*CIBTech Journal of Zoology ISSN: 2319–3883*
*Online, International Journal, Available at http://www.cibtech.org/cjz.htm*
*2026 Vol.15, pp.225-239/Parama and Sudipta*
***Review Article** (Open Access)*

# TRACING THE TOXIC FOOTPRINT OF BISPHENOL A: FROM ABIOTIC PATHWAYS TO METABOLIC FATE AND TOXICITY IN BIOTA

**Parama Sarkar and Sudipta Mandal***
*Post graduate Department of Zoology, Bangabasi College, Kolkata-700009,*
*West Bengal, India*
**Author for Correspondence: smzoology@gmail.com*

## ABSTRACT
Bisphenol A (BPA) is a synthetic organic compound widely used in the production of polycarbonate plastics and epoxy resins, resulting in its pervasive presence in the environment. Owing to its structural configuration with two phenolic rings and hydroxyl groups, BPA exhibits estrogen-like activity and is recognized as an endocrine-disrupting chemical. Its physicochemical properties, including moderate hydrophobicity and partial water solubility, facilitate persistence and widespread distribution across aquatic and terrestrial ecosystems. BPA primarily enters the environment through anthropogenic sources such as industrial effluents, domestic sewage, degradation of consumer products, and landfill leachates, resulting in continuous contamination of natural systems. Once released into the environment, BPA is transported through interconnected abiotic pathways, accumulating in water, sediments, and soils, where factors such as pH, temperature, and organic matter influence its fate and bioavailability. The compound enters biotic systems, particularly in aquatic organisms, through direct absorption and dietary intake. Although BPA undergoes metabolic detoxification via Phase I and Phase II biotransformation pathways, incomplete metabolism may cause persistence of bioactive forms in different tissues. This review highlights the environmental sources of BPA, its ecological hazards, and the physiological implications of BPA exposure in both aquatic and terrestrial organisms. The combined effects of continuous environmental exposure, bioaccumulation at lower trophic levels, and limited metabolic clearance underscore the ecological risk posed by this compound. Understanding its environmental dynamics and biological impacts is essential for assessing its long-term consequences on biota and ecosystem health.

***Keywords:** Bisphenol A (BPA), Environmental contamination, Anthropogenic sources, Environmental fate, Biotransformation, Ecotoxicity*

## INTRODUCTION
Bisphenol A (BPA) is a man-made organic chemical widely employed in the manufacture of polycarbonate plastics and epoxy-based materials, leading to its extensive presence in modern industrial and environmental systems (Zhang *et al.,* 2022). Chemically, BPA contains two phenolic rings connected through a methyl linkage, a structure responsible for its stability as well as its biological reactivity. The hydroxyl groups present in the molecule enable interactions with hormonal receptors, especially estrogen receptors, allowing BPA to function as an endocrine-disrupting chemical (EDC) (Rochester, 2013; Vandenberg *et al.,* 2007). Its moderate hydrophobic nature, limited volatility, and partial solubility in water contribute to its persistence and movement through different environmental compartments.

BPA contamination is largely associated with human activities rather than natural processes. Industrial wastewater from plastic and resin production facilities, municipal sewage, decomposition of consumer products such as plastic containers, thermal receipts, and landfill leachates all act as major contributors to environmental BPA release. Continuous discharge from these sources has resulted in frequent detection of BPA in water bodies, sediments, and soils (Staples *et al.,* 1998; Flint *et al.,* 2012). Although the compound can be degraded through microbial action, photochemical reactions, and other environmental processes, the constant input of BPA into environment maintains long-term exposure effects within ecosystems.

Movement of BPA through ecosystems occurs via interconnected abiotic pathways. In aquatic habitats, wastewater discharge, industrial runoff, and surface drainage introduce BPA into rivers, lakes, and ponds, where it may remain dissolved or bind with suspended particles and sediments. Terrestrial contamination occurs through sewage sludge application, disposal of solid wastes, and atmospheric deposition. These environmental compartments serve as temporary storage sites that influence the transport, mobility, and availability of BPA. Factors including temperature, pH, and organic matter content further regulate its environmental behaviour and bioavailability (Flint *et al.,* 2012; Rochester, 2013).

The transfer of BPA from environmental reservoirs into living organisms marks an important stage in its ecological impact. Aquatic organisms, like freshwater fish, absorb BPA directly through the gills because the chemical is present in dissolved form within water (Liu *et al.,* 2025). Exposure also occurs through ingestion of contaminated food items and sediments. Following uptake, BPA may accumulate in organs such as the liver, intestine, and muscle tissues. In soil ecosystems, microorganisms and small invertebrates are exposed to BPA directly or through feeding activities, allowing the compound to enter terrestrial food chains (Vandenberg *et al.,* 2007). Although BPA is not considered a strongly biomagnifying pollutant compared with highly lipophilic contaminants, its continuous environmental presence may still cause harmful biological effects at multiple trophic levels.

Inside living systems, BPA undergoes metabolic processing intended to reduce toxicity, though detoxification is often incomplete. In fish, the liver serves as the principal site of metabolism, involving both Phase I and Phase II biotransformation reactions (Dong *et al.,* 2019; Rochester, 2013). Additional transformation pathways, including cyclization and intramolecular rearrangements, have also been proposed and may yield metabolites with different biological properties. However, these pathways remain insufficiently understood and may vary considerably among species (Faheem and Bhandari 2021).

Thus, the widespread occurrence of BPA, its continuous entry into environmental compartments, its efficient transfer from abiotic to biotic systems, and its incomplete metabolic detoxification collectively highlight its ecological significance. Understanding its chemical nature, environmental pathways, and metabolic fate provides a critical foundation for evaluating its impact on aquatic and terrestrial biota.

## NATURAL AND ANTHROPOGENIC SOURCES OF BISPHENOL A

In the environment, Bisphenol A (BPA) is found in many places associated with large-scale manufacturing and industrial activity. Its persistence is largely due to continued industrial release linked to everyday activities. This compound is used to make polycarbonate plastics and is also found in the inner linings of widely used soup cans and paper cups. It is also commonly used in thermal paper, such as that used for printed receipts in malls, shops and other outlets (Miller *et al.,* 2023; Nasello *et al.,* 2022). Traces of these substances can also be found in everyday products such as water pipes and children's toys, often as a result of their manufacturing processes. Hospitals use many products made with BPA, creating another pathway through which it can enter the environment. Once discarded, these items can release harmful substances into the soil as they decompose or are burned (Vinković *et al.,* 2023). Rain carries waste into streams and rivers, where these fragments eventually accumulate. Year after year, the volume of discarded electronics continues to grow, placing an increasing burden on the environment. Evidence suggests that these substances are quickly accumulating in terrestrial environments as well as in flowing and stagnant waters (Wei *et al.,* 2023).

Factories pumping out waste play a big part in spreading BPA into nature. Wastewater streams may also contain microplastics capable of carrying BPA, providing an additional pathway for its transport into aquatic environments (Wang *et al.,* 2024). Everyday waste from our homes, careless disposal of plastic items, chemicals released from food packaging, and the gradual breakdown of products exposed to sunlight and heat all add to the problem (Mishra *et al.,* 2023).

When plastic is exposed to sunlight and heat, broken down by microorganisms, or simply worn away over time, its polymer structure gradually deteriorates. As this happens, BPA can slowly leach out and accumulate in the surrounding air, water bodies, and sediments. (Zhang *et al.,* 2022; Washington *et al.,* 2024).

Rainfall may carry traces of BPA from the atmosphere into agricultural land and surrounding water bodies. These particles are released from factories or carried in the air as dust (Li *et al.,* 2024). Once released into the air, they can travel long distances before settling on soil or water. BPA can leach from landfills with rainwater and eventually reach groundwater also (Liao *et al.,* 2024). As it spreads, more parts of the natural environment are exposed (Zhang *et al.,* 2024). It can travel through the air, while drainage provides another pathway into the environment. This movement helps contaminants travel across different parts of the landscape (Li *et al.,* 2022).

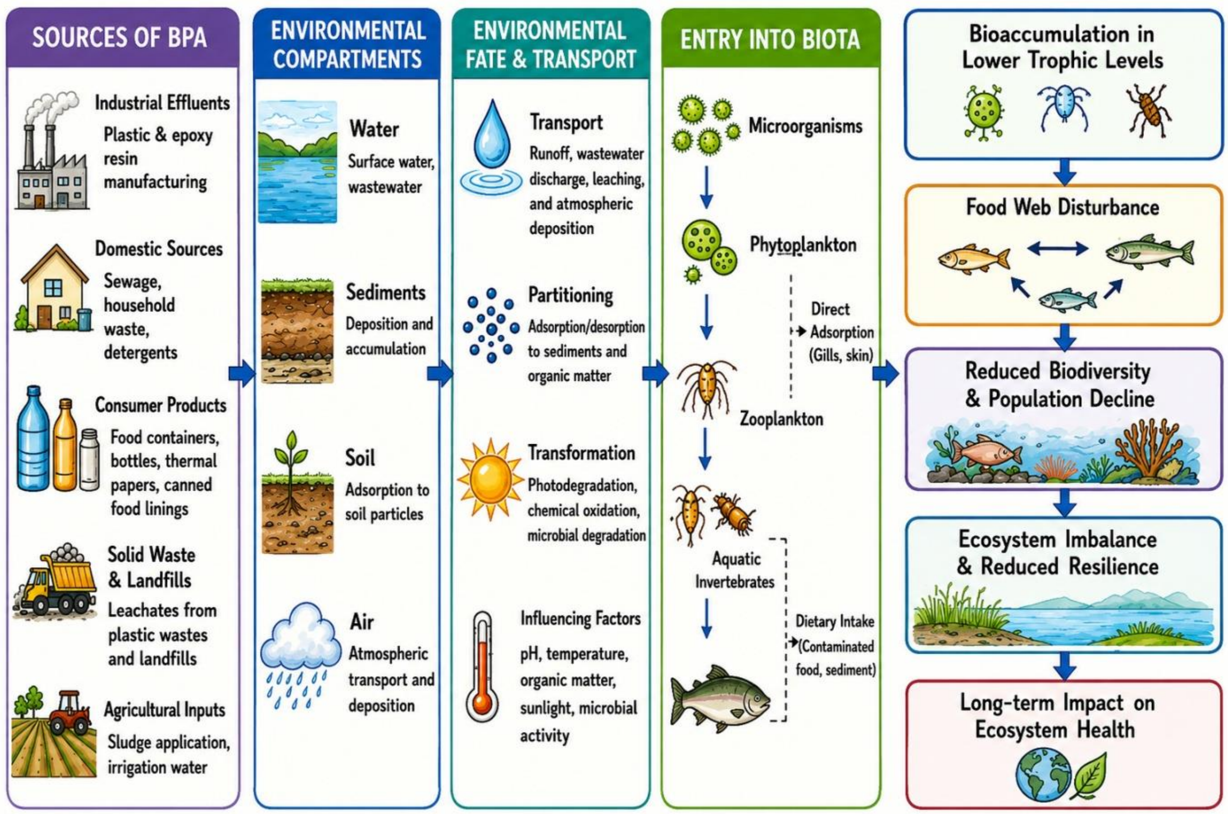


**Fig. 1: Source, Environmental fate, transport pathways and ecological impacts of Bisphenol A in aquatic and terrestrial ecosystems**

## ROUTE OF ENTRY TO THE ENVIRONMENT

BPA enters the environment through complex pathways, moving between non-living and living parts of natural ecosystems. Once BPA gets into the environment, it tends to accumulate first in non-living places such as soil, river sediments, surface water, groundwater, and even tiny particles suspended in the air (Swansborough *et al.,* 2025). Because BPA doesn't mix easily with water but binds readily to carbon-rich materials, it tends to stick to soil and suspended debris, allowing it to remain there for longer than expected (Liu *et al.,* 2025). Rivers, lakes, ponds, and coastal areas often receive runoff from industrial sites and urban sewage systems, where treatment processes may not fully remove chemicals like BPA before they are released (Cheng & Wang, 2024). Once it enters the water, BPA can either remain dissolved or attach itself to floating debris and suspended sediments (Wang *et al.,* 2023; Tang *et al.,* 2023). Industrial sites and urban sewage systems can therefore act as important pathways through which BPA enters aquatic environments (Puri *et al.,* 2024). When these contaminated particles are stirred back into the water by movement beneath the surface, the trapped BPA can be released again, allowing it to spread through wetlands and marine ecosystems (Du *et al.,* 2025; Pop *et al.,* 2024)

Beyond supporting life, soil can also act as an important reservoir for BPA. Agricultural fields exposed to sewage, contaminated irrigation water, plastic mulch, or industrial spills can gradually accumulate BPA over time. From there, BPA can seep into groundwater or be absorbed by plant roots, eventually making its way into terrestrial food chains (Liang *et al.,* 2024; Kim *et al.,* 2023). Because BPA persists in the environment and can be released again over time, it can spread through different parts of nature, including soil, plants, and water, increasing its overall impact (Zhao *et al.,* 2025; Wakim *et al.,* 2024).

## ENTRY INTO BIOTA AND TROPHIC TRANSFER

BPA can move from nonliving materials into plants and animals, marking an important step for its accumulation in ecosystems which eventually cause harm to living organisms. BPA has been detected in aquatic plants, algae, zooplankton and fish, indicating that multiple components of aquatic food webs can be exposed to the contaminant (Yang *et al.,* 2024). It starts with tiny organisms such as bacteria, algae, and fungi, which bring BPA into the food web early on. Some of these microorganisms can absorb BPA, transform it through natural processes, or partially break it down, allowing the chemical to move further into biological cycles (Atengueño-Reyes *et al.,* 2024; Noszczyńska *et al.,* 2023 ; Rybczyńska-Tkaczyk *et al.,* 2023). Although some microbes can break down BPA over time, excessive exposure can disrupt their populations, interfere with important enzymes, and upset the balance of aquatic and soil ecosystems (Fu *et al.,* 2023; Zhang *et al.,* 2022). Once microbes absorb BPA, it can move into small aquatic organisms such as phytoplankton and zooplankton (Zainuddin *et al.,* 2023). Since these organisms sit at the base of many aquatic food chains, they can readily transfer BPA to the organisms that feed on them (Czarny-Krzymińska *et al.,* 2022). Over time, BPA can build up in these organisms and then move to larger animals of higher trophic levels, including invertebrates and fish (Peskova and Blahova 2025; Paolella *et al.,* 2025). Freshwater fish may absorb more BPA because they are constantly exposed to contaminated water and also consume prey that has already taken in the chemical (Kundu *et al.,* 2024). In fish, BPA exposure has been linked to disrupted body functions, hormone imbalance, cellular damage, changes in energy metabolism, and alterations in enzymes involved in gut health (Peskova and Blahova 2025). BPA can move further up the food chain, affecting animals beyond fish and other aquatic organisms. Birds, frogs, and land animals can be exposed when they eat contaminated food or drink polluted water. They may also absorb BPA through direct contact with contaminated soil, sediment, or other surfaces, so exposure is not limited to ingestion. As BPA moves through each level of the food chain, it can accumulate in organisms and become more concentrated. This raises concerns about ecosystem balance, wildlife health, and the long-term survival of vulnerable species (Yuan *et al.,* 2026). It can disrupt hormone-related signals and interfere with normal cellular functions, creating effects that can build up with continued exposure. This gradual disruption can make BPA especially harmful over time, affecting multiple biological processes and putting the health of living organisms at risk. Studies have shown that BPA can persist in the environment and spread quietly through different ecosystems, making it a long-term pollutant of concern (Ighalo *et al.,* 2024).

## EFFECTS OF BPA ON ABIOTIC ENVIRONMENTAL COMPONENTS

BPA contamination in aquatic environments is a persistent and evolving ecological concern, largely because the chemical is continuously released into these systems and can behave differently depending on its surrounding conditions (Gupta *et al.,* 2024; Wu *et al.,* 2021). BPA is commonly detected in rivers, lakes, groundwater, and sediments. Its presence in these environments is mainly linked to industrial discharges, municipal wastewater, and urban runoff, which can introduce the chemical into aquatic systems (Flint *et al.,* 2012; Vandenberg *et al.,* 2007). Although wastewater treatment plants can remove some BPA, conventional treatment methods often cannot break it down completely. As a result, BPA can continue to pass through treatment systems and be released into nearby receiving waters.

Within aquatic environments, BPA can exist in two main forms: dissolved directly in the water or attached to suspended particles and sediments. This dual distribution allows BPA to settle into bottom sediments, where it can remain for long periods and later serve as a secondary source of contamination (Yuan *et al.,* 2026). Environmental factors such as pH, temperature, and microbial activity influence how quickly BPA breaks down. However, because it is continuously introduced into the environment, BPA can persist over time and behave as a pseudo-persistent pollutant (Rochester, 2013). BPA can also affect aquatic chemistry indirectly by disrupting microbial processes involved in nutrient cycling and oxygen balance, which may gradually alter how aquatic ecosystems function. Additionally, BPA trapped in sediments can be released again when environmental conditions change, prolonging its presence and extending exposure in aquatic ecosystems.

***Effects on Soil System***

Soil acts as an important reservoir for BPA, with contamination mainly coming from landfill leachate, the use of sewage sludge, irrigation with polluted water, and atmospheric deposition (Matharage *et al.,* 2024; Li *et al.,* 2022). BPA's interaction with soil organic matter plays an important role in determining how easily it moves, how available it is to organisms, and how long it remains in the environment (Staples *et al.,* 1998). Although adsorption onto soil particles can temporarily lower its bioavailability, it can also keep BPA in the soil for longer, extending its exposure to soil-dwelling organisms.

BPA exposure in soil ecosystems can alter both the soil's physicochemical properties and its biological activity, potentially affecting how these ecosystems function (Zaborowska *et al.,* 2021). Studies have shown that BPA can affect important soil enzymes, including dehydrogenase, phosphatase, and urease, which play key roles in nutrient transformation and cycling (Zaborowska *et al.,* 2021). Disrupting these enzyme-driven processes can reduce soil fertility and, in turn, affect the overall productivity and health of the ecosystem. Furthermore, BPA may affect the microbial processes that help bind soil particles together, which can indirectly influence soil structure and stability (Zaborowska *et al.,* 2021). The persistence of BPA in soil also raises concerns about its uptake by plants and its potential to move through terrestrial food chains.

## EFFECTS OF BPA ON BIOTA

BPA is an environmentally persistent contaminant that can affect a wide range of organisms after entering terrestrial and aquatic ecosystems. Its exposure has been associated with diverse biological responses, including changes in growth, reproduction, development, metabolism, and physiological functions across different groups of biota. The potential ecological risk may be further increased when BPA occurs together with structurally related bisphenols, as mixtures can produce stronger effects than individual compounds (Czarny-Krzymińska *et al.,* 2024)**.**

***Effects on Microorganisms (Bacteria and Fungi)***

Microorganisms are highly sensitive to environmental contamination, making them useful indicators of ecosystem health, while also playing a vital role in maintaining ecosystem functioning. BPA exposure has been shown to significantly affect microbial community structure, diversity, and metabolic activity, potentially altering how microbial communities function within ecosystems (Yang *et al.,* 2025). In bacteria, BPA exposure can damage cell membranes, disrupt enzyme activity, and interfere with gene expression (Rybczyńska-Tkaczyk *et al.,* 2023). These effects may slow bacterial growth and alter normal metabolic pathways (Flint *et al.,* 2012). These changes can reduce the efficiency of nutrient cycling and slow down the decomposition of organic matter within the ecosystem.

Certain bacterial strains can degrade BPA through enzymatic pathways and even use it as a carbon source (Razia *et al.,* 2024). However, this biodegradation is often incomplete, and the process may produce intermediate compounds that still have biological activity or, in some cases, may be even more biologically active (Yi *et al.,* 2025). In fungi, BPA exposure can slow hyphal growth, reduce spore production, and interfere with the production of extracellular enzymes (Acconcia et al. 2015). Since fungi play a key role in breaking down organic matter, disrupting their growth and activity can have wider, cascading effects throughout the ecosystem (Zhang *et al.,* 2022)**.**

***Effects on Planktons***

Planktonic organisms, which form the foundation of aquatic food webs, are particularly vulnerable to BPA exposure. In phytoplankton, BPA exposure can interfere with photosynthesis by lowering chlorophyll levels and disrupting the normal activity of photosystems (Atengueno-Reyes *et al.,* 2023; Theus *et al.,* 2023). This can reduce primary productivity, which in turn limits the amount of energy available to support higher levels of the aquatic food web.

Zooplankton exposed to BPA can experience reproductive problems, including reduced fecundity and slower development. Recent evidence in *Daphnia magna* indicates that environmentally realistic BPA concentrations can negatively affect life-history traits, with temperature modifying some of these responses **(**Alvarez *et al.,* 2024**).** In marine zooplankton, BPA exposure has been associated with impaired somatic growth, gonadal development, fecundity, fitness, and gene expression (Li *et al.,* 2024). Behavioral changes, such as altered feeding patterns and reduced movement, have also been observed in zooplankton exposed to BPA (Sanchez *et al.,* 2022). Because plankton play a key role in connecting primary producers with higher trophic levels, changes in their populations can ripple through the food web and contribute to broader ecological imbalances (Vandenberg *et al.,* 2007)**.**

***Effects on Aquatic Invertebrates***

Aquatic invertebrates are especially vulnerable to BPA because they have constant and close contact with contaminated water and sediments. BPA exposure has been linked to endocrine disruption in these organisms, potentially affecting reproductive cycles, normal development, and sex differentiation (Hockicková *et al.,* 2026).

At the cellular level, BPA can trigger oxidative stress by increasing the production of reactive oxygen species, which may damage important cellular components such as proteins, lipids, and DNA. This oxidative stress is often accompanied by weakened antioxidant defenses, making it harder for organisms to protect their cells from damage. Behavioral changes, such as reduced feeding efficiency and impaired movement, can further reduce their ability to survive and function normally. Together, these effects can significantly alter population dynamics and disrupt the ecological stability of invertebrate communities (Gilroy *et al.,* 2025; Rancière *et al.,* 2015).

***Effects on Fish***

Fish are a vital part of aquatic ecosystems and are particularly vulnerable to BPA because of their constant exposure to contaminated environments. BPA can enter fish through the gills, ingestion, and skin, after which it can be distributed to tissues such as the liver, intestine, and muscle (Peskova and Blahova, 2025). BPA exposure has also been shown to cause concentration- and time-dependent cytotoxicity and oxidative stress in zebrafish gill cells, indicating that the gill may represent an important early target of BPA toxicity (Kumar *et al.,* 2026). At the biochemical level, BPA can interfere with antioxidant defense by affecting enzymes such as catalase (CAT), superoxide dismutase (SOD), and glutathione-related enzymes, ultimately leading to oxidative stress. Importantly, BPA can also affect digestive enzymes such as proteases, amylases, and lipases, which may interfere with normal digestion and nutrient absorption. This can, in turn, affect growth and energy metabolism (Awe and Veronica 2025). Endocrine disruption is another major effect of BPA exposure, potentially altering hormone levels, affecting gonadal development, and reducing reproductive success. Neurotoxic effects of BPA, reflected in changes in acetyl cholinesterase activity, can lead to behavioral abnormalities such as reduced predator avoidance and altered swimming patterns (Wang *et al.,* 2022). Together, these effects can weaken overall fish health and potentially threaten the long-term stability and sustainability of fish populations (Flint *et al.,* 2012; Rochester, 2013).

***Effects on Plants***

Plants exposed to BPA through contaminated soil or irrigation water can experience a range of physiological and biochemical changes that may affect their normal growth and functioning (Yang *et al.,* 2025). BPA can interfere with early plant development by slowing seed germination and limiting the growth of both roots and shoots (Kaźmierczak *et al.,* 2022; Hussain *et al.,* 2023). This effect is mainly linked to BPA's ability to interfere with normal cell division and cell elongation, which are essential for healthy plant growth and development (Zhang *et al.,* 2025).

At the physiological level, BPA exposure can trigger oxidative stress in plant cells by causing an excessive build-up of reactive oxygen species (ROS). This excess of ROS can lead to lipid peroxidation, damage cell membranes, and ultimately compromise the overall integrity of plant cells (Siddiqiui *et al.,* 2021 ; Liang *et al.,* 2022). To protect themselves, plants often respond by changing the activity of antioxidant enzymes such as catalase, peroxidase, and superoxide dismutase. However, prolonged BPA exposure can overwhelm these natural defense mechanisms (Siddiqiui *et al.,* 2021) Photosynthetic efficiency can also be significantly affected by BPA exposure. BPA can lower chlorophyll levels and interfere with the activity of photosystem II, reducing carbon assimilation and ultimately limiting overall plant productivity (Liang *et al.,* 2022; Huang *et al.,* 2025; Yuan *et al.,* 2026). Additionally, BPA may interfere with nutrient uptake by altering root membrane permeability and disrupting the normal mechanisms responsible for ion transport (Abdelmoneim *et al.,* 2024; Yang *et al.,* 2025).

Importantly, plants can absorb BPA and transport it through their tissues, which may lead to its accumulation in edible parts of the plant (Xu *et al.,* 2021). This raises concerns about BPA entering the food chain and potentially exposing herbivores and humans through contaminated plant-based foods. Thus, BPA contamination can affect more than just plant health and productivity; it can also have wider ecological consequences and raise concerns about food safety.

***Effects on Terrestrial Animals***

Terrestrial animals are mainly exposed to BPA by consuming contaminated food, water, and soil particles. Because BPA has an affinity for lipids, it can be readily absorbed and distributed throughout the body, including tissues such as the liver, adipose tissue, and reproductive organs (Bhardwaj and Misra, 2026). One of the most significant effects of BPA exposure in terrestrial animals is endocrine disruption. BPA can interact with oestrogen receptors and interfere with normal hormonal signaling, potentially leading to reproductive problems. Reported effects include reduced fertility, abnormal development of reproductive organs, disrupted oestrous cycles, and decreased sperm quality (Hu et al. 2023; Cull & Winn, 2025). Recent evidence from mammalian studies further indicates that BPA exposure can impair testicular structure and steroidogenesis and contribute to abnormalities in sperm quality and reproductive hormones (Deng *et al.,* 2024). At the biochemical level, BPA can trigger oxidative stress, which may damage important cellular components such as lipids, proteins, and DNA (Bhardwaj and Misra, 2026). This is often accompanied by changes in antioxidant enzyme activity and reduced detoxification capacity in the liver (Sánchez *et al.,* 2022). BPA exposure has also been linked to immune-related effects, including altered immune cell function and a greater susceptibility to infections (Buoso *et al.,* 2025).

Neurological and behavioral changes have also been observed, particularly following prolonged or chronic exposure. These effects can include changes in cognitive function, stress responses, and normal activity patterns. Developmental exposure is particularly concerning because BPA can interfere with normal growth and organ development, potentially causing long-term physiological effects (Buoso *et al.,* 2025).

***Effect on Human***

Human are exposed to BPA through multiple pathways, including dietary intake from food and beverage containers, inhalation of contaminated dust, and dermal contact with products such as thermal paper. Due to its widespread presence, BPA has been detected in human biological fluids, including blood, urine, and even placental tissue, indicating continuous exposure (Rochester 2013; Acevedo *et al.,* 2025).

BPA primarily exerts its effects through endocrine disruption. By mimicking estrogen, it can bind to hormone receptors and interfere with normal hormonal signaling pathways. This disruption affects multiple physiological systems, including reproductive, metabolic, and developmental processes. In females, BPA exposure has been associated with ovarian dysfunction, menstrual irregularities, and conditions such as polycystic ovary syndrome (PCOS) (Urbanetz *et al.,* 2024). In males, it is linked to reduced sperm quality, altered testosterone levels, and impaired reproductive function (Heindel et al. 2015).

Beyond endocrine effects, BPA induces oxidative stress and inflammation at the cellular level. The generation of reactive oxygen species leads to damage of cellular components, including lipids, proteins, and DNA (Nirenjen et al. 2025). This contributes to the development of chronic health conditions. BPA has also been implicated in metabolic dysregulation, including obesity, insulin resistance, and type 2 diabetes, possibly through its influence on adipogenesis and glucose homeostasis (Xiao *et al.,* 2024).

Neurodevelopmental effects of BPA are particularly concerning, especially in fetuses and young children. BPA can cross the placental barrier, potentially affecting brain development and leading to behavioral and cognitive abnormalities. Associations with anxiety, hyperactivity, and learning impairments have been reported. Additionally, BPA exposure may influence immune function, contributing to increased susceptibility to allergies and autoimmune conditions (Rochester et al. 2023).

Neurological and behavioral changes have also been observed, particularly following prolonged or chronic exposure. These effects can include changes in cognitive function, stress responses, and normal activity patterns. Developmental exposure is particularly concerning because BPA can interfere with normal growth and organ development, potentially causing long-term physiological effects (Buoso *et al.,* 2025).

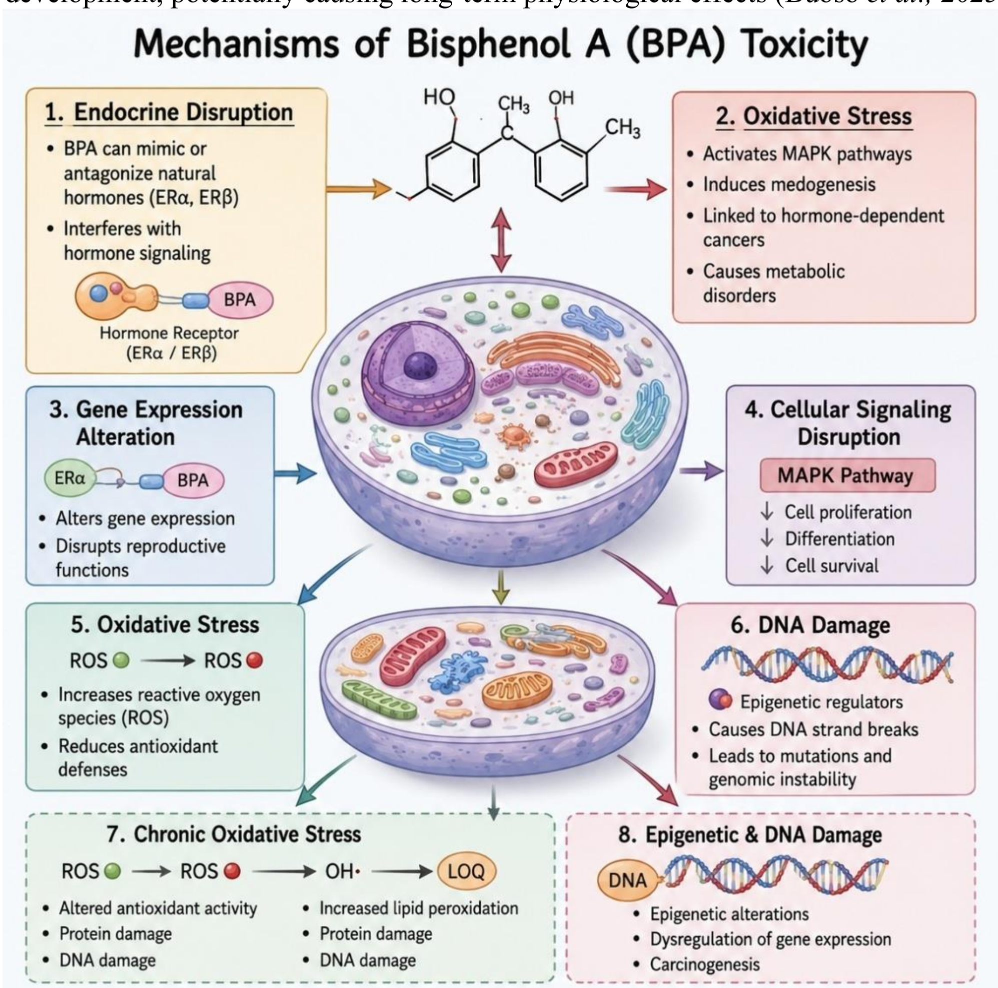


**Fig. 2:** Mechanism of Bisphenol A toxicity: illustrating endocrine disruption, oxidative stress, cellular signalling disruption and DNA damage

## CONCLUSION

Bisphenol A (BPA) has become a widespread environmental contaminant, raising growing concerns about its effects on ecosystem health and long-term environmental sustainability. Its widespread use in industrial and consumer products, along with its continuous release into the environment, has led to BPA remaining present in both aquatic and terrestrial ecosystems. The present review shows that BPA acts through a complex range of mechanisms, including endocrine disruption, oxidative stress, and interference with important cellular signalling pathways such as MAPK and PI3K/Akt. Together, these mechanisms can cause a wide range of physiological, biochemical, and molecular changes across many different organisms. In aquatic ecosystems, especially among freshwater teleosts, BPA can disrupt digestive enzyme activity, which may interfere with nutrient absorption, growth, and overall metabolic efficiency. These disruptions can affect not only individual organisms but also ripple through populations, potentially altering population dynamics and reducing overall ecosystem stability. Its ability to mimic natural hormones and interfere with normal regulatory pathways has made BPA a potent endocrine-disrupting chemical. In humans, BPA exposure has been linked to reproductive problems, metabolic disorders, neurological effects, and an increased risk of hormone-related cancers, making it an important public health concern (Vandenberg *et al.,* 2007; Rochester, 2013) Although considerable progress has been made in understanding BPA's toxic effects and underlying mechanisms, several important gaps remain. More long-term and low-dose studies are needed, especially under environmentally relevant conditions, to better capture the chronic effects and subtle physiological changes caused by ongoing exposure. Additionally, the combined effects of BPA and other environmental contaminants need further investigation, since organisms in natural ecosystems are rarely exposed to a single pollutant at a time. From a remediation perspective, advanced treatment technologies, bioremediation, and phytoremediation all show promise, but their large-scale use, regulatory measures and public awareness initiatives are also important for reducing BPA exposure and limiting its environmental impact. Stronger regulations, effective remediation strategies and greater public awareness combined together can help reduce BPA contamination and protect ecosystem health. Addressing its impact will require an integrated approach that brings together scientific research, technological innovation, effective policy measures, and public awareness. Continued efforts in these areas will be essential for reducing environmental contamination, protecting ecosystem health, and safeguarding human well-being.

**ACKNOWLEDGMENTS**
The authors thankfully acknowledge the help and support received from the Principal, Head of the Zoology Department and other faculty members of Bangabasi College, Kolkata.

***Conflict of Interest***
The authors declare no conflict of interest.

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