al. explained the adsorption of $Cd^{2+}$ and $Pb^{2+}$ using $H_2SO_4/KMnO_4$ oxidized pineapple fruit peel by the electrostatic attraction, and chelation mechanism (Ahmad et al., 2016). As illustrated in Fig. 14, the surface of the adsorbent possesses many carboxylic acid and hydroxyl groups, which can be deprotonated at pH > 3. As a result, $Cd^{2+}$ and $Pb^{2+}$ interacted with these negatively charged groups at optimum pH 4. Moreover, the coordination bond between empty d-orbitals of $Cd^{2+}/Pb^{2+}$ metals with lone pair electrons of oxygen from functional groups. This event may lead to the chelation between $Cd^{2+}/Pb^{2+}$ and functional groups on the surface of the adsorbent. By examining FT-IR spectra before and after adsorption of chromium anions on carbonized pineapple leaves, Ponou et al. (2011) suggested that both covalent bonding and electrostatic attraction strongly affected the adsorption of Cr(VI) over the pineapple leaf derived porous carbon. To sum up, plausible adsorption mechanisms such as electrostatic interaction, complexation, ion exchange, and chelation were included, but needed to be verified by physicochemical techniques such as FT-IR, and XPS.

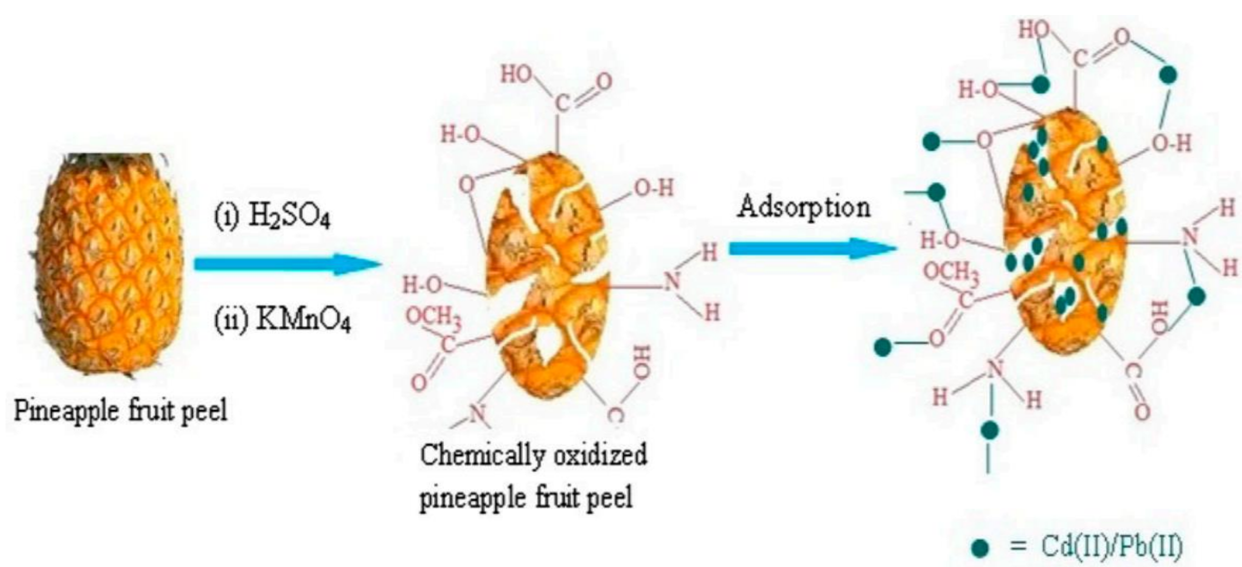


**Fig. 14.** Plausible mechanism of Cd(II) and Pb(II) adsorption using $H_2SO_4/KMnO_4$ oxidized pineapple fruit peel. Reproduced from the reference (Ahmad et al., 2016).

## 10. Potential of pineapple wastes towards circular economy

According to Food and Agriculture Organization (FAO), nearly 30 million tons of pineapple fruit are harvested for food and drinking industries each year, along with the release of a huge amount of the pineapple wastes. The proper conversion methods of the pineapple wastes into more valuable products such as biofuels, biochars, activated carbons, modified nanomaterials, magnetic nanocomposites, etc. have contributed proactively to strengthening a low-carbon economy as well as mitigating the environmental pollution and climate change. However, almost studies on the production of the pineapple waste-based adsorbents are just lab-scaled, or burgeoning, and it would be too early to claim that these bio-based products (biofuels and materials) are very attractive in the future bioenergy and wastewater treatment technologies. To pave the way for commercializing the pineapple wastes-derived products and other real applications, in this section, we propose a systematic expansion from lab-scale production to consumption and waste management in the context of circular economy.

Circular economy is an emerging model of how to extend the life cycle of products through the core processes of material design, production, distribution, consumption, repair, material collection, recycling and residual waste management. Although there is still a debatable topic of definition and scope of circular economy, it is generally believed that effective management of the agro-industrial by-products, especially for the pineapple wastes in the principles of circular economy may be environmentally beneficial. It is evitable that incorporation of many sectors such as research and development (R&D), logistic systems, treatment plants, maintenance services, etc.

in the usage and pineapple wastes management should be encouraged in circular economy. With the emphasis on nanotechnology and green chemistry, the potential of the pineapple wastes based products can be insightfully elucidated in the approaches of sustainable development.

Nine core processes are briefly described in Fig. 15. Initially, some pineapple by-products such as crown, leaf, and stem after harvesting juices are collected and treated to be ready for bioenergy and material production. To enhance the pineapple waste-based high-quality products, the material design process needs to be involved in lab-scale research, modification, and optimization. This process may be complicated and depended majorly on the purpose and availability of manufacturers. There are three types of main products derived from the pineapple wastes, including *(i)* value-added products, *(ii)* bioenergies, and *(iii)* materials. Natural compounds such as polyphenols, xylitol, antioxidants, enzymes, and organic acids can be extracted from the pineapple wastes through extraction processing technologies (Meena et al., 2021). They are used to synthesize value-added products for food and cosmetic, medicine applications (Aili Hamzah et al., 2021). Pineapple waste-based biofuels such as biogas, biohydrogen, bioethanol, bio-oil, and biomethane can be produced through anaerobic digestion technologies, biorefinery systems, and other bioconversion/catalytic processes. These biofuels are an integral part of low-carbon economy towards circular bioeconomy. Consequently, production of biofuels from the pineapple wastes minimize the energy loss and greenhouse gas emission. For the purpose of zero waste, this process should be integrated with the production of materials as a result of carbon residuals. Accordingly, residuals after bioenergy production can be converted into valuable materials such as biochars, activated carbons, modified nanomaterials, magnetic nanocomposites, and functionalized porous carbon for water treatment. The fourth process are storage and transportation of bioenergies and material for consumption. For example, the materials can be delivered to wastewater treatment plants or sewage treatment plants while bioenergies can be distributed to power stations through logistic and storage systems. A repairing or optimization process is required to improve the performance of these plants. The next process includes material replacement, and addition. The spent materials can be collected from the treatment systems and stored for regeneration or recycling. Finally, residual wastes need to be managed through post-treatment technologies such as impregnation, geopolymerisation, or modification, etc. Post-treatment materials can still be modified to be used as catalysts for biomass conversion into bioenergy, biofertilizers for soil amendment in agriculture, or any applications to prolong the life cycle of the pineapple waste-based products.

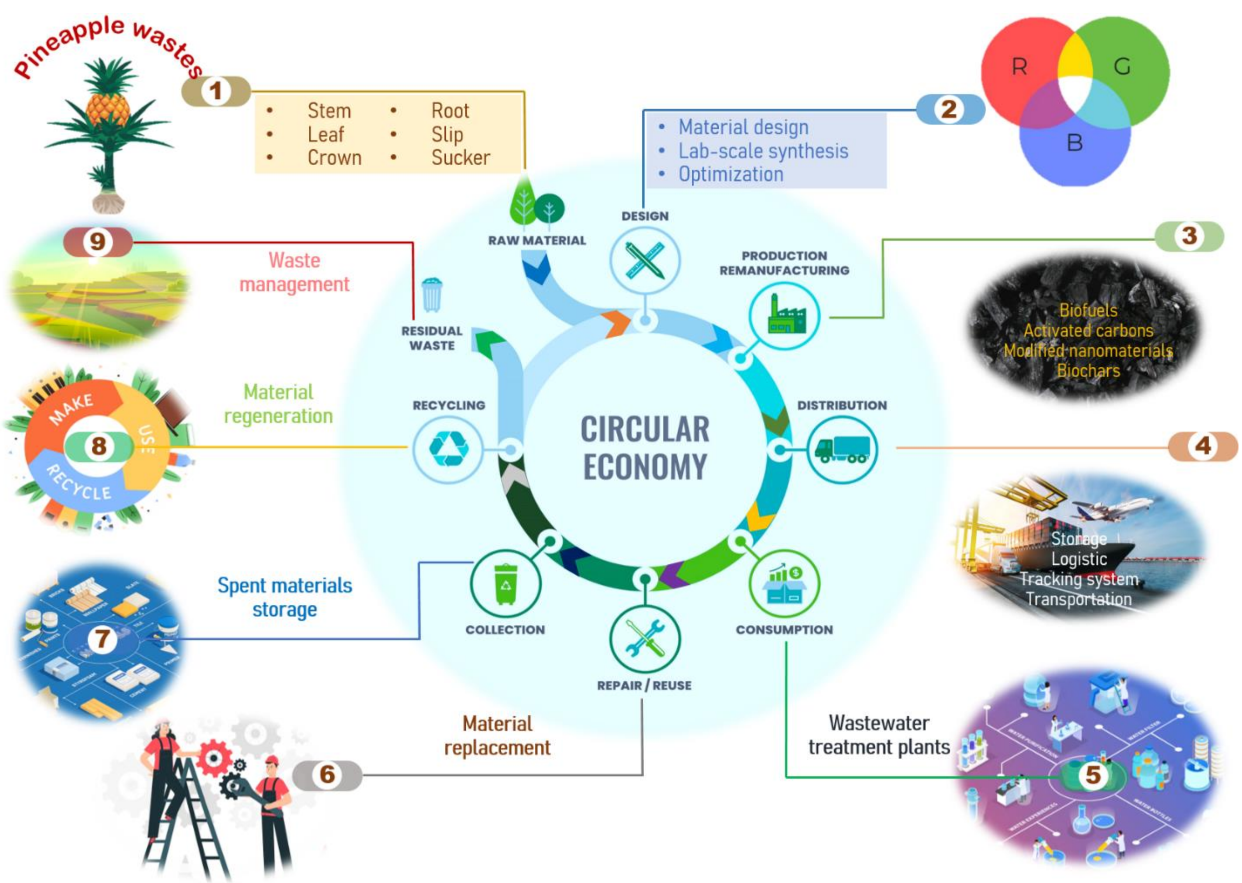



**Fig. 15.** Waste management and substantial contribution of the pineapple wastes to the circular economy.

# 11. Literature gaps and future prospects

## *11.1. Literature gaps*

The researchers demonstrated the great potential of the pineapple wastes derived adsorbents including biosorbents, biochars, modified sorbents, and activated carbon for the environmental remediation. However, there are still some unreported areas which may be very important to better illuminate. The first point is to extend the scope of the pollutants as the previous works only investigated the use of the pineapple derived adsorbents for the treatment of heavy metals and organic dyes. Many emerging contaminants such as persistent organic pollutants, polychlorinated biphenyls, pharmaceuticals and personal care products are highly harmful to the environment and human health, but not tested for treatment by such adsorbents. Secondly, one of the key activation of the pineapple wastes is the physical activation, but not still applied to produce low cost biochar or activated carbon. It may be also interesting to investigate several physical parameters such as activators (e.g., $CO_2$, steam), pyrolysis temperature, or heating power by microwave energy. Thirdly, the chemical activations of the pineapple wastes put many unanswered questions since the residuals of chemical reagents such as $H_2SO_4$, $KMnO_4$, NaOH, and $ZnCl_2$ after the activation can cause the secondary pollutions. The future works should focus on how to treat such residuals completely. Moreover, this review observed that the pineapple derived adsorbents could be desorbed for regeneration, but the selection of eluents has not been insightfully investigated. There are very few studies reported the desorption and regeneration of the pineapple wastes based adsorbents. The researchers should also improve the desorption efficiency to increase the number of reuse because the final cycle has drastically fallen.

### *11.2. Future prospects*

Over the past decades, the amount of agricultural wastes has continuously increased as a result of agricultural expansion to satisfy the demand for food and drinking. In the current context of serious environmental pollution caused by the agricultural by-products, the pineapple wastes need to be converted into more valuable products. In the future, the pineapple waste derived adsorbents may be still developed to contribute significantly to the environmental remediation. To realize this aspiration, the researchers should improve the adsorption efficiency of the pineapple waste derived adsorbents by new modification methods. Moreover, the green synthesis of nanoparticles using the pineapple wastes as precursors may be an interesting area since their applications are widely used in the nanotechnology, nano-scaled fertilizers, and nano-scaled sensors for the agricultural fields (N. T. T. Nguyen et al., 2022). Many new materials such as hydrogels, aerogels, and nanocomposites can be synthesized from the pineapple wastes, bringing great potential in the environmental remediation, material science, and electrical engineering.

## 12. Conclusion

In the present work, the highlighted experimental results of the production and application of the pineapple waste derived adsorbents for the environmental treatment applications were systematically overviewed. The synthesis of the pineapple derived biosorbents, modified biochars, and activated carbons and composites was discussed. Almost adsorption systems followed the pseudo second order kinetic model, and Langmuir isotherm model. The adsorption by the pineapple based adsorbents was majorly due to the contribution of electrostatic attraction, complexation, chelation, and ion exchange. The research works reported that the adsorption processes were thermodynamically spontaneous. The pineapple waste based adsorbents could be reused at 3–5 times using HCl or NaOH as eluents. For future prospects, the pineapple wastes may not only have potential for synthesis of materials such as nanoparticles, hydrogels, aerogels, and nanocomposites but also contribute proactively to circular economy.

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**Table 1.** Chemical modification and carbonization for the pineapple wastes based adsorbents

| Location | Part of pineapple | Particle size (µm) | Modification (chemicals, activation) | Activation (Tem, time, ramping rate) | Carbonization (Tem, time) | Characterization | Ref. |
|---|---|---|---|---|---|---|---|
| Local market, Johor, Malaysia | Fruit peel | 150–200 | 0.1 M $H_2SO_4$ and 0.1 M $KMnO_4$ | 60 ºC for 24 h | - | SEM, FT-IR, $pH_{pzc}$ | (Ahmad et al., 2016) |
| Kaohsiung, Taiwan | Leaf | - | - | 100 ºC for 20 min at 70 kPa | - | SEM, FT-IR, BET, $pH_{pzc}$ | (Weng and Wu, 2012) |
| Vigo, Pontevedra, Spain | Core | - | - | 80 °C for 48 h | - | SEM, FT-IR, $pH_{pzc}$ | (Rosales et al., 2019) |
| Istanbul, Turkey | Fruit peel | 841 | $ZnCl_2$ (3:1 by wt.%) and $H_2SO_4$ (3:1 by vol.) | 75 °C for 2 h, then treated by 0.1 M HCl for 1 h | - | FT-IR, TGA, SEM | (Turkmen et al., 2021) |
| Istanbul, Turkey | Fruit peel | 841 | - | - | Microwave 800 W, 4 min | FT-IR, TGA, SEM | (Turkmen et al., 2021) |
| Roorkee, India | Fruit peel | 500–3000 | - | - | - | FT-IR, SEM | (Mishra et al., 2010) |
| Assam, India | Crown leaf | 100 | 0.1 M NaOH for 2 h | 50 °C for overnight | - | Distribution of pore sizes, SEM, | (Gogoi et al., 2018) |
| Bangsaphan, Thailand | Leaf | - | 10% NaOH, EDTA | 100 °C for 1 h | - | SEM, EDX, FT-IR | (Daochalermwong et al., 2020) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dehradun, India | Leaf | 500 | - | 121°C for 15 min at 103.42 kPa | - | BET | (Mishra and Tadepalli, 2015) |
| Pontian, Johor, Malaysia | Fruit peel | - | 0.1 M $H_2SO_4$ and 0.1 M $KMnO_4$ | 60 °C for 24 h | - | - | (Yusoff et al., 2020) |
| Selangor, Malaysia | Leaf | 125–500 | 20% NaOH | 18 h | - | SEM, FT-IR, EDX | (Heba et al., 2019) |
| Selangor, Malaysia | Leaf | 180 | Iminodiacetic acid | 95 °C for 8 h | - | SEM, FT-IR, EDX | (Heba et al., 2019) |
| Istanbul, Turkey | Fruit rind | 180 | $ZnCl_2$ (3:1 by wt.%) | 75 °C for 2 h or 4 h | Microwave 800 W for 4 min | FT-IR | (Yılmaz and Tugrul, 2022) |
| Selangor, Malaysia | Stem | 105–250 | 0.5 M oxalic acid | Room temperature for 30 min | 120 °C for 90 min | $pH_{pzc}$ | (Vivian Loh Zing et al., 2019) |
| Tokyo, Japan | Leaf | 600 | - | - | 350 °C or 450 °C for 60 min | TGA, FT-IR, SEM, BET, Boehm titration | (Ponou et al., 2011) |
| Kaohsiung, Taiwan | Leaf | 75 | - | 80 °C for 48 h | - | BET-$N_2$, $pH_{pzc}$, SEM, FT-IR | (Weng et al., 2009) |
| Durgapur, India | Leaf | 100–125 | | 90 °C for 24 h | - | - | (Chakraborty et al., 2012) |
| Nibong Tebal, Malaysia | Leaf | 355–500 | - | 70 °C for 48 h | - | FT-IR, SEM, | (Krishni et al., 2014) |
| Tamil Nadu, India | Leaf | 150 | - | 100 °C for 48 h | - | $pH_{pzc}$, FT-IR | (Neupane et al., 2015) |
| Sepang, Malaysia | Stem | 106–250 | - | 90 ± 2 °C | - | SEM, FT-IR, BET, $pH_{pzc}$ | (Chan et al., 2016) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| West Bengal, India | Leaf | 100–125 µm | - | 90 °C for 24 h | - | SEM, FT-IR, BET | (Chowdhury et al., 2011) |
| Guangzhou, China | Peel | 150–200 µm | 1.25 M NaOH or 1.25 M $NaClO_2$ for 10 h, | 100 °C for 24 h | - | SEM, FT-IR, BET, XRD, TGA | (Das et al., 2016) |
| Johor, Malaysia | Crown, leaf, stem | 2000 µm | $ZnCl_2$ (1:1 by wt.%) for 24 h | 110 °C for 24 h | 500 °C, 1 h | SEM, FT-IR, BET, TGA | (Mahamad et al., 2015) |
| Johor, Malaysia | Leaf | - | CTAB (1.0–4.0 mM) | 90 °C for 24 h | - | SEM, FT-IR, | (Kamaru et al., 2016) |
| Assam, India | Stem | 300 µm | - | 70 °C for 24 h | - | SEM, FT-IR, BET, $pH_{pzc}$ | (Rajesh et al., 2014) |
| Guangzhou, China | Peel | 100 µm | Isopropyl alcohol (20%), 0.1 M NaOH | 50 °C for 24 h | - | XRD, FT-IR | (Hu et al., 2010) |
| Nasugbu Public Market, Philippines | Crown leaf | 149 µm | - | 90 °C | - | SEM, FT-IR, XRF | (Nieva et al., 2020) |
| Penang, Malaysia | Stem | 355–500 µm | - | 70 °C for 24 h | - | SEM, FT-IR | (Hameed et al., 2009) |
| Buriram, Thailand | Leaf | 3–80 µm | Treated with 5 wt.% NaOH, TEA, and cross-linked with PEI | 80 °C for 24 h | - | SEM, FT-IR, TGA/DTG, XPS | (Tangtubtim and Saikrasun, 2019a) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Buriram, Thailand | Leaf | 3–80 µm | Treated with 5 wt.% NaOH, TEA, and cross-linked with PEI | Stirring for 12 h | - | SEM, FT-IR, TGA, XPS | (Tangtubtim and Saikrasun, 2019b) |
| Pahang, Malaysia | Peel | Not reported | 1.0 M of $ZnCl_2$ | Room temperature for 24 h | 800 °C for 1 h | SEM, FT-IR | (Abd Ghapar et al., 2020) |
| Hainan, China | Peel | Not reported | Limited oxygen | 200 °C for 2 h | 350–650 °C, 10 °C/min, 3 h | SEM, FT-IR, EDX | (Fu et al., 2016) |
| Nantou City, Taiwan | Leaf | 2000 µm | - | 60 °C for 24 h | 600 °C, 10 °C/min, 2 h | $pH_{pzc}$, BET, SEM, EDX, FT-IR, XPS | (Iamsaard et al., 2022) |
| Guangzhou, China | Peel | 177 µm | - | 80 °C overnight | 300 °C for 1 h | Zeta potential, VSM, BET, FE-SEM, EDX, FT-IR, ICP, XPS | (Liao et al., 2018) |
| Guangzhou, China | Peel | 177 µm | $FeCl_2$/$FeCl_3$ (1:1), then NaOH | 60 °C for 0.5 h | 80 °C overnight | Zeta potential, VSM, BET, FE-SEM, EDX, FT-IR, ICP, XPS | (Liao et al., 2018) |
| Guangzhou, China | Peel | 177 µm | $La(OH)_3$ | Room temperature for 24 h | 80 °C overnight | Zeta potential, VSM, BET, FE-SEM, EDX, FT-IR, ICP, XPS | (Liao et al., 2018) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Semarang, Indonesia | Crown leaf | <150 µm | KOH | Microwave 800 W for 4 min | 500 °C for 90 min in limited air | VSM, BET, FE-SEM, EDX, FT-IR, XRD | (Astuti et al., 2019) |
| Guangzhou, China | Peel | 100–200 µm | Succinic anhydride (3:1 by wt.) | Room temperature for 24 h | - | FT-IR | (Hu et al., 2011) |
| Aligarh, India | Fruit leftover | - | 0.1 M NaOH | Room temperature for 2 h | 80 °C for 2 h | BET, SEM, EDX, FT-IR, AAS, $pH_{pzc}$ | (Veeramalai et al., 2022) |
| Paraná, Brazil | Leaf | - | $H_3PO_4$ (1:1 by vol./wt.) | 65 °C for 24 h | 500 °C, 5 °C/min, $N_2$ flow (100 mL/min) | BET, SEM, FT-IR, TGA, Raman, $pH_{pzc}$ | (Beltrame et al., 2018) |
| Delhi, India | Peel | - | - | - | 350–650 °C for 60 min, 5 °C/min | BET, EDX, SEM, FT-IR, TGA, $pH_{pzc}$ | (Shakya and Agarwal, 2019) |
| Resende-RJ, Brazil | Crown | 500 µm | NaOH (1:1 by wt.) | Room temperature for 24 h | 400 °C for 180 min | XRD, SEM, FT-IR, TGA | (da Silva et al., 2021) |
| Johor, Malaysia | Leaf | 300 µm | NaOH (2.18:1 by wt.) for 2h | 110 °C overnight | 464 °C for 180 min | - | (Abd Latif et al., 2021) |
| Chakdara, Pakistan | Fruit waste | - | $FeCl_3/FeSO_4$ (2:1), then 5 M NaOH | Room temperature for 50 min | - | XRD, SEM, FT-IR, TGA, BET, EDX | (Zahoor et al., 2019) |

**Note:** SEM, scanning electron microscopy; FT-IR, Fourier transform infrared spectroscopy; XRD, X-Ray diffraction pattern analysis; TGA, thermogravimetric analysis; BET, Brunauer-Emmett-Teller; BJH, Barrett-Joyner-Halenda; $pH_{pzc}$, point of zero charge; EDX, Energy dispersive X-ray analysis; XRF, X-ray fluorescence; CTAB, Hexadecyltrimethylammoniumbromide; TEA, trimethylamine; PEI, polyethyleneimine-carbamate.

1218 **Table 2.** Lignocellulosic composition, proximate, and ultimate analysis of the pineapple species

| Location | Part | Lignocellulosic composition | Proximate analysis | Ultimate analysis | Ref. |
|---|---|---|---|---|---|
| Cruz das Almas, Brazil | Leaf | Cellulose: 49–63%, Hemicellulose: 6–13%, Lignin: 20–36% | Ash: 1.2–3.3% | Not reported | (Sena Neto et al., 2015) |
| Johor, Malaysia | Leaf | Cellulose: 72.76%, Hemicellulose: 17.15%, Lignin: 4.76% | Ash: 0.59% | Not reported | (Nashiruddin et al., 2020) |
| São Paulo, Brazil | Crown leaf | Cellulose: 17.4%, Hemicellulose: 19.1%, Lignin: 24.3% | Ash: 5.2% | Not reported | (Pereira et al., 2021) |
| Araçagi, Brazil | Crown leaf | Cellulose: 12.93%, Hemicellulose: 35.49%, Lignin: 26.4% | Moisture: 8.96%, volatile matter: 78.84%, ash: 5.22%, fixed carbon: 6.98% | C: 44.05%, H: 5.81%, O: 49.27%, N: 0.87% | (Braga et al., 2015) |
| Johor, Malaysia | Leaf | Cellulose: 30%, Hemicellulose: 37%, Lignin: 22% | Moisture: 6.75%, volatile matter: 51.74%, ash: 7.35%, fixed carbon: 34.16% | C: 43.4%, H: 6.7%, O: 59.2%, N: 1.7%, S: 0.4% | (Mansor et al., 2019, 2018) |

| | | | | | |
|---|---|---|---|---|---|
| Johor, Malaysia | Stem | Cellulose: 37%, Hemicellulose: 34%, Lignin: 20% | Moisture: 9.1%, volatile matter: 58.25%, ash: 7.68%, fixed carbon: 25.18% | C: 41.1%, H: 6.7%, O: 57.3%, N: 1.45%, S: 0.56% | (Mansor et al., 2019, 2018) |
| Johor, Malaysia | Root | Cellulose: 42%, Hemicellulose: 32%, Lignin: 19% | Moisture: 4.55%, volatile matter: 41.56%, ash: 30.07%, fixed carbon: 28.82% | C: 38.7%, H: 5.4%, O: 75.4%, N: 1.0%, S: 0.23% | (Mansor et al., 2019, 2018) |
| Araçagi, Brazil | Crown leaf | Cellulose: 13.3%, Hemicellulose: 35.4%, Lignin: 26.4% | Moisture: 8.9%, volatile matter: 78.8%, ash: 5.2%, fixed carbon: 7.1% | C: 44.1%, H: 5.8%, O: 49.3%, N: 0.8% | (Calixto et al., 2022) |
| Mumbai, India | Peel | Cellulose: 20.9%, Hemicellulose: 31.8%, Lignin: 10.4% | Volatile matter: 94.04%, ash: 5.9% | C: 43.9%, H: 5.7%, N: 0.6% | (Banerjee et al., 2019) |
| Johor, Malaysia | Leaf | Cellulose: 31.2%, Hemicellulose: 13.6%, Lignin: 17.6% | Moisture: 4.56%, volatile matter: 80.4%, ash: 3.57%, fixed carbon: 11.2% | C: 40.5%, H: 6.91%, O: 50.3%, N: 1.78%, S: 0.36% | (Mathew et al., 2015) |
| Johor, Malaysia | Stem | Cellulose: 49.2%, Hemicellulose: 8.26%, Lignin: 5.42% | Moisture: 7.92%, volatile matter: 78.9%, ash: 4.87%, fixed carbon: 8.24% | C: 37.6%, H: 6.69%, O: 52.7%, N: 1.89%, S: 0.97% | (Mathew et al., 2015) |

| | | | | | |
|---|---|---|---|---|---|
| Haryana, India | Peel | Not reported | Moisture: 6.87%, volatile matter: 68.96%, ash: 4.75%, fixed carbon: 19.52% | C: 47.39%, H: 6.13%, O: 40.64%, N: 1.08% | (Shakya and Agarwal, 2019) |
| Guangdong, China | Crown and peel residue | Cellulose: 27.35%, Hemicellulose: 21.15%, Lignin: 10.25% | Moisture: 2.15%, volatile matter: 72.12%, ash: 6.24%, fixed carbon: 19.5% | C: 44.95%, H: 5.5%, O: 47.65%, N: 1.68%, S: 0.22% | (Wang et al., 2022) |

1220 **Table 3.** The effect of activating agents, and activation conditions on the point of zero charge,
1221 surface area and pore volume for the pineapple wastes based adsorbents

| Part of pineapple | Activating chemical | Activation (tem, time, ramping rate) | $pH_{pzc}$ or zeta potential (mV) | Method | Surface area ($m^2\ g^{-1}$) | Pore volume ($cm^3\ g^{-1}$) | Ref. |
|---|---|---|---|---|---|---|---|
| Leaf | - | - | 2.3 | BET | 4.26 | 0.033 | (Weng and Wu, 2012) |
| Crown leaf | 0.1 M NaOH for 2 h | - | 4.0 | BET | 32.9 | - | (Gogoi et al., 2018) |
| Leaf powder | - | - | - | BET | 14.55 | - | (Mishra and Tadepalli, 2015) |
| Leaf | - | 500 °C for 2 min | - | BJH | 44.775 | 8.183 | (Herlinawati et al., 2022) |
| Leaf | 1 M $H_2SO_4$ for 24 h | 500 °C for 2 min | - | BJH | 25.68 | 5.133 | (Herlinawati et al., 2022) |
| Leaf powder | - | - | 2.8 | BET | 6.84 | 0.29 | (Ponou et al., 2011) |
| Leaf-derived carbon | - | 350 °C for 60 min | 2.2 | BET | 44.08 | 0.93 | (Ponou et al., 2011) |
| Leaf-derived carbon | - | 450 °C for 60 min | 2.1 | BET | 374.9 | 3.66 | (Ponou et al., 2011) |
| Leaf powder | - | 80 °C for 48 h | 2.3 | BET | 5.24 | 1.53 | (Weng et al., 2009) |
| Leaf powder | - | 90 °C for 24 h | - | BET | 4.2 | 0.024 | (Chowdhury et al., 2011) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $ZnCl_2$-activated carbon | $ZnCl_2$ (0.5, 1.0, 1.5 by wt.%) for 24 h | 500 °C, 1 h | - | BET | 22.99–521.88 | 0.02–0.30 | (Mahamad et al., 2015) |
| Stem powder | - | - | 4.08 | BET | 11.47 | - | (Rajesh et al., 2014) |
| Peel powder | Limited oxygen | 200 °C for 2 h | - | BET | 0.352 | 0.001 | (Fu et al., 2016) |
| Peel biochar | Limited oxygen | 350 °C for 3 h | - | BET | 0.815 | 0.0015 | (Fu et al., 2016) |
| Peel biochar | Limited oxygen | 500 °C for 3 h | - | BET | 2.729 | 0.0022 | (Fu et al., 2016) |
| Peel biochar | Limited oxygen | 650 °C for 3 h | - | BET | 6.643 | 0.0031 | (Fu et al., 2016) |
| Leaf biochar | - | 600 °C for 2 h, $N_2$ atmosphere | <2.0 | BET | 7.3 | 0.0106 | (Iamsaard et al., 2022) |
| Peel biochar | - | 300 °C for 1 h | −4.49 mV | BET | 36.22 | - | (Liao et al., 2018) |
| Peel biochar | $FeCl_2/FeCl_3$ (1:1) | 80 °C overnight | −16.87 mV | BET | 1.18 | - | (Liao et al., 2018) |
| Peel biochar | $La(OH)_3$ | 80 °C overnight | 7.03 mV | BET | 84.89 | - | (Liao et al., 2018) |
| Crown leaf biochar | - | 500 °C for 90 min | - | BET | 17.03 | 0.0242 | (Astuti et al., 2019) |
| Crown leaf KOH-activated carbon | KOH | 105 °C for 24 h | - | BET | 71.75–383.17 | 0.027–0.1193 | (Astuti et al., 2019) |
| Crown leaf microwave | KOH | Microwave 800 W for 4 min | - | BET | 95.11–314.08 | 0.1056–0.1098 | (Astuti et al., 2019) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| KOH-activated carbon | | | | | | | |
| Leaf activated carbon | $H_3PO_4$ | 65 °C for 24 h | 2.8 | BET | 1031 | 1.27 | (Beltrame et al., 2018) |
| Peel biochar at 350 °C | - | - | 7.7 | BET | 5.548 | 0.004 | (Shakya and Agarwal, 2019) |
| Peel biochar at 450 °C | - | - | 7.9 | BET | 3.372 | 0.005 | (Shakya and Agarwal, 2019) |
| Peel biochar at 550 °C | - | - | 8.2 | BET | 11.112 | 0.017 | (Shakya and Agarwal, 2019) |
| Peel biochar at 650 °C | - | - | 8.2 | BET | 6.391 | 0.010 | (Shakya and Agarwal, 2019) |
| $Fe_3O_4$/activated carbon | $FeCl_3$/$FeSO_4$ (2:1), then 5 M NaOH | Room temperature for 50 min | 7.2 | BET | 39.0 | 0.2 | (Zahoor et al., 2019) |

**Note:** BET, Brunauer-Emmett-Teller; BJH, Barrett-Joyner-Halenda.

**Table 4.** Optimum adsorption conditions and adsorption performance (removal efficiency and maximum adsorption capacity) of the pineapple wastes based adsorbents for removal of various pollutants.

| Adsorbent | Pollutant | Optimized pH | Dose ($g L^{-1}$) | Time (min) | Removal (%) | Maximum capacity ($mg g^{-1}$) | Ref. |
|---|---|---|---|---|---|---|---|
| Chemically oxidized fruit peel | Cd(II) | 4 | 4.0 | 30 | 90.0 | 42.1 | (Ahmad et al., 2016) |
| Chemically oxidized fruit peel | Pb(II) | 4 | 4.0 | 30 | 87.0 | 28.55 | (Ahmad et al., 2016) |
| Leaf powder | Cu(II) | 5 | 0.2 | 20 | 90.0 | 9.28 | (Weng and Wu, 2012) |
| Core powder | Cr(VI) [a] | 2 | 30 | 1440 | 92.39 | 8.8 | (Rosales et al., 2019) |
| Fruit peel activated by $ZnCl_2$ | Zn(II) | - | 0.25 | 240 | 92 | 37.23 | (Turkmen et al., 2021) |
| Fruit peel activated by $H_2SO_4$ | Zn(II) | - | 0.25 | 240 | 94 | 36.99 | (Turkmen et al., 2021) |
| Fruit peel powder (0.5 mm) | Zn(II) | 5 | 1.0 | 480 | 23.0 | 0.45 | (Mishra et al., 2010) |
| Crown leaf | Cr(VI) | 2.5 | 60 | 120 | - | 2.503 | (Gogoi et al., 2018) |
| Crown leaf | Cr(III) | 5 | 60 | 120 | - | 4.42 | (Gogoi et al., 2018) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Leaf-derived cellulose | Pb(II) | 6.0 | 10 | 90 | 95 | 155.06 | (Daochalermwong et al., 2020) |
| Leaf-derived cellulose | Cd(II) | 6.0 | 10 | 90 | 93 | 37.26 | (Daochalermwong et al., 2020) |
| Leaf powder | Pb(II) | 7.0 | 15 | 450 | 92.67 | 2.16 | (Mishra and Tadepalli, 2015) |
| Leaf powder | Zn(II) | 7.0 | 15 | 450 | 85.77 | 1.33 | (Mishra and Tadepalli, 2015) |
| Leaf powder | Cr(III) | 7.0 | 15 | 450 | 92.67 | 0.86 | (Mishra and Tadepalli, 2015) |
| Fruit peel | Cd(II) | 9.0 | 120 | 90 | 98.44 | 1.91 | (Yusoff et al., 2020) |
| Fruit peel | Cr(VI) | 9.0 | 120 | 90 | 88.35 | - | (Yusoff et al., 2020) |
| Fruit peel | Pb(II) | 9.0 | 120 | 90 | 93.65 | - | (Yusoff et al., 2020) |
| Leaf powder | Pb(II) | 5.5 | 4.0 | 240 | 80.8 | 32.55 | (Heba et al., 2019) |
| Fruit rind activated by $ZnCl_2$ | Zn(II) | - | 5.0 | 240 | 30.50 | 12.2 | (Yılmaz and Tugrul, 2022) |
| Oxalic acid-activated stem | Pb(II) | 4.0 | 2.0 | 60 | - | 27.53 | (Vivian Loh Zing et al., 2019) |
| Stem powder | Pb(II) | 5.0 | 2.0 | 60 | - | 12.13 | (Vivian Loh Zing et al., 2019) |
| Leaf-derived carbon at 450 °C | Cr(VI) | 2.0 | 10 | 60 | 90.1 | 18.77 | (Ponou et al., 2011) |
| Succinic anhydride- | Cu(II) | 5.4 | 1.0 | 30 | 36.0 [b] | 31.78 | (Hu et al., 2011) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| modified peel fiber | | | | | | | |
| Succinic anhydride-modified peel fiber | Cd(II) | 7.5 | 1.0 | 30 | 42.0 [b] | 39.93 | (Hu et al., 2011) |
| Succinic anhydride-modified peel fiber | Pd(II) | 5.6 | 1.0 | 30 | 56.0 [b] | 75.58 | (Hu et al., 2011) |
| Modified peel powder | Cu(II) | 5.5 | 1.0 | 30 | 50 [b] | 65.98 | (Hu et al., 2010) |
| Modified peel powder | Cd(II) | 7.5 | 1.0 | 30 | 80 [b] | 102.92 | (Hu et al., 2010) |
| Modified peel powder | Pd(II) | 5.5 | 1.0 | 30 | 74 [b] | 111.41 | (Hu et al., 2010) |
| $KMnO_4$-modified pineapple cellulose | Cu(II) | 7.0 | 1.0 | 80 | 96.0 | 28.99 | (Zhuang et al., 2020) |
| Stem powder | Ni(II) | 5.0 | 0.1 | 300 | 85.24 | 2.4 | (Rajesh et al., 2014) |
| NaOH-treated leaf fiber | Cr(VI) | 3.0 | 0.1 | 60 | - | 133 | (Tangtubtim and Saikrasun, 2019a) |
| PEI-cross-linked leaf fiber | Cr(VI) | 3.0 | 0.1 | 60 | - | 222 | (Tangtubtim and Saikrasun, 2019a) |
| PEI-cross-linked leaf fiber | Cu(II) | 5.0 | 0.1 | 60 | - | 273 | (Tangtubtim and Saikrasun, 2019b) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| PEI-cross-linked leaf fiber | Pb(II) | 5.0 | 0.1 | 60 | - | 165 | (Tangtubtim and Saikrasun, 2019b) |
| $ZnCl_2$-activated carbon | Fe(III) | Not reported | 4.0 | 120 | 55.26 | - | (Abd Ghapar et al., 2020) |
| Leaf biochar at 600 °C | Ni(II) | 5.0 | 2.0 | 1440 | >94.0 | 44.88 | (Iamsaard et al., 2022) |
| Leaf biochar at 600 °C | Zn(II) | 5.0 | 2.0 | 1440 | >92.0 | 46.0 | (Iamsaard et al., 2022) |
| Leaf biochar at 600 °C | Cu(II) | 5.0 | 2.0 | 1440 | >96.0 | 53.14 | (Iamsaard et al., 2022) |
| NaOH-treated fruit leftover | Ni(II) | 4–6 | 10.0 | 60 | 97.60 | 8.98 | (Veeramalai et al., 2022) |
| Peel biochar at 350 °C | Cr(VI) | 2.0 | 5.0 | 480 | 99.19 | 41.67 | (Shakya and Agarwal, 2019) |
| Peel biochar at 450 °C | Cr(VI) | 2.0 | 5.0 | 480 | 82.63 | 33.33 | (Shakya and Agarwal, 2019) |
| Peel biochar at 550 °C | Cr(VI) | 2.0 | 5.0 | 480 | 58.22 | 32.26 | (Shakya and Agarwal, 2019) |
| Peel biochar at 650 °C | Cr(VI) | 2.0 | 5.0 | 480 | 40.78 | 23.81 | (Shakya and Agarwal, 2019) |
| $La(OH)_3$-modified magnetic biochar | $[PO_4]^{3-}$ | 2.0 | 1.0 | 1440 | 100.0 | 101.16 | (Liao et al., 2018) |
| Modified pineapple juice extracted residue | $F^-$ | 6.0 | 0.9 | 120 | 79.6 | 7.06 | (Reza and Ahmaruzzaman, 2022) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Leaf powder | Methylene blue | 7.5 | 3.0 | 20 | 95.0 | 284.03 | (Weng et al., 2009) |
| Leaf powder | Crystal violet | 8.0 | 3.0 | 180 | 96.0 | 78.22 | (Chakraborty et al., 2012) |
| Leaf powder | Methylene blue | 6.0 | 1.5 | 280 | - | 97.09 | (Krishni et al., 2014) |
| Leaf powder | Crystal violet | 8.0 | 1.0 | 120 | - | 158.73 | (Neupane et al., 2015) |
| Leaf powder | Basic green 4 | 9.0 | 5.0 | 150 | 99.36 | 54.64 | (Chowdhury et al., 2011) |
| Leaf powder | Rose Bengal | 5.0 | 1.0 | 180 | 92.53 | 58.80 | (Hassan et al., 2020) |
| Peel hydrogels | Congo red | 4.0 | 0.67 | 60 | - | 114.94 | (Das et al., 2016) |
| Peel hydrogels | Congo red | 4.0 | 0.67 | 60 | - | 138.89 | (Das et al., 2016) |
| $ZnCl_2$-activated carbon | Methylene blue | - | 2.0 | 240 | - | 288.34 | (Mahamad et al., 2015) |
| Stem powder | Methylene blue | 4.0 | 1.5 | 60 | 96.70 | 119.05 | (Hameed et al., 2009) |
| Leaf powder | Remazol Brilliant Blue R | - | 50 | 1440 | 96.2 | 42.02 | (Rahmat et al., 2016) |
| KOH-activated crown leaf-derived carbon | Methyl violet | 5.0 | 6.0 | 180 | 97.0 [b] | 31.24 | (Astuti et al., 2019) |
| Microwave-assisted KOH-activated crown leaf-derived carbon | Methyl violet | 5.0 | 6.0 | 180 | 93.0 [b] | 16.76 | (Astuti et al., 2019) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| NaOH-activated crown-derived carbon | Methylene blue | 6.0 | 0.3 | 60 | - | 292 | (da Silva et al., 2021) |
| NaOH-activated leaf-derived carbon | Reactive black 5 | - | 1.0 | 60 | 98.25 | 50 | (Abd Latif et al., 2021) |
| Bark powder | Dye mixture [a] (methylene blue, brilliant green, and Congo red) | 6.0 | 2.0 | 60 | 97.93 | 14.6 | (Fegousse et al., 2019) |
| Crown leaf powder | Crystal violet | 8.0 | 8.0 | 180 | 98 [b] | 6.49 | (Nieva et al., 2020) |
| Surfactant-modified leaf powder | Methylene blue | 11.0 | 10.0 | 120 | - | 52.63 | (Kamaru et al., 2016) |
| Surfactant-modified leaf powder | Methyl orange | 3.0 | 10.0 | 120 | - | 47.62 | (Kamaru et al., 2016) |
| Poly(acrylic acid)-grafted pineapple leaf | Methylene blue | 5.6 | 1.33 | 180 | 98 | - | (Pomicpic et al., 2020) |
| $HNO_3$-activated carbon | Methylene blue | 4.0 | 5.0 | 120 | 92.99 | 5.136 | (Veeramalai et al., 2022) |
| Peel biochar at 350 °C | Oxytetracycline | - | 10.0 | 1440 | 80 | 0.781 | (Fu et al., 2016) |
| Peel biochar at 500 °C | Oxytetracycline | - | 10.0 | 1440 | 80 | 0.897 | (Fu et al., 2016) |

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|---|---|---|---|---|---|---|---|
| Peel biochar at 650 °C | Oxytetracycline | - | 10.0 | 1440 | 80 | 1.072 | (Fu et al., 2016) |
| $Fe_3O_4$/activated carbon | Enrofloxacin | 6–8 | 0.8 | 80 | 80 [b] | 46.3 | (Zahoor et al., 2019) |
| $H_3PO_4$-activated biochar | Caffeine | 5.8 | 1.0 | 360 | - | 155.5 | (Beltrame et al., 2018) |

**Note:** [a] adsorption tests were optimized by response surface methodology, [b] data was estimated from figure of the reference.

1228 **Table 5.** Adherence and correlation coefficients of kinetic and isotherm models for adsorption of
1229 various pollutants by the pineapple wastes based adsorbents

| Adsorbent | Pollutant(s) | Kinetic model | $R^2$ | Isotherm model | $R^2$ | Ref. |
|---|---|---|---|---|---|---|
| Chemically oxidized fruit peel | Cd(II) | PSO | 0.995 | Langmuir | 0.9839 | (Ahmad et al., 2016) |
| Chemically oxidized fruit peel | Pb(II) | PSO | 0.993 | Langmuir | 0.9916 | (Ahmad et al., 2016) |
| Leaf powder | Cu(II) | PSO | 0.99 | Langmuir | 0.99 | (Weng and Wu, 2012) |
| Core powder | Cr(VI) | - | - | Freundlich | 0.97 | (Rosales et al., 2019) |
| Crown leaf | Cr(VI) | PSO | 0.9963 | Liu | 0.9938 | (Gogoi et al., 2018) |
| Crown leaf | Cr(III) | PSO | 0.9934 | Liu | 0.9963 | (Gogoi et al., 2018) |
| Leaf-derived cellulose | Pb(II) | PFO | 0.9982 | Langmuir | 0.9775 | (Daochalermwong et al., 2020) |
| Leaf-derived cellulose | Cd(II) | PFO | 0.9982 | Langmuir | 0.9746 | (Daochalermwong et al., 2020) |
| Leaf powder | Pb(II) | - | - | Langmuir | 0.96 | (Mishra and Tadepalli, 2015) |
| Leaf powder | Zn(II) | - | - | Langmuir | 0.95 | (Mishra and Tadepalli, 2015) |
| Leaf powder | Cr(III) | - | - | Langmuir | 0.97 | (Mishra and Tadepalli, 2015) |
| Leaf powder | Pb(II) | PSO | 0.998 | Langmuir | 0.94 | (Heba et al., 2019) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Oxalic acid-activated stem | Pb(II) | PSO | 0.9997 | Langmuir | 0.9997 | (Vivian Loh Zing et al., 2019) |
| Stem powder | Pb(II) | PSO | 0.9994 | Langmuir | 0.9992 | (Vivian Loh Zing et al., 2019) |
| Leaf-derived carbon at 450 °C | Cr(VI) | PSO | 0.99 | Langmuir | - | (Ponou et al., 2011) |
| $KMnO_4$-modified pineapple cellulose | Cu(II) | Lagergren | >0.999 | Freundlich | 0.9999 | (Zhuang et al., 2020) |
| Stem powder | Ni(II) | PSO | >0.99 | Freundlich | 0.9964 | (Rajesh et al., 2014) |
| Modified peel powder | Cu(II) | PSO | 0.99 | Langmuir | 0.999 | (Hu et al., 2010) |
| Modified peel powder | Cd(II) | PSO | 0.99 | Langmuir | 0.999 | (Hu et al., 2010) |
| Modified peel powder | Pd(II) | PSO | 0.99 | Langmuir | 0.999 | (Hu et al., 2010) |
| NaOH-treated leaf fiber | Cr(VI) | PSO | >0.98 | Langmuir | 0.998 | (Tangtubtim and Saikrasun, 2019a) |
| PEI-cross-linked leaf fiber | Cr(VI) | PSO | >0.98 | Langmuir | 0.991 | (Tangtubtim and Saikrasun, 2019a) |
| NaOH-treated leaf fiber | Cu(II) | PSO | >0.96 | Langmuir | 0.9998 | (Tangtubtim and Saikrasun, 2019b) |
| NaOH-treated leaf fiber | Pb(II) | PSO | >0.98 | Langmuir | 0.9906 | (Tangtubtim and Saikrasun, 2019b) |
| PEI-cross-linked leaf fiber | Cu(II) | PSO | >0.99 | Langmuir | 0.9825 | (Tangtubtim and Saikrasun, 2019b) |
| PEI-cross-linked leaf fiber | Pb(II) | PSO | >0.98 | Langmuir | 0.9752 | (Tangtubtim and Saikrasun, 2019b) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Leaf biochar at 600 °C | Ni(II) | PFO | 0.998 | Langmuir | >0.99 | (Iamsaard et al., 2022) |
| Leaf biochar at 600 °C | Zn(II) | PFO | 0.999 | Langmuir | >0.99 | (Iamsaard et al., 2022) |
| Leaf biochar at 600 °C | Cu(II) | PFO | 1.000 | Langmuir | >0.99 | (Iamsaard et al., 2022) |
| NaOH-treated fruit leftover | Ni(II) | PSO | 0.99 | Langmuir | ≥0.96 | (Veeramalai et al., 2022) |
| Peel biochar at 350 °C | Cr(VI) | PSO | 0.986 | Freundlich | 0.972 | (Shakya and Agarwal, 2019) |
| Peel biochar at 450 °C | Cr(VI) | PSO | 0.981 | Freundlich | 0.968 | (Shakya and Agarwal, 2019) |
| Peel biochar at 550 °C | Cr(VI) | PSO | 0.993 | Freundlich | 0.967 | (Shakya and Agarwal, 2019) |
| Peel biochar at 650 °C | Cr(VI) | PSO | 0.994 | Freundlich | 0.957 | (Shakya and Agarwal, 2019) |
| $La(OH)_3$-modified magnetic biochar | $[PO_4]^{3-}$ | PSO | 0.98 | Langmuir | 0.99 | (Liao et al., 2018) |
| Leaf powder | Methylene blue | PSO | 0.999 | Langmuir | 0.993 | (Weng et al., 2009) |
| Leaf powder | Crystal violet | PSO | 0.992 | Langmuir | 0.999 | (Chakraborty et al., 2012) |
| Leaf powder | Methylene blue | PSO | >0.99 | Langmuir | 0.9952 | (Krishni et al., 2014) |
| Leaf powder | Crystal violet | PSO | 0.99 | Langmuir | 0.98 | (Neupane et al., 2015) |
| Leaf powder | Basic Green 4 | PSO | 0.999 | Langmuir | 1.000 | (Chowdhury et al., 2011) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Surfactant-modified leaf powder | Methylene blue | PSO | - | Langmuir | >0.97 | (Kamaru et al., 2016) |
| Surfactant-modified leaf powder | Methyl orange | PSO | - | Langmuir | >0.99 | (Kamaru et al., 2016) |
| Crown leaf powder | Crystal violet | - | - | Langmuir | 0.99 | (Nieva et al., 2020) |
| Stem powder | Methylene blue | PSO | >0.99 | Langmuir | 0.998 | (Hameed et al., 2009) |
| Leaf powder | Remazol Brilliant Blue R | PSO | 1.0000 | Langmuir | 0.9945 | (Rahmat et al., 2016) |
| KOH-activated crown leaf-derived carbon | Methyl violet | - | - | Redlich-Peterson | 0.995 | (Astuti et al., 2019) |
| Microwave-assisted KOH-activated crown leaf-derived carbon | Methyl violet | - | - | Redlich-Peterson | 0.991 | (Astuti et al., 2019) |
| $HNO_3$-activated carbon | Methylene blue | PFO | 1.00 | Langmuir | >0.85 | (Veeramalai et al., 2022) |
| Peel biochar at 350 °C | Oxytetracycline | PSO | 0.999 | Langmuir | >0.999 | (Fu et al., 2016) |
| Peel biochar at 500 °C | Oxytetracycline | PSO | 0.999 | Langmuir | >0.95 | (Fu et al., 2016) |
| Peel biochar at 650 °C | Oxytetracycline | PSO | 0.999 | Langmuir | >0.81 | (Fu et al., 2016) |
| $Fe_3O_4$/activated carbon | Enrofloxacin | PSO | 0.999 | Langmuir | 0.99 | (Zahoor et al., 2019) |

**Note:** PFO, pseudo first-order model; PSO, pseudo second-order model; $R^2$, coefficient of determination.

1232 **Table 6.** A summary on the parameters for the thermodynamic model of the adsorption of
1233 various pollutants by the pineapple wastes based adsorbents

| Adsorbent | Pollutant(s) | Tem (K) | ΔG° (kJ $mol^{-1}$) | ΔH° (kJ $mol^{-1}$) | ΔS° (J $mol^{-1}$ $K^{-1}$) | Ref. |
|---|---|---|---|---|---|---|
| Chemically oxidized fruit peel | Cd(II) | 298–323 | −3.499 | −26.089 | −75.017 | (Ahmad et al., 2016) |
| Chemically oxidized fruit peel | Pb(II) | 298–323 | −0.857 | −63.530 | −217.66 | (Ahmad et al., 2016) |
| Crown leaf | Cr(VI) | 303–328 | −32.77 | 25.449 | 192.210 | (Gogoi et al., 2018) |
| Crown leaf | Cr(III) | 303–328 | −32.874 | 21.358 | 179.00 | (Gogoi et al., 2018) |
| Leaf-derived carbon at 450 °C | Cr(VI) | 323–343 | −1.14 | 77.89 | 28.93 | (Ponou et al., 2011) |
| Leaf-derived carbon at 350 °C | Cr(VI) | 323–343 | −2.72 | 77.89 | 9.48 | (Ponou et al., 2011) |
| Leaf powder | Cr(VI) | 323–343 | −1.52 | 77.89 | 23.23 | (Ponou et al., 2011) |
| $KMnO_4$-modified pineapple cellulose | Cu(II) | 298–333 | −2.42 | 9.49 | 39.84 | (Zhuang et al., 2020) |
| Leaf biochar at 600 °C | Ni(II) | 298–323 | −17.59 | 24.26 | 59.11 | (Iamsaard et al., 2022) |
| Leaf biochar at 600 °C | Zn(II) | 298–323 | −5.83 | 7.62 | 19.61 | (Iamsaard et al., 2022) |

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|---|---|---|---|---|---|---|
| Leaf biochar at 600 °C | Cu(II) | 298–323 | −10.40 | 14.78 | 34.94 | (Iamsaard et al., 2022) |
| NaOH-treated fruit leftover | Ni(II) | 303–323 | −7.61 | 32.55 | 132 | (Veeramalai et al., 2022) |
| Leaf powder | Methylene blue | 277–327 | −26.12 | −5.93 | 76.4 | (Weng et al., 2009) |
| Leaf powder | Crystal violet | 293–303 | −18.25 | −68.47 | −171.29 | (Chakraborty et al., 2012) |
| Leaf powder | Basic green 4 | 298–318 | −17.96 | −101.40 | −280.0 | (Chowdhury et al., 2011) |
| Surfactant-modified leaf powder | Methylene blue | 308–333 | −4.3 | −2.79 | 4.0 | (Kamaru et al., 2016) |
| Surfactant-modified leaf powder | Methyl orange | 308–333 | −3.7 | −8.75 | 16.0 | (Kamaru et al., 2016) |
| Bark powder | Dye mixture (methylene blue, brilliant green, and Congo red) | 293–323 | −38.1 | −22.44 | −51.68 | (Fegousse et al., 2019) |
| Peel biochar at 350 °C | Oxytetracycline | 298–303 | −13.47 | 11.49 | 84 | (Fu et al., 2016) |
| Peel biochar at 500 °C | Oxytetracycline | 298–303 | −13.88 | 19.37 | 113 | (Fu et al., 2016) |
| Peel biochar at 650 °C | Oxytetracycline | 298–303 | −15.42 | 23.12 | 130 | (Fu et al., 2016) |
| $Fe_3O_4$/activated carbon | Enrofloxacin | 298–333 | –0.27 | - | - | (Zahoor et al., 2019) |

**Note:** ΔG° (kJ $mol^{-1}$) at 298K, standard free energy change; ΔH° (kJ $mol^{-1}$), standard enthalpy change; ΔS° (J $mol^{-1}$ $K^{-1}$), standard entropy change.

**Table 7.** A summary on the desorption eluent and recyclability study for adsorption of various pollutants by the pineapple wastes based adsorbents

| Adsorbent | Pollutant(s) | Eluent | Number of cycle | Ref. |
|---|---|---|---|---|
| Chemically oxidized fruit peel | Cd(II), Pb(II) | 0.1 M HCl | - | (Ahmad et al., 2016) |
| Crown leaf | Cr(III), Cr(VI) | 0.2–2 M NaOH | - | (Gogoi et al., 2018) |
| Leaf-derived cellulose | Cd(II) | 1 M HCl | 5 (90% for the final run) [a] | (Daochalermwong et al., 2020) |
| Leaf-derived cellulose | Pb(II) | 1 M HCl | 5 (90% for the final run) [a] | (Daochalermwong et al., 2020) |
| Leaf powder | Pb(II) | - | 4 (87% for the final run) [a] | (Heba et al., 2019) |
| NaOH-treated leaf fiber | Cr(VI) | 0.1 M NaOH | 5 (30 mg/g for the final run) [a] | (Tangtubtim and Saikrasun, 2019a) |
| PEI-cross-linked leaf fiber | Cr(VI) | 0.1 M NaOH | 5 (110 mg/g for the final run) [a] | (Tangtubtim and Saikrasun, 2019a) |
| NaOH-treated leaf fiber | Cu(II) | 0.1 M HCl | 5 (50 mg/g for the final run) [a] | (Tangtubtim and Saikrasun, 2019b) |
| NaOH-treated leaf fiber | Pb(II) | 0.1 M HCl | 5 (39 mg/g for the final run) [a] | (Tangtubtim and Saikrasun, 2019b) |
| PEI-cross-linked leaf fiber | Cu(II) | 0.1 M HCl | 5 (160 mg/g for the final run) [a] | (Tangtubtim and Saikrasun, 2019b) |
| PEI-cross-linked leaf fiber | Pb(II) | 0.1 M HCl | 5 (67 mg/g for the final run) [a] | (Tangtubtim and Saikrasun, 2019b) |

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|---|---|---|---|---|
| Leaf biochar at 600 °C | Ni(II), Zn(II), Cu(II) | Acid washing | 6 (72% for the final run) | (Iamsaard et al., 2022) |
| Leaf biochar at 600 °C | Ni(II), Zn(II), Cu(II) | Wet air oxidation | 6 (11% for the final run) | (Iamsaard et al., 2022) |
| $La(OH)_3$-modified magnetic biochar | $[PO_4]^{3-}$ | 3.0 M NaOH | 3 (92.93% for the final run) | (Liao et al., 2018) |
| Peel biochar at 350 °C | Cr(VI) | 1 M HCl | 5 (32% for the final run) [a] | (Shakya and Agarwal, 2019) |
| Peel biochar at 450 °C | Cr(VI) | 1 M HCl | 5 (11% for the final run) [a] | (Shakya and Agarwal, 2019) |
| Peel biochar at 550 °C | Cr(VI) | 1 M HCl | 5 (14% for the final run) [a] | (Shakya and Agarwal, 2019) |
| Peel biochar at 650 °C | Cr(VI) | 1 M HCl | 5 (6% for the final run) [a] | (Shakya and Agarwal, 2019) |
| Leaf powder | Crystal violet | 1 N acetic acid | - | (Neupane et al., 2015) |
| Peel hydrogel | Congo red | - | 4 | (Das et al., 2016) |
| Surfactant-modified leaf powder | Methylene blue, methyl orange | Acid solution at pH 3 | - | (Kamaru et al., 2016) |
| $Fe_3O_4$/activated carbon | Enrofloxacin | 3% NaOH | 6 (40% for the final run) [a] | (Zahoor et al., 2019) |

1238 **Note:** [a] data was estimated from figure of the reference.

**Table 8.** Plausible mechanism of adsorption of various pollutants by the pineapple-based adsorbents.

| Adsorbent | Pollutant(s) | Plausible mechanism | Ref. |
|---|---|---|---|
| Chemically oxidized fruit peel | Cd(II), Pb(II) | Electrostatic attraction, chelation | (Ahmad et al., 2016) |
| Leaf powder | Cu(II) | Complexation, electrostatic interaction | (Weng and Wu, 2012) |
| Crown leaf | Cr(III), Cr(VI) | Electrostatic interaction | (Gogoi et al., 2018) |
| Oxalic acid-activated stem, stem powder | Pb(II) | Ion-exchange, electrostatic attraction, monolayer chemisorption | (Vivian Loh Zing et al., 2019) |
| Leaf-derived carbon | Cr(VI) | Covalent bonding, electrostatic attraction | (Ponou et al., 2011) |
| $La(OH)_3$-modified magnetic biochar | $[PO_4]^{3-}$ | Precipitation, electrostatic interaction, ligand exchange and inner-sphere complexation. | (Liao et al., 2018) |
| Leaf biochar at 600 °C | Ni(II), Zn(II), Cu(II) | Cation exchange, surface complexation | (Iamsaard et al., 2022) |
| Leaf powder | Methylene blue | Chemical interaction, electrostatic interaction | (Weng et al., 2009) |

**Declaration of interests**

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

**Author contribution statement**

*Thuan Van Tran: contributed to conceptualization, writing - original draft, investigation, project administration*

*Duyen Thi Cam Nguyen: contributed to conceptualization, investigation, methodology, writing - original draft*

*Thi Thanh Thuy Nguyen: contributed to English editing, preliminary comments, data curation*

*Dai Hai Nguyen: contributed to English editing, validation, review & editing, data curation*

*Mansur Alhassan: contributed to English editing, validation, review & editing, data curation*

*A.A. Jalil: contributed to writing – review and editing, and validation*

*Walid Nabgan: contributed to writing – review and editing, and validation*

*Taeyoon Lee: contributed to English editing, validation, review & editing, supervision*

***All authors read and approved the final manuscript.***