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REVIEW ARTICLE

# Endocrine Disrupting Chemicals and their Ecological Effects on Reproduction and Development: A Review

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**ABSTRACT**

Endocrine disrupting chemicals (EDCs) are exogenous substances capable of interfering with the normal functioning of the endocrine system, thereby causing adverse effects on reproduction, development, metabolism, and other physiological processes in humans and wildlife. The widespread use of these chemicals in agriculture, industry, pharmaceuticals, plastics, and personal care products has led to their ubiquitous presence in terrestrial and aquatic environments, raising significant ecological and public health concerns. This study examined endocrine disrupting chemicals and their ecological effects on reproduction and development. Specifically, the study discussed the concept, characteristics, historical development, classification, sources, and types of endocrine disrupting chemicals. It also reviewed the mechanisms through which endocrine disrupting chemicals disrupt endocrine functions, including hormone mimicry, receptor blocking, alteration of hormone synthesis and metabolism, epigenetic modifications, and transgenerational effects. Environmental pathways such as agricultural runoff, industrial effluents, municipal wastewater, atmospheric deposition, bioaccumulation, and biomagnification were highlighted. The study further examined the ecological impacts of endocrine disrupting chemicals on aquatic organisms, amphibians, reptiles, birds, and mammals, as well as their implications for human health, including reproductive disorders, hormone-dependent cancers, neurodevelopmental abnormalities, metabolic diseases, and thyroid dysfunction. Methods employed in the detection and monitoring of endocrine disrupting chemicals, control and management strategies, and emerging research issues were also discussed. The study concluded that endocrine disrupting chemicals pose substantial threats to biodiversity, ecosystem stability, and human wellbeing, necessitating strengthened regulatory frameworks, improved environmental monitoring, sustainable chemical management practices, and continued research to mitigate their adverse effects.

**Keywords:** Endocrine disruptors; Ecological effects; Environmental contamination; Environmental toxicology; Reproductive toxicology; Wildlife; Ecological risk.

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## 1.0 INTRODUCTION

The increasing production and use of synthetic chemicals have significantly contributed to agricultural productivity, industrial development, healthcare delivery, and improvements in the quality of human life worldwide. However, the widespread use of these chemicals has also resulted in their continuous release into the environment, where they may persist and interact with living organisms in ways that compromise ecosystem integrity and human well-being. Among these contaminants, endocrine-disrupting chemicals (EDCs) have emerged as a major environmental and public health concern because of their ability to interfere with hormonal signalling pathways that regulate growth, metabolism, reproduction, development, and behaviour in humans and wildlife (Gore et al., 2015; Heindel et al., 2020). Unlike conventional toxic substances whose effects may become apparent primarily at relatively high concentrations, some EDCs can produce biological effects at very low doses, particularly during sensitive periods of embryonic, fetal, and juvenile development (Nadal et al., 2017; Vandenberg et al., 2017). Understanding the environmental and biological significance of these contaminants therefore requires an examination of their nature, sources, mechanisms of action, and effects on living organisms. Endocrine-disrupting chemicals are exogenous substances or mixtures that alter the functions of the endocrine system and consequently cause adverse health effects in an intact organism, its offspring, or populations of organisms (Gore et al., 2019). These chemicals may mimic naturally occurring hormones, block hormone receptors, interfere with hormone synthesis and transport, or modify hormonal metabolism and elimination, thereby disrupting physiological homeostasis (Zoeller et al., 2018; OECD, 2021). EDCs comprise a broad range of substances, including pesticides, plasticizers, pharmaceuticals, industrial chemicals, heavy metals, personal-care products, bisphenols, phthalates, per- and polyfluoroalkyl substances (PFAS), polychlorinated biphenyls (PCBs), dioxins, and naturally occurring compounds such as phytoestrogens (Olea et al., 2020; WHO & UNEP, 2022). Their widespread occurrence in environmental media and consumer products has increased concerns about their distribution, persistence, and potential effects on humans and wildlife (Parent et al., 2025). EDCs are continuously introduced into the environment through industrial effluents, agricultural runoff, municipal wastewater discharges, atmospheric deposition, improper disposal of pharmaceuticals, and the degradation of plastic materials (Bornman et al., 2019; Demeneix et al., 2021). Agricultural activities are particularly important sources of endocrine-disrupting contaminants because pesticides and related chemicals can move from treated areas into surrounding soils and water bodies, thereby exposing non-target organisms. Once released, some EDCs may persist because of their resistance to degradation and physicochemical properties. They can occur in soils, sediments, surface water, groundwater, and biological tissues and may be transferred through food webs through bioaccumulation and, for some substances, biomagnification (Nagel et al., 2020; WHO & UNEP, 2022). Consequently, aquatic organisms, amphibians, reptiles, birds, mammals, and humans may be exposed through ingestion, inhalation, dermal absorption, contaminated food and water, and occupational activities.

Endocrine disruption occurs through diverse molecular and cellular mechanisms. Some EDCs act as agonists by binding to hormone receptors and initiating inappropriate physiological responses, whereas others act as antagonists by preventing endogenous hormones from binding to their target receptors (Gore et al., 2019; Zoeller et al., 2020). Other endocrine disruptors can interfere with steroidogenesis, alter thyroid hormone synthesis and metabolism, modify hormone transport and clearance, influence intracellular signalling pathways, and affect gene expression (Heindel et al., 2020; Demeneix et al., 2021). In addition, EDC exposure has been associated with epigenetic alterations, including changes in DNA methylation and histone regulation, which may influence the expression of genes involved in reproduction and development (Liang et al., 2025). These mechanisms are particularly important because endocrine systems coordinate highly sensitive physiological processes, and disruption during critical developmental windows may result in effects that persist into adulthood.

Reproduction is one of the biological processes particularly vulnerable to endocrine disruption because it depends on precisely coordinated hormonal pathways. Exposure to EDCs can interfere with the hypothalamic-pituitary-gonadal (HPG) axis, which regulates reproductive development and function. Developmental exposure may alter pituitary hormone production, gene expression, steroidogenesis, and the balance of endocrine cell populations, potentially producing long-term reproductive consequences. In females, EDC exposure has been associated with disturbances in ovarian reserve, follicular development, puberty, ovulation, and fertility. Reported reproductive outcomes include abnormal puberty, impaired fertility, premature menopause, and polycystic ovary syndrome (Parent et al., 2025). In males, EDCs may interfere with testicular development, spermatogenesis, steroidogenesis, and other processes essential for reproductive competence. An additional concern is that humans and wildlife are generally exposed to mixtures of EDCs rather than to individual chemicals in isolation. Low-dose exposure to combinations of environmental chemicals and pharmaceuticals may produce effects that are difficult to predict from studies of individual substances. Recent research therefore emphasizes the importance of investigating chemical mixtures and exposure levels that more accurately represent real-life environmental conditions (Mohajer & Culty, 2025). This approach is particularly relevant for wildlife inhabiting contaminated ecosystems, where organisms may simultaneously encounter pesticides, industrial pollutants, pharmaceuticals, plastic-associated chemicals, and other contaminants. EDCs can also affect growth and development through hormonal, physiological, and epigenetic mechanisms. Exposure during sensitive developmental periods may interfere with sexual differentiation, organ development, neurological development, metabolism, and immune function. A recent review reported that chemicals such as bisphenol A (BPA), phthalates, dioxins, and PCBs can modify DNA methylation and histone regulation in reproductive tissues. Such alterations may affect genes involved in ovarian function, implantation, and placental development, suggesting that developmental exposure can produce biological effects that persist beyond the initial period of chemical exposure (Liang et al., 2025). These findings demonstrate the importance of considering developmental exposure when evaluating the long-term consequences of endocrine disruption.

The effects of EDCs extend beyond individual organisms to populations, communities, and ecosystems. Laboratory and field studies have associated exposure to endocrine-disrupting chemicals with reduced fertility, impaired gamete production, abnormal sexual differentiation, developmental deformities, behavioural alterations, and increased susceptibility to disease among wildlife populations (Flaws et al., 2020; Nagel et al., 2020). Feminization of male fish, intersex conditions in amphibians, reproductive abnormalities in birds, and reproductive failure in mammals have been reported in contaminated environments. Such effects may reduce reproductive success, alter population dynamics, threaten biodiversity, and ultimately affect ecosystem stability (Bornman et al., 2019; Swan et al., 2021). In agricultural environments, pesticide-derived endocrine disruption is of particular concern because contaminants can move beyond target areas and affect non-target organisms, including aquatic species, pollinators, livestock, and wildlife. Recent evidence indicates that agricultural EDCs may threaten reproductive function and ecosystem health, although important knowledge gaps remain concerning population-level effects and reproductive consequences in livestock and wildlife (Payne & Pool, 2026).

Similar concerns have been raised regarding human health. Prenatal, childhood, and lifelong exposure to EDCs has been associated with reproductive disorders, hormone-dependent cancers, metabolic disturbances, thyroid dysfunction, neurodevelopmental abnormalities, and impaired immune function (Bourguignon et al., 2018; Olea et al., 2020). The potential for effects to occur during critical developmental windows, together with the possibility of long-term or transgenerational consequences, makes endocrine disruption an important environmental sustainability and public health issue. The growing recognition of these risks has increased the need for effective environmental monitoring, improved detection methods, appropriate risk assessment, and regulatory strategies aimed at reducing exposure. Despite the growing body of scientific evidence, important uncertainties remain regarding the occurrence, persistence, combined effects, low-dose responses, and long-term ecological consequences of EDC exposure. In particular, further research is required to clarify how mixtures of endocrine-disrupting chemicals affect reproductive and developmental processes across different species and how individual-level effects translate into population- and ecosystem-level consequences. Greater attention is also needed to developmental exposure, epigenetic mechanisms, environmentally relevant concentrations, and the cumulative effects of multiple contaminants.

Therefore, this review aims to comprehensively examine endocrine-disrupting chemicals and their ecological effects on reproduction and development in wildlife and humans. Specifically, the review will examine the major sources and classes of EDCs, their mechanisms of action, environmental pathways and fate, and their effects on reproductive and developmental processes. It will also evaluate methods used for their detection and monitoring, current approaches to their control and management, and emerging research needs. By integrating evidence from environmental, toxicological, ecological, and human-health studies, this review seeks to provide a comprehensive understanding of endocrine disruption and its implications for biodiversity, ecosystem health, and human well-being, while highlighting strategies that can support effective mitigation, environmental management, and policy development.

## 2.0 MATERIALS AND METHODS

This study employed a narrative literature review approach to examine endocrine-disrupting chemicals (EDCs) and their ecological effects on reproduction and development. Relevant scientific literature was obtained from electronic databases, including Google Scholar, PubMed, ScienceDirect, Scopus, and Web of Science. Searches were conducted using combinations of keywords such as “endocrine-disrupting chemicals,” “endocrine disruptors,” “reproductive toxicity,” “developmental effects,” “wildlife,” “aquatic organisms,” “reproduction,” and “ecological effects.” Boolean operators such as AND and OR were used to refine the search. Peer-reviewed articles published in English and focusing on EDC exposure, endocrine disruption, reproductive impairment, developmental abnormalities, or ecological consequences were considered for inclusion. Duplicate publications and articles that did not directly address the objectives of the review were excluded. Relevant information was extracted from selected publications, including the type and source of EDC, exposed organisms, route of exposure, mechanism of endocrine disruption, reproductive effects, developmental effects, and ecological consequences. The collected information was organized according to major EDC categories and affected biological processes. Findings from the reviewed studies were compared and qualitatively synthesized to identify common effects, differences among organisms, potential mechanisms, and knowledge gaps regarding the influence of EDCs on reproduction, development, and ecological health.

## 3.0 Concept of endocrine disrupting chemicals

Endocrine disrupting chemicals (EDCs) are external substances or mixtures that interfere with the normal functions of the endocrine system and may cause adverse effects in organisms, their offspring, or populations (Gore et al., 2019). The endocrine system regulates growth, metabolism, reproduction, development, immunity, and behaviour through hormones. EDCs can disrupt these processes by mimicking natural hormones, blocking hormone receptors, altering hormone synthesis, transport, metabolism, or excretion (Zoeller et al., 2018; OECD, 2021). Unlike many conventional toxicants, EDCs may produce effects at very low concentrations, particularly during sensitive developmental periods such as fetal life, infancy, and puberty (Nadal et al., 2017; Vandenberg et al., 2017). EDCs are characterized by persistence, resistance to degradation, lipophilicity, and the ability to bioaccumulate and biomagnify through food chains (Nagel et al., 2020). They may also exhibit non-monotonic dose-response relationships, whereby low doses can produce effects different from those observed at higher doses (Gore et al., 2019). Exposure during critical developmental stages may cause lasting physiological changes, including epigenetic modifications that can potentially affect subsequent generations (Demeneix et al., 2021; Heindel et al., 2020). Scientific understanding of endocrine disruption has developed substantially over recent decades. Early observations of reproductive abnormalities in wildlife exposed to environmental contaminants led to investigations of chemicals capable of disrupting endocrine functions. Studies involving compounds such as dichlorodiphenyltrichloroethane (DDT), polychlorinated biphenyls, and bisphenol A provided evidence of endocrine-related effects in humans and wildlife (Zoeller et al., 2020). The Endocrine Society's scientific statements in 2009 and 2015 further increased recognition of endocrine disruption as a global public health concern. Research has since expanded to include low-dose exposure, mixture toxicity, metabolic effects, and transgenerational inheritance, contributing to greater regulatory attention and international efforts to manage EDCs (Gore et al., 2019; WHO & UNEP, 2022). EDCs can be classified according to their origin, chemical composition, and use. They may be synthetic or naturally occurring and include organochlorine pesticides, plasticizers, industrial chemicals, pharmaceuticals, personal care products, perfluorinated compounds, and heavy metals. Based on their use, they may be grouped into agricultural, industrial, pharmaceutical, household, and consumer chemicals (Olea et al., 2020; Demeneix et al., 2021). This classification helps identify major exposure pathways and develop appropriate control strategies.

### 3.1 Sources and types of endocrine disrupting chemicals

EDCs originate from agricultural, industrial, domestic, pharmaceutical, and waste-disposal activities. Their continuous release has resulted in contamination of soils, sediments, surface water, groundwater, and living organisms (Bornman et al., 2019; WHO & UNEP, 2022). Major sources include agricultural chemicals, industrial compounds, pharmaceuticals, and substances used in personal care products.

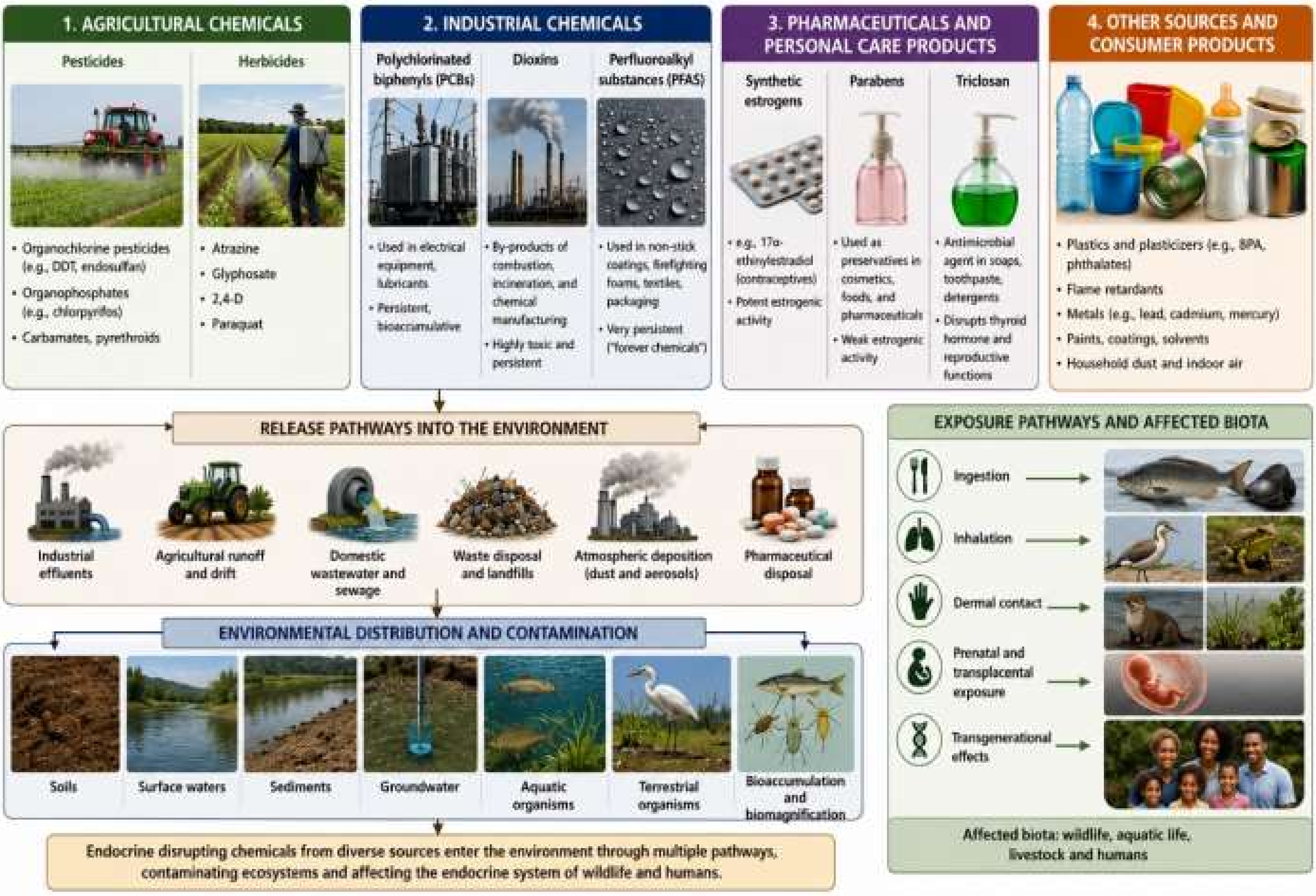

Figure 1. Source and types of Endocrine disrupting chemicals.

#### 3.1.1 Agricultural chemicals

Agricultural activities are major pathways through which endocrine disrupting chemicals (EDCs) enter the environment. Pesticides and herbicides used to improve crop productivity may persist in soil and water and adversely affect non-target organisms by disrupting endocrine functions (Bornman et al., 2019).

##### 3.1.1.1 Pesticides

Several pesticides act as EDCs by mimicking or inhibiting natural hormones. Organochlorines such as DDT have been associated with reproductive impairment, altered sexual development, and reduced fertility in wildlife. Other pesticides, including chlorpyrifos, methoxychlor, vinclozolin, and endosulfan, exhibit estrogenic, anti-androgenic, or thyroid-disrupting activities (Gore et al., 2019; Demeneix et al., 2021). Their residues may contaminate soil, water, and food.

##### 3.1.1.2 Herbicides

Atrazine is a widely studied herbicide associated with reproductive abnormalities, feminization of male amphibians, and disruption of steroid hormone synthesis (Bornman et al., 2019). Glyphosate-based herbicides have also been investigated for possible endocrine effects, although findings remain inconsistent (WHO & UNEP, 2022).

##### 3.1.1.3 Industrial chemicals

Industrial activities release EDCs through manufacturing, combustion, waste disposal, and accidental releases. Many industrial chemicals are persistent and bioaccumulative.

##### 3.1.1.4 Polychlorinated Biphenyls

Polychlorinated biphenyls (PCBs) were historically used as dielectric fluids, lubricants, and heat-transfer agents. Although restricted or banned in many countries, they remain environmentally persistent (Heindel et al., 2020). Exposure has been associated with thyroid disruption, reproductive impairment, developmental abnormalities, and neurobehavioral effects (Bourguignon et al., 2018).

#### 3.1.1.5 Dioxins
Dioxins are highly toxic compounds produced during activities such as waste incineration, metal processing, and chemical manufacturing. They disrupt hormone signalling and gene expression and have been associated with infertility, immune dysfunction, developmental defects, and hormone-dependent cancers (Zoeller et al., 2020; Flaws et al., 2020).

#### 3.1.1.6 Perfluoroalkyl substances
Perfluoroalkyl and polyfluoroalkyl substances (PFAS) are used in food packaging, firefighting foams, textiles, and non-stick products. Their extreme persistence has earned them the term "forever chemicals" (Demeneix et al., 2021). PFAS exposure may interfere with thyroid function, reproduction, immunity, and fetal development (Olea et al., 2020).

### 3.1.2 Pharmaceuticals and personal care products
Pharmaceuticals and personal care products enter the environment through domestic wastewater, hospital effluents, and improper disposal. Many remain biologically active at low concentrations.

#### 3.1.2.1 Synthetic estrogens
17α-ethinylestradiol, used in contraceptives and hormone therapies, is frequently detected in wastewater-impacted aquatic environments. It has been associated with feminization of male fish, reduced sperm production, intersex conditions, and impaired reproduction (Nagel et al., 2020; Gore et al., 2019).

#### 3.1.2.2 Parabens and triclosan
Parabens are preservatives used in cosmetics, pharmaceuticals, foods, and hygiene products. Methylparaben, propylparaben, and butylparaben possess weak estrogenic properties and may affect reproductive hormone regulation (Olea et al., 2020). Triclosan, an antimicrobial compound used in consumer products, has been detected in wastewater and sediments and may interfere with thyroid, reproductive, and developmental processes (WHO & UNEP, 2022; Heindel et al., 2020).

#### 3.1.2.3 Plastics and plasticizers
Plastics and plasticizers are widely used in packaging, medical equipment, toys, cosmetics, and household products. Some chemicals can leach into food, water, air, and dust (Olea et al., 2020; WHO & UNEP, 2022).

#### 3.1.2.4 Bisphenol A
Bisphenol A (BPA), used in polycarbonate plastics and epoxy resins, has estrogenic activity because it can interact with estrogen receptors (Vandenberg et al., 2017). Exposure has been associated with reproductive and developmental abnormalities, obesity, diabetes, neurobehavioral effects, and hormone-dependent cancers (Gore et al., 2019; Heindel et al., 2020).

#### 3.1.2.5 Phthalates
Phthalates are plastic additives used in PVC products, medical equipment, toys, cosmetics, and food packaging. They possess anti-androgenic properties and have been associated with disrupted testosterone production, poor sperm quality, reduced fertility, and developmental abnormalities (Hunt et al., 2017; Swan et al., 2021).

### 3.1.3 Heavy metals
Heavy metals such as lead, cadmium, mercury, and arsenic can act as endocrine disruptors and persist in the environment because they are non-biodegradable (Demeneix et al., 2021).

***3.1.3.1 Lead (Pb)**:* can interfere with reproductive and thyroid functions and has been associated with infertility, reduced sperm count, delayed puberty, and neurological effects (Bourguignon et al., 2018; Bornman et al., 2019).

***3.1.3.2 Cadmium (Cd):*** is released through mining, smelting, batteries, fertilizers, and cigarette smoke. It can interact with estrogen receptors and has been associated with reproductive dysfunction, altered fetal growth, and endocrine-related cancers (Flaws et al., 2020; Demeneix et al., 2021).

***3.1.3.3 Mercury (Hg):*** enters ecosystems through mining, coal combustion, waste incineration, and industrial activities. Methylmercury bioaccumulates in aquatic food chains and may disrupt thyroid function, reproduction, and neurodevelopment (WHO & UNEP, 2022; Nagel et al., 2020).

***3.1.3.4 Arsenic (As):*** occurs naturally but is increased by mining, pesticides, and industrial emissions. It can interfere with glucocorticoid, thyroid, and estrogen signalling and may contribute to reproductive and developmental problems (Heindel et al., 2020; Demeneix et al., 2021).

### 3.2 Natural endocrine disruptors
Some naturally occurring substances also possess endocrine-modulating properties.

### 3.2.1 Phytoestrogens
Phytoestrogens are plant compounds found in soybeans, flaxseeds, legumes, and other foods. They can bind to estrogen receptors and produce estrogenic or anti-estrogenic effects depending on concentration and physiological conditions (Soto et al., 2017). Excessive exposure may affect reproductive functions and fertility (Olea et al., 2020).

### 3.2.2 Mycotoxins
Mycotoxins are fungal metabolites that contaminate cereals, nuts, feeds, and stored foods. Zearalenone has strong estrogenic activity and may cause reproductive abnormalities, reduced fertility, and impaired embryonic development (WHO & UNEP, 2022; Flaws et al., 2020).

## 4.0 Mechanisms of endocrine disruption
EDCs interfere with hormone synthesis, secretion, transport, receptor binding, metabolism, and regulation. Major mechanisms include hormone mimicry, hormone receptor blocking, alteration of hormone synthesis, modification of hormone transport and metabolism, epigenetic alterations, and transgenerational effects (Gore et al., 2019; Zoeller et al., 2020).

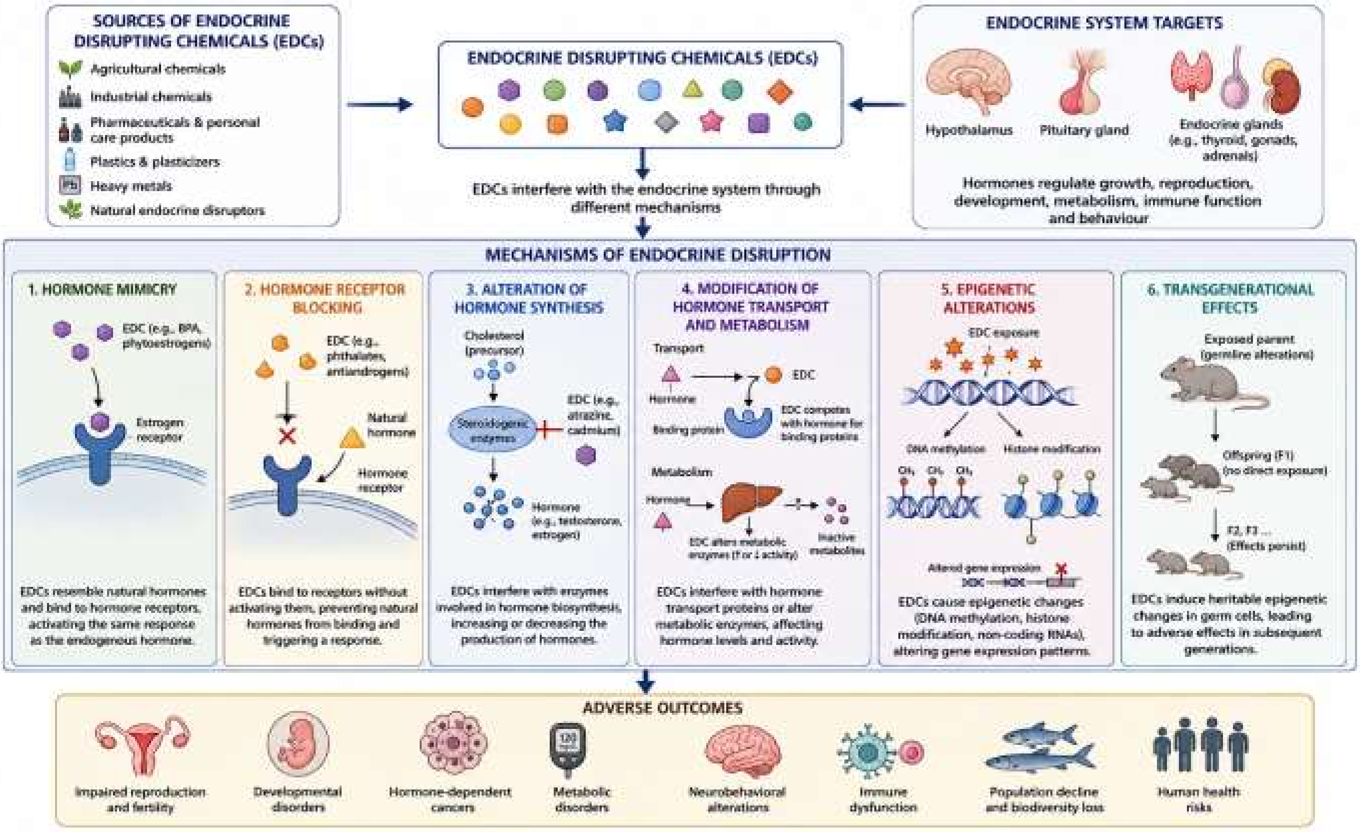


Figure **2**. Mechanisms of endocrine disruption

### 4.1 Mechanisms and environmental pathways of endocrine disrupting chemicals

#### 4..1 Hormone mimicry

Hormone mimicry occurs when endocrine disrupting chemicals (EDCs) structurally resemble natural hormones and bind to hormone receptors, activating inappropriate physiological responses (Gore et al., 2019). Bisphenol A, phthalates, parabens, synthetic estrogens, pesticides, and phytoestrogens can mimic estrogen and alter reproductive and developmental processes (Vandenberg et al., 2017; Olea et al., 2020). These effects may cause feminization in male fish, abnormal gonadal development, reduced fertility, and reproductive failure (Flaws et al., 2020). In humans, prolonged exposure has been associated with early puberty, infertility, metabolic disorders, and hormone-dependent cancers (Heindel et al., 2020; Bourguignon et al., 2018).

#### 4.1.2 Hormone receptor blocking

Some EDCs act as hormone antagonists by binding to receptors without activating them, thereby preventing natural hormones from functioning normally (Zoeller et al., 2018; OECD, 2021). Vinclozolin and some phthalates can block androgen receptors, reducing testosterone activity and affecting male reproductive development (Hunt et al., 2017; Swan et al., 2021). Receptor blocking may also interfere with thyroid, glucocorticoid, and progesterone receptors, resulting in developmental, metabolic, and reproductive abnormalities (Demeneix et al., 2021).

#### 4.1.3 Alteration of hormone synthesis

EDCs can interfere with enzymes responsible for hormone production, disrupting normal hormonal balance (Gore et al., 2019). Atrazine, for example, can increase aromatase activity, promoting conversion of androgens to estrogens and altering reproductive hormone levels (Bornman et al., 2019). Dioxins, cadmium, and perfluoroalkyl substances may also interfere with steroid hormone synthesis (Demeneix et al., 2021). These disruptions can affect reproductive maturation, gamete production, pregnancy, and fetal development (Flaws et al., 2020).

#### 4.1.4 Modification of hormone transport and metabolism

EDCs can alter hormone transport and metabolism by competing for transport proteins, modifying metabolic enzymes, or changing hormone degradation rates (Heindel et al., 2020). PCBs and perfluoroalkyl substances can interfere with thyroid hormone transport, reducing hormone availability to target tissues (Bourguignon et al., 2018). Other EDCs may accelerate or inhibit hormone metabolism, contributing to thyroid dysfunction, reproductive disorders, metabolic abnormalities, and developmental impairment (Zoeller et al., 2020).

#### 4.1.5 Epigenetic alterations

EDCs can cause epigenetic changes, including DNA methylation, histone modification, and altered non-coding RNA activity, without changing the DNA sequence itself (Demeneix et al., 2021). Exposure to bisphenol A, phthalates, dioxins, and pesticides may alter genes involved in reproduction, metabolism, and neurodevelopment (Heindel et al., 2020; Nagel et al., 2020). These changes may increase susceptibility to infertility, obesity, diabetes, and hormone-related cancers (Soto et al., 2017).

#### 4.1.6 Transgenerational effects

Some EDC-induced epigenetic changes may affect subsequent generations. Experimental studies have shown that exposure to vinclozolin, bisphenol A, and phthalates during pregnancy can produce reproductive, metabolic, behavioural, and developmental effects in descendants (Heindel et al., 2020; Nagel et al., 2020). Similar concerns exist regarding prenatal human exposure and potential effects on future generations (Swan et al., 2021).

### 4.2 Environmental pathways of endocrine disrupting chemicals

EDCs enter the environment through agricultural, industrial, domestic, and commercial activities. They can subsequently be transported, transformed, accumulated, and redistributed, resulting in contamination of soils, sediments, rivers, lakes, groundwater, marine environments, and living organisms (Bornman et al., 2019; WHO & UNEP, 2022). Understanding these pathways is essential for assessing exposure risks and developing effective strategies to control endocrine-disrupting pollution.

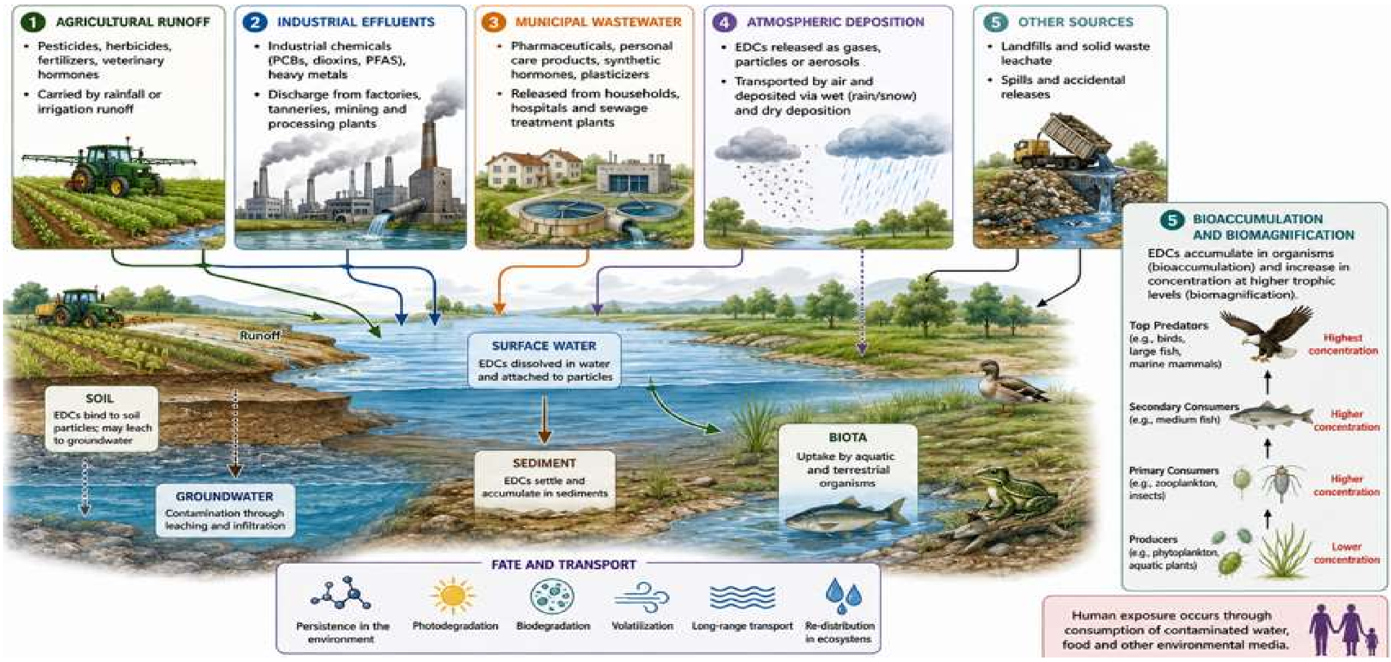


Figure **3**. Environmental pathways of endocrine disrupting chemicals

### 4.2.1 Agricultural runoff

Agricultural runoff is a major pathway through which endocrine disrupting chemicals (EDCs) enter the environment. Modern agriculture relies on pesticides, herbicides, fertilizers, and veterinary pharmaceuticals. During rainfall or irrigation, residues are washed from agricultural land into rivers, streams, lakes, wetlands, and groundwater (Bornman et al., 2019; Anozie et al,. 2026). Contaminated soil particles may also transport adsorbed endocrine-disrupting compounds into receiving water bodies. Chemicals such as atrazine, chlorpyrifos, methoxychlor, and glyphosate have been detected in surface waters near agricultural areas and associated with reproductive and developmental abnormalities in aquatic organisms (Gore et al., 2019; Demeneix et al., 2021). Livestock operations may also release natural and synthetic hormones through manure, which can leach into surrounding ecosystems (Nagel et al., 2020). Agricultural runoff is therefore an important exposure pathway for endocrine-active chemicals.

### 4.2.2 Industrial effluents

Industrial effluents are another significant source of EDCs. Manufacturing, petrochemical, textile, pharmaceutical, mining, and waste-treatment activities may generate wastewater containing polychlorinated biphenyls (PCBs), dioxins, heavy metals, plastic additives, and perfluoroalkyl substances (Heindel et al., 2020). In developing countries, inadequate wastewater treatment and weak regulatory enforcement may result in untreated or partially treated effluents entering rivers and coastal waters.
Many industrial contaminants are persistent and bioaccumulative. PCBs and dioxins can remain in sediments for decades, while cadmium, lead, mercury, and arsenic may accumulate in soils and aquatic organisms (Bourguignon et al., 2018; Demeneix et al., 2021). Continued exposure has been associated with endocrine alterations, reduced reproductive success, and biodiversity loss (Flaws et al., 2020).

### 4.2.3 Municipal wastewater

Municipal wastewater is an important pathway for EDCs entering aquatic ecosystems. Domestic sewage contains pharmaceuticals, personal care products, detergents, plasticizers, hormones, and household chemicals (Olea et al., 2020). Although wastewater treatment plants remove many conventional pollutants, several EDCs may only be partially removed and can enter receiving waters through treated effluents (WHO & UNEP, 2022).

Bisphenol A, triclosan, parabens, phthalates, and synthetic estrogens have been detected in municipal wastewater and downstream ecosystems (Vela-Soria et al., 2021). Sewage sludge may also contain concentrated EDCs and reintroduce them into the environment when applied to agricultural land (Nagel et al., 2020).

### 4.2.4 Atmospheric deposition

Atmospheric deposition transports EDCs, particularly semi-volatile and persistent compounds, over long distances. Industrial emissions, combustion, waste incineration, agricultural spraying, and volatilization from contaminated soils and water release chemicals as gases, aerosols, or particles (WHO & UNEP, 2022). These contaminants may subsequently be deposited through rainfall, snowfall, or dry settling. Persistent pollutants such as dioxins, PCBs, and some pesticides have been detected far from their original sources, demonstrating the importance of atmospheric transport (Demeneix et al., 2021). Atmospheric deposition can contaminate agricultural land, forests, rivers, and marine ecosystems, increasing exposure risks for wildlife and humans (Bornman et al., 2019).

### 4.2.5 Bioaccumulation and biomagnification

Bioaccumulation occurs when organisms absorb contaminants faster than they can eliminate them, while biomagnification refers to increasing contaminant concentrations at successive trophic levels (Heindel et al., 2020). EDCs such as PCBs, dioxins, mercury, and perfluoroalkyl substances can accumulate in organisms and biological tissues (Bourguignon et al., 2018; WHO & UNEP, 2022). Predatory species may contain particularly high concentrations because they consume contaminated prey. Accumulation of EDCs has been associated with reproductive impairment, developmental abnormalities, immunosuppression, and population declines in wildlife (Flaws et al., 2020; Swan et al., 2021).

### 4.3 Ecological effects of endocrine disrupting chemicals on reproduction and development

EDCs can interfere with hormonal signalling that regulates growth, sexual differentiation, maturation, and reproduction. Exposure during sensitive developmental stages may cause lasting physiological changes, reduce reproductive fitness, and threaten populations (Gore et al., 2019; Flaws et al., 2020). These effects have been documented in aquatic organisms, amphibians, reptiles, birds, and mammals.

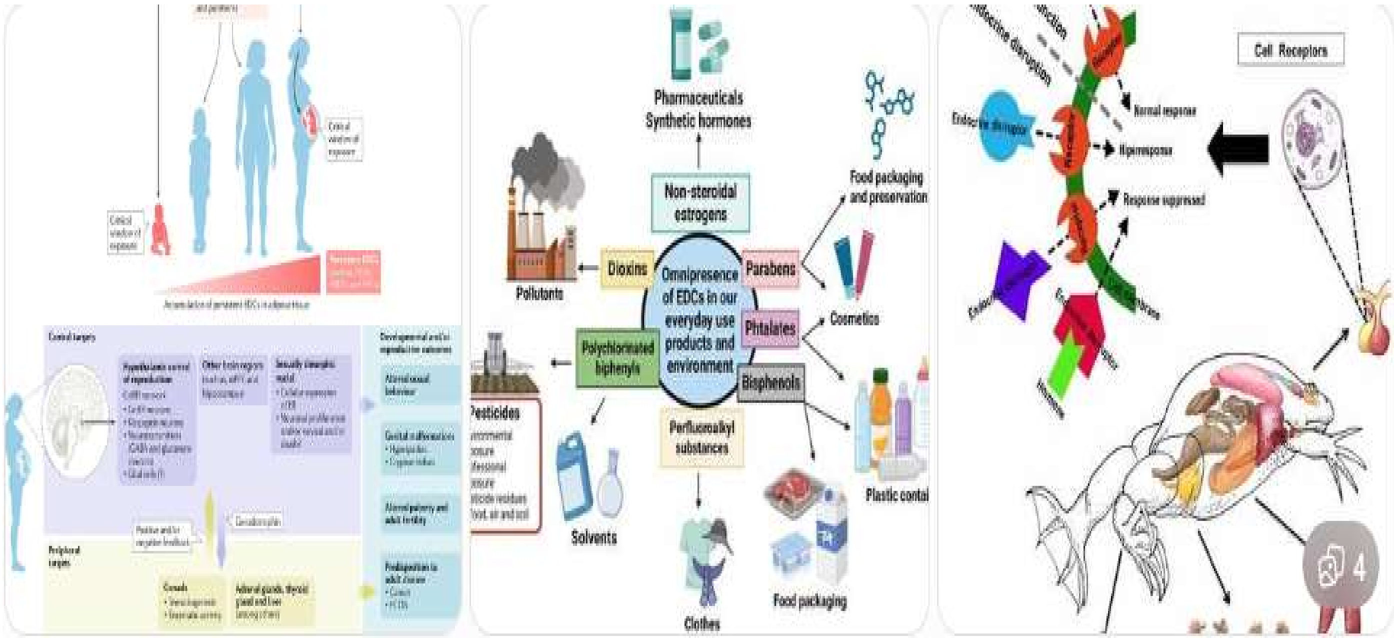


Figure **4.** EDCs and reproductive/developmental effects

### 4.3.1 Effects on aquatic organisms

Aquatic ecosystems often receive EDCs from agricultural, industrial, and domestic sources, resulting in continuous exposure of fish and other organisms (WHO & UNEP, 2022). A common effect in fish is feminization, in which males develop female characteristics following exposure to estrogenic substances such as bisphenol A, synthetic estrogens, and some pesticides (Gore et al., 2019). Effects may include production of egg yolk proteins, ovarian tissue development, and altered reproductive behaviour. EDCs have also been associated with intersex conditions in fish exposed to wastewater containing hormones and pharmaceutical residues (Nagel et al., 2020). Long-term exposure may reduce egg production, sperm quality, fertilization success, and larval survival, ultimately affecting fish populations and aquatic biodiversity (Flaws et al., 2020).

### 4.3.2 Effects on amphibians and reptiles

Amphibians and reptiles are particularly vulnerable because of their permeable skin, aquatic developmental stages, and sensitivity to hormonal regulation. Exposure may cause developmental deformities such as limb malformations, spinal abnormalities, craniofacial defects, and impaired organ development (Bornman et al., 2019). Altered sex differentiation is another important consequence. Atrazine exposure has been associated with feminization and hermaphroditism in male frogs through increased aromatase activity and estrogen synthesis (Demeneix et al., 2021). Similar endocrine-related abnormalities have been reported in reptiles from contaminated environments (WHO & UNEP, 2022).

### 4.3.3 Effects on birds and mammals

Birds and mammals may be exposed through contaminated food, inhalation, and maternal transfer. EDCs can reduce avian hatchability and increase embryonic mortality (Flaws et al., 2020). Persistent pollutants such as dioxins and PCBs may accumulate in eggs, impair embryonic development, and reduce chick survival. In mammals, EDC exposure has been associated with reduced fertility, abnormal reproductive cycles, decreased sperm production, and spontaneous abortions (Bourguignon et al., 2018). Studies involving bisphenol A, phthalates, and pesticides have also reported reproductive organ abnormalities, hormonal imbalance, and reduced offspring viability (Heindel et al., 2020).

### 4.3.4 Developmental effects

Exposure during embryonic, fetal, or juvenile development can cause embryotoxicity, including impaired growth, developmental arrest, or death (Nagel et al., 2020). EDCs have also been associated with congenital abnormalities affecting reproductive organs, the skeleton, brain, and endocrine glands (Soto et al., 2017). Prenatal exposure may result in delayed maturation, reduced growth, and altered developmental processes in wildlife and humans (Demeneix et al., 2021). Such effects can reduce survival and reproductive capacity later in life.

### 4.3.5 Population-level consequences

The combined effects of reproductive impairment, developmental abnormalities, and reduced offspring survival may result in population decline, particularly among species with low reproductive rates or restricted habitats (Bornman et al., 2019). Declining populations may become more vulnerable to extinction and environmental change. Changes in species abundance can also cause biodiversity loss and alter predator-prey relationships, nutrient cycling, and ecosystem stability (WHO & UNEP, 2022). Thus, EDCs may contribute to ecosystem imbalance and reduced ecological resilience.

## 5.0 Human health implications of exposure to endocrine disrupting chemicals

Humans may be exposed to EDCs through contaminated food and water, polluted air, skin contact, and occupational activities. Because hormones regulate many physiological processes, endocrine disruption may increase susceptibility to chronic diseases (Gore et al., 2019; Heindel et al., 2020).

### 5.1 Reproductive disorders

EDCs such as bisphenol A, phthalates, pesticides, and heavy metals have been associated with reduced sperm concentration and motility, poor semen quality, infertility, and testicular dysfunction in men (Hunt et al., 2017; Swan et al., 2021, Olugbenga et al., 2023). In women, exposure may contribute to menstrual irregularities, polycystic ovarian syndrome, endometriosis, miscarriage, and reduced fertility (Flaws et al., 2020). Prenatal exposure may also affect reproductive development.

### 5.2 Hormone-dependent cancers

Some EDCs possess estrogenic or anti-androgenic properties that can influence abnormal cell proliferation. Exposure to bisphenol A, dioxins, cadmium, and certain pesticides has been associated with breast, ovarian, prostate, and testicular cancers (Bourguignon et al., 2018; Heindel et al., 2020). Possible mechanisms include altered hormone receptor activity, oxidative stress, and changes in gene expression.

### 5.3 Neurodevelopmental disorders

The developing nervous system is particularly sensitive to hormonal disturbances. EDC exposure has been linked to cognitive and behavioural abnormalities and may affect neurodevelopment (Demeneix et al., 2021). Mercury, lead, PCBs, and bisphenol A can interfere with thyroid hormone signalling and neuronal development (Nagel et al., 2020).

### 5.4 Metabolic diseases
Some EDCs act as metabolism-disrupting chemicals by affecting lipid metabolism, insulin sensitivity, and energy balance (Heindel et al., 2020). Bisphenol A, phthalates, and perfluoroalkyl substances have been associated with obesity, type 2 diabetes, hypertension, and cardiovascular disease (Nadal et al., 2017). These effects may involve altered adipogenesis, pancreatic function, and appetite-regulating hormones.

### 5.5 Thyroid dysfunction
EDCs can interfere with thyroid hormone synthesis, transport, receptor binding, and metabolism (Zoeller et al., 2018). PCBs, perchlorates, bisphenol A, and perfluoroalkyl substances have been associated with altered thyroid hormone concentrations and developmental effects (Bourguignon et al., 2018; WHO & UNEP, 2022). Because thyroid hormones are essential for metabolism, growth, and neurodevelopment, thyroid disruption represents an important health concern.

## 6.0 Detection and monitoring of endocrine disrupting chemicals
Effective management requires accurate detection, identification, and monitoring of EDCs. Because these chemicals often occur at very low concentrations and as complex mixtures, sensitive analytical methods are necessary (Vela-Soria et al., 2021; WHO & UNEP, 2022). Major approaches include chromatography, biosensors, bioassays, laboratory toxicity tests, and environmental monitoring programmes.

### 6.1 Chromatographic techniques
Chromatography is widely used because of its sensitivity, selectivity, and ability to separate complex mixtures (Vela-Soria et al., 2021).

### 6.2 GC–MS
Gas Chromatography–Mass Spectrometry (GC–MS) is used to detect volatile and semi-volatile EDCs, including pesticides, PCBs, dioxins, and plasticizers. Its high sensitivity makes it suitable for trace analysis in water, sediments, and biological tissues (WHO & UNEP, 2022).

### 6.3 LC–MS/MS
Liquid Chromatography–Tandem Mass Spectrometry (LC–MS/MS) is particularly useful for non-volatile, thermally unstable, and polar compounds. It can detect pharmaceuticals, synthetic hormones, perfluoroalkyl substances, bisphenol A, and personal care product residues, often allowing multiple compounds to be measured simultaneously (Vela-Soria et al., 2021).

### 6.4 HPLC
High-Performance Liquid Chromatography (HPLC) is used to analyse parabens, phytoestrogens, pharmaceuticals, and industrial chemicals (Olea et al., 2020). Its versatility allows coupling with ultraviolet, fluorescence, or mass spectrometric detectors.

### 6.5 Biosensors and bioassays
Biosensors use biological recognition elements such as enzymes, antibodies, receptors, or nucleic acids to detect EDCs and may provide rapid or real-time monitoring (Vela-Soria et al., 2021). Bioassays evaluate biological activity rather than simply measuring chemical concentrations. Reporter gene, receptor-binding, and yeast estrogen-screen assays can assess estrogenic, androgenic, and thyroid-related activity (Gore et al., 2019). They are particularly useful for evaluating mixtures.

### 6.6 *In vivo* and *in vitro* assays
In vivo assays use organisms such as fish, amphibians, rodents, and birds to assess physiological, developmental, and reproductive effects (OECD, 2021). In vitro assays use cells, tissues, enzymes, or receptors to investigate specific endocrine mechanisms. These methods are generally faster, less expensive, and reduce animal use (Gore et al., 2019). Both approaches can complement each other in comprehensive assessments.

## 7.0 Environmental monitoring programs
Environmental monitoring involves systematic sampling of rivers, lakes, groundwater, soil, sediments, wastewater, and biological organisms to determine the occurrence and distribution of EDCs (WHO & UNEP, 2022). Monitoring programmes may combine chemical analysis, biological assessments, and human biomonitoring to identify contamination hotspots and evaluate pollution-control measures (European Environment Agency, 2020).

### 7.1 Control and management strategies
Controlling EDCs requires regulatory measures, improved treatment technologies, sustainable production, safer chemical design, and public education (WHO & UNEP, 2022).

### 7.2 Regulatory measures
Governments and international organizations develop policies to identify, assess, restrict, and phase out hazardous endocrine-active chemicals (OECD, 2021). PCBs, some pesticides, and other industrial chemicals have been banned or restricted because of their persistence and adverse effects (WHO & UNEP, 2022). Stronger enforcement and international cooperation remain important.

### 7.3 Advanced wastewater treatment technologies
Conventional treatment may not completely remove EDCs. Advanced technologies, including activated carbon, membrane filtration, advanced oxidation, ozonation, photocatalysis, and biological treatment, can improve contaminant removal (Vela-Soria et al., 2021). These approaches can reduce concentrations of hormones, pharmaceuticals, pesticides, and other endocrine-active compounds before wastewater enters aquatic ecosystems (WHO & UNEP, 2022).

### 7.4 Sustainable agricultural practices
Integrated pest management, biological control, crop rotation, precision agriculture, and reduced pesticide use can decrease agricultural chemical inputs and runoff (Bornman et al., 2019). Sustainable livestock management and responsible veterinary pharmaceutical use can further reduce hormone contamination (Flaws et al., 2020).

### 7.5 Green chemistry approaches
Green chemistry promotes chemicals and production processes with lower toxicity, persistence, and environmental impact (Heindel et al., 2020). Replacing hazardous substances with safer alternatives can reduce EDC contamination in consumer products and industrial systems (WHO & UNEP, 2022).

### 7.6 Public awareness and risk communication
Public education about EDC sources, exposure pathways, and health effects can encourage safer consumer choices and environmental behaviour (European Environment Agency, 2020). Effective communication should involve governments, researchers, industries, educational institutions, healthcare professionals, and the media. Clear evidence-based information can help communities reduce exposure and support pollution prevention (WHO & UNEP, 2022).

## 8.0 Emerging issues and future research directions
Important uncertainties remain concerning the occurrence, toxicity, environmental fate, and long-term effects of EDCs. Current research increasingly focuses on mixture toxicity, low-dose exposure, epigenetic biomarkers, safer alternatives, and computational tools (Gore et al., 2019; WHO & UNEP, 2022).

### 8.1 Chemical mixtures and combined effects
Humans and wildlife are usually exposed to mixtures rather than individual EDCs. Pesticides, industrial chemicals, pharmaceuticals, plasticizers, and natural hormones may interact to produce additive, synergistic, or antagonistic effects (Heindel et al., 2020). Some mixtures can cause biological responses even when individual chemicals occur below their toxicity thresholds (Gore et al., 2019). Future research should therefore emphasize mixture toxicology and cumulative exposure assessment.

### 8.2 Low-dose exposure effects
EDCs may produce non-monotonic dose-response relationships in which low doses cause effects not observed at higher concentrations (Vandenberg et al., 2017). Low-level exposure to bisphenol A, phthalates, synthetic estrogens, and other EDCs during prenatal or early-life development may cause persistent endocrine, metabolic, or neurological changes (Demeneix et al., 2021; Nagel et al., 2020). Further research is needed to clarify these mechanisms and establish protective exposure limits.

### 8.3 Epigenetic biomarkers

EDCs can alter DNA methylation, histone modification, and non-coding RNA expression, potentially producing effects that persist beyond initial exposure (Heindel et al., 2020). These changes have been linked to reproductive, metabolic, neurodevelopmental, and cancer-related outcomes. Genomics, transcriptomics, and epigenomics may improve understanding of endocrine disruption and support early detection of health effects (Demeneix et al., 2021).

### 8.4 Safer chemical design

Safer chemical design aims to produce substances that perform useful functions while minimizing toxicity, persistence, and bioaccumulation (WHO & UNEP, 2022). Replacing hazardous substances with safer alternatives can reduce contamination. Future research should evaluate the endocrine-disrupting potential of substitute chemicals before widespread commercialization (Heindel et al., 2020).

### 8.5 Artificial intelligence and high-throughput screening in EDC research

Artificial intelligence and high-throughput screening are increasingly being applied to endocrine-disruption research. Machine-learning models and computational toxicology can identify chemical characteristics associated with endocrine activity and predict toxicity while reducing reliance on animal testing (OECD, 2021). High-throughput platforms can simultaneously evaluate large numbers of chemicals using assays measuring receptor interactions, gene expression, and cellular responses (Gore et al., 2019). Integrating these technologies may accelerate hazard identification, improve risk assessment, and support evidence-based regulation.

## Findings

The findings indicate that endocrine-disrupting chemicals (EDCs) are important environmental contaminants because they interfere with normal hormonal functions and consequently affect reproduction, development, metabolism, immunity, and behaviour. EDCs can mimic natural hormones, block hormone receptors, alter hormone synthesis, interfere with hormone transport and metabolism, and induce epigenetic changes. Their effects may occur even at low concentrations, particularly during sensitive developmental periods such as embryonic development, fetal life, infancy, and puberty. The study identifies agricultural, industrial, domestic, pharmaceutical, and consumer activities as major sources of EDCs**.** Agricultural pesticides and herbicides, including DDT, atrazine, chlorpyrifos, and methoxychlor, can contaminate soils and water bodies. Industrial chemicals such as polychlorinated biphenyls (PCBs), dioxins, and per- and polyfluoroalkyl substances (PFAS) are persistent and may remain in the environment for long periods. Pharmaceuticals and personal-care products, including synthetic estrogens, parabens, and triclosan, enter aquatic systems mainly through wastewater. Plastics and plasticizers, particularly bisphenol A (BPA) and phthalates, are also significant sources of endocrine-active contaminants. The findings further show that EDCs are transported through agricultural runoff, industrial effluents, municipal wastewater, atmospheric deposition, and waste disposal**.** Persistent chemicals can bioaccumulate in organisms and biomagnify through food chains, resulting in higher concentrations in organisms at higher trophic levels. This increases the exposure of predators and may intensify ecological impacts.

A major finding is that EDCs adversely affect reproduction in aquatic and terrestrial organisms**.** In fish, exposure to synthetic estrogens and other endocrine-active chemicals can cause feminization of males, intersex conditions, reduced sperm production, decreased egg production, impaired fertilization, and reduced reproductive success. Amphibians and reptiles may experience abnormal sexual differentiation, developmental deformities, and impaired metamorphosis. Birds and mammals may experience reduced fertility, abnormal reproductive development, embryonic mortality, and reduced offspring survival.

The findings also demonstrate that developmental exposure can produce persistent biological effects**.** Exposure during embryonic, fetal, or juvenile development may interfere with sexual maturation, organ development, nervous-system development, and endocrine function. Epigenetic mechanisms, including changes in DNA methylation and histone modification, may contribute to long-term effects. Experimental evidence further suggests that some EDC-related effects may extend to subsequent generations. At the population level, reduced fertility, developmental abnormalities, and decreased offspring survival may contribute to population decline, biodiversity loss, and disruption of food-web relationships**.** These effects demonstrate that endocrine disruption is not limited to individual organisms but can influence ecosystem stability.

Overall, the findings establish that EDCs pose significant risks to reproductive health, development, biodiversity, and ecosystem sustainability. The review highlights the need for stronger environmental monitoring, improved wastewater treatment, sustainable agricultural practices, stricter chemical regulation, and safer chemical alternatives. Future research should particularly address low-dose exposure, chemical mixtures, epigenetic effects, transgenerational consequences, and population-level impacts to improve environmental risk assessment and management.

## Conclusion

Endocrine disrupting chemicals constitute a diverse group of environmental contaminants capable of interfering with the normal functioning of hormonal systems in humans and wildlife. Their widespread occurrence in agricultural products, industrial materials, pharmaceuticals, plastics, personal care products, and natural substances has contributed to increasing levels of environmental contamination. Through mechanisms such as hormone mimicry, receptor antagonism, alteration of hormone synthesis and metabolism, and epigenetic modifications, these chemicals adversely affect reproductive processes, developmental outcomes, and ecosystem stability. Evidence from experimental and epidemiological studies indicates that exposure to endocrine disrupting chemicals is associated with reproductive disorders, developmental abnormalities, metabolic diseases, neurodevelopmental impairments, thyroid dysfunction, and hormone-dependent cancers. Their persistence, tendency to bioaccumulate, and potential for transgenerational effects further amplify ecological and public health concerns. Although significant advances have been made in the detection, monitoring, and regulation of endocrine disrupting chemicals, emerging challenges such as mixture toxicity, low-dose effects, and the identification of safer alternatives require sustained scientific attention. Effective management of endocrine disrupting chemicals therefore remains essential for protecting biodiversity, maintaining ecosystem balance, and safeguarding human health.

## Recommendations

Based on the findings of this study, governments should strengthen regulations on the production, use, and disposal of endocrine-disrupting chemicals (EDCs). Industries should adopt green chemistry and develop safer alternatives, while advanced wastewater treatment and sustainable agricultural practices should be promoted. Environmental monitoring programmes should be expanded to detect EDCs in environmental and biological samples. Public education should also be intensified to reduce exposure risks. Finally, researchers should prioritize investigations into chemical mixtures, low-dose effects, epigenetic changes, and transgenerational impacts of EDC exposure.

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