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A Review on Tea Leaves and Tea Fibre as Adsorbents for Heavy Metals Removal

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Abstract
Heavy metal pollution is a significant environmental concern due to its detrimental effects on ecosystems and human health. The conventional techniques for the eliminating heavy metals from water-based solutions, like chemical precipitation and ion exchange, have certain drawbacks in terms of effectiveness, expenses, and ecological impact. In recent years, researchers have explored the use of natural materials, including tea leaves and tea fibre, as alternative adsorbents for heavy metal removal. From research, tea leaves and tea fibre, derived from the camellia sinensis plant, have emerged as promising adsorbent due to their abundance, low cost, and potential for heavy metal adsorption from aqueous phase. This comprehensive review aims to summarize and evaluate the current state of knowledge regarding the use of tea leaves and tea fibre in the removal of heavy metals from aqueous solutions. It will discuss the adsorption mechanisms, influencing factors, and potential applications of these natural materials. The research will also covers a comparative analysis of this adsorbent with other adsorbents, isotherms, kinetics and equilibrium studies, as well as regeneration and reusability of tea-based adsorbents.

Keywords: Adsorption, chemisorption, physisorption, isotherms, kinetics, thermodynamics.

1. Introduction

Tea leaves and tea fibre has been gaining attention as potential adsorbents the removal of heavy metals due to their abundance, availability, low cost and biodegradability. However, this serves as an advantage when compared to other adsorbents. Several studies have investigated the effectiveness of tea leaves and tea fibre in the removal of heavy metals from aqueous solutions, and the results have been promising (Samuel *et al.*, 2023). One study has found that tea leaves were effective in the removal of heavy metals such as lead, cadmium, and copper from aqueous solutions, with removal efficiencies ranging from 70% to 90%. The high removal was attributed to the presence of functional groups such as carboxyl, hydroxyl and phenolic groups in the tea leaves, which can form complexes with the heavy metals ions. Tea leaves and tea fibre possess unique chemical compositions and physical properties that makes them promising candidates for the removal of heavy metals from aqueous solutions (Etim, *et al.*, 2022). By comprehensively reviewing the current state of knowledge on the use of tea leaves and tea fibre in heavy metal removal, this review aims to contribute to the understanding of sustainable and cost-effective methods for addressing heavy metal pollution in aqueous environments. The study explores the utilization of tea leaves and tea fibre as adsorbents for eliminating heavy metals from water-based solutions and also the utilization of these adsorbents, adsorption mechanisms involved, the factors influencing the adsorption process, and the potential applications of these natural materials.

2. Overview of Heavy Metal Pollution

Heavy metals, such as lead, mercury, cadmium, and arsenic, are toxic substances that can enter ecosystems through various sources, including industrial activities, mining, and agricultural practices. These metals have the ability to persist in the environment for long periods, accumulating in soil, water, and air. The consequences of heavy metal pollution are far-reaching. In ecosystems, heavy metals can disrupt the balance of natural processes, leading to reduced biodiversity and impaired ecosystem functioning. They can also contaminate water bodies, making them unsuitable for aquatic life and posing a risk to human populations that rely on these water sources for drinking and irrigation (Onen *et al.*, 2017). Human exposure to heavy metals can occur through various pathways, including inhalation, ingestion, and dermal contact. Once inside the body, heavy metals can cause a range of health problems. They can damage organs such as the liver, kidneys, and central nervous system, leading to chronic diseases and even death. Additionally, heavy metals have been linked to developmental issues in children and can accumulate in the body over time, resulting in long-term health effects. (Etim, *et al.,* 2017). Addressing heavy metal pollution requires comprehensive strategies; including the implementation of strict regulations such as fortify interagency collaboration to reduce avenues for heavy metal exposure and more stringent controls of heavy metals emissions, the development of environmentally friendly industrial practices, and the promotion of sustainable agriculture. Additionally, the use of innovative technologies for heavy metal removal and remediation is crucial in minimizing the adverse effects of heavy metal pollution and safeguarding both the environment and human health. There is a pressing need for the development and implementation of effective and sustainable methods for heavy metal removal. Traditional techniques such as chemical precipitation and ion exchange have limitations in terms of cost, efficiency, and environmental impact (Humphrey *et al.,* 2023). Therefore, alternative approaches that can efficiently and safely remove heavy metals from various sources, including water, soil, and air, are crucial. Sustainability is another key aspect that needs to be considered in heavy metal removal methods. Sustainable approaches should minimize the use of chemicals, energy, and other resources, reducing the overall environmental footprint. Additionally, the generated waste should be properly managed and disposed of to prevent secondary pollution. (Islam, 2018). Innovative technologies, such as adsorption, phytoremediation, and electrochemical methods, offer promising solutions for heavy metal removal. Adsorption using natural materials or modified adsorbents has shown great potential due to its high efficiency and low cost. Phytoremediation, which utilizes plants to extract heavy metals from contaminated soil or water, offers a sustainable and environmentally friendly approach. Electrochemical methods, such as electrocoagulation and electro kinetics, have also demonstrated effectiveness in heavy metal removal (Samuel *et al.,* 2023). To ensure the widespread adoption of these methods, further research and development are needed to optimize their performance, cost-effectiveness, and scalability. Collaboration between scientists, engineers, policymakers, and industry stakeholders is essential to drive innovation and implement sustainable heavy metal removal methods on a larger scale. By addressing the need for effective and sustainable methods, we can mitigate the adverse effects of heavy metal pollution and protect the environment and human health (Wani, *et al.,* 2020).

3. Tea Leaves and Tea Fibre

Camellia sinensis is a species of evergreen shrub or small tree in the flowering plant family Theaceae. Its leaves and leaf buds are used to produce the popular beverage, tea. White tea, yellow tea, green tea, dark tea and black tea are all harvested from one of two major varieties grown today, Camellia sinensis var. sinensis and Camellia sinensis var. assamica, but are processed differently to attain varying levels of oxidation with black tea being the most oxidized and green being the least. (Meegahakumbura, *et al.*, 2018). Camellia sinensis is native to East Asia, the Indian Subcontinent, and Southeast Asia, but it is today cultivated all around the world in tropical and subtropical regions. It is an evergreen shrub or small tree that is usually trimmed to below 2 m (6.6 ft) when cultivated for its leaves. It has a strong taproot. The flowers are yellow-white, 2.5–4 cm (0.98–1.57 inch) in diameter, with seven or eight petals. The seeds of Camellia sinensis and Camellia oleifera can be pressed to yield tea oil, a sweetish seasoning and cooking oil that should not be confused with tea tree oil, an essential oil that is used for medical and cosmetic purposes and originates from the leaves of a different plant. (Wang, *et al.*, 2019). Below is a picture of fresh tea leaves and dried tea fibre.

Figure 1. Tea Leaves (*Camellia sinensis*) plants. Nikon Corporation, Nikon D5200 (2020)

Figure 2. Tea Fibre. Science Photo Library Limited (2023)

3.1. Chemical Composition of Tea Leaves and Tea Fibre

Camellia sinensis is the primary source of tea leaves and tea fibre. The chemical composition of tea leaves can vary depending on factors such as tea variety, growing conditions, and processing methods. (Wang, *et al.*, 2019).

i. Tea leaves contain various bioactive compounds, including polyphenols, catechins, flavonoids, alkaloids, amino acids, and volatile compounds.
ii. Polyphenols, particularly catechins, are one of the major components in tea leaves. Epigallocatechin gallate (EGCG), epicatechin gallate (ECG), epigallocatechin (EGC), and epicatechin (EC) are commonly found catechins in tea. (Wang, *et al.*, 2019).
iii. Tea fibre, also known as tea residue or tea waste, is the byproduct generated during the processing of tea leaves. It contains cellulose, hemicellulose, lignin, and other organic compounds. The chemical composition of tea fibre may vary depending on the

processing methods used to produce different types of tea (e.g., black tea, green tea, oolong tea). (Zhou, *et al.,* 2018).

The presence of functional groups, such as carboxyl and hydroxyl groups, in tea leaves and tea fibre contributes to their potential for heavy metal adsorption. The diagram below show the physical and biological conversion technology of tea leaves waste which is used as adsorbents resulting from the functional groups present in them.

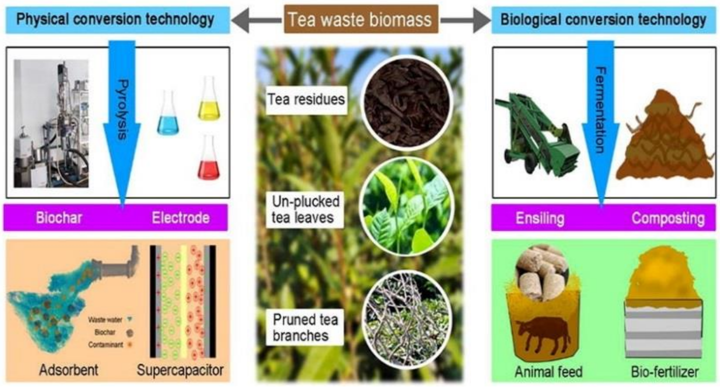

Figure 3. Conversion and application of tea waste biomass. (Shasha, *et al.,* 2021)

In addition to the main compounds above, tea leaf extract contains B vitamins, lipids such as: linoleic and alpha-linolenic acids, and trace minerals, including magnesium, calcium, iron, zinc, and selenium. The minerals with the greater amount in green tea leaves are potassium, calcium, phosphorus, and magnesium. In a lesser amount we have manganese, zinc, copper and iron. (Ricardo and Cacedo. 2018).

3.2 Physical and Structural Properties Relevant to Heavy Metal Adsorption

i. Surface area and Pore size distribution: Materials with a higher surface area have more sites available for heavy metal adsorption. This can be achieved through physical or chemical modifications, such as increasing the porosity or creating new functional groups on the surface. The size of the pores in a material can affect the adsorption capacity for different heavy metals. Materials with a range of pore sizes can be more effective for adsorption of a variety of heavy metal species.

ii. Surface charge: The surface charge of a material can affect the attraction or repulsion of heavy metal ions. Materials with a high surface charge can attract heavy metal ions with opposite charges, while materials with a low surface charge may be more effective for heavy metal ions with similar charges (Gavrilescu, 2004).

iii. Functional groups: Materials with functional groups, such as carboxyl, hydroxyl, or amino groups, can form complexation bonds with heavy metal ions, increasing the adsorption capacity. For the tea leaves and tea fibre research has confirmed that the contain –OH, -OR functional groups.

iv. Chemical composition: The chemical composition of a material can affect its adsorption properties, as some elements or compounds may compete with heavy metal ions for adsorption sites. Materials with a low concentration of interfering elements may be more effective for heavy metal adsorption. (Gavrilescu, 2004).

4. Adsorption Mechanism

Several methods and techniques have been employed for the removal of heavy metal ions from aqueous wastes include; ion exchange, membrane technologies, chemical precipitation, adsorption on activated carbon, electrochemical treatment, reverse osmosis, ultrafiltration, electrodialysis, phytoremediation etc. The specific mechanisms involved depend on the various factors, including the properties of the adsorbent material and the nature of the pollutants being removed. Surface complexation: This refers to the formation of complexes between the adsorbent surface and the adsorbate molecules. This mechanism typically involves chemical reactions, such as coordination or electrostatic interactions, between functional groups on the adsorbent surface and the adsorbate species (Andrew *et al.,* 2020).

i. Ion exchange: Involves the exchange of ions between the adsorbent surface and the solution. In this mechanism, ions in the solution are attracted to the charged sites on the adsorbent surface and replace ions that are already present. This process can be selective, depending on the relative affinities of the ions involved.
ii. Precipitation: This occurs when the adsorbate species undergo a chemical reaction on the adsorbent surface, leading to the formation of solid precipitates. This mechanism is typically observed when the adsorbate species react with certain functional groups or compounds present on the adsorbent surface.
iii. Electrostatic attraction is a significant mechanism in adsorption processes, involving an attractive force between charged particles. In the context of adsorption, this attraction can occur between the charged functional groups on the surface of the adsorbent material and the charged species in the solution. Oppositely charged ions or molecules are drawn to each other, resulting in their adsorption onto the surface. This mechanism holds particular relevance when addressing charged pollutants or adsorbent materials. (Islam, 2018).

Physical Adsorption, also known as physisorption, is a mechanism of adsorption where weak van der Waals forces or London dispersion forces are involved. It occurs when the adsorbate molecules are attracted to the surface of the adsorbent material through relatively weak intermolecular forces. Physisorption is typically reversible and can occur at any temperature. Chemical Adsorption, also known as chemisorption, is a mechanism of adsorption where chemical bonds are formed between the adsorbate molecules and the adsorbent surface. It involves stronger interactions, such as covalent or ionic bonding, between the adsorbate and the adsorbent. Chemisorption is often more specific and selective than physisorption and is typically irreversible. It usually requires higher temperatures or specific activation energies for the chemical reactions to occur. The distinction between physisorption and chemisorption is based on the strength of the interactions involved and the nature of the bonding between the adsorbate and adsorbent. Physisorption is generally weaker and involves non-specific interactions, while chemisorption involves stronger and more specific chemical bonding. Understanding the mechanisms of physisorption and chemisorption is crucial for designing adsorbent materials and optimizing adsorption processes for various applications, such as pollution control, gas separation, and catalysis.

5. Factors Influencing Heavy Metal Adsorption

- pH: The pH of the solution plays a significant role as it affects the chemical speciation and solubility of metals, as well as the overall charge of the biosorbent. At low pH (acidic pH), the hydroxonium ions are closely associated with the active ligands of the biosorbent and therefore, there exists a competition between the protons and metal ions for the binding sites (Feng, *et al.,* 2011). At higher pH, there exists lower number of H^+ ions, and the number of active sites of the functional groups is free and exposed (negative charge) which results in increased biosorption by attracting positive charged metal ions. At higher pH, the metal might begin to precipitate and form hydroxides and as a consequence hinder the biosorption process. (Joo and Hassan, 2010). Also, different heavy metals have different adsorption behaviors at different pH levels. For example, metals like lead and copper tend to have higher adsorption capacities at lower pH values, while metals like cadmium and zinc have higher adsorption capacities at higher pH values (Etim *et al.,* 2020).

- Concentration of heavy metals: The initial concentration of heavy metals in the solution can affect the adsorption process. Generally, higher initial concentrations of heavy metals lead to higher adsorption capacities until the saturation point is reached. (Ayawei, *et al.,* 2007). This is because, at higher concentrations, the number of metal ions remaining unbound in the solution is high due to the saturation of available binding sites. The higher biosorption efficiency at low metal concentration is due to the complete interaction of ions with the available binding which sites results in higher rates of efficiency.
- Contact time: The duration of contact between the material and the heavy metal solution can impact the adsorption process. Initially, the adsorption rate is usually high, and it gradually decreases until equilibrium is reached. The contact time required for equilibrium depends on factors such as the material's surface area and the concentration of heavy metals. (Ho and McKay, 2003).
- Temperature: Temperature can influence the adsorption capacity and rate of heavy metals onto materials. Generally, higher temperatures increase the adsorption rate, but the adsorption capacity can be influenced by the specific material and heavy metal. (Ayawei, *et al.,* 2007). Optimum temperature for efficient biosorption has to be chosen for the maximum binding of metal ions, because high temperature may results to structural damage of the biosorbents.
- Presence of competing ions: The presence of other ions in the solution can compete with heavy metals for adsorption sites on the material. Some ions may have a higher affinity for the material, leading to reduced adsorption of heavy metals. (Tchounwou, *et al.,* 2012).

These factors can differ based on the specific material and heavy metal under investigation. Therefore, it is crucial to take these factors into account when designing and optimizing adsorption processes for the removal of heavy metals from aqueous phase.

6. Kinetics, Isotherms and Thermodynamic studies on Adsorption

6.1. Adsorption Kinetic

Adsorption kinetics describes the rate of retention or release of adsorbate from aqueous solution to solid-phase interface. In adsorption, linear or non-linear analysis of the kinetics is applied. The goodness of fit index is applied to determine the model that best describe the process (Musah, *et al.,* 2018). Kinetics of adsorption onto the surface of activated carbon can be ascertained by the following models:

- Pseudo First Order (Largergren Model)

The model considers the rate of change that occurs in the uptake of adsorbate at a particular reaction time to be directly proportional to the difference in the concentration and rate at which the adsorbate is removed with time. The model also known as Largergren model is represented by the equation below. (Vesna and Kristic 2021).

$$\frac{dqt}{dt} = K1\ (Qe - Qt)$$

Where:

qe is the adsorption capacity of the adsorbent at equilibrium (mg.g-1), qt is the adsorption capacity of the adsorbent at time t (mg.g-^{1}), Kt is the rate constant for pseudo first order adsorption ($^{-1}$). After the above equation is integrated and boundary conditions are applied, t = 0 to t = t and qt = 0 to qt = qe, the integrated form of the above equation becomes:

$$log\ (qe - qt) = \ log\ qe - \frac{k1}{2.303} t$$

Where

q_e = the amount of metal uptake, q_t = amount adsorbed at any instant of time, k_1 = first order constant, t = temperature. If the first order is applicable, a plot of (q_e-q_t) versus t should provide a linear relationship. The constant k_1 and predicted q_e respectively can be determined from the slope and intercept of the plot.

- Second-Order and Pseudo–Second-Order Kinetic Model

The pseudo–second-order kinetic model is based on the assumption that the rate-limiting step is chemical sorption or chemisorption and predicts the behavior over the whole range of adsorption. In this condition, the adsorption rate is dependent on adsorption capacity not on concentration of adsorbate. (Vesna and Kristic 2021). One major advantage of this model over Lagergren first order is that the equilibrium adsorption capacity can be calculated from the model; therefore, there is theoretically no need to evaluate adsorption equilibrium capacity from experiment. The differential equation for the pseudo–second-order kinetics is given by

$$\frac{\boldsymbol{dqt}}{\boldsymbol{dt}} = k2\ (qe - qt)^2$$

After mathematical development, and taking into account the boundary conditions, the pseudo–second-order kinetic model is finally expressed as follows:

$$\frac{t}{qt} = t\frac{1}{k2q2t} + \frac{t}{qe}$$

The plot of $\frac{t}{qe}$ against t will a straight line graph whose slope is equal to the rate constant $k_{2.}$ (Vesna and Kristic 2021).

6.2. Adsorption Isotherms

The process of adsorption is usually studied using graphs known as adsorption isotherms. Adsorption isotherm is a graph that shows the relationship between the amount of the adsorbates on an adsorbent as a function of its pressure (if gas) or concentration at constant temperature. Or a graph that represents the variation in the amount of adsorbate(x) adsorbed on the surface of the adsorbent with the change in pressure at a constant temperature.

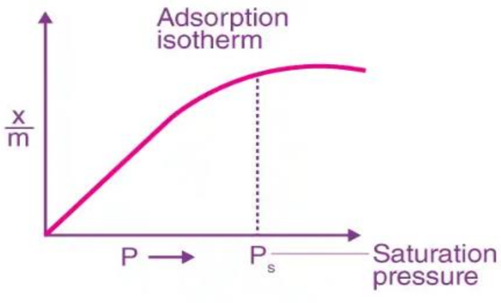

Figure 4. Graphical representation of adsorption isotherm

From the graph, we observe that after attaining a pressure Ps, that is the saturation pressure, the variation in the amount of adsorbent adhering to the adsorbate becomes zero. This happens because the surface area available for adsorption is limited and as all the sites are occupied, a further increase in pressure does not cause any difference. (Mahdieh, *et al.*, 2010; 2020). Different adsorption isotherms have been proposed by different scientists namely, Freundlich isotherm and Langmuir isotherm

6.2.1. Freundlich Adsorption Isotherm

Freundlich in 1909 gave an empirical relationship between the quantities of gas adsorbed by a unit mass of solid adsorbent with the change in pressure of the system for a given temperature. The expression for the Freundlich isotherm can be represented by the following equation:

$$\frac{x}{m} = kP\frac{1}{n}$$

Where n>1

Where x is the mass of substance adsorbed, m is the mass of the adsorbent, P is the pressure and n are constants which depend upon the nature of the adsorbent and the substance at a given temperature. Taking the logarithm on both the sides of the equation, we get,

$$log\frac{x}{m} = logk + \frac{1}{n}logP$$

The plot of the above equation is usually a straight line as shown below.

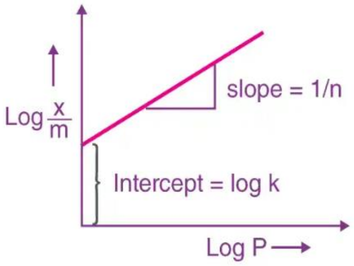

Figure 5. Graphical representation of Freundlich Adsorption Isotherm

From the equation,

$$log\,qe = logKf + \frac{1}{n} + log\,Ce$$

Where K_F is Freundlich isotherm constant (mg/g or dm^3/g) associated with adsorbent adsorption capacity and n is the adsorption intensity related to the heterogeneity of the adsorbent surface. A plot of logq_e against logC_e gives a straight-line of slope $\frac{1}{n}$ and an intercept equal to logK_F. Favorable adsorption is typically indicated by a Freundlich constant (n) of between 1 and 10. n = 1 points towards a linear adsorption process with uniform (constant) energy across the entire adsorbent surface such that the binding strength is increased as more adsorbate binds. (Mahdieh, *et al.,* 2010; 2020).

6.2.2. Langmuir Adsorption Isotherms

In 1916, Iiring Langmuir derived an isotherm from the kinetic mechanism. The isotherm assumed that an adsorbate behaves as an ideal gas and that dynamic equilibrium exceed between the adsorbed and free gaseous molecules. The adsorption isotherm predicts linear adsorption at low adsorption densities and a maximum surface coverage at higher solute metal concentrations. The Langmuir adsorption isotherm has the form:

$$\theta = \frac{Kp}{1 + Kp}$$

Where

θ is the fraction of the surface covered by the adsorbed molecule, K is an equilibrium constant known as the adsorption coefficient, {K= $\frac{Ka}{Kd}$ = rate constant for adsorption/ rate constant for desorption}, p is the pressure.

The linear form of the Langmuir isotherm model is expressed as

$$\frac{Ce}{Qe} = \frac{1}{bQo} + \frac{Ce}{Qo}$$

Where C_e is the equilibrium concentration (mg/L), q_e is the amount of adsorbate adsorbed on the adsorbent at equilibrium, b is the Langmuir isotherm constant (L/mg) and Q_o is the maximum monolayer coverage capacity (mg/g) i.e. adsorption capacity of the adsorbent. A straight-line plot of $\frac{Ce}{qe}$ against C_e gives a slope of $\frac{1}{Qo}$ and an intercept equal to $\frac{1}{bQo}$. The constant b corresponds to attraction of the adsorbate for the adsorbent and relates a dimensionless constant called separation factor (R_L) expressed as:

$$R_L = \frac{1}{1+bCo}$$

Where C_o is the initial concentration of adsorbate (mg/L). The R_L value is an indication of the nature of adsorption as either unfavorable (R_L >1), linear (R_L =1), favorable (0<R_L <1) or irreversible (R_L =0). (Mahdieh, *et al.,* 2010; 2020). The Langmuir adsorption is applicable for monolayer adsorption onto a homogeneous surface when no interaction occurs between adsorbed species.

6.3. Thermodynamics of Adsorption

The nature of an adsorption process is confirmed by the evaluation of its thermodynamic parameters. Thermodynamic parameters like free energy change (ΔG_{ads}), enthalpy change (ΔH_{ads}) and entropy change (ΔS_{ads}) of adsorption are calculated to evaluate the feasibility and spontaneity of the process. (Şeker, *et al.,* 2008).

The standard free energy change of adsorption:

$$\Delta G^{\circ} = -2.303RTlogK$$

Is then expressed as:

$$\Delta G^{\circ} = -2.303RTlog(bQo)$$

Where R is the gas constant and T is the thermodynamic temperature. Negative values of ΔG^o_{ads} are usually characteristic of spontaneity of the adsorption process. Generally, values of ΔG^{o}_{ads} up to −20 kJmol.$^{-1}$ are consistent with the electrostatic interaction between the charged adsorbate species and the adsorbent surface (physisorption) while ΔG^{o} values around −40 kJmol.$^{-1}$ or less are associated with chemisorption as a result of sharing or transfer of electrons ton form a coordinate type of bond. (Şeker, *et al.,* 2008). The Van't Hoff expression:

$$log(k) = \frac{1}{2.303}\times\frac{\Delta S^{\circ}}{R}+\frac{\Delta H^{\circ}}{RT}$$

It is commonly used to evaluate the standard enthalpy (ΔH^{o}) and standard entropy change (ΔS^{o}) of the adsorption process. From the linear regression equation of the Van't-Hoff plot of log (K_{ads}) versus $\frac{1}{T}$, values of ΔH^{o} and ΔS^{o} are obtained from the slope and the intercept respectively. For a meaningful adsorption to occur, the free energy change on adsorption (ΔG) must be negative.

Since $\Delta G=\Delta H-T\Delta S$

The condition of meaningful adsorption requires that ΔH be negative (i.e. exothermic adsorption). This is generally true for adsorption from liquid phase also, though exceptions are possible (Akhatar, *et al.,* 2007).

7. Regeneration and Reusability

7.1. Desorption and Regeneration of Tea-Based Adsorbents

After tea-based adsorbents have been used for heavy metal removal, they may need to be regenerated to restore their adsorption capacity. Here are some common methods for desorption and regeneration of tea-based adsorbents: (Li, *et al.,* 2014) and (Gao, *et al.,* 2017).

- Acid and alkaline desorption: Tea-based adsorbents can be desorbed using an acid solution, such as hydrochloric acid or sulfuric acid. The acid solution can break the bond between the heavy metal ions and the adsorbent, releasing the metal ions into the solution. The adsorbent can then be washed and rinsed to remove any remaining acid before reuse. Alkaline solutions, such as sodium hydroxide or potassium hydroxide, can also be used to desorb heavy metal ions from tea-based adsorbents. The alkaline solution can change the pH of the solution, causing the metal ions to detach from the adsorbent. The adsorbent can then be washed and rinsed before reuse.
- Chelating agents: Chelating agents, such as ethylenediaminetetraacetic acid (EDTA) or citric acid, can be used to desorb heavy metal ions from tea-based adsorbents. Chelating agents can form complexes with the metal ions, breaking the bond between the metal ions and the adsorbent. The adsorbent can then be washed and rinsed before reuse.
- Thermal regeneration: Thermal regeneration involves heating the adsorbent to a high temperature, typically between 200-500°C, to remove the adsorbed heavy metal ions. The high temperature can cause the metal ions to vaporize or decompose, leaving behind a regenerated adsorbent. This method is typically used for activated carbon adsorbents, but it can also be applied to tea-based adsorbents. (Gao, *et al.,* 2017).

7.2 Assessment of Reusability and Stability of Tea Leaves and Tea Fibre

- Reusability assessment: The reusability of tea leaves and tea fiber as adsorbents can be evaluated by conducting multiple adsorptions-desorption cycles. After each cycle, the adsorbent can be regenerated using appropriate desorption methods (as mentioned earlier) and then tested again for its adsorption capacity. The number of cycles that the adsorbent can undergo while maintaining a satisfactory adsorption capacity can be used as an indicator of its reusability.

- Stability assessment: The stability of tea leaves and tea fiber as adsorbents can be assessed by evaluating their physical and chemical properties before and after adsorption cycles. Techniques such as scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and X-ray diffraction (XRD) can be used to analyze any changes in the adsorbent's morphology, functional groups, and crystalline structure. A stable adsorbent should exhibit minimal changes in these properties after repeated use. (Li, *et al.,* 2014).

8. Potential Applications of Tea Leaves and Tea Fibre in Wastewater Treatment

Tea leaves and tea fiber have shown potential for various applications in wastewater treatment due to their adsorption properties and availability. (Chen, *et al.,* 2011). Some potential applications include:

- Heavy metal removal: Tea-based adsorbents have been studied for their effectiveness in removing heavy metals from wastewater. Heavy metals, such as lead, chromium, cadmium, and copper, can be adsorbed onto the surface of tea leaves or tea fiber, effectively reducing their concentration in the wastewater. As shown in the diagram below, the removal of Cr^{2+}.
- Dye and Organic pollutant removal: Tea leaves and tea fiber has also been investigated for their ability to remove dyes from wastewater. The adsorbent can interact with the dye molecules through electrostatic interactions, hydrogen bonding, or other mechanisms, resulting in the removal of the dye from the wastewater. Tea-based adsorbents have shown potential for removing organic pollutants, such as phenols, pesticides, and pharmaceuticals, from wastewater. The adsorbent can absorb the organic molecules onto its surface, effectively reducing their concentration in the wastewater.
- Nutrient recovery: Tea leaves and tea fiber can also be used for nutrient recovery from wastewater. The adsorbents can selectively adsorb nutrients, such as phosphorus and nitrogen, from the wastewater, allowing for their subsequent recovery and reuse in agricultural or other applications. (Chen, *et al.,* 2011).

9. Future Prospects of Tea Leaves and Tea Fibre

- Optimization of modification techniques: Further research is needed to optimize the modification techniques used for tea-based adsorbents. This includes determining the optimal conditions for chemical or physical modifications to enhance their adsorption properties without compromising their stability or reusability.
- Environmental impact assessment: It is important to evaluate the environmental impact of tea-based adsorbents, including any potential leaching of adsorbent components or the fate of the adsorbed pollutants. Environmental assessments can help ensure that the use of tea-based adsorbents does not introduce any unintended environmental consequences (Etim et al., 2018).
- Combination with other treatment technologies: Tea-based adsorbents can be used in combination with other treatment technologies, such as membrane filtration or advanced oxidation processes, to enhance overall wastewater treatment efficiency.

Further research is needed to explore the synergistic effects of integrating tea-based adsorbents with other treatment methods (Samuel *et al.*, 2023).

- Novel modification techniques: Exploring novel modification techniques, such as the use of green chemistry principles or innovative surface engineering approaches, can further enhance the adsorption properties and performance of tea-based adsorbents.

Conclusion

Tea leaves and tea fibre have been found to be effective adsorbents for the removal of heavy metals from water. The high content of polyphenols and other organic compounds in tea leaves and fibre make them effective in binding heavy metals such as lead, cadmium, and copper. The adsorption process involves the binding of heavy metals to the surface of the tea leaves or fibre, thereby removing them from the water. This method is cost-effective, environmentally friendly, and has the potential for large-scale applications in water treatment. Additionally, the spent tea leaves and fibre can be easily disposed of or reused for other purposes. The use of tea leaves and tea fibre as adsorbents for heavy metals removal shows promise as a sustainable and efficient solution for water purification, and also potential for various applications in wastewater treatment due to their adsorption properties and availability. The adsorption process can be verified using adsorption Isotherms, Kinetic models and thermodynamic which confirms the feasibility and spontaneous nature of the adsorption process. Nevertheless, there are some challenges and future prospects toward the use of these adsorbent in waste water treatments which include: optimization of modification techniques, understanding adsorption mechanisms, scale-up and practical applications, environmental impact assessment, combination with other treatment technologies.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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