Advances in the Removal of Oestrogenic Compounds from Wastewater Using Carbonaceous Adsorbents: A Review

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***Abstract* - Oestrogenic pollutants have been detected in water bodies, raising serious concerns due to their endocrine-disrupting effects, which interfere with the normal metabolic functions of both humans and aquatic life. Conventional wastewater treatment technologies, such as biological wastewater treatment processes, are not designed to remove oestrogenic contaminants from water bodies. Conversely, the adsorption technique has gained attention as an effective and sustainable alternative due to its simple operation, high efficiency, and demonstrated ability to remove oestrogenic pollutants without producing harmful toxins. The carbonaceous adsorbents have shown high efficiencies in oestrogenic pollutants removal, but the quest for environmentally green and economically feasible adsorbents is still not yet over. This paper reviews research published between 2015 and 2025, highlighting key trends of carbonaceous adsorbents, such as chitosan, for the sorption of oestrogenic compounds in aqueous environments. The search engines that were adopted include Web of Science ® and PubMed ® to compare publications on adsorption technology and the application of chitosan-based adsorbent. Chitosan is a promising adsorbent as a low-cost feedstock for developing novel applications, as it has easy processing steps, and requires low energy consumption. Furthermore, this work reviews the influence of key operating parameters, such as pH, initial concentration of the adsorbate, and adsorbent dose, on the uptake mechanisms of model contaminants. The results revealed that carbonaceous adsorbents are effective in removing oestrogenic compounds, primarily due to the presence of functional groups and surface properties. Prospects towards the development of cost-effective hybrid adsorbents with tailored functionalities capable of simultaneously removing a wide range of endocrine-disrupting chemicals.**

***Keywords* — Adsorption, Carbonaceous-adsorbents, Endocrine disruptors, Oestrogenic-pollutants**

I. INTRODUCTION

Oestrogenic pollutants have been detected in water systems, raising serious concerns due to their endocrine-disrupting effects, which harm both humans and aquatic life. They are categorized as emerging contaminants of environmental concern, and they are widely recognised as the third most significant global environmental issue after ozone layer depletion and global warming [1]. Other authors have reported that in the whole world, there are over 200 endocrine-disrupting chemicals detected in surface water, precisely in rivers, usually in concentrations ranging from nanograms to micrograms per litre [2]. Most of the oestrogen that is defecated into the water bodies is from humans, animals, and improper disposal methods, such as hospital discharge. These are the main contributing sources of the increase in oestrogen levels found in surface water and sediments, which pose a threat to the environment [2], [3], [4]. For many years, these quantities have either been overlooked, complicated to quantify, or impossible to measure utilizing existing analytical techniques [5]. Therefore, this growing challenge emphasizes the urgent need for developing novel and effective water treatment technology capable of addressing oestrogen contaminants in water systems. Technologies like oxidation ditches, filters, anaerobic, anoxic, and oxic systems are not designed to eliminate micropollutants present in wastewater [6]. However, treatment technologies such as reverse osmosis, ultrafiltration, nanofiltration, ozonation, and photolysis are highly successful in eradicating micropollutants; their implementation is often constrained by the high installation and operational costs, particularly in developing countries such as Sub-Saharan African countries [7]. In contrast, the adsorption technique has gained attention as an effective and sustainable alternative due to its straightforward operation, high efficiency, and ability to remove oestrogenic pollutants without producing harmful byproducts [8]. Although the adsorption technology may be effective, it largely depends on the selection of the specific carbonaceous adsorbents, such as chitosan, biochar, and activated carbon, to effectively eradicate oestrogenic hormones from water bodies. European nations have enacted laws and regulations to protect the aquatic environment; however, the Sub-Saharan Africa region lacks strong legislative measures and regulations regarding the limitations of oestrogen waste in water bodies [7]. It is worth noting that risk assessment is necessary as an instrument for managing environmental impacts and preventing future pollution.

Carbonaceous adsorbents have been applied to a wide range of sustainable water and wastewater treatments because of their exceptional physical structure, homogeneous pore size distribution, high specific surface area, and strong interaction with different pollutants, which has drawn some attention for environmental remediation [9]. Carbon-based adsorbent have been demonstrated to be effective adsorbents with a remarkable adsorption capacity and significant market value. Furthermore, they have advantages such as the ability to alter pore structure

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and surface properties through preparation method, coupled with their cost-effectiveness due to the availability of resources such as coal and biomass [10].

Despite the growing body of literature on carbonaceous adsorbents for oestrogen removal, a comprehensive synthesis of recent findings is lacking. This paper aims to comprehensively review recent advancements in using chitosan-based adsorbents for the removal of oestrogenic compounds from wastewater, with a focus on understanding their adsorption efficiency, underlying mechanisms, and key operating parameters that influence performance. Furthermore, the analysis will extend to assess the environmental and operational feasibility of these materials in real-world applications, identifying emerging trends and research gaps for future investigation.

II. METHODOLOGY

Web of Science and PubMed database tools were applied to carry out the search trend related to adsorption and removal of oestrogenic pollutants from wastewater, with an emphasis on the adsorption process. The literature search was performed with the keywords: ("Adsorption" OR "wastewater treatment" AND "Removal efficiency") and ("Chitosan-based adsorbent" OR "Oestrogenic pollutants") in a span of 10 years (2015-2025), and only experimental articles were selected.
The publication counts were generated, then extracted and plotted in Microsoft Excel. Data retrieved from Web of Science (430360 and 504) and PubMed (120050 and 43) as shown in Fig. 1 and 2.

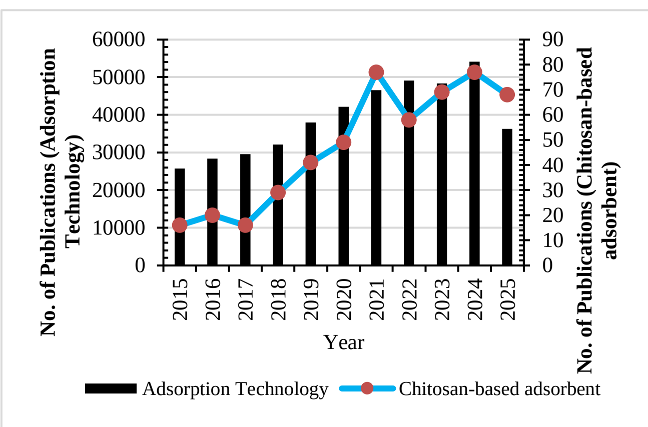

Fig. 1. Web of Science survey data publication for adsorption, wastewater, and removal efficiency.

The bibliometric analysis reflects a significant gap between broad research output on adsorption technology and relatively studies on the application of chitosan for eradicating emerging contaminants from water and wastewater. Data extracted from Web of Science and PubMed demonstrates that while adsorption remains a widely researched topic, the specific focus on chitosan as an adsorbent for emerging contaminants such as oestrogenic compounds is still less explored. The gap is critical considering that oestrogenic compounds such as estrone (E1), estradiol (E2), estriol (E3), and ethinylestradiol (EE2) are increasingly recognized and detected in the aquatic environments [11]. These pollutants pose ecological risks and potential human health concerns due to their interference with the endocrine system. Although the current publication trend shows a gradual increase in the number of studies utilizing chitosan, relatively low volume emphasizes the need for intensified research efforts in this direction.

Furthermore, disciplinary analysis in Fig. 3 indicates that publications are concentrated in a few leading fields, namely Chemical Engineering, Chemistry Physical, Materials Science Multidisciplinary, and Environmental Sciences. While these disciplines drive significant progress in adsorption technology research, it remains necessary to broaden interdisciplinary collaboration, especially in the chitosan application for oestrogenic removal. Expanding this research domain would not only advance adsorption technology but also provide practical and environmentally friendly solutions for reducing water contamination from oestrogenic residue.

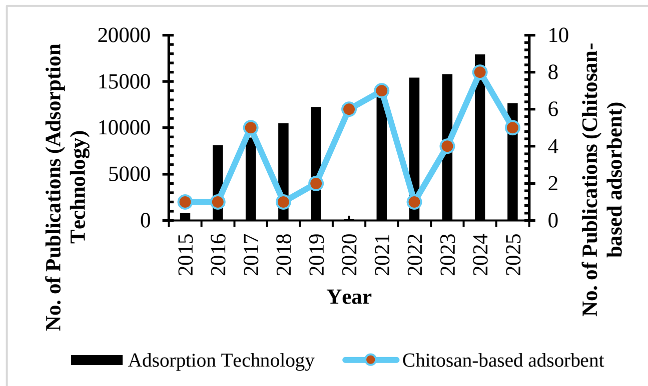

Fig. 2. PubMed survey data publications for chitosan-based adsorbent and oestrogenic pollutants.

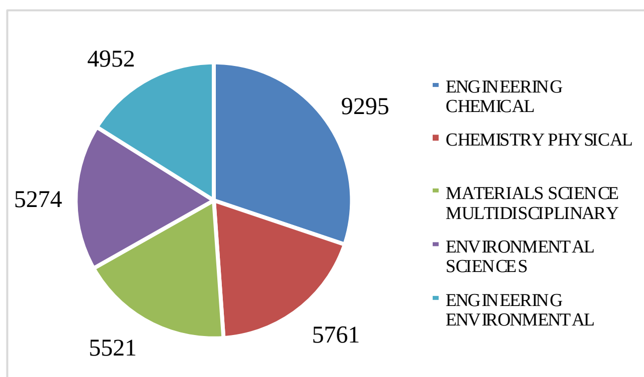

Fig. 3 Web of Science survey data publication in various leading disciplines for the application of chitosan-based adsorbent.

III. THE OCCURRENCE OF OESTROGENIC COMPOUNDS IN URBAN WASTEWATER

Oestrogen is a cluster of natural occurrences and synthetic hormones that play an important role in the endocrine system, regulating the reproductive process in humans, animals, and plants [5]. In contemporary times, rising attention was directed towards the presence of oestrogenic compounds such as E1, E2, E3, and EE2 in urban wastewater, which originated in the feces and urine of humans and livestock [14]. When discharged into urban sewage, such as municipal wastewater, these pollutants can persist through the traditional treatment process and the aquatic environment, as reported in Table I. The contributing factors to the occurrence of oestrogenic compounds in urban wastewater can be ascribed to unregulated disposal of hospital waste, untreated industrial effluents from producing companies, and wastewater treatment plants (WWTPs) effluent streams[4], [16]. In addition, oestrogen concentration excreted by humans also plays a role, with reported concentrations of approximately 1.5 µg/day in men, 4.71 µg/day in women, and in pregnant women, it can go up to 347 µg/day of natural hormone [17]. Furthermore, synthetic oestrogen such as ethinylestradiol, excretion is estimated to be 8 µg/day/person due to prescribed medication such as oral contraceptive pills, which then further contributes to the increase of oestrogenic pollutants in urban wastewater [18], [19]. Table I shows the traces of oestrogenic pollutants detected in wastewater streams in different countries, and these pollutants are classified as endocrine-disrupting chemicals, which can reach levels as high as 15 µg/L in drinking water, which is sufficient to mimic the standard hormonal systems [20]. The concentrations are projected to increase further due to the extensive use of oestrogen hormones in humans, animals, and agricultural applications. This growing presence highlights the urgent need for effective monitoring, regulatory measures, and removal strategies to preserve the aquatic ecosystem and safeguard public health.

TABLE I: THE COMPOSITION OF OESTROGENIC COMPOUNDS IN URBAN WASTEWATER

E1 (ng/L)	**E2** (ng/L)	**E3** (ng/L)	**EE2** (ng/L)	**Country**	**Ref.**
62.9	17.9 - 62.9	62.6	-	China	[12]
41 -95	45 – 78	680 -1020	199 – 600	North Africa	[13]
123.6 +/- 77.8	0.6 +/- 0.3	0.2 +/- 0.1	11.6 +/- 1.3	South Africa	[14]
8.69	2.03	20.56	5.54	Australia	[15]

IV. CHITOSAN

Chitosan is a widely utilized biopolymer derived from the deacetylation of chitin, primarily sourced from crustaceans such as shrimps [21]. Globally recognized as a promising adsorbent, it offers numerous advantages, including cost-effectiveness, environmental sustainability, high abundance, excellent adsorption capacity, non-toxicity, and the presence of hydroxyl and amino functional groups [22]. The existence of hydroxyl (-OH) and amino (-NH_2) functional groups in the chitosan structure, as depicted in Fig. 4, makes it exceptional for accessibility to reagents and soluble compared to chitin. While most aqueous acids are capable of dissolving chitosan, chitin is insoluble in most acid solvents. The protonation of amino groups along a chain generates numerous cationic sites, which elevates their polarity and thereby improves their solubility. This distinctive characteristic broadens the potential applications of chitosan, particularly its capacity to adsorb a variety of pollutants [23]. The functional groups and chemical properties of chitosan depend on the source of raw material and the preparation technique [24]. However, there are a few challenges related to chitosan application, such as low solubility in a basic environment, and other challenges are related to its source, such as molecular structure with differences in their composition, size, and monomer distribution [25]. Therefore, cross-linking is normally applied to enhance the chemical and mechanical stabilities of chitosan, which often leads to decreased adsorption capacity for pollutant removal, and the adsorption performance of cross-linked chitosan can be improved by modifications such as grafting, hybrid adsorbents, and combinations of these approaches [26]. Available literature suggests that some different modifications have been studied to upgrade the physicochemical properties of chitosan, and modified chitosan is found to be more effective in removing antibiotics, hormones, metals, pesticides, and microplastics from wastewater [27]. The growing recognition of chitosan-based adsorbents is due to good properties such as biodegradability, non-toxicity, and hydrophilicity, which collectively make chitosan an environmentally friendly adsorbent [28].

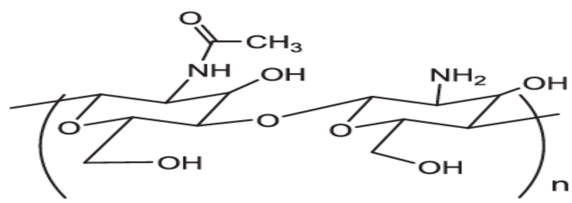

Fig. 4. Chemical structure of Chitosan [26].

V. ADSORPTION

Among other water treatment technologies, adsorption using carbon-based adsorbent has emerged as one of the most efficient and affordable. Carbon-based adsorbents are widely used because of their high surface area, porosity, and carboxyl group that facilitates strong interactions with oestrogenic compounds [22]. The uptake mechanism of oestrogenic compounds by carbon-based adsorbents normally involves a combination of physisorption, such as hydrogen bonds, and chemisorption, such as covalent bonds, as shown in Table II [29]. Ref. [30] reported that hydrogen bonds are stronger than van der Waals forces which plays crucial role in adsorption of oestrogenic compounds, as each molecule's hydroxyl group (-OH) can act as proton donor, while the presence of a nucleophilic carbonyl group (-C=O) allows it to behave as both a donor and acceptor which results to the increase in the removal efficiency. Furthermore, the adsorption behavior of oestrogenic compounds is also examined by utilizing kinetics models such as pseudo-first order (PFO) and pseudo-second order (PSO). The PFO model assumes that the adsorption rate is proportional to the number of available sites, making it suitable for characterizing physical adsorption processes governed by relatively weak forces like van der Waals interactions [23]. On the other hand, the PSO model implies that the rate is dependent on the square of the available sites, which is typically indicative of chemical adsorption involving stronger interactions, such as electron sharing [24]. It is worth noticing that developing cost-

TABLE II: ADSORPTION CAPACITY, MECHANISM, KINETICS, AND ISOTHERMS.

Adsorbent	Adsorbate	Capacity (mg/g)	Mechanism	Best fit kinetics	Best fit isotherm	Reference
Mesoporous carbons	EE2	157	Physisorption	PSO	Freundlich	[31]
Yeast biomass	E1	0.93	Electrostatic interactions	PSO	Freundlich	[32]
Carbon nanotube derived from mining tailings	EE2	21.60	π-π interaction	PSO	Freundlich	[33]
Lotus seedpod BC	E2	147.12	Chemisorption, Electrostatics, and π-π interaction	PSO	Langmuir	[34]
Plastic-char	EE2	82.30	Covalent and π-π interaction	PSO	Freundlich	[35]
Rice straw–derived biochar	E2	26.91	Electrostatic attraction and π-π interaction	PSO	Freundlich	[8]
Carbonized montmorillonite	E2	139.0	H-Bonding, pore-filling, and π-π interaction	R-NOKM	Freundlich	[36]

effective and environmentally friendly methods to eliminate diverse and persistent emerging contaminants from water bodies remain a great challenge. Chitosan is promising as the adsorbent due to its abundance, inexpensive, proven effectiveness in other pharmaceuticals removal, and ability to be regenerated for reuse [37].

VI. EFFECT OF OPERATING PARAMETERS

A. *Solution pH*

The pH of the solution plays a vital role as it influences both the surface charge of the adsorbent and the ionization state of oestrogenic pollutants, which in turn affects the nature and strength of interactions [27]. Carbon-based adsorbents such as chitosan and its derivatives contain functional groups like (-COOH, -OH, -C=O), whose protonation and deprotonation are sensitive to pH changes. Similarly, emerging contaminants such as oestrogenic hormones have functional groups with specific pKa values, causing their ionization to vary across the pH range. Therefore, solution pH determines whether adsorption occurs through electrostatic attraction, hydrogen bonding, or pore filling. Additionally, when pH values are below the point of zero charge (pH_{PZC}) of the carbonaceous adsorbent, the surface is positively charged, which enhances the uptake of partially deprotonated pollutants. Conversely, when the pH exceeds the pHpzc, the surface becomes negatively charged, promoting cationic adsorption but inhibiting anionic uptake due to repulsion. This explains why optimal adsorption usually occurs within an intermediate pH range of 4 to 10 rather than under strongly acidic or alkaline conditions [24].

B. *Adsorbate concentration*

Adsorbate concentration is a crucial factor that has an impact on the adsorption performance of carbonaceous adsorbents in the eradication of emerging contaminants. It is ideal to note that at lower concentrations, high adsorption efficiency is obtained because of the availability of active sites on the adsorbent's surface, enhancing greater interaction between adsorbate molecules and functional groups [24]. The mass transfer from the solution is supported by the availability of the active site in the carbonaceous adsorbent. Therefore, as the adsorbate concentration increases, the available active site becomes saturated [24]. Once super-saturation is achieved, the adsorbate remains unadsorbed in the solution, resulting in a decrease in pollutant removal efficiency as reported when pH and chitosan dose were kept constant at 7 and 100 mg/L and varying oestrogen concentration between 2 to 50 mg/L [38]. This trend shows the limited number of binding sites on carbonaceous absorbents, which cannot accommodate unlimited amounts of pollutants. Thus, adsorption efficiency tends to decrease gradually with increasing adsorbate concentration, emphasizing the importance of optimizing parameters, such as increasing the adsorbent dose, in industrial applications [39].

C. *Adsorbent dose*

Adsorbent dosage, such as chitosan, is one of the factors that influence adsorption efficiency, as it directly affects the number of active sites available for removing the adsorbate. Increasing the dosing rate of the adsorbent results in obtaining a high removal efficiency by providing a large surface area [10]. Therefore, when the adsorbent is applied at a low dose, the limited available active site on the adsorbent surface results in reduced adsorption efficiency, particularly when adsorbate concentrations are high. However, as the adsorbent dosing increases, removal efficiency improves because more adsorbate molecules in a solution are captured until the system reaches a saturation point where further addition of an adsorbent makes no difference, and at this stage, the adsorption curve reaches a straight line [40]. This plateau occurs because, beyond a certain dosage, the excess adsorbent sites remain unused, as the available pollutant molecules are insufficient to occupy them. Moreover, at high adsorbent loadings, the distribution of adsorbate molecules across an excessive number of active sites decreases the driving force for mass transfer, further limiting the improvement in removal efficiency. Consequently, while increasing the adsorbent dose initially promotes uptake, there is an optimal dose beyond which additional adsorbent does not significantly enhance any removal efficiency [41].

D. Regeneration of the adsorbent using different solvents

The regeneration and recovery of spent carbonaceous adsorbents is a major issue for sustainable and cost-effective. Different solvents such as hydrochloric acid (HCl), sodium hydroxide (NaOH), and nitric acid (HNO_3) have been utilized for desorbing emerging contaminants and recovering the adsorbent [42]. The highest desorption efficiency, reaching up to 99.5%, has been achieved using chemical solvents, with regeneration typically sustained from 1–10 cycles with an energy demand of 6.6 kWh/kg [43]. Current challenges in regenerating and recovering saturated adsorbents include high operational costs, secondary waste generation, the need for environmental methods, preservation of adsorbent stability and efficiency [44]. Furthermore, there are many adsorbent regeneration approaches that have been explored with varying levels of effectiveness such as solvent washing, thermal treatment, chemical, and electrochemical regeneration. Solvent washing has been proven effective in recovering carbonaceous adsorbents [45].

VII. Conclusion

The effectiveness of carbonaceous adsorbents such as chitosan in eradicating oestrogenic contaminants from water bodies has been examined across academic research. The performance is influenced by factors such as surface properties, pore geometry, and functional groups. Therefore, different modifications of adsorbents are advised to improve the surface properties, and distinct structures that play an important role in defining removal efficacy. Their efficacy in treating complex real-world wastewater and water is not yet fully understood, emphasizing the necessity for more extensive pilot systems to do further research. Tailoring surface functionalities with targeted functional groups can improve selectivity and adsorption efficiency. However, this detailed understanding of the underlying mechanism through kinetics and isotherms model, such as electrostatic interactions depending on the type of endocrine disrupting chemicals. There is another important aspect, which is the cost and sustainability of the modified adsorbent. Engineering processes often demand significant energy input and chemical usage, increasing production costs and potentially impacting the environmental footprint. Therefore, optimization of synthesis methods is necessary to balance performance with affordability. Moreover, improving the reusability of a modified adsorbent is vital for long-term viability. High regeneration potential not only minimizes secondary waste generation but also enhances the economic feasibility of these materials. Lastly, locally available materials and conditions should be considered during adsorbent selection to ensure accessibility, affordability, and alignment with improving wastewater challenges. Advancing these areas through focused research will be key to enabling the practical, sustainable use of carbonaceous adsorbents such as chitosan in oestrogenic pollutant removal. In conclusion, the ability to regenerate and reuse waste-derived material in their synthesis makes them outstanding alternatives in the removal of endocrine-disrupting compounds.

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