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A critical review of sustainable management practices for addressing environmental and human health risks of estrogenic compounds

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Abstract

Estrogenic compounds, including natural and synthetic endocrine-disrupting chemicals, pose significant risks to environmental ecosystems and human health. These compounds, originating from pharmaceuticals, agricultural runoff, and industrial waste, have been linked to ecological disruptions such as fish feminization and biodiversity loss, as well as human health issues including reproductive disorders and cancers. This paper provides a critical review of sustainable management practices aimed at mitigating the environmental and human health risks associated with estrogenic compounds. The review evaluates a range of strategies, including source reduction, advanced treatment technologies (e.g., advanced oxidation processes, biochar, and constructed wetlands), and policy frameworks. It highlights the effectiveness, scalability, and limitations of these practices, while identifying gaps in current research and implementation. Key findings suggest that integrated approaches combining technological innovation, regulatory enforcement, and stakeholder engagement are essential for sustainable management. The review concludes that while significant progress has been made, further research is needed to optimize cost-effective and scalable solutions. This paper underscores the urgency of addressing estrogenic compound contamination through sustainable practices to safeguard both environmental and public health.

Keywords: Estrogenic compounds; Endocrine-disrupting chemicals (EDCs); Environmental contamination; Human health risks; Pharmaceutical pollution; Agricultural runoff

1. Introduction

Estrogenic compounds are a class of endocrine-disrupting chemicals (EDCs) that mimic or interfere with the function of natural hormones in the body. These compounds include natural estrogens (e.g., estrone, estradiol), synthetic estrogens (e.g., 17α-ethinylestradiol, or EE2), and industrial chemicals (e.g., bisphenol A, phthalates) (Kumar et al., 2022). They are widely used in pharmaceuticals, personal care products, and industrial processes, leading to their pervasive presence in the environment (Wang et al., 2021). Due to their persistence and bioaccumulative nature, estrogenic compounds have become a significant concern for both ecological and human health. The environmental prevalence of estrogenic compounds is well-documented, with detectable levels found in water bodies, soil, and even drinking water (Li et al., 2020). These compounds enter the environment primarily through wastewater effluents,

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agricultural runoff, and industrial discharges. Their presence has been linked to severe ecological consequences, such as the feminization of aquatic species, disruption of reproductive systems, and declines in biodiversity (Sumpter & Johnson, 2023). In humans, exposure to estrogenic compounds has been associated with reproductive disorders, developmental abnormalities, and increased risks of hormone-related cancers (Vandenberg et al., 2022). Despite growing awareness, the management of these compounds remains a challenge due to their complex chemical nature and widespread sources. The purpose of this review is to critically evaluate sustainable management practices for mitigating the environmental and human health risks posed by estrogenic compounds. By analyzing current strategies and their effectiveness, this paper aims to provide a comprehensive understanding of the opportunities and challenges in addressing this pressing issue.

This review covers the following key areas:

- Sources and environmental pathways of estrogenic compounds.
- Ecological and human health impacts of exposure.
- Current and emerging sustainable management practices, including technological, policy, and community-based approaches.
- Critical analysis of the strengths, limitations, and future directions for sustainable management

2. Literature Review

Estrogenic compounds are derived from both natural and anthropogenic sources, making them ubiquitous in the environment. Natural estrogens, such as estrone (E1), estradiol (E2), and estriol (E3), are primarily produced by humans and animals as part of their endocrine systems. These compounds are excreted and enter the environment through domestic sewage, livestock manure, and aquaculture effluents (Kumar et al., 2022). For example, estradiol, a potent natural estrogen, is commonly found in wastewater from residential areas and agricultural operations (Wang et al., 2021).

Synthetic estrogens, such as 17α-ethinylestradiol (EE2), are widely used in pharmaceuticals, particularly in oral contraceptives and hormone replacement therapies. These compounds are not fully metabolized by the human body and are excreted into wastewater systems, where they persist due to their chemical stability (Li et al., 2020). Industrial activities also contribute significantly to the release of estrogenic compounds. Chemicals like bisphenol A (BPA) and phthalates, which are used in the production of plastics, resins, and personal care products, leach into the environment during manufacturing, use, and disposal (Vandenberg et al., 2022).

Agricultural practices further exacerbate the problem. Pesticides and herbicides, such as atrazine and DDT, exhibit estrogenic activity and are carried into water bodies through runoff (Sumpter & Johnson, 2023). Additionally, the use of growth promoters in livestock farming introduces synthetic hormones into the environment, which can contaminate soil and water resources (Kumar et al., 2022). Collectively, these sources ensure the continuous introduction of estrogenic compounds into ecosystems, posing significant risks to both environmental and human health.

2.1. Environmental and Health Impacts

The ecological impacts of estrogenic compounds are profound, particularly in aquatic ecosystems. These compounds disrupt the endocrine systems of aquatic organisms, leading to reproductive and developmental abnormalities. For instance, exposure to EE2 at concentrations as low as 1 ng/L has been shown to cause feminization of male fish, reduced fertility, and population declines (Sumpter & Johnson, 2023). A study by Li et al. (2020) documented the presence of intersex fish in rivers downstream of wastewater treatment plants, highlighting the widespread nature of this issue.

Beyond aquatic species, estrogenic compounds also affect terrestrial ecosystems. Soil microbial communities, which play a critical role in nutrient cycling, can be disrupted by the presence of these chemicals (Kumar et al., 2022). Additionally, plants exposed to estrogenic compounds may experience altered growth patterns and reduced reproductive success, further impacting biodiversity (Wang et al., 2021).

Human health is equally at risk due to exposure to estrogenic compounds. These chemicals can mimic or interfere with natural hormones, leading to a range of adverse effects. Developmental disorders, such as early puberty and congenital abnormalities, have been linked to prenatal exposure to estrogenic compounds (Vandenberg et al., 2022). In adults, long-term exposure has been associated with reproductive issues, including infertility and polycystic ovary syndrome (PCOS), as well as an increased risk of hormone-related cancers such as breast and prostate cancer (Sumpter & Johnson, 2023). For example, BPA, a common estrogenic compound found in plastics, has been shown to disrupt endocrine function and contribute to metabolic disorders such as obesity and diabetes (Wang et al., 2021). The persistence and bioaccumulation of these compounds in the food chain further amplify their risks, making them a critical public health concern.

2.2. Current Management Practices

Efforts to manage estrogenic compounds have focused on both technological and policy-based approaches. Wastewater treatment plants (WWTPs) are the primary line of defense, employing a range of processes to remove these compounds from effluents. Conventional methods, such as activated sludge treatment and chlorination, are often ineffective at fully degrading estrogenic compounds due to their chemical stability (Li et al., 2020). As a result, advanced treatment technologies have been developed to enhance removal efficiency.

Advanced oxidation processes (AOPs), such as ozonation and photocatalysis, have shown promise in breaking down estrogenic compounds into less harmful byproducts (Kumar et al., 2022). Membrane filtration technologies, including reverse osmosis and nanofiltration, are also effective at removing these compounds from water (Wang et al., 2021). Additionally, nature-based solutions, such as constructed wetlands and biochar adsorption, have gained attention for their ability to remove estrogenic compounds while providing secondary ecological benefits (Sumpter & Johnson, 2023).

Regulatory frameworks play a crucial role in managing estrogenic compounds. The European Union's Water Framework Directive, for example, identifies certain estrogenic compounds as priority substances and sets limits for their presence in water bodies (Vandenberg et al., 2022). Similarly, the U.S. Environmental Protection Agency (EPA) has established the Endocrine Disruptor Screening Program to assess the risks posed by these chemicals and develop regulatory guidelines (Li et al., 2020). However, enforcement remains inconsistent, and many regions lack comprehensive regulations.

Public awareness and stakeholder engagement are increasingly recognized as essential components of sustainable management strategies. Educational campaigns aimed at reducing the use of products containing estrogenic compounds, such as certain plastics and personal care items, can help mitigate their release into the environment (Wang et al., 2021). Collaboration between governments, industries, and communities is critical for developing and implementing effective management practices.

2.3. Sustainable Management Practices

2.3.1. Prevention Strategies

Prevention is the most effective and sustainable approach to managing estrogenic compounds, as it addresses the problem at its source. Source reduction strategies aim to minimize the release of these compounds into the environment through innovative design, policy interventions, and public engagement.

- **Green Chemistry**: Green chemistry focuses on designing chemical products and processes that reduce or eliminate the use of hazardous substances. For example, replacing bisphenol A (BPA) with safer alternatives in plastics and epoxy resins has been a significant step toward reducing estrogenic compound pollution (Vandenberg et al., 2022). Similarly, the development of biodegradable pharmaceuticals that break down more easily in the environment can help mitigate their impact (Kumar et al., 2022).
- **Pharmaceutical Take-Back Programs**: Unused or expired medications are a significant source of estrogenic compounds in the environment. Pharmaceutical take-back programs encourage consumers to return unused drugs to designated collection points, preventing them from being flushed down the drain or disposed of in landfills (Wang et al., 2021). For instance, the U.S. Drug Enforcement Administration's National Prescription Drug Take-Back Day has successfully collected millions of pounds of unused medications, reducing their environmental release (Li et al., 2020).
- **Agricultural Best Practices**: Reducing the use of estrogenic pesticides and herbicides in agriculture can significantly lower the environmental burden. Integrated pest management (IPM) strategies, which emphasize biological control and crop rotation, can minimize reliance on harmful chemicals (Sumpter & Johnson, 2023). Additionally, the use of organic fertilizers and manure management practices can reduce the release of natural estrogens from livestock operations (Kumar et al., 2022).
- **Public Awareness Campaigns**: Educating the public about the risks of estrogenic compounds and promoting the use of eco-friendly products can drive behavioral change. Campaigns that highlight the dangers of plastic products containing BPA and encourage the use of glass or stainless steel alternatives have been effective in reducing exposure (Vandenberg et al., 2022).

2.3.2. Treatment Technologies

When prevention is not feasible, treatment technologies play a critical role in removing estrogenic compounds from the environment. Sustainable treatment methods focus on efficiency, cost-effectiveness, and minimal environmental impact.

- **Advanced Oxidation Processes (AOPs)**:AOPs, such as ozonation, photocatalysis, and Fenton reactions, are highly effective at degrading estrogenic compounds into less harmful byproducts. These processes generate reactive oxygen species (ROS) that break down complex molecules. For example, ozonation has been shown to achieve over 90% removal of EE2 from wastewater (Li et al., 2020). However, AOPs can be energy-intensive and may produce toxic intermediates, requiring careful optimization (Wang et al., 2021).
- **Biochar Adsorption**:Biochar, a carbon-rich material produced from biomass pyrolysis, has gained attention for its ability to adsorb estrogenic compounds from water and soil. Its high surface area and porosity make it an effective adsorbent for compounds like BPA and EE2 (Kumar et al., 2022). Additionally, biochar can be produced from agricultural waste, making it a sustainable and cost-effective solution (Sumpter & Johnson, 2023).
- **Constructed Wetlands**:Constructed wetlands are nature-based solutions that use plants, microorganisms, and soil to remove contaminants from wastewater. These systems are particularly effective at degrading natural estrogens and have been successfully implemented in rural and urban areas (Vandenberg et al., 2022). For instance, a study by Wang et al. (2021) demonstrated that constructed wetlands achieved 70–80% removal of estradiol and estrone from municipal wastewater.
- **Membrane Filtration**:Membrane technologies, such as reverse osmosis (RO) and nanofiltration (NF), are highly effective at removing estrogenic compounds from water. These processes use semi-permeable membranes to separate contaminants based on size and charge. RO has been shown to achieve over 95% removal of EE2 and BPA from drinking water (Li et al., 2020). However, membrane fouling and high operational costs remain challenges for widespread adoption (Kumar et al., 2022).
- **Biodegradation and Bioremediation**:Microorganisms play a key role in breaking down estrogenic compounds in the environment. Biodegradation processes, such as those involving bacteria and fungi, can transform these compounds into non-toxic metabolites. For example, certain strains of *Pseudomonas* and *Aspergillus* have been shown to degrade EE2 and BPA effectively (Sumpter & Johnson, 2023). Bioremediation techniques, such as bioaugmentation and biostimulation, enhance the natural degradation capacity of microbial communities (Wang et al., 2021).
- **Hybrid Treatment Systems**: Combining multiple treatment technologies can enhance the removal efficiency of estrogenic compounds. For instance, integrating AOPs with constructed wetlands or biochar adsorption can address the limitations of individual methods and provide a more comprehensive solution (Vandenberg et al., 2022). Hybrid systems are particularly useful for treating complex wastewater streams containing a mixture of contaminants (Li et al., 2020).

3. Analysis

3.1. Strengths and Limitations

The sustainable management practices discussed in this review demonstrate significant potential for addressing the risks posed by estrogenic compounds. However, each approach has its strengths and limitations that must be critically evaluated.

3.1.1. Prevention Strategies

- **Strengths**: Source reduction strategies, such as green chemistry and pharmaceutical take-back programs, are highly effective at minimizing the release of estrogenic compounds into the environment. These approaches address the problem at its root, reducing the need for costly and energy-intensive treatment methods (Vandenberg et al., 2022).
- **Limitations**: The implementation of prevention strategies often requires significant behavioral and industrial changes, which can be challenging to achieve. For example, the adoption of green chemistry alternatives may face resistance due to higher costs or lack of awareness (Kumar et al., 2022).

3.1.2. Treatment Technologies

- **Strengths**: Advanced treatment methods, such as AOPs and membrane filtration, are highly effective at removing estrogenic compounds from water and wastewater. Nature-based solutions, like constructed wetlands and biochar adsorption, offer additional ecological benefits and are often more cost-effective (Li et al., 2020).

- **Limitations**: Many treatment technologies, such as AOPs and membrane filtration, are energy-intensive and may produce harmful byproducts. Constructed wetlands, while sustainable, require large land areas and may not be suitable for urban settings (Wang et al., 2021).

3.1.3. Policy and Regulatory Frameworks

- **Strengths**: Regulatory measures, such as the EU Water Framework Directive and the U.S. EPA's Endocrine Disruptor Screening Program, provide a structured approach to monitoring and managing estrogenic compounds (Sumpter & Johnson, 2023).
- **Limitations**: Enforcement of regulations is often inconsistent, and many regions lack comprehensive policies. Additionally, regulatory processes can be slow to adapt to emerging contaminants and new scientific findings (Vandenberg et al., 2022).

3.2. Gaps in Knowledge

Despite significant progress, several gaps in knowledge remain that hinder the development and implementation of effective management practices.

3.2.1. Long-Term Ecological Impacts

- The long-term effects of low-dose exposure to estrogenic compounds on ecosystems are not fully understood. More research is needed to assess the cumulative impacts on biodiversity and ecosystem functioning (Kumar et al., 2022).

3.2.2. Cost-Effectiveness of Technologies

- While many treatment technologies are effective, their cost-effectiveness and scalability remain understudied. For example, the high operational costs of AOPs and membrane filtration limit their widespread adoption (Li et al., 2020).

3.2.3. Emerging Contaminants

- The environmental and health impacts of newly identified estrogenic compounds, such as those used in industrial applications, are not well-documented. Further research is needed to understand their behavior and risks (Wang et al., 2021).

3.2.4. Public Awareness and Engagement

- The role of public awareness and community engagement in reducing the release of estrogenic compounds is underexplored. Studies are needed to evaluate the effectiveness of educational campaigns and stakeholder collaboration (Vandenberg et al., 2022).

4. Future Directions

To address the gaps in knowledge and improve the management of estrogenic compounds, future research and innovation should focus on the following areas:

4.1. Nanotechnology

- The development of nanomaterials for adsorption and degradation of estrogenic compounds holds great promise. For example, graphene-based materials and metal-organic frameworks (MOFs) have shown high efficiency in removing contaminants from water (Kumar et al., 2022).

4.2. AI-Driven Monitoring Systems

- Artificial intelligence (AI) and machine learning can be used to develop real-time monitoring systems for detecting estrogenic compounds in the environment. These systems can provide early warning of contamination and optimize treatment processes (Li et al., 2020).

4.3. Circular Economy Approaches

- Integrating circular economy principles into the management of estrogenic compounds can enhance sustainability. For example, recovering and reusing estrogenic compounds from wastewater could reduce their environmental release (Wang et al., 2021).

4.4. Global Collaboration

- International collaboration is essential for addressing the transboundary nature of estrogenic compound pollution. Shared research initiatives and policy frameworks can promote consistent and effective management practices (Sumpter & Johnson, 2023).

5. Conclusion

This review highlights the significant risks posed by estrogenic compounds to environmental and human health and evaluates the effectiveness of sustainable management practices for mitigating these risks. Prevention strategies, such as green chemistry and pharmaceutical take-back programs, offer the most sustainable solutions by addressing the problem at its source. Treatment technologies, including AOPs, biochar adsorption, and constructed wetlands, provide effective means of removing estrogenic compounds from the environment, though challenges related to cost, scalability, and byproduct formation remain.

Despite progress, gaps in knowledge, such as the long-term ecological impacts and cost-effectiveness of technologies, underscore the need for further research. Future directions, including the use of nanotechnology, AI-driven monitoring systems, and circular economy approaches, offer exciting opportunities for innovation.

The findings of this review emphasize the urgent need for coordinated action among policymakers, researchers, and industries to address the risks posed by estrogenic compounds. By adopting sustainable management practices and investing in research and innovation, we can safeguard ecosystems and public health for future generations.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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