Advances in Bioresearch
Adv. Biores., Vol 17 (5) May 2026: 39-67

Print ISSN 0976-4585; Online ISSN 2277-1573
Journal's URL:http://www.soeagra.com/abr.html
CODEN: ABRDC3
DOI: 10.15515/abr.0976-4585.17.5.3967

Advances in Bioresearch

REVIEW ARTICLE

Developmental Exposure to Endocrine Disrupting Chemicals: An Emerging Risk Factors for Neuro-Cardio-Renal Health

Nishant Tiwari, Sangeeta Dwivedi* and G.N. Dharwekar
Department of Pharmacology, Acropolis Institute of Pharmaceutical Education and Research, Indore, M.P-4533771
***Corresponding Author**: Sangeeta Dwivedi
Email: sangeetadwivedi@acropolis.edu.in
Orchid id: 0000-0001-7106-4210

ABSTRACT
The Developmental Origins of Health and Disease (DOHaD) premise suggest that early life exposure to endocrine-disrupting chemicals (EDCs) can have long-term health consequences, including intensified susceptibility to chronic disease in adult life. Epidemiological studies and experimental finding suggest that an unsuitable fetal conditions, particularly EDC exposure, leaves a enduring impact on development and jeopardizes long-term health consequences. EDC exposure in utero interferes with endocrine signaling, which disrupts the development and functioning of neuro, cardio and renal health. This review feature epigenetic mechanisms such as DNA methylation, histone modification, and regulation of non-coding RNA (ncRNA) as central mechanisms of prime concern. Such interference shows increased vulnerability to subsequent late-life neuro-cardio-renal health outcomes, with gene expression and organ development perturbed in a manner that predisposes to disease. The prenatal exposure to EDCs affects neuro-cardio-renal health not only informing disease aetiology, but provides a wider context to explore the impact of other environmental stressors on developmental impairment and adult disease.
Keywords: *Prenatal, EDCs, Brain, Cardiovascular, Kidney, Epigenetics*

Received 24.12.2025 Revised 04.03.2026 Accepted 18.05.2026

How to cite this article:
Nishant T, Sangeeta D and Dharwekar, G.N. Developmental Exposure to Endocrine Disrupting Chemicals: An Emerging Risk Factors for Neuro-Cardio-Renal Health. Adv. Biores. Vol 17 [5] May 2026. 39-67

INTRODUCTION

Endocrine disrupting chemicals (EDCs) a wide range of chemicals agents which can be natural or anthropogenic, these compounds have capability of interfering with the biosynthesis storage, release, transport, and/or receptor binding of endogenous hormones, ultimately interfering with the proper functions of these hormones, signaling processes, protein synthesis, gene expression etc (1). The United State-Environmental Protection Agency (US-EPA) identified more than 86,000 substances as endocrine disruptors through the Toxic Substances Control Act, however small fraction of these EDCs has been tested for their potential health outcomes (2). EDCs includes variety of chemicals, pesticides, herbicides, heavy metals, flame retardants, UV filter components, triclosan, persistent organic pollutants (POPs), and organochlorines, plastics and plasticizers such as phenols, phthalates, parabens, bisphenols, and polychlorinated biphenyls (PCBs), polybrominated biphenyls (PBBs), dichlorodiphenyltrichloroethane (DDT), vinclozolin, diethylstilbestrol (DES), Per- and polyfluoroalkyl substances (PFAS) such as Perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS). On a daily basis, people could be exposed to EDCs through packaged foods, plastics, cosmetics, and pharmaceuticals in multiple personal and occupational settings. Various epidemiological and animals-based studies have had been shown that exposure of these EDCs in adult stage has been linked abnormal reproductive male and female health, obesity, diabetes, metabolic disorders, hypertension, neurological disorder, immune alterations, kidney disease, lungs problems, hormonal imbalance (3, 4). Gradual exposure to EDCs presents significant health risks to the exposed individuals (5). Numerous studies, including those conducted by the National Health and Nutrition Examination Survey (NHANES), indicate that an alarming 75% to 97% of adults in the

United States and Asia have detectable levels of harmful substances such as phthalates and phenols—most notably bisphenol A (BPA) and polyfluoroalkyl substances—in their urine. Apart from the exposure in adults, various studies prove that children are also sensitive to the EDCs. This concerning prevalence highlights the urgent need for increased awareness and action regarding the widespread impact of EDCs on public health. Research indicates that while exposure to (EDCs) can have negative health effects in adults, developing fetuses may be even more susceptible due to their rapid growth and cellular development (6, 7). The harmful effects on a developing fetus can be significantly amplified at EDC concentrations that are much lower than currently accepted limits. Numerous epidemiological studies indicate that pregnant women are almost universally exposed to (EDCs) (8-11). During gestational period the Brain, Heart and kidney are the most vital, sensitive, immature and have relatively less potential to hold the burden of drugs and chemicals to minimize & eliminate their effects on the body. Animal studies using real-world EDC mixtures (NeuroMix) have shown sex-specific alterations in puberty timing, anxiety, social behavior, and mate preference**,** with gene expression changes in the brain (12)**.** Notably, prenatal BPA exposure disrupted hippocampal gene networks tied to both autism and Alzheimer's disease, with upregulated NF-κB, Bace1, and TNF, suggesting early inflammatory programming that may increase Alzheimer's risk (13). Additionally, rodent studies indicate that EDCs can induce epigenetic alterations that are transgenerational, affecting cardio and renal health (14-16). In the present review, the effects of EDCs exposure on the neuro-cardio-renal health in prenatal, perinatal, and early-life have been described based on experimental and epidemiological evidence available. What are the common and unifying molecular mechanisms, which may be involved across multiple EDCs, have been also explained.

PREVALENCE OF EDCS-ASSOCIATED NEURODEVELOPMENTAL, CARDIOVASCULAR, AND RENAL DISORDER SURVEILLANCE 2020-2025

The data presented in the (fig 1). illustrates a markable upward trajectory in EDCs exposure incidence across three vital organ systems from 2020 to 2025. Neurodevelopmental disorders show the soaring pervasiveness, increasing from 14.6% to 16.9%, followed by cardiovascular disorders rising from 12.2% to 14.5%, and renal disorders climbing from 9.8% to 11.4%. This epidemiological correlation aligns with boundless research showing that EDC exposure during crucial developmental windows can disrupt hormonal signaling pathways essential for proper organ system maturation and function. Neurodevelopmental impact research has built concrete associations between prenatal EDC exposure and cognitive dysfunction, with metals showing particularly destructive effects (β coefficient: -0.55; 95% CI: -1.08 to -0.02) on offspring cognition in children aged 1-3 years. Studies proves that approximately 12% of children in the United States are affected by neurodevelopmental disorders, including attention deficit hyperactivity disorder, learning disabilities, and autism spectrum disorders. The mechanistic insight involves EDCs' ability to interfere with thyroid hormone signaling and affect neural development through incomplete gene methylation regions in the developing brain. Studies have demonstrated that prenatal exposure to metals, phthalates, and per-fluoroalkyl substances particularly impairs motor development (17), with phthalates showing β coefficient of -0.69 (95% CI: -1.05 to -0.33) for motor function decline. The effect on CVS is mediated through various pathways, with BPA shows significant cardiotoxic potential through disruption of Ca^{+} channel functioning and oxidative stress. Studies reveals that BPA exposure at concentrations as minimal as 1 nmol/L can rapidly induce arrhythmogenic effects in female cardiac myocytes and alter Ca^{+} handling mechanisms. Epidemiological studies have established strong relation between EDC exposure and elevated risk of hypertension, endothelial dysfunction, and arterial stiffness. The effect on CVS is particularly noticeable through hormone receptor binding, where EDCs mimic, block and alter natural hormones balance, leading to abnormal signaling pathways that result in metabolic disruption and atherosclerosis development. Renal system dysfunction from EDC exposure has been reported through longitudinal studies indicating elevated mono-(2-ethylhexyl) phthalate (MEHP) levels associated with increased urinary albumin-to-creatinine ratio and predicting >15% decline in estimated GFR (18). Chronic exposure to di(2-ethylhexyl) phthalate has been demonstrated to cause significant decline in kidney function, as demonstrated by reduced creatinine clearance in animal studies (19). Additional studies indicates that phthalate exposure is associated with increased mortality risk, noticeably in CKD patients, with lethal ratios of 1.47 (95% CI: 1.18, 1.84) for co-exposure to multiple phthalates.

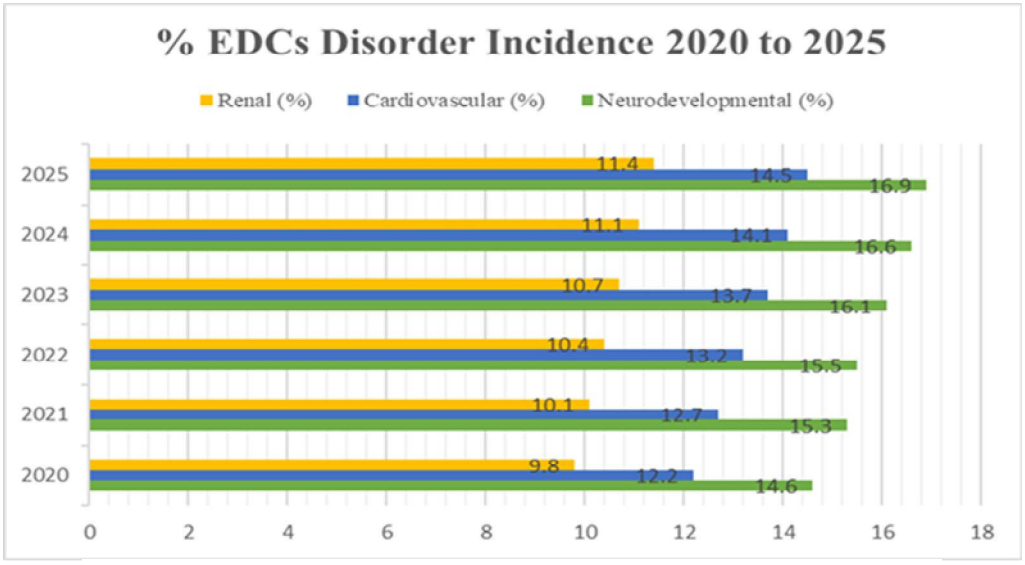

Figure 1: The Growing Burden of Environmental Endocrine Disruption

Multi-System Health Impact Assessment 2020-2025: The chart presents the annual percentages of EDC-associated disorder incidence from 2020 to 2025, highlighting the progressive increase in neurodevelopmental, cardiovascular, and renal health impacts due to developmental exposure to endocrine disrupting chemicals. The data underscores the higher burden on neurodevelopmental health, followed by cardiovascular and renal systems, emphasizing the urgent need for mitigation and prevention strategies in environmental health surveillance.

PRENATAL EXPOSURE TO EDCS AND ASSOCIATIONS WITH NEUROLOGICAL DISORDERS

During fetal development, the brain undergoes rapid growth and differentiation, making it highly susceptible to environmental insults. (9, 20) Among these, prenatal exposure to EDCs has emerged as a growing concern (21, 22). Common EDCs such as PFAS, bisphenol substitutes (BPS, BPF), flame retardants (PBDEs), phthalates, parabens, pesticides, heavy metals, and triclosan can cross the placenta and interfere with hormonal and epigenetic regulation (23-25). Such disruptions during critical windows of development may impair neuronal maturation, synaptic connectivity, and neurotransmitter signaling, thereby increasing the risk of cognitive impairments, autism spectrum disorders, ADHD, and later-life neurodegenerative conditions (26-28). EDCs including organochlorines, PFAS, phthalates, bisphenols (BPA, BPAF), flame retardants (PBDEs), PCBs, dioxins, perchlorate, heavy metals, siloxane (D4), atrazine, neonicotinoids, phytoestrogens, methoxychlor, and complex mixtures, have been consistently associated with adverse neurodevelopmental and cognitive outcomes in human populations across diverse study designs, including prospective birth cohorts, case-control and longitudinal studies, registry analyses, population-based assessments, and systematic reviews/meta-analyses shown in (table 1) (29-33). Evidence from studies published between 2016 and 2023 demonstrates that prenatal and early-life exposures are linked to language delays (34-37), reduced IQ, impaired executive function and memory, diminished attention span, behavioural inflexibility, social skill delays, increased risk of autism spectrum disorder (ASD) and attention-deficit/hyperactivity disorder (ADHD), seizure and epilepsy disorders, emotional dysregulation, sensory processing deficits, anxiety, depression, and even elevated susceptibility to neurodegenerative disease later in life (38-43). Mechanistic findings converge across studies: EDCs disrupt hormone receptor signaling (ER, AR, ERβ, thyroid, GABAergic, cholinergic, nicotinic), reduce thyroid hormone levels critical for brain development (9), act as estrogenic or anti-androgenic modulators altering synaptogenesis and myelination (23, 25, 31) impair neuronal progenitor proliferation and induce apoptosis (24), disrupt excitatory/inhibitory neurotransmitter balance and dopaminergic/serotonergic pathways (21, 36), and cause persistent oxidative stress, mitochondrial dysfunction, microglial activation, and chronic neuroinflammation (22, 27). Several studies demonstrate that exposures interfere with neurogenesis and network stability, for example, PBDEs/PCBs through thyroid hormone transport interference (29), perchlorate via direct synthesis inhibition (42), and pesticides including atrazine and neonicotinoids through GABAergic and nicotinic dysregulation (41). Importantly, EDC mixtures produce synergistic and additive effects through multi-receptor antagonism, heightened oxidative burden, and coordinated endocrine-immune dysregulation, often amplifying risks

beyond those of single compounds (20, 26, 35, 44). Across these epidemiological findings represented in (table 1), epigenetic reprogramming emerges repeatedly as a unifying pathway, involving DNA methylation alterations, histone modifications, and disturbed gene expression in synaptic and neurotransmitter pathways, with some studies reporting transgenerational inheritance of neurobehavioural abnormalities following maternal exposure to mixtures (26). Collectively, this expanding body of evidence indicates that prenatal and early postnatal periods represent critical windows of vulnerability, during which even low-dose exposures to EDCs can durably re-shape brain developmental trajectories.

Table 1: Epidemiological studies related to Developmental exposure to Endocrine disrupting chemicals affecting the brain and neurological health.

S. No.	EDC Category	Study Type	Detailed Key Findings & Mechanism of Action in Neurological Disorders/Inferences	Year	Reference
1	Heavy Metals, Phthalates, PFAS	Cohort study	Exposures linked to poorer neurocognitive scores, language delays; mechanisms are oxidative stress, calcium/thyroid hormone disruption, and neuroinflammatory signaling in the developing brain.	2025	(27)
2	Phthalates	Longitudinal Study	In utero phthalate exposure correlated with delayed social skill acquisition and emotional dysregulation; involves androgen/estrogen receptor modulation and altered brain myelination.	2025	(31)
3	BPA, PBDE, Perchlorate	Cohort/Meta-analysis	Higher exposure associated with greater incidence of memory impairment and slower mental processing in childhood; mechanisms involve thyroid hormone axis interference and increased neuronal oxidative stress.	2025	(33)
4	Heavy metals, EDC Mixtures	Prospective Population Study	Increased incidence of language impairments and IQ deficits; mechanism includes calcium/thyroid hormone disruption, oxidative stress, and chronic glial activation.	2025	(27)
5	Multi-EDC Exposure	Registry Study	Increased rates of sleep, mood, and behavioural disorders in exposed populations; mechanisms include hormone receptor interference, neurotransmitter imbalance, and neuroimmune modulation.	2024	(44)

6	Atrazine, Neonicotinoids	Birth Cohort	Increased risk of motor skill deficits and language delays; caused by GABAergic/nicotinic dysregulation, reduced synaptic maturation, and oxidative injury.	2024	(41)
7	Multiple (Organophosphates, Phthalates, Heavy Metals, PFAS)	Review/Meta-analysis	Identified epigenetic reprogramming and persistent gene expression changes as common pathways for neurodevelopmental toxicity across exposure groups.	2023	(38)
8	DDT, Methoxychlor, PCBs	Meta-analysis/Systematic Review	Exposure correlated with increased risk of neurodegenerative disorders and cognitive impairment; persistent estrogenic and thyroid receptor disruption, oxidative stress, and gene methylation changes.	2023	(38)
9	Bisphenols, Phthalates	Population-Based Study	Higher bisphenol and phthalate exposure related to increased anxiety and depression; acts via ER/AR disruption, serotonin pathway alteration, and chronic neuroinflammation.	2023	(36)
10	Flame Retardants, BPA	Cohort/Longitudinal Study	Childhood learning and sensory processing deficits linked to PBDE/BPA exposure; relates to disrupted thyroid signaling, neurogenesis, and excitatory neurotransmitter balance.	2023	(37)
11	EDC Mixtures	Cohort Study	Early-life mixture exposure linked to increased neurodevelopmental disorders; synergistic endocrine receptor antagonism, oxidative stress, and epigenetic remodelling disrupt brain maturation.	2022	(20)
12	Organochlorines, PFAS	Meta-analysis	Prenatal organochlorine/PFAS exposure reduces neonatal thyroxine; maternal thyroid hormone axis disruption impairs fetal brain development and cognitive outcomes.	2022	(9)
13	Heavy metals, organochlorine, PFAS	Prospective Study	Neurocognitive impairment linked to	2021	(30)

			combined exposures; acts via oxidative stress, impaired calcium dynamics, and chronic microglial activation.		
14	Multiple EDCs	Review	Developmental EDC exposure alters neurodevelopment, increases psychiatric disorder risks; mechanisms include hormone receptor modulation, neuroinflammation, epigenetic gene regulation.	2021	(21)
15	Phthalates, PFAS, Heavy Metals	Prospective Cohort Study	Prenatal exposure to phthalates, PFAS, metals correlate with altered adolescent brain white matter; related to neuroimmune changes, oxidative stress, androgen/thyroid hormone signaling disruption.	2021	(22)
16	Siloxane (D4)	Population-Based Study	Prenatal exposure impairs proliferation/survival of neuronal progenitors; mechanism involves apoptosis induction and impaired synaptogenesis, impacting cortical development.	2021	(24)
17	Phthalates, PFAS	Cohort/Population Study	Higher levels during pregnancy related to delayed social skills and increased anxiety; mechanism: androgen/estrogen receptor modulation, myelination deficits, and neuroinflammation.	2021	(22)
18	Multiple EDCs	Longitudinal Cohort Study	Higher prenatal exposure correlated with neurodevelopmental delay, increased prevalence of depression and anxiety in school-age children; action through epigenetic changes and neurotransmitter imbalance.	2021	(43)
19	BPA, Dioxins, PCBs	Systematic Review	Maternal EDC exposure linked to increased rates of ADHD and autistic traits; induction of neuroinflammation, synaptic plasticity disruption, and receptor-mediated transcriptional changes.	2021	(30)

20	Phthalates, Flame Retardants	Birth Cohort	Prenatal phthalate and PBDE exposures associated with lower IQ and working memory in childhood; mechanism through thyroid hormone signaling interference and neurogenesis impairment.	2021	(29)
21	BPA, PCBs	Cross-sectional	Childhood exposure associated with impaired memory and increased risk of ADHD symptoms; involves ER/AR cross-talk, dopamine and serotonin signaling dysregulation, and glial activation.	2021	(21)
22	PCBs, PBDEs	Prospective Cohort	Correlated with decreased attention span and behavioural flexibility; relates to interference with thyroid hormone transport, synapse formation, and neuronal network stability.	2021	(29)
23	Multiple EDCs	Prospective Cohort	Early exposure increased risk for ASD-like behaviours and diminished attention span; multi-receptor dysregulation, oxidative DNA damage, and persistent synaptic connectivity errors are implicated.	2021	(39)
24	Methoxychlor	Retrospective Cohort	Lower verbal memory and executive function in exposed children; estrogen receptor agonist activity, neuroinflammation, and persistent epigenetic changes are contributing factors.	2020	(23)
25	EDC Mixtures	Birth Registry/Case Series	Associations found between EDC mixture exposure and developmental delay in school-aged children; involved multi-receptor antagonism, additive oxidative stress, and methylation changes in neurodevelopmental genes.	2020	(35)
26	BPA, Phthalates	Case-Control	Higher prenatal BPA/phthalate metabolites associated with lower cognitive and executive function scores; mechanisms include ER/AR receptor	2020	(23)

			disruption, neuroinflammation, and synaptic dysfunction.		
27	Multiple EDCs	Prospective Cohort Study	Maternal EDC exposures increased risk of epilepsy and seizure disorders in offspring; mechanism includes thyroid, estrogen, and GABAergic signaling disruption during neurogenesis.	2019	(32)
28	PCB, PBDE, DDT, BPA	Prospective Birth Cohorts	Higher maternal EDC levels increase risk of ASD, ADHD, and cognitive impairment; mechanisms include hormone receptor crosstalk, oxidative stress, and dysregulation of synaptic genes.	2019	(28)
29	PBDE, PCBs, DDT, BPA	Meta-analysis	Association with reduced intelligence and working memory; linked to interference in thyroid hormone pathways, excitatory/inhibitory balance, and persistent oxidative stress.	2019	(28)
30	Phytoestrogens	Population Study	Developmental phytoestrogen exposure correlated with increased anxious behaviours and cognitive delays; ERβ activation, neuroendocrine axis modulation, and altered synaptic gene expression implicated.	2018	(40)
31	BPAF (Bisphenol AF)	Case-Control	Higher BPAF exposure during pregnancy linked to increased behavioural problems in children; ERβ agonism and disruption of synaptic differentiation implicated.	2018	(25)
32	BPAF (Bisphenol AF)	Population Study	Higher perinatal BPAF exposure linked to behavioural deficits in children; associated with ERβ agonist activity, disruption of synaptic formation, and altered neuronal differentiation.	2018	(25)

Animal studies provide compelling mechanistic evidence given in (table 2) that (EDCs) impair neurodevelopment across species. Developmental exposure to BPA in mice impaired hippocampal synaptic plasticity and memory via estrogen receptor agonism, disrupting excitatory–inhibitory balance and long-term potentiation (12). In rats, prenatal BPA induced depression-like phenotypes through serotonergic disruption, HPA-axis dysregulation, and epigenetic stress gene modifications (45), while another rat study reported autism-like stereotyped behaviours linked to cortical transcriptional changes, neuroinflammation, and aberrant synaptogenesis represented in (table 2) (46). In zebrafish, low-dose

BPA altered dopamine/glutamate neurotransmission producing hyperactivity (47). Analogue compounds such as BPS and BPF disrupted neuronal differentiation and memory in zebrafish through estrogen receptor mimicry, oxidative damage, and synaptic maturation defects (48-50). Phthalates including DEHP and DBP in rats triggered anxiety- and depression-like behaviours via androgen/estrogen signaling disruption and mitochondrial ROS impairing dopamine/serotonin pathways (51), while in mice DEHP reduced hippocampal neurogenesis and spatial learning through oxidative stress and steroid receptor interference (52); mixtures of phthalates with pesticides amplified hippocampal neuroinflammation and memory deficits (53), and perinatal exposure in rats produced serotonergic disruption leading to depressive phenotypes (54). Chlorpyrifos, an organophosphate, caused cholinergic dysfunction with hypoactivity and memory deficits in zebrafish via acetylcholinesterase inhibition and synaptic disruption (55), while rats showed impaired attention and ADHD-like hyperactivity accompanied by glial activation and cortico-striatal abnormalities (table 2) (56). PCBs reduced dendritic spine density, cortical connectivity, and spatial memory in mice by disrupting thyroid hormone-regulated maturation and calcium homeostasis (57). PBDEs induced hyperactivity and attention deficits in rats ((58), autistic-like traits in mice through thyroid hormone disruption and oxidative DNA damage (59), and impaired working memory in rats when exposed as mixtures through reduced synaptogenesis and thyroid interference (60). PCB+PBDE mixtures provoked persistent memory impairment and glial activation in rats (61). PFAS such as PFOS impaired hippocampal neurogenesis and memory in rats by inducing mitochondrial ROS and deregulating calcium signaling (62), and in mice, combined PFOA/PFOS exposure impaired synaptic plasticity and cognitive flexibility through disrupted calcium handling and microglial activation (table 2) (63). Dioxins (TCDD) altered dopaminergic development in rats, increasing vulnerability to Parkinsonian outcomes via AhR activation and oxidative stress (64), while in zebrafish they caused hypothalamic dysfunction and aberrant brain sexual differentiation through sustained AhR–ER cross-talk (65). Mixtures consistently showed synergistic toxicity: in zebrafish, BPA plus phthalates impaired learning by nuclear receptor cross-talk and oxidative stress (66), BPA plus PFAS induced anxiety-like phenotypes through estrogenic deregulation and neurotransmitter disruption (67), BPA plus dioxins in mice caused memory impairment due to synergistic AhR–ER disruption (68), BPA plus pesticides produced enhanced dopaminergic and inflammatory dysfunction (46), BPA with organophosphates severely impaired locomotor performance in zebrafish (69), and broad mixtures of pesticides, plasticizers, or EDCs consistently elicited stronger cognitive failures than single exposures by simultaneously disrupting ER, AhR, and thyroid pathways while converging on oxidative mitochondrial stress (70, 71). Atrazine reduced dopaminergic survival and caused motor deficits in rats by impairing differentiation and mitochondrial function (72), in frogs disrupted GABAergic and dopaminergic circuits altering vocalization behaviours (73), and in zebrafish combined with neonicotinoids enhanced larval anxiety due to GABAergic and nicotinic cholinergic disruption (74). DDT exposure in mice led to Alzheimer's-like amyloid pathology via estrogenic signaling, calcium dysregulation, and epigenetic amyloidogenic priming (75), while maternal exposure produced transgenerational neurobehavioural impairments through DNA methylation reprogramming in dopaminergic pathways (76). Other EDCs also demonstrated strong effects: organotins (tributyltin) induced autism-like behaviours through PPARγ/RXR activation and neuroinflammation (77); methoxychlor disrupted hippocampal synaptogenesis via ER agonism and epigenetic modulation (78); phytoestrogens such as genistein caused anxiety and learning deficits via ERβ activation in both mice and rats (79); nicotine exposure modelled EDC-like effects with ADHD-like outcomes through altered nicotinic receptor expression and dopamine reward circuitry vulnerability (80); and PAHs impaired motor and cognitive development in zebrafish by AhR-mediated ROS and disrupted connectivity (81). Glyphosate and AMPA in zebrafish altered motor activity and induced anxiety through mitochondrial oxidative stress and NMDA receptor disruption (82), glyphosate in rats caused anxiety and locomotor deficits by perturbing serotonergic and NMDA receptor pathways (83), and in mice impaired memory through hippocampal oxidative injury and acetylcholinesterase interference (84). Finally, perchlorate blocked thyroid hormone synthesis in rats, disrupting neuronal migration and synapse formation (85).

Table 2: Experimental studies on developmental exposure to EDCs affecting the neurodevelopmental health

S. No.	EDC Category	Animal Model	Key Findings	Year	Reference
1	BPA + Dioxins	Mouse	Memory deficits, increased oxidative stress; mechanism: AhR and ER crosstalk causes synergistic disruption of developmental transcription factors, oxidative neuronal damage.	2025	(68)
2	PFAS (PFOA, PFOS)	Mouse	Impaired synaptic plasticity and cognitive inflexibility; mechanism: interference with Ca^{2+} handling and lipid signaling, mitochondrial ROS, sustained microglial activation.	2025	(63)
3	Pesticide–phthalate mixture	Mouse	Memory impairments, neuroinflammation; mechanism: additive ROS signaling, microglial activation, transcriptional reprogramming affecting hippocampal pathways.	2025	(53)
4	Plasticizer + pesticides (mixtures)	Rat	Dopamine system impairment and learning/memory deficits; mechanism: combined oxidative stress, endocrine receptor mimicry, persistent neuroinflammation.	2025	(71)
5	PBDEs	Rat	Prenatal PBDE exposure caused hyperactivity and attention deficits; mechanism: interference with thyroid hormone transport, induction of oxidative stress, and disruption of synaptic pruning.	2024	(58)
6	Phthalates (DEHP, DBP)	Rat	Offspring showed increased anxiety/depressive behaviours; mechanism: phthalates disrupt androgen and estrogen signaling, impair steroidogenesis, and cause mitochondrial ROS generation leading to dopamine and serotonin system dysregulation.	2024	(51)
7	Chlorpyrifos (organophosphate)	Zebrafish	Cholinergic dysfunction, hypoactivity, and cognitive deficits observed; mechanism: inhibition of AChE leads to acetylcholine accumulation, neuroinflammation, and synaptic signal disruption during neuronal wiring.	2024	(55)
8	PBDEs (flame retardants)	Mouse	Hyperactivity, autistic-like traits; mechanism: thyroid hormone interference, altered Ca^{2+} signaling, oxidative DNA damage leading to impaired synaptic pruning.	2024	(59)
9	Organophosphate + BPA mixtures	Zebrafish	Severe locomotor impairments; mechanism: additive cholinergic disruption, ROS induction, impaired neurotransmitter network formation.	2024	(69)
10	BPA + Pesticides	Mouse	Enhanced dopaminergic and inflammatory disruption; mechanism: synergistic oxidative stress burden, ER receptor cross-talk, glial activation.	2024	(46)
11	TCDD (dioxins)	Zebrafish	Altered brain sexual differentiation, hypothalamic dysfunction; mechanism: sustained AhR activation, cross-talk with estrogen pathways, aberrant synaptic maturation.	2024	(86)
12	BPA + PFAS (mixtures)	Zebrafish	Offspring displayed anxiety-like phenotypes and reduced exploratory behaviour; mechanism: synergistic	2023	(87)

			estrogen receptor dysregulation, oxidative imbalance, and neurotransmitter disruption (mainly dopamine, serotonin).		
13	BPA analogues (BPS, BPF)	Zebrafish	Disrupted differentiation of neurons, causing impaired learning; mechanism: estrogen receptor mimicry, oxidative DNA/RNA damage, defective synapse maturation.	2023	(49)
14	EDC mixtures	Zebrafish	Severe cognitive failures and disrupted learning compared to single exposures; mechanism: simultaneous disruption of ER, AhR, and thyroid signaling with convergent oxidative mitochondrial stress.	2023	(88)
15	BPA	Rat	Autism-like behaviours, repetitive stereotypies; mechanism: altered transcriptional control of cortical genes, chronic neuroinflammation, aberrant synaptogenesis.	2023	(89)
16	Glyphosate & AMPA	Zebrafish	Anxiety and motor impairments; mechanism: oxidative mitochondrial stress, excitotoxicity through NMDA receptor dysregulation, and serotonergic impairment.	2022	(82)
17	BPA + Phthalates	Zebrafish	Additive impairments in memory/learning; mechanism: cross-talk at nuclear receptors, synergistic ROS generation, and broader transcriptional dysregulation across neurotransmitter pathways.	2021	(66)
18	Glyphosate (herbicide)	Mouse	Memory impairment, oxidative neurotoxicity; mechanism: hippocampal neuronal ROS generation, disruption of acetylcholinesterase activity, impaired synaptic connectivity.	2021	(84)
19	Bisphenol S & analogues	Zebrafish	Neurogenesis dysfunction, learning/memory impairment; mechanism: estrogen receptor activation similar to BPA, altered gene transcription, and oxidative stress impairing neuronal circuit formation.	2020	(48)
20	Chlorpyrifos	Rat	Prenatal exposure impaired attention and increased ADHD-like hyperactivity; mechanism: chronic cholinergic overactivation, glial activation leading to neuroinflammation, and synaptic architecture disruption in cortico-striatal circuits.	2020	(90)
21	PCBs	Mouse	Perinatal PCBs reduced dendritic spine density and cortical connectivity, impairing spatial memory; mechanism: disrupt thyroid hormone–regulated cortical maturation, alter calcium homeostasis, and induce oxidative neuronal stress.	2020	(57)
22	PAHs	Zebrafish	Motor and cognitive impairments with reduced neurodevelopment; mechanism: AhR activation, upregulation of xenobiotic metabolism, ROS overproduction, loss of neuronal connectivity.	2020	(81)
23	PCB + PBDE mixtures	Rat	Persistent memory impairment, neuroinflammation; mechanism: additive thyroid hormone disruption, ROS, and chronic glial activation.	2020	(61)

24	Phytoestrogens (genistein, isoflavones)	Mouse	Offspring displayed increased anxiety and impaired hippocampal development; mechanism: ERβ-selective activation, disruption of HPG axis, and epigenetic modifications altering neuroendocrine maturation.	2020	(91)
25	TCDD (dioxin)	Rat	Altered dopaminergic neurodevelopment increasing Parkinsonian risk; mechanism: AhR receptor activation leads to neurodevelopmental gene dysregulation, oxidative burden, and selective dopaminergic vulnerability.	2020	(64)
26	Organotins (tributyltin)	Mouse	Autism-like behaviours (poor social interaction, repetitive behaviours); mechanism: activation of PPARγ and RXR pathways, induction of neuroinflammation, and synaptic function impairment.	2020	(77)
27	Atrazine	Rat	Reduced dopaminergic neuron survival and motor deficits; mechanism: disruption of hypothalamic–pituitary–gonadal axis, impaired DA neuron differentiation, and mitochondrial damage.	2020	(72)
28	Atrazine + neonicotinoids	Zebrafish	Increased larval anxiety and reduced locomotor resilience; mechanism: GABAergic and nicotinic cholinergic disruption with additive endocrine action.	2020	(74)
29	Genistein (phytoestrogen)	Rat	Cognitive impairment, anxiety changes; mechanism: ERβ activation, altered hippocampal synaptic gene expression, neuroendocrine feedback disruption.	2019	(92)
30	Bisphenol F	Zebrafish	Oxidative neuronal stress, abnormal neural circuitry, reduced locomotor activity; mechanism: endocrine mimicry of BPA, induction of ROS and apoptosis-related signaling.	2019	(50)
31	Atrazine	Frog (Xenopus)	Altered GABA/dopamine pathways, abnormal vocalization behaviours; mechanism: HPG axis disruption altering neurotransmitter balance and GABAergic neuronal development.	2019	(73)
32	DEHP (phthalate)	Mouse	Impaired hippocampal neurogenesis, reduced spatial learning accuracy; mechanism: downregulation of neuronal differentiation genes, oxidative mitochondrial stress, and steroid receptor interference.	2018	(52)
33	Nicotine (EDC-like behaviour)	Rat	Offspring showed ADHD-like behavioural phenotypes; mechanism: prenatal nicotine altered nicotinic acetylcholine receptor expression, disrupted DA reward circuitry, and enhanced cortico-striatal vulnerability.	2018	(80)
34	Perchlorate	Rat	Neuronal migration and synapse formation defects; mechanism: thyroid hormone synthesis blockade (TSH receptor interference), affecting neurodevelopmental timing.	2018	(85)
35	BPA (low-dose)	Zebrafish	Altered dopamine/glutamate systems and hyperactivity; mechanism: nanomolar ER binding, low-dose non-monotonic effects on neurotransmitter circuits, oxidative stress.	2018	(47)

36	DDT	Mouse	Alzheimer's-like changes (increases amyloid precursor protein), spatial learning deficits; mechanism: estrogen-like activity of DDT, disruption of calcium homeostasis, persistent epigenetic modifications enhancing amyloidogenic pathways.	2018	(75)
37	BPA	Rat	Depression-like phenotype in adult life; mechanism: serotonergic neurotransmission disturbed, HPA-axis dysregulation, epigenetic modification of stress-related genes.	2017	(45)
38	Phthalates	Rat	Depression-like phenotypes, impaired serotonin metabolism; mechanism: perinatal disruption of monoaminergic signaling, mitochondrial dysfunction, neuroinflammation.	2016	(54)

ASSOCIATIONS BETWEEN PRENATAL EDCS AND CARDIOVASCULAR DYSFUNCTION

Emerging human epidemiological evidence strongly implicates developmental exposure to EDCs in shaping long-term cardiovascular risk given in (table 3). Prenatal and early-life exposure to bisphenol A (BPA) has been associated with an increased incidence of hypertension, obesity, and insulin resistance in children, with mechanistic pathways involving disrupted estrogen receptor signaling, DNA methylation, histone modifications, and epigenetic reprogramming that collectively enhance baseline inflammation and predispose to cardiometabolic syndrome (93, 94). Similarly, pregnancy and childhood studies on phthalates such as DEHP, MBP, and MEHP demonstrate links to obesity, vascular dysfunction, and elevated blood pressure, primarily mediated through perturbation of the PPAR pathway, endothelial nitric oxide synthase (eNOS) signaling, and epigenetic modifications influencing developmental metabolic set points (table 3) (95). Exposure to persistent organic pollutants (POPs) including PCBs, DDT, TCDD, and DDE during critical developmental periods has been associated with increased risks of atherosclerosis, stroke, and hypertension, mechanistically through nuclear receptor disruption, metabolic reprogramming, and epigenetic inheritance across generations (96). Parallel findings from birth cohorts and community-based studies identify perfluoroalkyl substances (PFAS) such as PFOA and PFOS as contributors to elevated cholesterol, systemic hypertension, and metabolic syndrome, mediated by lipid homeostasis dysregulation, oxidative stress, and vascular endothelial dysfunction via receptor- and epigenetic-driven pathways (97). Likewise, developmental exposure to toxic metals including lead, cadmium, and mercury has been linked to arrhythmias, impaired cardiac contractility, vascular dysfunction, and hypertension, largely due to calcium signaling interference, oxidative stress enhancement, and persistent inflammation (98), (99). Pesticides such as DDT and atrazine exert similar adverse effects, with birth cohort studies reporting increased blood pressure, dyslipidemia, obesity, and higher risk of cardiovascular and cerebrovascular disease, mechanistically tied to metabolic reprogramming, nuclear receptor perturbation, and epigenetic disruption (100). Importantly, reviews and meta-analyses highlight that combined or mixture exposures amplify cardiovascular risk via summative or synergistic mechanisms, including broad epigenetic modifications, receptor dysregulation, and altered metabolic programming during sensitive developmental windows (101). At a broader scale, systematic evaluations confirm that universal gestational exposure to EDCs is associated with fetal growth restriction, preterm birth, and increased childhood and adolescent cardiovascular disease risk, with underlying biological themes centered on hormonal imprinting, disrupted energy balance, persistent epigenetic alterations, and chronic inflammatory reprogramming given in (table 3) (102).

Table 3: Epidemiological studies on developmental exposure to EDCs affecting cardiovascular health

S. No.	EDC Category	Study type	Year	Key Findings (Mechanism of Action Related to Cardiovascular Health)	Reference
1	Bisphenol A (BPA)	Human (birth cohort, maternal/fetal)	2021–24	Prenatal and early childhood exposure to BPA linked to increased CVD risk (hypertension, obesity, insulin resistance). Mechanisms involve altered estrogen receptor signaling, DNA methylation, histone modification, epigenetic reprogramming, and increased baseline inflammation, predisposing to cardiometabolic syndrome and higher blood pressure in children.	(93), (94)
2	Phthalates (DEHP, MBP, MEHP)	Human (birth cohort, maternal/fetal)	2020–24	Epidemiological associations with higher risk of hypertension, obesity, and impaired vascular function. Mechanisms include disruption of PPAR pathway, eNOS signaling, epigenetic changes and altered metabolic set points during key developmental windows.	(95)
3	Persistent Organic Pollutants (POPs: PCBs, DDT, TCDD, DDE)	Human (birth cohort)	2017–23	Long-term exposure associated with elevated risk for atherosclerosis, stroke, and hypertension. Mechanisms mediated via nuclear receptor interaction, metabolic dysregulation, and epigenetic inheritance across generations.	(96)
4	Perfluoroalkyl Substances (PFOA, PFOS)	Human (birth cohort, community studies)	2018–23	Epidemiological studies reveal increased cholesterol levels, hypertension, and metabolic syndrome. Mechanisms include lipid homeostasis disruption, increased oxidative stress, and altered vascular function via nuclear receptor and epigenetic pathways.	(97)
5	Heavy Metals (Lead, Cadmium, Mercury)	Human (child cohort, maternal)	2022–24	Developmental exposure linked to arrhythmias, impaired cardiac contractility, vascular dysfunction, and hypertension. Mechanisms include calcium signaling interference, increased oxidative stress, and chronic inflammation.	(98), (99)
6	Pesticides (e.g., DDT, atrazine)	Human (birth cohort)	2021–23	Elevated blood pressure, dyslipidemia, and obesity, higher risk of cardiovascular and cerebrovascular disease. Mechanistically linked to metabolic reprogramming, nuclear receptor effects, and epigenetic disruption.	(100)
7	Multiple EDC Mixtures	Human (review/meta-analysis)	2020–24	Mixtures of EDCs found to have summative and sometimes synergistic impacts, amplifying cardiovascular outcomes, particularly in sensitive developmental periods. Mechanisms include broad epigenetic modification, receptor disruption, and altered metabolic programming.	(101)
8	All EDCs (General, meta-analysis)	Human (meta-analysis, epidemiological)	2020–24	Universal gestational exposure demonstrated; exposure associated with fetal growth restriction, preterm birth, elevated childhood/adolescent CVD risk. Mechanisms unify around hormonal imprinting, loss of energy homeostasis, persistent epigenetic changes, and altered inflammatory set point.	(102)

EDCs has emerged as a significant contributor to cardiovascular and metabolic dysfunction across animal models and human studies. For instance, Bisphenol A (BPA) disrupts estrogen signaling, alters cardiac gene expression such as Myh6, impairs calcium handling proteins (SERCA2a, PLB, NCX1), induces fibrosis via microRNA dysregulation, and activates hypertrophic pathways, thereby exacerbating atherosclerosis and hypertension through receptor-mediated and epigenetic mechanisms (103, 104). Similarly, phthalates including DEHP, MBP, and MEHP impair vascular function, elevate blood pressure, interfere with lipid and glucose signaling, downregulate genes important for β-cell development, modify the gut

microbiome, and induce epigenetic alterations that heighten the risk of metabolic syndrome and hypertension through PPAR- and eNOS-related pathways (105, 106) (table 4). Developmental exposure to diethylstilbestrol (DES) further illustrates these risks, as it disrupts cardiac morphogenesis, reduces ventricular size and aortic diameter while increasing heart rate in experimental models, and is linked epidemiologically with elevated risks of myocardial infarction, hypertension, and coronary artery disease in exposed offspring, driven by epigenetic modifications of cardiac developmental regulators given in (table 4) (103). In parallel, toxic metals such as lead, cadmium, mercury, and arsenic impair calcium signaling leading to arrhythmias and contractile dysfunction, while inducing oxidative stress, endothelial dysfunction, inflammatory activation, mitochondrial damage, and decreased nitric oxide bioavailability, ultimately promoting hypertension, atherosclerosis, and plaque instability (107, 108). Persistent exposures to organic pollutants (POPs) like DDT, PCBs, DDE, and TCDD also elevate blood pressure, worsen lipid profiles, promote hyperinsulinemia, adiposity, and renal dysfunction, with evidence of transgenerational inheritance through nuclear receptor disruption and epigenetic modulation (104, 109). In addition, perfluoroalkyl substances (PFAS) such as PFOA, PFOS, and PFNA are strongly linked to elevated LDL cholesterol, vascular dysfunction, carotid intima-media thickening, and metabolic syndrome, mediated by oxidative stress and nuclear receptor–dependent gene dysregulation (104). Likewise, long-term pesticide exposure, particularly to DDT, has been associated with hypertension, dyslipidemia, obesity, diabetes, and a two- to six-fold increased risk of cardiovascular and cerebrovascular disease, reflecting the persistent bioaccumulation and receptor-level disruptions characteristic of these compounds (109). Finally, combined exposures to multiple EDCs produce additive or synergistic effects, amplifying epigenetic alterations, receptor disturbances, and metabolic dysfunction, leading to enhanced cardiovascular risk and variability in disease phenotypes across generations and populations given in (table 4) (105, 110).

Table 4: Experimental studies on developmental exposure to EDCs affecting the cardiovascular health

S. No.	EDC Category	Animal Model	Key Mechanistic Findings	Year	Reference
1	Bisphenol A (BPA)	Sheep, Rodent, Zebrafish, Apes	Disrupts estrogen signaling, alters cardiac gene expression (e.g., Myh6), impairs calcium homeostasis (SERCA2a, PLB, NCX1), induces cardiac fibrosis via miRNA dysregulation, upregulates pro-hypertrophic pathways, alters cardiac development gene expression, exacerbates atherosclerosis, increases risk of hypertension and cardiometabolic syndrome through epigenetic and receptor-mediated mechanisms.	2014–21	(110), (104)
2	Phthalates (DEHP, MBP, MEHP)	Rodent, Human (children)	Impairs vascular function, induces elevated blood pressure, disrupts lipid metabolism and glucose signaling pathways, downregulates β-cell development genes, alters gut microbiota, causes DNA methylation changes, enhances risk of metabolic syndrome and hypertension through PPAR and eNOS pathway modulation.	2016–20	(105), (104)
3	Diethylstilbestrol (DES)	Rat, Zebrafish, Human	Disrupts cardiac morphogenesis; associated with decreased ventricle size/aorta diameter, increased heartbeat, elevated risk of MI, hypertension, and coronary artery disease in exposed offspring, epigenetic modification of cardiac development regulators.	2019–20	(103)
4	Heavy Metals (Lead, Cadmium, Mercury, Arsenic)	Rodent, Mouse, Human cohort	Interferes with calcium signaling leading to arrhythmias and contractility defects, promotes oxidative stress and endothelial dysfunction, activates inflammatory	2016–23	(107), (108)

			5pathways, reduces NO bioavailability, mitochondrial dysfunction, epigenetic disruptions, elevates risk for hypertension, atherosclerosis, and plaque vulnerability.		
5	Persistent Organic Pollutants (POPs: DDT, PCBs, DDE, TCDD)	Rodent, Human cohort	Induces hypertension, lipid profile changes, hyperinsulinemia, increased adiposity, renal dysfunction, metabolic and cardiovascular risk through persistent organic pollutant actions, nuclear receptor disruption, and epigenetic inheritance across generations.	2016–22	(109),
6	Perfluoroalkyl Substances (PFOA, PFOS, PFNA)	Rodent, Human	Elevates LDL-cholesterol, blood pressure; disrupts cholesterol and vascular homeostasis, increases carotid intima-media thickness, oxidative stress, and metabolic syndrome risk through epigenetic and nuclear receptor-driven gene expression.	2018–20	(104)
7	Pesticides (e.g., DDT)	Human, Rodent	Elevates blood pressure, dyslipidemia, induces diabetes and obesity, 2–6-fold higher risk of cardiovascular and cerebrovascular disease, mediated by receptor signaling, persistent organic pollutant accumulation and metabolic dysregulation.	2014–20	(109)
8	Mixtures/Multiple EDCs	Multiple models	Combined exposures exacerbate risk; mechanisms include summative effects on epigenetic, receptor, and metabolic pathways, increased phenotypic variability in cardiovascular endpoints.	2020–24	(105), (110)

Prenatal exposure EDCs and renal disorders

Elevated Bisphenol A (BPA) levels are associated with increased kidney disease risk, particularly in individuals with diabetes or hypertension, affecting glomerular filtration rate (GFR) and albuminuria through oxidative stress and nephrotoxicity mechanisms (111), (112). Exposure to Perfluoroalkyl substances (PFAS) is linked to reduced renal function and increased proteinuria, worsened by anemia and diabetes, involving inflammation and renal toxicity pathways (113), (112). Early-life phthalate exposure alters renal biomarkers, likely via endocrine disruption and oxidative stress (114). Polycyclic aromatic hydrocarbons (PAHs) increase pediatric kidney abnormalities through aryl hydrocarbon receptor activation and oxidative DNA damage (115). Prenatal and childhood exposure to heavy metals like cadmium and lead is tied to reduced kidney function, albuminuria, and hypertension, driven by oxidative stress and epigenetic changes (116). Elevated polychlorinated biphenyls (PCBs) and dioxins impair kidney function through persistent activation of aryl hydrocarbon receptor pathways causing nephron loss and fibrosis (117). Organophosphate pesticide exposure is linked to subclinical renal injury involving mitochondrial and endocrine disruption (118). Prenatal exposure to environmental tobacco smoke reduces kidney size and function, increasing chronic kidney disease risk via oxidative stress and hypoxia (119) (table 5).

Table 5: Epidemiological studies on developmental exposure to EDCs affecting renal health and CKD

S. No.	EDC Category	Study Type	Key Findings	Year	References
1	Microplastics-associated EDCs	Emerging Cohort	Initial epidemiologic evidence suggests microplastics carrying EDCs may contribute to renal oxidative stress, inflammation, and dysfunction in exposed populations; however, mechanisms remain under investigation.	2025	(120)
2	Mixtures of EDCs	Cross-sectional, Cohort	Exposure to complex mixtures of EDCs during pregnancy and early childhood exhibits compounded adverse effects on renal biomarkers, including impaired urinary albumin excretion and reduced eGFR. Mechanistic pathways involve additive oxidative stress, endocrine receptor interference, and epigenetic modulation affecting nephron development.	2023	(121), (122)
3	Polycyclic Aromatic Hydrocarbons (PAHs)	Case-Control, Cohort	Developmental and environmental PAH exposure correlates with increased risk of pediatric kidney abnormalities and chronic renal impairment, potentially through activation of the aryl hydrocarbon receptor (AHR) and oxidative stress-mediated DNA damage.	2023	(123)
4	Bisphenol A (BPA)	Systematic Review, Meta-Analysis, Cohort	Elevated blood and urinary BPA concentrations are associated with increased risk of kidney disease, particularly in individuals with pre-existing conditions like diabetes or hypertension. Higher BPA exposure correlates with reductions in glomerular filtration rate (GFR) and elevations in albuminuria. The mechanisms implicate oxidative stress, inflammatory pathways, and direct nephrotoxicity potentially mediated via estrogen receptor signaling and mitochondrial dysfunction.	2022	(124), (112)
5	Organophosphate pesticides	Case-Control	Studies suggest developmental exposure to organophosphate pesticides is related to subclinical renal injury characterized by increased urinary biomarkers of tubular damage and reduced GFR. The mechanism likely involves mitochondrial impairment and endocrine disruption.	2022	(125)
6	Perfluoroalkyl substances (PFAS)	Cross-sectional, Cohort	Exposure to PFAS is linked with decreased renal function (eGFR reductions) and increased proteinuria among children with chronic kidney disease (CKD) and the general population. Anemia and diabetes exacerbate the association. Proposed mechanisms include systemic inflammation, renal tubular toxicity, and disruption of lipid and antioxidant metabolism pathways	2019, 2022	(126), (112)

			mediated via PPAR and Nrf2 signaling.		
7	Flame retardants (PBDEs)	Cross-sectional	Cord blood PBDE concentrations predict impaired renal function and increased biomarkers of inflammation and oxidative stress in children, suggesting developmental immunotoxicity and oxidative damage as primary mechanisms.	2021	(127)
8	Phthalates	Prospective Cohort	Prenatal and early life exposure to phthalates is associated with alterations in renal biomarkers, including albuminuria and impaired renal function during childhood. Suggested mechanisms include endocrine disruption leading to altered nephrogenesis and oxidative stress pathways.	2019	(128)
9	Perchlorate and Nitrate	Cross-sectional	Exposure to perchlorate and nitrate during pregnancy is associated with altered thyroid hormone status and modest reductions in neonatal kidney function, implicating thyroid disruption as a potential mechanism for renal developmental effects.	2018	(129)
10	Polychlorinated Biphenyls (PCBs) & Dioxins	Cross-sectional	Elevated PCB and dioxin levels in cord blood and early life are linked with impaired kidney function and increased risk of renal disease later in life. The effect is thought to be mediated by persistent activation of the AHR pathway causing nephron deficit and renal fibrosis.	2018	(117)
11	Heavy Metals (Cadmium, Lead)	Longitudinal Cohort	Epidemiological data show prenatal and childhood heavy metal exposure is significantly associated with reduced kidney function, albuminuria, and elevated blood pressure in children and adults. Mechanisms involve oxidative stress, inflammation, disruption of glomerular and tubular structures, and epigenetic modifications.	2015	(116)
12	Environmental Tobacco Smoke	Prospective Cohort	Prenatal exposure to environmental tobacco smoke is associated with reduced kidney size and function in infancy and childhood, potentially increasing CKD susceptibility. Mechanisms include oxidative stress and hypoxia-induced renal developmental impairments.	2012	(130)

Exposure to perchlorate and nitrate during pregnancy disrupts thyroid hormones and modestly reduces neonatal kidney function (129). Complex mixtures of (EDCs) during early life worsen renal biomarkers through additive oxidative stress, receptor interference, and epigenetic modulation (121), (122). Cord blood PBDE flame retardants predict impaired renal function and inflammation (127) (table 5). Emerging data suggest microplastics-associated EDCs contribute to renal oxidative stress and dysfunction, though mechanisms remain under investigation (120). Developmental exposure to Bisphenol A (BPA) in rats and mice reduces nephron number, causes kidney structural damage, fibrosis, hypertension, proteinuria, and increases CKD risk. Mechanisms include oxidative stress, epigenetic changes, estrogen receptor disruption, mitochondrial impairment, and renin-angiotensin system alterations (14, 131, 132). Early phthalate exposure lowers nephron count and raises glomerulosclerosis, proteinuria, fibrosis, and hypertension risk via oxidative stress, PPAR activation, anti-androgen effects, and apoptosis (14) (table

6). Perinatal dioxin and PCB exposure decreases nephron numbers, causes glomerular damage and hypertension through AHR activation, oxidative DNA damage, and increased renin-angiotensin activity (14). Developmental PFAS exposure reduces kidney function, nephron number, and increases CKD risk by activating PPAR-α and Nrf2, disrupting lipid metabolism, and inducing inflammation and fibrosis (14, 133) (table 6). Prenatal heavy metal exposure causes nephron loss, proteinuria, and hypertension mediated by oxidative stress, impaired nephrogenesis, epigenetic changes, and apoptosis (14). Early PBDE and flame-retardant exposure leads to glomerular loss, tubular damage, hormone disruption, and CKD risk due to hormone receptor modulation, increased ROS, DNA damage, and renal epithelial cytotoxicity (14, 112). Gestational benzo[a]pyrene (PAH) exposure reduces nephron endowment, causes glomerulosclerosis, hypertension, and proteinuria via AHR activation and oxidative DNA damage (14). Early exposure to PM2.5 and microplastics increases hypertension, decreases nephron number, and promotes CKD risk by inducing oxidative stress, inflammation, impaired growth factor signaling, and enhancing nephrotoxicity through microplastic-associated toxicants (14, 112). Persistent organic pollutants disrupt nephrogenesis, causing fibrosis, hypertrophy, and CKD risk through chronic AHR activation, oxidative stress, and inflammation (14).

Table 6: Experimental studies on Developmental exposure to EDCs affecting renal injury and CKD

S.No.	EDC Category	Animal Model	Detailed Key Findings	Mechanism of Action	Year	References
1	Bisphenol A (BPA)	Rats (Sprague-Dawley), Mice	Developmental BPA reduces nephron number, glomerular/tubular atrophy, fibrosis, hypertension, increased CKD risk, proteinuria, and kidney structural abnormalities in offspring.	Increases oxidative stress (↑ROS, 8-OHdG), causes epigenetic changes in nephrogenic genes, disrupts estrogen receptor signaling, impairs mitochondria, alters renin-angiotensin system.	2018–2023	(14), (131), (132)
2	Phthalates (DEHP, DBP)	Wistar, SD Rats	Early exposure reduces nephron number, raises risk of glomerulosclerosis, proteinuria, tubular injury, fibrosis, and adult hypertension.	Induces oxidative/metabolic stress (ROS, GSH depletion), stimulates PPARs, anti-androgenic impacts on nephron differentiation, triggers apoptosis.	2017–2018	(14)
3	Dioxins (TCDD), PCBs	C57BL/6, SD Rats, Mice	Perinatal exposure decreases nephron number, glomerular hypertrophy, glomerulosclerosis, tubular dilation, sodium retention, and hypertension in offspring.	AHR activation disrupts nephron differentiation; persistent oxidative DNA damage; histone modification in renal genes; increases RAS activity, leading to hypertension/nephron loss.	2016–2021	(14)
4	PFAS (PFOA, PFOS)	Mice, Rats, Humans	Developmental PFAS reduces kidney function (eGFR), alters mineral/protein regulation, decreases nephron number, increases population CKD risk.	Activates PPAR-α and Nrf2, disrupts lipid/antioxidant defense; induces renal inflammation/fibrosis; impairs signaling for nephrogenesis.	2018–2023	(133)
5	Heavy metals (Cd, Pb, Hg, As)	Rats, Mice	Prenatal/early-life exposure causes nephron loss,	Induces oxidative stress, disrupts nephrogenesis (growth	2015–2021	(14)

			tubular injury, proteinuria, hypertension, electrolyte handling impairment, and long-term kidney disease risk.	factors, tight junctions), epigenetic changes, and apoptosis; impairs tubular reabsorption/secretion.		
6	PBDEs, Flame Retardants	Mice, Rats	Prenatal and early-life exposure causes glomerular loss, tubular/cystic lesions, proteinuria, glomerulosclerosis, hormone disruption, increased CKD risk.	Modulates hormone receptor activity (thyroid, retinoid); increases ROS and DNA damage; direct cytotoxicity to renal epithelium causes cysts and nephron deficits.	2018–2023	(112)
7	PAHs (Benzo[a]pyrene)	LEH Rat, Mouse	Gestational BaP leads to reduced nephron endowment, glomerulosclerosis, hypertension, proteinuria, and increased adult CKD risk.	AHR pathway disrupts nephron formation; persistent ROS causes DNA breaks; inflammatory activation leads to fibrosis/scarring.	2015–2021	(14)
8	PM2.5, Microplastics	SD Rat, C57BL/6N Mouse	Early-life exposure increases hypertension, reduces nephron number, glomerular injury, and later-life CKD risk. Microplastics may further amplify EDC nephrotoxicity.	Promotes inflammation/oxidative stress; impairs hormonal/growth factor signaling (e.g. FGF, VEGF); microplastics act as vectors for additional toxicants, enhancing renal toxicity.	2020–2023	(112)
9	Persistent Organic Pollutants	Mouse, Rat	Alters nephrogenesis, causes hypertrophy, fibrosis, and increased CKD risk via chronic AHR/inflammatory activation.	Chronic AHR activation, oxidative stress, ECM remodelling disruption, increased inflammation and apoptosis lead to abnormal renal structure/function.	2021	(14); (134)

PRENATAL EXPOSURE TO EDC AND ROLE OF EPIGENETICS MECHANISMS IN NEURO-CARDIO-RENAL DISEASES

Epigenetic regulation encompasses DNA methylation, histone modification, and non-coding RNA mechanisms, which together orchestrate gene expression and ensure proper cellular differentiation during development (52, 135). In the brain, these mechanisms are fundamental for neurogenesis, synaptic organization, and functional maturation. Disruption of the epigenetic landscape leads to abnormalities in brain architecture and contributes to the onset of neurological disorders (60, 67, 85, 136). In cardiovascular development, precise epigenetic control is required for cardiac lineage specification and morphogenesis, where aberrant methylation or acetylation patterns can result in defects and cardiometabolic risk (108, 137-141). Similarly, the formation and function of nephrons in the kidney are tightly regulated by dynamic chromatin states, and altered epigenetic marks predispose to developmental anomalies and chronic kidney diseases (142-146) as shown in (fig 2). Exposure to (EDCs) during critical developmental periods perturbs these regulatory epigenetic processes. EDCs induce abnormal DNA methylation and histone modifications, resulting in persistent changes to gene expression.

These modifications not only affect the exposed individual but can be transmitted across generations via epigenetic inheritance (47, 49, 55, 147). In the brain, EDC-associated epigenetic dysregulation impairs neuronal maturation and has been linked to increased risk and early onset of neurodevelopmental and neurodegenerative disorders (60, 140, 148). Cardiovascular tissues exposed to EDCs demonstrate altered gene expression impacting cardiac structure and metabolism, with DNA methylation changes driving susceptibility to cardiometabolic disease (109, 149-151). EDC-exposed kidneys often show disrupted methylome signatures and chromatin remodelling, which reduce nephron endowment and increase the likelihood of renal dysfunction later in life (142-144, 146, 152).

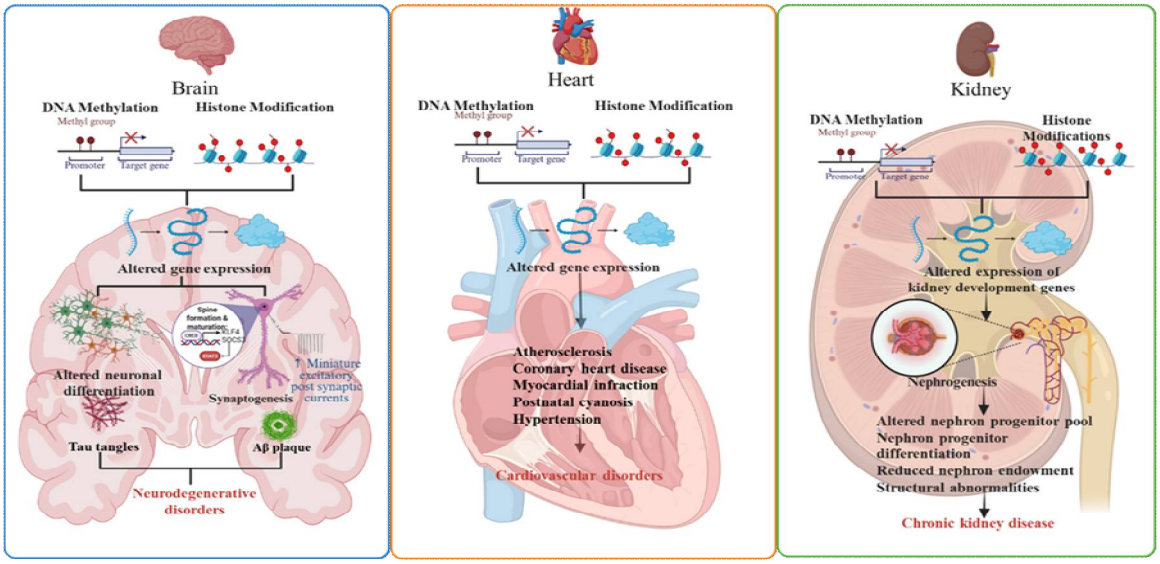

Figure 2: Exposure to endocrine-disrupting chemicals (EDCs) during development has profound effects.

These chemicals are known to disrupt normal behavior and organ function at the cellular level through various mechanisms. Early-life exposure to EDCs leads to significant epigenetic changes, including DNA methylation, histone modifications, and altered gene expression. Such changes directly impact the morphology, cellular signaling, and overall homeostasis of neuro-cardiovascular-renal health in a developing fetus, leading to serious complications in adulthood. Understanding this connection is crucial for protecting future generations.

In summary, DNA methylation, histone modifications, and ncRNA activity are central to the developmental programming of neuro, cardiovascular, and renal systems (153-156). EDC-induced epigenetic reprogramming impairs organogenesis and promotes disease states by mis-regulating critical genes at both tissue-specific and systemic levels (61, 157-160). The persistence and inheritance of these alterations heighten the risk for neurological, cardiometabolic, and kidney disorders, emphasizing the need for strategies to identify, mitigate, and prevent epigenetic disruption during development (109, 161-171).

CONCLUSION

The developmental exposure of EDCs brings with it lifelong neuro-cardio-renal health deficit. The epidemiological investigations and biological experiments indicate that exposure in fetal or early-life is disturbing to organ development by epigenetic mechanisms, DNA methylation, histone modification, and ncRNA activity. Such converging factors during developmental phases are associated with enhanced predispositions to neurological diseases and cognitive deficits, CVD and CKD in later life. Across the organ system, EDCs interfere with hormonal balance, promote oxidative stress, inflammation, and permanent epigenetic remapping. In light of the extensive and permanent effects of EDCs, it is imperative to implement stricter regulations, minimize exposure and develop specific interventions during windows of greatest susceptibility. The prevalence of EDCs exposure demands future research should highlight on unifying mechanisms, risk- population and early biomarkers for the early detection of the disease and therapeutics.

ACKNOWLEDGEMENT
I am deeply grateful to the anonymous researcher Dr. Sukhveer Singh, Systems Toxicology Groups, FEST division, CSIR-Indian Institute of Toxicology Research, Lucknow, Uttar Pradesh, India 226001, for his constant support, dedicated time & expert advice throughout this review. His knowledge sharing and dedication towards this review is truly appreciable.

AUTHORS CONTRIBUTIONS
NT draft and wrote the review. SD and G.N.D conceived the idea, reviewed and provided the guidance. All authors read and approved the final manuscript.

DECLARATIONS

CONFLICT OF INTERESTS: The authors show no competing interests.

REFERENCES
1. Gore A.C., Chappell V.A., Fenton S.E., Flaws J.A., Nadal A., Prins G.S., et al. (2015). Executive Summary to EDC-2: The Endocrine Society's Second Scientific Statement on Endocrine-Disrupting Chemicals. Endocr Rev, 36(6):593-602.
2. Agency U.S.E.P. Overview of Endocrine Disruption 2025 [Available from: https://www.epa.gov/ endocrine-disruption/ overview-endocrine-disruption.
3. Howard S.G., Lee D.H. (2012). What is the role of human contamination by environmental chemicals in the development of type 1 diabetes? J Epidemiol Community Health, 66(6):479-81.
4. Helal I., Fick-Brosnahan G.M., Reed-Gitomer B., Schrier R.W. (2012). Glomerular hyperfiltration: definitions, mechanisms and clinical implications. Nat Rev Nephrol, 8(5):293-300.
5. Crews D., Putz O., Thomas P., Hayes T., Howdeshell K. (2003). Wildlife as models for the study of how mixtures, low doses, and the embryonic environment modulate the action of endocrine-disrupting chemicals. Pure and Applied Chemistry, 75(11-12):2305-20.
6. Barker D.J. (2004). The developmental origins of chronic adult disease. Acta Paediatr Suppl, 93(446):26-33.
7. Grandjean P., Barouki R., Bellinger D.C., Casteleyn L., Chadwick L.H., Cordier S., et al. (2015). Life-Long Implications of Developmental Exposure to Environmental Stressors: New Perspectives. Endocrinology, 156(10):3408-15.
8. Montazeri P., Guil-Oumrait N., Marquez S., Cirugeda L., Beneito A., Guxens M., et al. (2023). Prenatal Exposure to Multiple Endocrine-Disrupting Chemicals and Childhood BMI Trajectories in the INMA Cohort Study. Environ Health Perspect, 131(10):107006.
9. Sun M., Cao X., Wu Y., Shen L., Wei G. (2022). Prenatal exposure to endocrine-disrupting chemicals and thyroid function in neonates: A systematic review and meta-analysis. Ecotoxicol Environ Saf, 231(113215).
10. Lee W.C., Fisher M., Davis K., Arbuckle T.E., Sinha S.K. (2017). Identification of chemical mixtures to which Canadian pregnant women are exposed: The MIREC Study. Environ Int, 99(321-30.
11. Rosofsky A., Janulewicz P., Thayer K.A., McClean M., Wise L.A., Calafat A.M., et al. (2017). Exposure to multiple chemicals in a cohort of reproductive-aged Danish women. Environ Res, 154(73-85.
12. Gore A.C., Moore T., Groom M.J., Thompson L.M. (2022). Prenatal Exposure to an EDC Mixture, NeuroMix: Effects on Brain, Behavior, and Stress Responsiveness in Rats. Toxics, 10(3)
13. Sukjamnong S., Thongkorn S., Kanlayaprasit S., Saeliw T., Hussem K., Warayanon W., et al. (2020). Prenatal exposure to bisphenol A alters the transcriptome-interactome profiles of genes associated with Alzheimer's disease in the offspring hippocampus. Sci Rep, 10(1):9487.
14. Singh R.D., Koshta K., Tiwari R., Khan H., Sharma V., Srivastava V. (2021). Developmental Exposure to Endocrine Disrupting Chemicals and Its Impact on Cardio-Metabolic-Renal Health. Front Toxicol, 3(663372.
15. Wong H., Mylrea K., Feber J., Drukker A., Filler G. (2006). Prevalence of complications in children with chronic kidney disease according to KDOQI. Kidney Int, 70(3):585-90.
16. Martin A., Connelly A., Bland R.M., Reilly J.J. (2017). Health impact of catch-up growth in low-birth weight infants: systematic review, evidence appraisal, and meta-analysis. Matern Child Nutr, 13(1):
17. Yang Z., Zhang J., Wang M., Wang X., Liu H., Zhang F., et al. (2024). Prenatal endocrine-disrupting chemicals exposure and impact on offspring neurodevelopment: A systematic review and meta-analysis. Neurotoxicology, 103(335-57.
18. Chen C.Y., Lee C.C., Hsu H.J., Wu I.W., Chen Y.C., Pan H.C., et al. (2024). Long-term impacts of endocrine-disrupting chemicals exposure on kidney function: A community-based cohort study. Environ Toxicol Pharmacol, 106(104379.
19. Crocker J.F., Safe S.H., Acott P. (1988). Effects of chronic phthalate exposure on the kidney. J Toxicol Environ Health, 23(4):433-44.
20. Caporale N., Leemans M., Birgersson L., Germain P.L., Cheroni C., Borbely G., et al. (2022). From cohorts to molecules: Adverse impacts of endocrine disrupting mixtures. Science, 375(6582):eabe8244.
21. Lopez-Rodriguez D., Franssen D., Bakker J., Lomniczi A., Parent A.S. (2021). Cellular and molecular features of EDC exposure: consequences for the GnRH network. Nat Rev Endocrinol, 17(2):83-96.

22. Shen C.Y., Weng J.C., Tsai J.D., Su P.H., Chou M.C., Wang S.L. (2021). Prenatal Exposure to Endocrine-Disrupting Chemicals and Subsequent Brain Structure Changes Revealed by Voxel-Based Morphometry and Generalized Q-Sampling MRI. Int J Environ Res Public Health, 18(9):
23. Weng J.C., Hong C.I., Tasi J.D., Shen C.Y., Su P.H., Wang S.L. (2020). The association between prenatal endocrine-disrupting chemical exposure and altered resting-state brain fMRI in teenagers. Brain Struct Funct, 225(5):1669-84.
24. Tran D.N., Park S.M., Jung E.M., Jeung E.B. (2021). Prenatal Octamethylcyclotetrasiloxane Exposure Impaired Proliferation of Neuronal Progenitor, Leading to Motor, Cognition, Social and Behavioral Functions. Int J Mol Sci, 22(23):
25. Arambula S.E., Jima D., Patisaul H.B. (2018). Prenatal bisphenol A (BPA) exposure alters the transcriptome of the neonate rat amygdala in a sex-specific manner: a CLARITY-BPA consortium study. Neurotoxicology, 65(207-20.
26. Huang Y., Fang F., Chen Y., He X., Chen Q., Wang H., et al. (2023). Prenatal exposure to per- and polyfluoroalkyl substances and infant sleep disturbance: A prospective cohort study. Environ Int, 178(108070.
27. Wang S.M., Wen H.J., Huang F., Sun C.W., Huang C.M., Wang S.L. (2025). White matter microstructural integrity mediates associations between prenatal endocrine-disrupting chemicals exposure and intelligence in adolescents. Neuroimage Clin, 45(103758.
28. Patel N.B., Xu Y., McCandless L.C., Chen A., Yolton K., Braun J., et al. (2019). Very low-level prenatal mercury exposure and behaviors in children: the HOME Study. Environ Health, 18(1):4.
29. Hudson K.M., Shiver E., Yu J., Mehta S., Jima D.D., Kane M.A., et al. (2021). Transcriptomic, proteomic, and metabolomic analyses identify candidate pathways linking maternal cadmium exposure to altered neurodevelopment and behavior. Sci Rep, 11(1):16302.
30. Tong M., Yu J., Liu M., Li Z., Wang L., Yin C., et al. (2021). Total mercury concentration in placental tissue, a good biomarker of prenatal mercury exposure, is associated with risk for neural tube defects in offspring. Environ Int, 150(106425.
31. Peixoto-Rodrigues M.C., Monteiro-Neto J.R., Teglas T., Toborek M., Soares Quinete N., Hauser-Davis R.A., et al. (2025). Early-life exposure to PCBs and PFAS exerts negative effects on the developing central nervous system. J Hazard Mater, 485(136832.
32. Witchey S.K., Fuchs J., Patisaul H.B. (2019). Perinatal bisphenol A (BPA) exposure alters brain oxytocin receptor (OTR) expression in a sex- and region- specific manner: A CLARITY-BPA consortium follow-up study. Neurotoxicology, 74(139-48.
33. Kou X., Millan M.P., Canals J., Moreno V.R., Renzetti S., Arija V. (2025). Effects of prenatal exposure to multiple heavy metals on infant neurodevelopment: A multi-statistical approach. Environ Pollut, 367(125647.
34. Yang W., Vuong A.M., Xie C., Dietrich K.N., Karagas M.R., Lanphear B.P., et al. (2020). Maternal cadmium exposure and neurobehavior in children: The HOME study. Environ Res, 186(109583.
35. Biffen S.C., Warton C.M.R., Dodge N.C., Molteno C.D., Jacobson J.L., Jacobson S.W., et al. (2020). Validity of automated FreeSurfer segmentation compared to manual tracing in detecting prenatal alcohol exposure-related subcortical and corpus callosal alterations in 9- to 11-year-old children. Neuroimage Clin, 28(102368.
36. Reardon A.J.F., Hajihosseini M., Dinu I., Field C.J., Kinniburgh D.W., MacDonald A.M., et al. (2023). Maternal co-exposure to mercury and perfluoroalkyl acid isomers and their associations with child neurodevelopment in a Canadian birth cohort. Environ Int, 178(108087.
37. Liew Z., Meng Q., Yan Q., Schullehner J., Hansen B., Kristiansen S.M., et al. (2023). Association Between Estimated Geocoded Residential Maternal Exposure to Lithium in Drinking Water and Risk for Autism Spectrum Disorder in Offspring in Denmark. JAMA Pediatr, 177(6):617-24.
38. Beck I.H., Bilenberg N., Andersen H.R., Trecca F., Bleses D., Jensen T.K. (2023). Association between prenatal or early postnatal exposure to perfluoroalkyl substances and language development in 18 to 36-month-old children from the Odense Child Cohort. Environ Health, 22(1):46.
39. Oh J., Bennett D.H., Calafat A.M., Tancredi D., Roa D.L., Schmidt R.J., et al. (2021). Prenatal exposure to per- and polyfluoroalkyl substances in association with autism spectrum disorder in the MARBLES study. Environ Int, 147(106328.
40. de Water E., Proal E., Wang V., Medina S.M., Schnaas L., Tellez-Rojo M.M., et al. (2018). Prenatal manganese exposure and intrinsic functional connectivity of emotional brain areas in children. Neurotoxicology, 64(85-93.
41. Bauer J.A., Romano M.E., Jackson B.P., Bellinger D., Korrick S., Karagas M.R. (2024). Associations of Perinatal Metal and Metalloid Exposures with Early Child Behavioral Development Over Time in the New Hampshire Birth Cohort Study. Expo Health, 16(1):135-48.
42. McKean S.J., Bartell S.M., Hansen R.L., Barfod G.H., Green P.G., Hertz-Picciotto I. (2015). Prenatal mercury exposure, autism, and developmental delay, using pharmacokinetic combination of newborn blood concentrations and questionnaire data: a case control study. Environ Health, 14(62.
43. Akter R., Sugino H., Akhter N., Brown C.L., Thilsted S.H., Yagi N. (2021). Micronutrient Adequacy in the Diet of Reproductive-Aged Adolescent Girls and Adult Women in Rural Bangladesh. Nutrients, 13(2):
44. Ouyang L., Li Q., Yang S., Yan L., Li J., Wan X., et al. (2024). Interplay and long-lasting effects of maternal low-level Pb, Hg, and Cd exposures on offspring cognition. Ecotoxicol Environ Saf, 287(117315.
45. Varma G., Sobolewski M., Cory-Slechta D.A., Schneider J.S. (2017). Sex- and brain region- specific effects of prenatal stress and lead exposure on permissive and repressive post-translational histone modifications from embryonic development through adulthood. Neurotoxicology, 62(207-17.

46. Wang Y., Peng D., Zhang X., Chen J., Feng J., Zhang R., et al. (2024). PLCbeta4 driven by cadmium-exposure during gestation and lactation contributes to cognitive deficits by suppressing PIP2/PLCgamma1/CREB/BDNF signaling pathway in male offspring. J Hazard Mater, 474(134756.
47. Cheong A., Johnson S.A., Howald E.C., Ellersieck M.R., Camacho L., Lewis S.M., et al. (2018). Gene expression and DNA methylation changes in the hypothalamus and hippocampus of adult rats developmentally exposed to bisphenol A or ethinyl estradiol: a CLARITY-BPA consortium study. Epigenetics, 13(7):704-20.
48. Tran D.N., Jung E.M., Yoo Y.M., Lee J.H., Jeung E.B. (2020). Perinatal Exposure to Triclosan Results in Abnormal Brain Development and Behavior in Mice. Int J Mol Sci, 21(11):89-95
49. Li C., Qi T., Ma L., Lan Y.B., Luo J., Chu K., et al. (2023). In utero bisphenol A exposure disturbs germ cell cyst breakdown through the PI3k/Akt signaling pathway and BDNF expression. Ecotoxicol Environ Saf, 259(115031.
50. Krishnan K., Hasbum A., Morales D., Thompson L.M., Crews D., Gore A.C. (2019). Endocrine-disrupting chemicals alter the neuromolecular phenotype in F2 generation adult male rats. Physiol Behav, 211(112674.
51. Kaimal A., Hooversmith J.M., Mansi M.H.A., Holmes P.V., MohanKumar P.S., MohanKumar S.M.J. (2024). Prenatal Exposure to Bisphenol A and/or Diethylhexyl Phthalate Impacts Brain Monoamine Levels in Rat Offspring. J Xenobiot, 14(3):1036-50.
52. Xin F., Fischer E., Krapp C., Krizman E.N., Lan Y., Mesaros C., et al. (2018). Mice exposed to bisphenol A exhibit depressive-like behavior with neurotransmitter and neuroactive steroid dysfunction. Horm Behav, 102(93-104.
53. Streifer M., Hilz E.N., Raval R., Wylie D.C., Gore A.C. (2025). Transcriptomic analysis of effects of developmental PCB exposure in the hypothalamus of female rats. Mol Cell Endocrinol, 599(112460.
54. Allam A.A., Maodaa S.N., Abo-Eleneen R., Ajarem J. (2016). Protective Effect of Parsley Juice (Petroselinum crispum, Apiaceae) against Cadmium Deleterious Changes in the Developed Albino Mice Newborns (Mus musculus) Brain. Oxid Med Cell Longev, 2016(2646840.
55. England-Mason G., Merrill S.M., Liu J., Martin J.W., MacDonald A.M., Kinniburgh D.W., et al. (2024). Sex-Specific Associations between Prenatal Exposure to Bisphenols and Phthalates and Infant Epigenetic Age Acceleration. Epigenomes, 8(3):
56. Repouskou A., Papadopoulou A.K., Panagiotidou E., Trichas P., Lindh C., Bergman A., et al. (2020). Long term transcriptional and behavioral effects in mice developmentally exposed to a mixture of endocrine disruptors associated with delayed human neurodevelopment. Sci Rep, 10(1):9367.
57. Hernandez Scudder M.E., Kunkel M.N., Gore A.C. (2020). Exposure to prenatal PCBs shifts the timing of neurogenesis in the hypothalamus of developing rats. J Exp Zool A Ecol Integr Physiol, 333(8):550-60.
58. Kaimal A., Hooversmith J.M., Al Mansi M.H., Cherry A.D., Garrity J.T., Holmes P.V., et al. (2024). Prenatal bisphenol A and/or diethylhexyl phthalate exposure followed by adult estradiol treatment affects behavior and brain monoamines in female rat offspring. Front Endocrinol (Lausanne), 15(1479838.
59. O'Shaughnessy K.L., Bell K.S., Sasser A.L., Gilbert M.E., Riutta C., Ford J.L., et al. (2024). The pollutant perfluorohexane sulfonate (PFHxS) reduces serum thyroxine but does not alter thyroid action in the postnatal rat brain. Environ Int, 190(108838.
60. Lopez-Rodriguez D., Aylwin C.F., Delli V., Sevrin E., Campanile M., Martin M., et al. (2021). Multi- and Transgenerational Outcomes of an Exposure to a Mixture of Endocrine-Disrupting Chemicals (EDCs) on Puberty and Maternal Behavior in the Female Rat. Environ Health Perspect, 129(8):87003.
61. Sobolewski M., Abston K., Conrad K., Marvin E., Harvey K., Susiarjo M., et al. (2020). Lineage- and Sex-Dependent Behavioral and Biochemical Transgenerational Consequences of Developmental Exposure to Lead, Prenatal Stress, and Combined Lead and Prenatal Stress in Mice. Environ Health Perspect, 128(2):27001.
62. Shu L., Meng Q., Diamante G., Tsai B., Chen Y.W., Mikhail A., et al. (2019). Prenatal Bisphenol A Exposure in Mice Induces Multitissue Multiomics Disruptions Linking to Cardiometabolic Disorders. Endocrinology, 160(2):409-29.
63. Khalifa M., Khalil H.M.A., Rashad E., El Henafy H.M.A., Fayed R.H. (2025). Dual-parent di-(2-ethylhexyl) phthalate (DEHP) exposure: A multigenerational assessment of neurocognitive outcomes in male pups. Food Chem Toxicol, 204(115620.
64. Wiersielis K.R., Samuels B.A., Roepke T.A. (2020). Perinatal exposure to bisphenol A at the intersection of stress, anxiety, and depression. Neurotoxicol Teratol, 79(106884.
65. Qi Y., Sun J., Wang H., Yu H., Jin X., Feng X., et al. (2024). Effects of arsenic exposure on the PI3K/Akt/NF-kappaB signaling pathway in the hippocampus of offspring mice at different developmental stages. Ecotoxicol Environ Saf, 283(116830.
66. Hernandez Scudder M.E., Young R.L., Thompson L.M., Kore P., Crews D., Hofmann H.A., et al. (2021). EDCs Reorganize Brain-Behavior Phenotypic Relationships in Rats. J Endocr Soc, 5(5):bvab021.
67. Di Criscio M., Lodahl J.E., Stamatakis A., Kitraki E., Bakoyiannis I., Repouskou A., et al. (2023). A human-relevant mixture of endocrine disrupting chemicals induces changes in hippocampal DNA methylation correlating with hyperactive behavior in male mice. Chemosphere, 313(137633.
68. Hilz E.N., Schnurer C., Bhamidipati S., Deka J., Thompson L.M., Gore A.C. (2025). Cognitive effects of early life exposure to PCBs in rats: Sex-specific behavioral, hormonal and neuromolecular mechanisms involving the brain dopamine system. Horm Behav, 169(105697.
69. Ma Q., Yang Z., Yang C., Lin M., Gong M., Deng P., et al. (2024). A single-cell transcriptomic landscape of cadmium-hindered brain development in mice. Commun Biol, 7(1):997.

70. Stubner C., Nielsen C., Jakobsson K., Gillberg C., Miniscalco C. (2023). Early-Life Exposure to Perfluoroalkyl Substances (PFAS) and Child Language and Communication Development: A Systematic Review. Int J Environ Res Public Health, 20(24):
71. Plunk E.C., Manz K.E., Gomes A., Pennell K.D., Sobolewski M.E., Majewska A.K. (2025). Gestational and Lactational Exposure to Perfluorohexanoic Acid Affects Behavior in Adult Male Mice: A Preliminary Study. Eur J Neurosci, 62(1):e70174.
72. Kaur S., Sarma S.J., Marshall B.L., Liu Y., Kinkade J.A., Bellamy M.M., et al. (2020). Author Correction: Developmental exposure of California mice to endocrine disrupting chemicals and potential effects on the microbiome-gut-brain axis at adulthood. Sci Rep, 10(1):12524.
73. Fu Y., Dong J., You M., Cong Z., Wei L., Fu H., et al. (2019). Maternal di-(2-ethylhexyl) phthalate exposure inhibits cerebellar granule precursor cell proliferation via down-regulating the Shh signaling pathway in male offspring. Chemosphere, 215(313-22.
74. Zhou F., Yin G., Gao Y., Liu D., Xie J., Ouyang L., et al. (2019). Toxicity assessment due to prenatal and lactational exposure to lead, cadmium and mercury mixtures. Environ Int, 133(Pt B):105192.
75. 75. Reilly M.P., Weeks C.D., Crews D., Gore A.C. (2018). Application of a novel social choice paradigm to assess effects of prenatal endocrine-disrupting chemical exposure in rats (Rattus norvegicus). J Comp Psychol, 132(3):253-67.
76. Simmet T., Wittenberg H.R., Peskar B.A. (1985). Modulation of eicosanoid release from anaphylactic guinea-pig heart with 5-benzoyl-a-methyl-2-thiophene acetic acid (tiaprofenic acid). Arch Int Pharmacodyn Ther, 278(2):207-14.
77. Kaur S., Sarma S.J., Marshall B.L., Liu Y., Kinkade J.A., Bellamy M.M., et al. (2020). Developmental exposure of California mice to endocrine disrupting chemicals and potential effects on the microbiome-gut-brain axis at adulthood. Sci Rep, 10(1):10902.
78. Ishitobi H., Stern S., Thurston S.W., Zareba G., Langdon M., Gelein R., et al. (2010). Organic and inorganic mercury in neonatal rat brain after prenatal exposure to methylmercury and mercury vapor. Environ Health Perspect, 118(2):242-8.
79. Foguth R.M., Flynn R.W., de Perre C., Iacchetta M., Lee L.S., Sepulveda M.S., et al. (2019). Developmental exposure to perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) selectively decreases brain dopamine levels in Northern leopard frogs. Toxicol Appl Pharmacol, 377(114623.
80. Zhang H.J., Liu Y.N., Xian P., Ma J., Sun Y.W., Chen J.S., et al. (2018). Maternal exposure to TCDD during gestation advanced sensory-motor development, but induced impairments of spatial learning and memory in adult male rat offspring. Chemosphere, 212(678-86.
81. Hernandez Scudder M.E., Weinberg A., Thompson L., Crews D., Gore A.C. (2020). Prenatal EDCs Impair Mate and Odor Preference and Activation of the VMN in Male and Female Rats. Endocrinology, 161(9):
82. Shao J., Wang S., Liu L. (2022). Maternal omega-3 fatty acid supplementation against prenatal lead exposure induced cognitive impairment in offspring mice. J Toxicol Sci, 47(5):183-92.
83. Nuñez P., Arguelles J., Perillan C. (2022). Sex-specific influence of maternal exposure to bisphenol A on sodium and fluid balance in response to dipsogenic challenges in rats. Appetite, 176(106091.
84. Htway S.M., Suzuki T., Kyaw S., Nohara K., Win-Shwe T.T. (2021). Effects of maternal exposure to arsenic on social behavior and related gene expression in F2 male mice. Environ Health Prev Med, 26(1):34.
85. Gillette R., Son M.J., Ton L., Gore A.C., Crews D. (2018). Passing experiences on to future generations: endocrine disruptors and transgenerational inheritance of epimutations in brain and sperm. Epigenetics, 13(10-11):1106-26.
86. Qi Y., Sun J., Wang H., Yu H., Jin X., Feng X., et al. (2024). Effects of arsenic exposure on the PI3K/Akt/NF-κB signaling pathway in the hippocampus of offspring mice at different developmental stages. Ecotoxicol Environ Saf, 283(116830.
87. Di Criscio M., Lodahl J.E., Stamatakis A., Kitraki E., Bakoyiannis I., Repouskou A., et al. (2023). A human-relevant mixture of endocrine disrupting chemicals induces changes in hippocampal DNA methylation correlating with hyperactive behavior in male mice. Chemosphere, 313(137633.
88. Stübner C., Nielsen C., Jakobsson K., Gillberg C., Miniscalco C. (2023). Early-Life Exposure to Perfluoroalkyl Substances (PFAS) and Child Language and Communication Development: A Systematic Review. Int J Environ Res Public Health, 20(24):
89. Wang Y., Peng D., Zhang X., Chen J., Feng J., Zhang R., et al. (2024). PLCβ4 driven by cadmium-exposure during gestation and lactation contributes to cognitive deficits by suppressing PIP2/PLCγ1/CREB/BDNF signaling pathway in male offspring. J Hazard Mater, 474(134756.
90. Repouskou A., Papadopoulou A.K., Panagiotidou E., Trichas P., Lindh C., Bergman Å., et al. (2020). Long term transcriptional and behavioral effects in mice developmentally exposed to a mixture of endocrine disruptors associated with delayed human neurodevelopment. Sci Rep, 10(1):9367.
91. Raja G.L., Lite C., Subhashree K.D., Santosh W., Barathi S. (2020). Prenatal bisphenol-A exposure altered exploratory and anxiety-like behaviour and induced non-monotonic, sex-specific changes in the cortical expression of CYP19A1, BDNF and intracellular signaling proteins in F1 rats. Food Chem Toxicol, 142(111442.
92. Foguth R.M., Flynn R.W., de Perre C., Iacchetta M., Lee L.S., Sepúlveda M.S., et al. (2019). Developmental exposure to perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) selectively decreases brain dopamine levels in Northern leopard frogs. Toxicol Appl Pharmacol, 377(114623.

93. Zhang M., Aris I.M., Lin P.D., Rifas-Shiman S.L., Brady T.M., James-Todd T., et al. (2023). Prenatal and Childhood Per- and Polyfluoroalkyl Substance (PFAS) Exposures and Blood Pressure Trajectories From Birth to Late Adolescence in a Prospective US Prebirth Cohort. J Am Heart Assoc, 12(17):e030760.
94. Rahimlou M., Mousavi M.A., Chiti H., Peyda M., Mousavi S.N. (2024). Association of maternal exposure to endocrine disruptor chemicals with cardio-metabolic risk factors in children during childhood: a systematic review and meta-analysis of cohort studies. Diabetol Metab Syndr, 16(1):82.
95. Starling A.P., Liu C., Shen G., Yang I.V., Kechris K., Borengasser S.J., et al. (2020). Prenatal Exposure to Per- and Polyfluoroalkyl Substances, Umbilical Cord Blood DNA Methylation, and Cardio-Metabolic Indicators in Newborns: The Healthy Start Study. Environ Health Perspect, 128(12):127014.
96. Cropper M., Dunlop S., Hinshaw H., Landrigan P., Park Y., Symeonides C. (2024). The benefits of removing toxic chemicals from plastics. Proc Natl Acad Sci U S A, 121(52):e2412714121.
97. Zhang M., Yu C.H., Wang G., Buckley J.P., Hong X., Pearson C., et al. (2022). Longitudinal trajectories and determinants of plasma per- and polyfluoroalkyl substance (PFAS) levels from birth to early childhood and metabolomic associations: A pilot study in the Boston Birth Cohort. Precis Nutr, 1(1):
98. Li Z., Wang G., Hong X., Brady T.M., Pearson C., Buckley J.P., et al. (2025). Prenatal Per- and Polyfluoroalkyl Substance Exposures and Longitudinal Blood Pressure Measurements in Children Aged 3 to 18 Years: Findings From a Racially and Ethnically Diverse US Birth Cohort. J Am Heart Assoc, 14(12):e039949.
99. Jones M.J., Lotfi A., Lin A., Gievers L.L., Hendrickson R., Sheridan D.C. (2022). Prenatal marijuana exposure and neonatal outcomes: a retrospective cohort study. BMJ Open, 12(9):e061167.
100. Mao Z., Chen Y., Li H., Lu Q., Zhou K. (2024). TLR4 as a Potential Target of Me-PFOSA-AcOH Leading to Cardiovascular Diseases: Evidence from NHANES 2013-2018 and Molecular Docking. Toxics, 12(10):
101. Kable J.A., Coles C.D., Jones K.L., Yevtushok L., Kulikovsky Y., Zymak-Zakutnya N., et al. (2021). Infant Cardiac Orienting Responses Predict Later FASD in the Preschool Period. Alcohol Clin Exp Res, 45(2):386-94.
102. Rappazzo K.M., Warren J.L., Davalos A.D., Meyer R.E., Sanders A.P., Brownstein N.C., et al. (2019). Maternal residential exposure to specific agricultural pesticide active ingredients and birth defects in a 2003-2005 North Carolina birth cohort. Birth Defects Res, 111(6):312-23.
103. Yujiao C., Meng Z., Shanshan L., Wei W., Yipeng W., Chenghong Y. (2023). Exposure to Bisphenol A induces abnormal fetal heart development by promoting ferroptosis. Ecotoxicol Environ Saf, 255(114753.
104. Marrone A., De Bartolo A., Rago V., Conforti F., Urlandini L., Angelone T., et al. (2025). Prenatal Bisphenol A Exposure Impairs Fetal Heart Development: Molecular and Structural Alterations with Sex-Specific Differences. Antioxidants (Basel), 14(7):
105. Spinder N., Bergman J.E., Kromhout H., Vermeulen R., Corsten-Janssen N., Boezen H.M., et al. (2020). Maternal occupational exposure and congenital heart defects in offspring. Scand J Work Environ Health, 46(6):599-608.
106. Marrone A., De Bartolo A., Rago V., Conforti F., Urlandini L., Angelone T., et al. (2025). Prenatal Bisphenol A Exposure Impairs Fetal Heart Development: Molecular and Structural Alterations with Sex-Specific Differences. Antioxidants (Basel), 14(7):
107. 107. Martínez-Peña A.A., Lee K., Pereira M., Ayyash A., Petrik J.J., Hardy D.B., et al. (2022). Prenatal Exposure to Delta-9-tetrahydrocannabinol (THC) Alters the Expression of miR-122-5p and Its Target Igf1r in the Adult Rat Ovary. Int J Mol Sci, 23(14):
108. Cao N., Lan C., Chen C., Xu Z., Luo H., Zheng S., et al. (2022). Prenatal Lipopolysaccharides Exposure Induces Transgenerational Inheritance of Hypertension. Circulation, 146(14):1082-95.
109. Wang K., Li M., Sartor M.A., Colacino J.A., Dolinoy D.C., Svoboda L.K. (2025). Perinatal Exposure to Lead or Diethylhexyl Phthalate in Mice: Sex-Specific Effects on Cardiac DNA Methylation and Gene Expression across Time. Environ Health Perspect, 133(6):67014.
110. Shorey-Kendrick L.E., Roberts V.H.J., D'Mello R.J., Sullivan E.L., Murphy S.K., McCarty O.J.T., et al. (2023). Prenatal delta-9-tetrahydrocannabinol exposure is associated with changes in rhesus macaque DNA methylation enriched for autism genes. Clin Epigenetics, 15(1):104.
111. Moreno-Gómez-Toledano R., Arenas M.I., Vélez-Vélez E., Coll E., Quiroga B., Bover J., et al. (2021). Bisphenol a Exposure and Kidney Diseases: Systematic Review, Meta-Analysis, and NHANES 03-16 Study. Biomolecules, 11(7):
112. Zhang X., Flaws J.A., Spinella M.J., Irudayaraj J. (2022). The Relationship between Typical Environmental Endocrine Disruptors and Kidney Disease. Toxics, 11(1):
113. Sood S., Ojo A.O., Adu D., Kannan K., Ghassabian A., Koshy T., et al. (2019). Association Between Perfluoroalkyl Substance Exposure and Renal Function in Children With CKD Enrolled in H3Africa Kidney Disease Research Network. Kidney Int Rep, 4(11):1641-5.
114. Elliott W.J., Murphy M.B. (1988). Reduced specificity of the clonidine suppression test in patients with normal plasma catecholamine levels. Am J Med, 84(3 Pt 1):419-24.
115. Lozano-Paniagua D., Parrón T., Alarcón R., Requena M., Lacasaña M., Hernández A.F. (2023). Renal tubular dysfunction in greenhouse farmers exposed to pesticides unveiled by a panel of molecular biomarkers of kidney injury. Environ Res, 238(Pt 2):117200.
116. Aroonvilairat S., Kespichayawattana W., Sornprachum T., Chaisuriya P., Siwadune T., Ratanabanangkoon K. (2015). Effect of pesticide exposure on immunological, hematological and biochemical parameters in thai orchid farmers- a cross-sectional study. Int J Environ Res Public Health, 12(6):5846-61.

117. Bowe B., Xie Y., Li T., Yan Y., Xian H., Al-Aly Z. (2018). Particulate Matter Air Pollution and the Risk of Incident CKD and Progression to ESRD. J Am Soc Nephrol, 29(1):218-30.
118. Rasking L., Vanbrabant K., Bové H., Plusquin M., De Vusser K., Roels H.A., et al. (2022). Adverse Effects of fine particulate matter on human kidney functioning: a systematic review. Environ Health, 21(1):24.
119. Sassa H., Takaishi Y., Terada H. (1990). The triterpene celastrol as a very potent inhibitor of lipid peroxidation in mitochondria. Biochem Biophys Res Commun, 172(2):890-7.
120. Mu J., Li Y., He L., Ma M., Zhang M., Wang X., et al. (2025). Differential associations between synthetic endocrine disruptors and renal function impairment across varying degrees in middle-aged and older adult populations. Front Public Health, 13(1526070.
121. Eklund A., Taj T., Dunder L., Lind P.M., Lind L., Salihovic S. (2025). Longitudinal and cross-sectional analysis of perfluoroalkyl substances and kidney function. J Expo Sci Environ Epidemiol,
122. Yun J., Jang E.C., Kwon S.C., Min Y.S., Lee Y.J. (2023). The association of perfluoroalkyl substances (PFAS) exposure and kidney function in Korean adolescents using data from Korean National Environmental Health Survey (KoNEHS) cycle 4 (2018-2020): a cross-sectional study. Ann Occup Environ Med, 35(e5.
123. Lozano-Paniagua D., Parron T., Alarcon R., Requena M., Lacasana M., Hernandez A.F. (2023). Renal tubular dysfunction in greenhouse farmers exposed to pesticides unveiled by a panel of molecular biomarkers of kidney injury. Environ Res, 238(Pt 2):117200.
124. Moreno-Gomez-Toledano R., Arenas M.I., Velez-Velez E., Coll E., Quiroga B., Bover J., et al. (2021). Bisphenol a Exposure and Kidney Diseases: Systematic Review, Meta-Analysis, and NHANES 03-16 Study. Biomolecules, 11(7):
125. Rasking L., Vanbrabant K., Bove H., Plusquin M., De Vusser K., Roels H.A., et al. (2022). Adverse Effects of fine particulate matter on human kidney functioning: a systematic review. Environ Health, 21(1):24.
126. Sood S., Ojo A.O., Adu D., Kannan K., Ghassabian A., Koshy T., et al. (2019). Association Between Perfluoroalkyl Substance Exposure and Renal Function in Children With CKD Enrolled in H3Africa Kidney Disease Research Network. Kidney Int Rep, 4(11):1641-5.
127. Shearer J.J., Sandler D.P., Andreotti G., Murata K., Shrestha S., Parks C.G., et al. (2021). Pesticide use and kidney function among farmers in the Biomarkers of Exposure and Effect in Agriculture study. Environ Res, 199(111276.
128. Lin P.D., Cardenas A., Hauser R., Gold D.R., Kleinman K.P., Hivert M.F., et al. (2021). Per- and polyfluoroalkyl substances and kidney function: Follow-up results from the Diabetes Prevention Program trial. Environ Int, 148(106375.
129. Blake B.E., Pinney S.M., Hines E.P., Fenton S.E., Ferguson K.K. (2018). Associations between longitudinal serum perfluoroalkyl substance (PFAS) levels and measures of thyroid hormone, kidney function, and body mass index in the Fernald Community Cohort. Environ Pollut, 242(Pt A):894-904.
130. Vandenberg L.N., Colborn T., Hayes T.B., Heindel J.J., Jacobs D.R., Jr., Lee D.H., et al. (2012). Hormones and endocrine-disrupting chemicals: low-dose effects and nonmonotonic dose responses. Endocr Rev, 33(3):378-455.
131. Gonzalez-Parra E., Herrero J.A., Elewa U., Bosch R.J., Arduan A.O., Egido J. (2013). Bisphenol a in chronic kidney disease. Int J Nephrol, 437857.
132. Pei J., Peng J., Wu M., Zhan X., Wang D., Zhu G., et al. (2025). Analyzing the potential targets and mechanisms of chronic kidney disease induced by common synthetic Endocrine Disrupting Compounds (EDCs) in Chinese surface water environment using network toxicology and molecular docking techniques. Sci Total Environ, 958(177980.
133. Conway B.N., Badders A.N., Costacou T., Arthur J.M., Innes K.E. (2018). Perfluoroalkyl substances and kidney function in chronic kidney disease, anemia, and diabetes. Diabetes Metab Syndr Obes, 11; 707-16.
134. Curran C.S., Kopp J.B. (2022). Aryl Hydrocarbon Receptor Mechanisms Affecting Chronic Kidney Disease. Front Pharmacol, 13(782199.
135. Heindel J.J., Belcher S., Flaws J.A., Prins G.S., Ho S.M., Mao J., et al. (2020). Data integration, analysis, and interpretation of eight academic CLARITY-BPA studies. Reprod Toxicol, 98;29-60.
136. Martini M., Corces V.G., Rissman E.F. (2020). Mini-review: Epigenetic mechanisms that promote transgenerational actions of endocrine disrupting chemicals: Applications to behavioral neuroendocrinology. Horm Behav, 119(104677.
137. Baldacci S., Gorini F., Santoro M., Pierini A., Minichilli F., Bianchi F. (2018). Environmental and individual exposure and the risk of congenital anomalies: a review of recent epidemiological evidence. Epidemiol Prev, 42(3-4 Suppl 1):1-34.
138. Wu T., Zhou K., Hua Y., Zhang W., Li Y. (2023). The molecular mechanisms in prenatal drug exposure-induced fetal programmed adult cardiovascular disease. Front Pharmacol, 14(1164487.
139. Svoboda L.K., Wang K., Goodrich J.M., Jones T.R., Colacino J.A., Peterson K.E., et al. (2023). Perinatal Lead Exposure Promotes Sex-Specific Epigenetic Programming of Disease-Relevant Pathways in Mouse Heart. Toxics, 11(1):
140. Elkin E.R., Higgins C., Aung M.T., Bakulski K.M. (2022). Metals Exposures and DNA Methylation: Current Evidence and Future Directions. Curr Environ Health Rep, 9(4):673-96.

141. Kunovac A., Hathaway Q.A., Pinti M.V., Taylor A.D., Hollander J.M. (2020). Cardiovascular adaptations to particle inhalation exposure: molecular mechanisms of the toxicology. Am J Physiol Heart Circ Physiol, 319(2):H282-H305.
142. Liu Y., Eliot M.N., Papandonatos G.D., Kelsey K.T., Fore R., Langevin S., et al. (2022). Gestational Perfluoroalkyl Substance Exposure and DNA Methylation at Birth and 12 Years of Age: A Longitudinal Epigenome-Wide Association Study. Environ Health Perspect, 130(3):37005.
143. Ma N., Liu X., Zhao L., Liu Y., Peng X., Ma D., et al. (2024). Bisphenol P induces increased oxidative stress in renal tissues of C57BL/6 mice and human renal cortical proximal tubular epithelial cells, resulting in kidney injury. Sci Total Environ, 949(175159.
144. Zhu Y., Liu X., Shi Y., Liu X., Li H., Ru S., et al. (2024). Prenatal exposure to bisphenol AF causes toxicities in liver, spleen, and kidney tissues of SD rats. Food Chem Toxicol, 192(114939.
145. McCabe C.F., Goodrich J.M., Bakulski K.M., Domino S.E., Jones T.R., Colacino J., et al. (2023). Probing prenatal bisphenol exposures and tissue-specific DNA methylation responses in cord blood, cord tissue, and placenta. Reprod Toxicol, 115(74-84.
146. Fuhrmann L., Lindner S., Hauser A.T., Hose C., Kretz O., Cohen C.D., et al. (2021). Effects of Environmental Conditions on Nephron Number: Modeling Maternal Disease and Epigenetic Regulation in Renal Development. Int J Mol Sci, 22(8):
147. Topper V.Y., Walker D.M., Gore A.C. (2015). Sexually dimorphic effects of gestational endocrine-disrupting chemicals on microRNA expression in the developing rat hypothalamus. Mol Cell Endocrinol, 414(42-52.
148. Ghasemzadeh-Hasankolaei M., Elcombe C.S., Powls S., Lea R.G., Sinclair K.D., Padmanabhan V., et al. (2024). Preconceptional and in utero exposure of sheep to a real-life environmental chemical mixture disrupts key markers of energy metabolism in male offspring. J Neuroendocrinol, 36(1):e13358.
149. Sala-Hamrick K.E., Wang K., Perera B.P.U., Sartor M.A., Svoboda L.K., Dolinoy D.C. (2025). Sex-stratified piRNA expression analysis reveals shared functional impacts of perinatal lead (Pb) exposure in murine hearts. Epigenetics, 20(1):2542879.
150. Everson T.M., Sehgal N., Barr D.B., Panuwet P., Yakimavets V., Perez C., et al. (2024). Placental PFAS concentrations are associated with perturbations of placental DNA methylation at loci with important roles on cardiometabolic health. medRxiv,
151. Shi H., Zhang Z., Shen A., Ding T., Zhao R., Shi Y., et al. (2025). Maternal di(2-ethylhexyl) phthalate exposure increases the risk of congenital heart disease in mice offspring. Pediatr Res,
152. Cheng M.D., Li C.L., Pei X.Y., Zhang Y.F., Jia D.D., Zuo Y.B., et al. (2023). Integrative analysis of DNA methylome and transcriptome reveals epigenetic regulation of bisphenols-induced cardiomyocyte hypertrophy. Ecotoxicol Environ Saf, 263(115391.
153. Lee Y.J., Lin H.T., Chaudhary M.A., Lee Y.C., Wang D.C. (2021). Effects of Prenatal Phthalate Exposure and Childhood Exercise on Maternal Behaviors in Female Rats at Postpartum: A Role of Oxtr Methylation in the Hypothalamus. Int J Mol Sci, 22(18):
154. Merrill S.M., Letourneau N., Giesbrecht G.F., Edwards K., MacIsaac J.L., Martin J.W., et al. (2024). Sex-Specific Associations between Prenatal Exposure to Di(2-ethylhexyl) Phthalate, Epigenetic Age Acceleration, and Susceptibility to Early Childhood Upper Respiratory Infections. Epigenomes, 8(1):
155. Villani L., Pezzullo A.M., Pastorino R., Maio A., Stollagli F., Tirone C., et al. (2025). Environmental maternal exposures and the risk of premature birth and intrauterine growth restriction: The Generation Gemelli study protocol of newborn exposome. PLoS One, 20(1):e0317458.
156. Tehrani J.M., Kennedy E., Tung P.W., Burt A., Hermetz K., Punshon T., et al. (2023). Human placental microRNAs dysregulated by cadmium exposure predict neurobehavioral outcomes at birth. Pediatr Res, 93(5):1410-8.
157. Pamphlett R., Kum Jew S., Cherepanoff S. (2019). Mercury in the retina and optic nerve following prenatal exposure to mercury vapor. PLoS One, 14(8):e0220859.
158. Liu S.X., Ramakrishnan A., Shen L., Gewirtz J.C., Georgieff M.K., Tran P.V. (2024). Chromatin accessibility and H3K9me3 landscapes reveal long-term epigenetic effects of fetal-neonatal iron deficiency in rat hippocampus. BMC Genomics, 25(1):301.
159. Lertpeerapan P., Kanlayaprasit S., Thongkorn S., Kasitipradit K., Panjabud P., Songsritaya K., et al. (2025). Sex-dependent epigenetic disruption of YY1 binding by prenatal BPA exposure downregulates Matr3 and alters Agap1 splicing in the offspring hippocampus. Biol Sex Differ, 16(1):63.
160. Liu K., Tao T., Li R., Wang H., Wang L., Wu H. (2025). Early-Life Arsenic Exposure Induces Histone H3K9 Methylation Causing PANoptosis and Neurodevelopmental Impairments in Offspring. Biol Trace Elem Res,
161. Rosenfeld C.S. (2024). Should Pregnant Women Consume Probiotics to Combat Endocrine-Disrupting Chemical-Induced Health Risks to Their Unborn Offspring? Biomedicines, 12(8):
162. Sirasanagandla S.R., Al-Huseini I., Sofin R.G.S., Das S. (2022). Perinatal Exposure to Bisphenol A and Developmental Programming of the Cardiovascular Changes in the Offspring. Curr Med Chem, 29(24):4235-50.
163. Svoboda L.K., Neier K., Wang K., Cavalcante R.G., Rygiel C.A., Tsai Z., et al. (2021). Tissue and sex-specific programming of DNA methylation by perinatal lead exposure: implications for environmental epigenetics studies. Epigenetics, 16(10):1102-22.
164. Docea A.O., Cirstea A.E., Cercelaru L., Drocas A.I., Dinca V., Mesnage R., et al. (2023). Effect of perinatal exposure to glyphosate and its mixture with 2,4-D and dicamba on rat dam kidney and thyroid function and offspring's health. Environ Res, 237(Pt 1):116908.

165. Bozack A.K., Boileau P., Hubbard A.E., Sille F.C.M., Ferreccio C., Steinmaus C.M., et al. (2022). The impact of prenatal and early-life arsenic exposure on epigenetic age acceleration among adults in Northern Chile. Environ Epigenet, 8(1):dvac014.
166. Liu J., Chen X., Liu J., Peng C., Wang F., Huang X., et al. (2025). Prenatal Inflammatory Exposure Predisposes Offspring to Chronic Kidney Diseases Via the Activation of the eIF2alpha-ATF4 Pathway. Inflammation, 48(2):747-59.
167. Singh R.D., Tiwari R., Sharma V., Khan H., Gangopadhyay S., Singh S., et al. (2022). Prenatal arsenic exposure induces immunometabolic alteration and renal injury in rats. Front Med (Lausanne), 9(1045692.
168. Tiwari R., Singh R.D., Singh S., Singh D., Srivastav A.K., Kumar M., et al. (2022). Gestational exposure to silver nanoparticles enhances immune adaptation and protection against streptozotocin-induced diabetic nephropathy in mice offspring. Nanotoxicology, 16(4):450-71.
169. Wei Y., Wang X., Sun Q., Shi W., Zhang W., Gao X., et al. (2024). Associations of environmental cadmium exposure with kidney damage: Exploring mediating DNA methylation sites in Chinese adults. Environ Res, 251(Pt 1):118667.
170. Zhao S., Pan L., Chen M., Zhu Y.P., Han B.M., Xia S.J., et al. (2020). In utero di-n-butyl phthalate exposure induced abnormal autophagy in renal tubular cells via hedgehog signaling in newborn rats. Chem Biol Interact, 328(109189.
171. Jacobson M.H., Wu Y., Liu M., Attina T.M., Naidu M., Karthikraj R., et al. (2020). Serially assessed bisphenol A and phthalate exposure and association with kidney function in children with chronic kidney disease in the US and Canada: A longitudinal cohort study. PLoS Med, 17(10):e1003384.