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Review Article

Chronic microplastic exposure: a growing threat to metabolic health in India

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ABSTRACT

Microplastics have emerged as widespread environmental contaminants. These particles originate from the breakdown of larger plastic waste, which is now prevalent in ecosystems, including water, soil, air, and food sources, making human exposure inevitable. If current trends continue, global plastic pollution will reach alarming levels by 2050. Microplastics primarily enter the human body via ingestion, inhalation, as well as dermal contact, along with significant exposure occurring through contaminated water, food, and urban air pollution. Various studies indicate that microplastics can disturb gut microbiota, trigger systemic inflammation, hinder lipid metabolism, and encourage issues such as insulin resistance, obesity, and cardiovascular diseases. They also serve as vehicles for toxic substances, increasing their harmful effects. This review synthesizes current evidence by searching PubMed, PubMed Central, Scopus, and Google Scholar for studies published between 2010-2025 on microplastic exposure and metabolic health, focusing on India. The scenario in India is especially concerning due to high plastic consumption, poor waste management, and a significant rate of metabolic disorders; thus, further research in this field is crucial. This review highlights the pathways of microplastic exposure to humans, along with their potential to disrupt metabolic health, emphasizing the vulnerability among the Indian population. It calls for urgent, region-specific research to explore these health risks and advocates for stricter policies on plastic waste management to mitigate the growing public health crisis.

Keywords: Microplastics, Plastic pollution, Environmental pollutants, Metabolic health, Diabetes

INTRODUCTION

Microplastics are small plastic particles ranging from 100 nm to 5 mm; a large portion of these microplastics is derived from non-biodegradable, single-use macroplastic items (>5 mm), which accumulate in ecosystems instead of decomposing naturally.[1-3] Any substance foreign to the environment acts as a contaminant and, when present in sufficient amounts, can become a pollutant. Microplastics have been observed in natural environments, including aquatic and terrestrial ecosystems, air, food and drinking water, rendering human exposure virtually inevitable and exacerbating an escalating environmental crisis.[1,4,5] If existing trends in plastic production, along with the current waste management, persist, it is estimated that approximately 12,000 metric tons of plastic waste could accumulate within landfills or the natural environment by the year 2050.[2] The pervasive presence of microplastics in aquatic and terrestrial ecosystems raises issues concerning their potential health effects, particularly on metabolic health.

Recent research has increasingly linked chronic microplastic exposure to disruption in metabolic health, particularly due to its effect on gut microbiota, carbohydrate, lipid, and amino acid metabolism.[6] Additionally, they may increase the risk of nervous system and reproductive system dysfunction, while inhalation of burning microplastics can affect the cardiovascular and respiratory systems.[3,7] Focusing on India's population is particularly important as India, with its rapid urbanisation and vast population, is among the largest global plastics consumers. This situation is compounded by the country's lenient environmental laws, weak imposition of existing laws, and inadequate waste management practices, including collection, segregation, disposal, and recycling techniques.[4] The Indian population already faces a significant burden of metabolic disorders, which could potentially be worsened by microplastic exposure.

This review was conducted using a narrative approach to synthesize current evidence on the impact of chronic microplastic exposure on metabolic health, focusing on the Indian context. A comprehensive literature search was performed using databases, including PubMed, PubMed Central, Scopus, and Google Scholar, for articles published between 2010-2025. Search terms used included microplastics, plastic pollution, metabolic disorders, insulin resistance, obesity, diabetes, lipid metabolism, gut microbiota, and India. Both human and animal studies were considered. We included peer-reviewed original articles, review articles, and government/agency reports. Studies were included which addressed microplastic exposure through different routes, biological mechanisms linking microplastics to metabolic processes and/or data from India related to microplastic prevalence or public health concerns.

This review aims to focus on two primary areas of concern. The first involves identifying the sources of microplastics and understanding the different pathways through which microplastic particles enter and accumulate in the environment, eventually exposing human populations. This includes exposure through contaminated water, air, soil, and food sources, highlighting the pervasive nature of microplastic pollution. The second area addresses the potential health risks related to microplastic exposure, with a strong focus on metabolic health. Our article emphasises India's population due to the country's unique environmental and waste management issues challenges. By exploring these interconnected factors, the review aims to deliver insights into the public health implications of microplastics and underscore the need for region-specific research and policy interventions.

MICROPLASTIC SOURCE AND EXPOSURE PATHWAY

According to the Central Pollution Control Board (CPCB) annual report 2020-21, India produced approximately 4.12 million tonnes per annum (TPA) of plastic waste during 2020-21.[8] Due to improper disposal as well as mismanagement, a significant proportion of this plastic waste breaks down into microplastics, leading to widespread environmental contamination. Indian freshwater sources, especially in the areas of Andaman and Nicobar Islands, Gujarat, Goa, Karnataka, Lakshadweep, Kerala, Maharashtra and Puducherry, were heavily impacted by this pollution.[9-11] Due to the extensive network of roads in India, wear and tear of vehicle tyres during driving is one of the major contributors to microplastic pollution. Heavy traffic, frequent acceleration and braking, and poorly maintained road conditions exacerbate tyre abrasion, releasing microplastics into the environment.[12,13] Furthermore, untreated wastewater due to runoff from urban areas, in conjunction with activities from the agricultural sector, has exacerbated groundwater pollution caused by plastic pollutants.[14,15]

After entering the human body through ingestion, inhalation, and dermal contact, microplastics get degraded into monomers, which pose serious health hazards.[16-18] Ingestion is the primary pathway, with microplastics detected in seafood, drinking water, and food items like salt and sugar, often due to polluted rivers and agricultural runoff.[14,15,19,20] Inhalation pathways include airborne microplastics found in urban dust, particularly in regions with high vehicular traffic. Although less studied, dermal exposure occurs through polluted water sources and personal care products containing microbeads.[21]

The rapid increase in tourism along India's coastal regions has significantly contributed to heightened microplastic pollution, particularly on the beaches of Puducherry and the western coast.[9,14,21] Most of the coastal population consumes seafood, increasing the exposure to microplastics in these communities. Microplastics have been detected in both edible and inedible tissues of nine commercially important pelagic fish species typically used for human consumption along the Cochin coast in Kerala, India.[22] Kerala's Vembanad Lake and estuary are significant sources of microplastic pollution, particularly in the form of fragments, fibre/line and foam in coastal waters and beach sediments due to river runoff and proximity to urban dwellings.[23,24] Dowarah et al carried out research on microplastics ingested by 2 bivalve species, *Perna viridis* and *Meretrix meretrix*, collected from 3 estuaries: Ariyankuppam, Panithittu, and Chunnambar in Pondicherry, India. The study found that a person living nearby is likely to ingest 3,917.79±144.71 microplastic particles per year via mussel consumption.[25]

MICROPLASTICS – IMPACT OF CHRONIC EXPOSURE TO MICROPLASTICS ON METABOLIC HEALTH

Microplastics pose significant risks to human health because of their pervasive presence in the environment and ability to enter the body through ingestion, inhalation, and dermal contact.[17] Microplastics have been detected in various human tissues, raising serious concerns about their potential health risk due to their accumulation.

Microplastics can induce inflammatory responses and damage to organs. Studies have shown that they can cause fibrosis in targeted organs and systemic immunological effects, which may lead to chronic conditions over time, including metabolic disorders, cardiovascular diseases, and even cancer.[18,26] Furthermore, microplastics act as carriers for harmful chemicals and pathogens, intensifying their toxicity.[17]

In regards to the effect on the gastrointestinal system, microplastics disrupt the symbiotic relationship between the host and the gut microbiota, leading to gut dysbiosis.[27] Microplastics promote the expansion of pathogenic and opportunistic bacteria while reducing the abundance of beneficial commensals like Bacteroidetes, which are crucial in maintaining gut health and immune function. This shift can escalate susceptibility to infections and inflammatory diseases.[28] In addition, microplastics can induce inflammation and histological changes in the intestinal epithelium, such as edema, villi cracking, and increased permeability, leading to a "leaky gut" condition that allows harmful substances to enter systemic circulation.[29] Microplastics also affect mucus-secreting cells, resulting in reduced mucin production. This impairment compromises the protective mucus layer essential for gut barrier integrity and immune defence.[28,30] Furthermore, microplastics facilitate the formation of biofilms, allowing pathogens to thrive and resist antimicrobial treatments, further disrupting the microbial balance in the gut.[30]

Microplastic exposure has been increasingly recognized as a disruptor of critical metabolic processes, including amino acid metabolism. Ingested dietary tryptophan undergoes distinct metabolic pathways depending on the presence of microplastics, as illustrated in Figure 1. Under normal conditions, tryptophan metabolism produces indole-3-aldehyde, facilitating non-alcoholic fatty liver disease (NAFLD) remission through immunomodulatory effects. However, microplastic exposure diverts this process, generating idole sulfate, a toxic compound that exacerbates oxidative stress and contributes to NAFLD progression.[15]

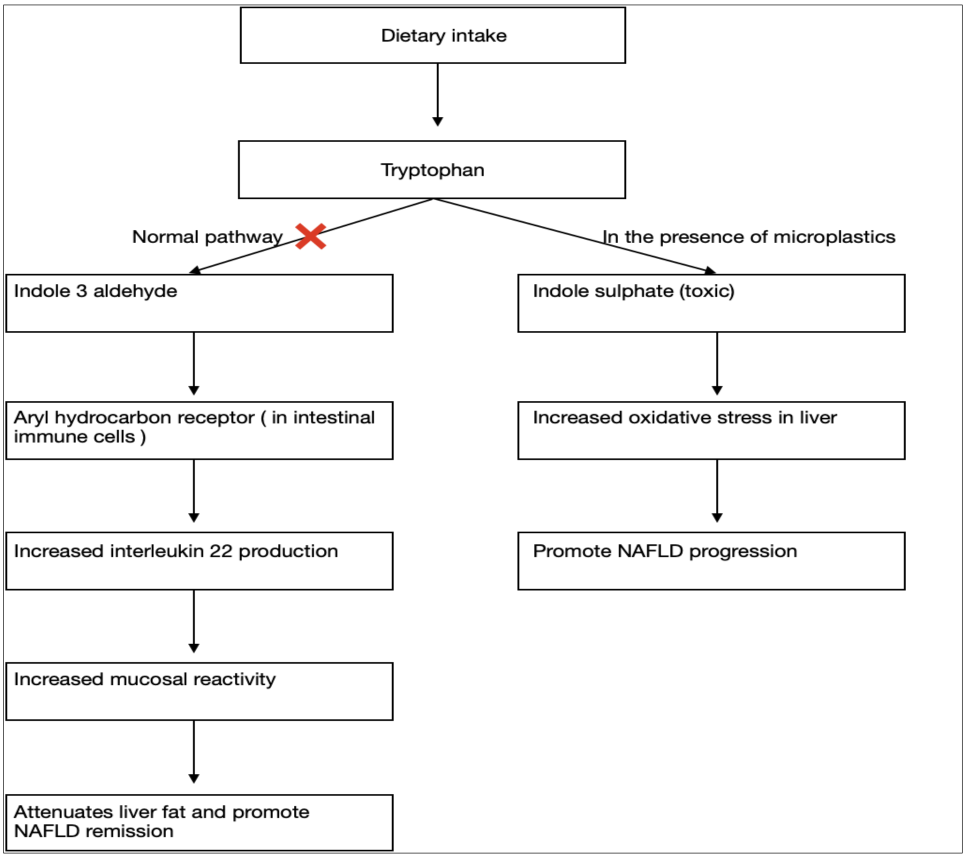

Figure 1: Effect of microplastics on tryptophan metabolism and NAFLD progression.

Microplastics, particularly polystyrene, significantly impair lipid metabolism in humans. Exposure to polystyrene nanoplastics can lead to lipid droplet accumulation in macrophages, promoting foam cell formation linked to atherosclerosis.[31] Microplastic nanoparticles have also been reported to increase the risk of obesity via inhibition of the pentose phosphate metabolism pathway.[32] Organotin compounds (OTCs), which are used in the production of polyvinyl chloride plastics, are also considered adipogenic by both in-vivo and in-vitro studies. Moreover, its exposure also affects appetite regulation by upregulating neuropeptide Y (NPY) and proopiomelanocortin (POMC). These changes reduce anorexigenic signalling, thus stimulating appetite.

Additionally, studies indicate that microplastics alter metabolic pathways related to lipid metabolism in various tissues, including the liver.[33]

The liver is highly susceptible to microplastic-induced damage due to its central role in metabolizing foreign substances (xenobiotics).[34] These disruptions can result in dyslipidemia and increased cardiovascular risks, as evidenced by changes in cholesterol and triglyceride levels in animal models.[35] Microplastics can disrupt gut microbiota, leading to dysbiosis associated with insulin resistance. Microplastics induce inflammation and increase intestinal permeability, allowing harmful substances like lipopolysaccharides (LPS) to enter the bloodstream, activating immune responses that impair insulin signalling pathways, thus promoting insulin resistance.[36] This chronic low-grade inflammation is a significant factor in the development of metabolic disorders such as obesity and type 2 diabetes.[37] Moon et al also established that microplastics disrupt the adipogenic differentiation, and that the TNF- mediated chronic inflammation leads to cellular senescence and aging.[38]

Microplastics can induce oxidative stress within cells, resulting in mitochondrial dysfunction and cellular damage. This process is linked to diseases, including cancer and neurodegenerative disorders.[39] Polystyrene microplastics have also been shown to increase HNF4A and CYP2E1 expression in the liver, leading to liver steatosis and fibrosis. They have been shown to damage mitochondrial cristae and lipid peroxidation.[37] On entering the target cell, they activate the oxidative processes, mitochondrial dysfunction and ER stress, which results in the repression of cell functions, thus inducing cytotoxicity.[28] Microplastics can contain and absorb various chemicals from the surroundings, including endocrine-disrupting compounds (EDCs).[32] When ingested or in contact with organisms, microplastics can release these EDCs, which hinder hormonal functions, contributing to reproductive toxicity and developmental issues.[40] These microplastic additives or EDCs interfere with the synthesis and activity of numerous hormones, especially thyroid hormone, which further leads to disruption of the energy metabolism in cells of the whole body, thereby increasing the risk of obesity and diabetes. Moreover, many of these EDCs are lipophilic, which causes them to accumulate in the adipose tissue and persist in the body for a significant time, leading to continued exposure. These obesogenic chemicals have been shown to alter serum lipid profiles and raise the risk of hypertension and other cardiovascular diseases as well.

India is experiencing a rapid epidemiological transition, with non-communicable diseases (NCDs) responsible for nearly 60% of all deaths.[41] Among these, metabolic diseases such as diabetes and cardiovascular conditions are significant contributors. The National Centre for Disease Control (NCDC), in their Communicable Disease Alert (CD Alert), highlights that India ranks second in the world for diabetes prevalence, with projections estimating over 109 million cases by 2035.[42] Emerging environmental stressors, including microplastic exposure, further compound this escalating metabolic health crisis.

THE ROAD AHEAD: STRATEGIC INTERVENTIONS FOR MICROPLASTIC REDUCTION

India is facing significant challenges due to plastic pollution and its associated health impacts. Traditional bans and cleanup drives are effective but are not enough. India needs national-level policies that focus on reducing single-use plastics, enforcing extended producer responsibility, and upgrading municipal waste management infrastructure, emphasizing microplastic filtration and recycling. Coastal states and urban centers must be prioritized for pollution surveillance and remediation.

India should adopt several strategies inspired by successful international models to address these issues effectively. One transforming step would be to launch a "Microplastic National Registry," a database tracking plastic particles in rivers, soil, packed food items, and seafood, which can be modeled after the European Union's REACH regulation but customized to India's needs.[43] India can also consider implementing extended microplastic liability laws inspired by Germany's dual-role packaging waste management system under Germany's green dot framework, which serves as a precedent in making producers responsible for the recycling and disposal of packaging materials.[44] Like Germany's green dot system, India can assign every plastic product a "health footprint label," a QR code showing its potential to disrupt hormones or accumulate in the body, much like the health warnings displayed on cigarette packaging. Inspired by Sweden's UPRISE model, which integrates environmental health into formal education and training systems.[45] India can introduce a nationwide "Plastic and Health" curriculum in schools, blending science, fieldwork, and real-time learning. Around the world, policies like Canada's ban on plastic microbeads in personal care products have led to measurable reductions of up to 86% in microbeads detected in wastewater and lake waters, demonstrating the effectiveness of their regulatory actions.[46] Inspired by the statewide microplastics strategy under the California Ocean Protection Council, India can develop its own national framework that prioritizes pollution prevention, strengthens regulatory action, and integrates health-focused interventions to reduce microplastic exposure.[47]

At the household level, India can promote the use of point-of-use water filtration devices equipped with membrane technology, which have been shown to remove 100% of certain microplastic types from drinking water.[48] Improving ventilation, reducing the use of synthetic textiles, and regularly cleaning with HEPA-filter vacuums can help limit airborne and dust-borne microplastic, especially in urban households.[49] Cox et al compared bottled water and tap water and found that bottled water contained significantly more microplastics, with some estimates showing up to 90,000 additional particles consumed annually.[50] In the Indian context, encouraging the use of filtered tap water can address two challenges at once: reducing dependency on single-use plastic bottles while simultaneously lowering microplastic intake. Filtered tap systems, especially those using membrane or carbon technologies, offer a practical, low-cost intervention that can provide a feasible and immediate risk-reduction strategy, particularly in high-risk urban and coastal populations, while implementing broader waste management reforms. The government should actively promote public awareness campaigns that discourage the use of plastic containers for heating food, as this practice contributes to microplastic leaching.[51] Additionally, national guidelines should advise households and food services to minimize plastic packaging wherever possible, encouraging a shift towards safer, sustainable alternatives.[51] Promoting these everyday behavioral changes through public education and targeted campaigns can make a significant impact in reducing microplastic exposure among the Indian population and help prevent microplastic-induced metabolic disturbances.

DISCUSSION

Microplastic poses significant risks to metabolic health through chronic exposure via ingestion, inhalation, and dermal contact, accumulating in organs such as gut, liver, and lungs. Their interaction with cellular systems induces oxidative stress, inflammation, and disruption of metabolic processes. Studies link chronic exposure to microplastic with gut dysbiosis, systemic inflammation, insulin resistance, and lipid metabolism disorders, increasing risks for obesity, type 2 diabetes mellitus, and cardiovascular diseases. India faces unique challenges due to high plastic consumption, coupled with inadequate waste management and a significant metabolic health burden, with one of the highest global prevalences of conditions such as diabetes, obesity, and NAFLD. Coastal and urban populations are particularly at risk from heightened exposure to contaminated water, food, and air. Microplastics also carry toxic chemicals and endocrine disputors, further exacerbating metabolic and reproductive health issues.

Despite growing scientific awareness, the current understanding of microplastic exposure and its health consequences, particularly in the Indian population, remains limited. Most available data stem from in vitro and animal studies, with a significant lack of epidemiological research in human populations. There is minimal data quantifying actual microplastic load in biological samples such as blood, feces, or tissue in high-risk communities. In India, where urban density, poor waste segregation, and dietary patterns may increase exposure risk, there is an urgent need for population-based studies. Furthermore, standardized and accessible methods for detecting microplastics in clinical or environmental settings impede routine surveillance. Key knowledge gaps include the long-term, low-dose effects of chronic exposure, the health risks posed by microplastic-bound chemicals such as endocrine disruptors and persistent organic pollutants, and the cumulative burden on metabolic health. Filling these gaps with India-specific, multi-disciplinary research is essential for establishing a strong evidence base for public response.

India must move beyond the traditional plastic ban and adopt systemic strategies to reduce microplastic exposure. A microplastic National Registry, modeled after the European Union's REACH regulation, can help monitor contamination levels. Extended microplastic liability laws, health footprint labels on plastic products, and the "Plastic and Health" curriculum in schools are policy innovations inspired by successful models in Germany and Sweden. While point-of-use water filtration devices can provide a feasible and immediate risk-reduction strategy at the household level, international regulations action, such as Canada's ban on microbeads and Statewide Microplastics Strategy under the California Ocean Protection Council, provide additional frameworks that India can adapt to address metabolic health risks from microplastic exposure.

CONCLUSION

The emerging threat of microplastic exposure compounds India's high burden of metabolic diseases. This review highlights the pervasive presence of microplastics in India's environment and their potential to disrupt critical metabolic processes, including gut microbiota balance, lipid metabolism, and hormonal regulation. Despite increasing evidence, critical data gaps persist, especially regarding human exposure levels and long-term health impacts. Addressing this issue requires an integrated approach that combines improved waste management, region-specific research, policy innovation, and public health interventions. Using successful ideas from other countries and adapting them to India's situation can help reduce microplastic risks and protect people's health.

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