Journal of Basrah Researches (Sciences) **52**(1), 97 (2026)
DOI: https://DOI.org/10.56714/bjrs.52.1.8

The Plastic Problem in Yemen and the Impact of Nano-plastics on Humans, Animals, and the Environment

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ARTICLE INFO

Received 13 January 2026
Revised 21 February 2026
Accepted 02 March 2026
Published 30 June 2026

Keywords:
Nano-Plastic, Plastic, Human Health, Ecosystem, Environment, Aquaculture.

Citation: H. M. Al-gabr et al., J. Basrah Res. (Sci.) **52**(1), 97 (2026).
DOI:https://DOI.org/10.56714/bjrs.52.1.8

ABSTRACT

Plastic pollution indicates a widespread environmental crisis, decline of plastic into micro- and nanoplastics (NPs) showing big threats to human health and ecological system. This paper approaches this issue with a prior focus on Yemen climate, a county going through unprecedented plastic pollution worsened by weak and fragile waste mechanism infrastructure in Yemen. The review examines the broad reliance on non-biodegradable polymers such as polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) all over Yemen, thus covering the agricultural , industrial, and local fields , fostering renewal sources of environmental crisis. The fragile system of recycling plastic waste into nano-scale particles (<100 nm) is seen as an important objective due to their remarkable bioavailability, capacity, and fluent mobility to subvert biological materials . A combination of current testimony asserts that human liability to nanoplastics happens principally through ingestion of unhealthy food and water, also the process of inhaling polluted air. This stage leads to the collection of plastic wastes and relevant toxic materials (bisphenol A, phthalates) in key organs, especially the bloodstream, placenta, and not to mention lung. The health awarenesses are of great importance, spanning many diseases, endocrine disruption, constant toxicity, and high crisis of chronic factors like cardiovascular issues. While the formulae of bio-treatment using fungi and bacteria facilitate a potential of widespread mitigation, they are not sufficient to face the current management of ecological crisis. The paper finally concludes that dealing with the nanoplastics issue in Yemen prioritize an urgent need for strategy involving enhanced management and policy, as well as focused awareness and investment in waste materials strategies and targeted national research projects.

1. Introduction

The plastic problems have been studied extensively from differential countries and environments in recent years. The features of Plastic a complex chemical structure that doesn't readily break down under natural environmental conditions, ultimately creating a significant ecological and human health

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ISSN: 1817-2695 (Print); 2411-524X (Online)
Online at: https://jou.jobrs.edu.iq

problem. Plastic materials are existent in modern life, used across almost every industry and business sector, because to their low cost, flexibility, lightness, and durability, allowing them to be molded into any shape. These materials pervade soil, air, water, and food chains as macro- and microplastic particles [54], constituting major physical and chemical pollutants in ecosystems. Current global plastic production exceeds 400 million tons annually, equating to approximately 11 tons per second or about 68 kg per person per year. The ocean alone contains over 150 million tons of plastic [1]. Estimates suggest that between 1950 and 2017, about 9.2 billion tons of plastic were produced, with only 14% of the current annual production of 400 million tons collected for recycling [2]. Since 1950, more than 8,300 million metric tons (MMt) of virgin plastic have been produced roughly one metric ton for every person on the planet [3]. Annual production of new plastic has grown from under 2 MMt in 1950 to more than 400 MMt today and is on track is projected to double by 2040 and triple by 2060 [4, 5]. According to one study, about 5 trillion plastic particles weighing roughly 250,000 tons are floating in marine environments [6]. The amount of plastic waste as of 2015 was 6300 million tons worldwide, and 79% of this was placed in landfills or left in the natural environment. By 2050, an estimated 12,000 million tons of plastic waste will have accumulated on earth [7]. Microplastic particles are now omnipresent, from the air we breathe to the food we eat [8]. Humans can be exposed to microplastics by ingesting contaminated water and food or inhaling contaminated air. Microplastics have been detected in human lungs, blood, placenta, and feces and may cause various health effects, including DNA damage, cellular damage, inflammation, oxidative stress, cancer, impacts on fetal growth, and inflammatory bowel disease [9, 51]. Their physical and chemical composition primarily determines their ecotoxicological risks [10]. The toxic effects of Micro-Plastics (MPs) and nanoplastics are determined by their characteristics, and the source of production i.e., synthetic or natural sources. Majorly synthetic plastic fibers degrade very slowly and persist long as organic pollutants [11, 12]. This paper aims to review the problem of plastic pollution with a focus on the case of Yemen, while direct measurements of (NPs) concentrations in Yemeni environments are currently absent in the literature, the high reliance on single-use plastics, limited formal waste management, and extensive use of plastic in agriculture, create conditions conducive to the generation and dispersion of (MPs and NPs), mirroring pathways established in global studies. Track the route of its breakdown into nanoplastics particles, evaluate their exposure pathways, health effects on humans and animals, and eventually provide solutions and recommendations[51]. The literature search used in this narrative review included Scopus, ScienceDirect, and Google Scholar databases covering literature that was published mainly during the period of 20102024. The major key search terms were microplastics, nanoplastics, health effects, Yemen plastic pollution, and plastic degradation. We prioritized the recent review articles, high-impact original studies, and reports of international bodies (UNEP). The paper generalizes global processes and hazards to the Yemeni population using the actual data obtained about the types of plastic use in Yemen and the difficulties in handling the waste.

2. The Chemical Structure in nanoplastics formal and Common Plastic Polymers.

About 45 commercial types of plastic are available among which are polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), polystyrene (PS), polyurethane (PU), polyvinyl chloride (PVC) and polycarbonate (PC) [13]. Recently, there has been the emergence of rise attention on the degradation of these polymers into (NPs) particles in the name of human health, and animal. The polypropylene surging in use throughout Yemen, in agriculture, industry, and individual quarters, generates a number of exposure pathways. the knowledge of the chemical structures of the polymers is vital in predicting the environmental stability and the possible biological consequences. This section offers a systematic overview of major plastic types, organized to their molecular architecture and functional groups The Table (1) provides an overview of key plastic types which the molecular structure of a polymer plays a crucial role in determining both its resistance to degradation and it's tendency to fragment into (NPs).

Table 1. key types of plastic a resistance to degradation and propensity to fragment into nanoplastics.

Health and environmental relevance	Common properties and uses	Chemical structure	Polymer types	References
Non-biodegradable prone to mechanical fragmentation into persistent nanoplastics in soil and water	Low density (LDPE) branched chains, flexible. Used in bags, films. High density (HDPE): Linear chain, rigid. Used in bottles, pipes.	(--CH_2-CH_2--)-n-	Polyethylene (PE)	[15,16]
Resistant to microbial degradation, contributes to airborne and foodborne nanoplastics contamination.	Lightweight, heat-resistant. Used in packaging, mechanical components	(--CH_2—$CH(CH_3)$--)-n	Polypropylene (PP)	[17, 18]
Releases chlorine-containing particles upon degradation, potential for respiratory and aquatic toxicity	Chemically resistant can be rigid or flexible with plasticizers. Used in pipes cables flooring.	(--CH_2—CHCI--)-n--	Polyvinyl chloride (PVC)	[17, 19]
Brittle nature facilitates fragmentation. nanoplastics my leach neurotoxic styrene monomers.	Brittle, transparent. Used in food containers, packaging , insulation.	(--CH_2—$CH(C_6H_5)$--)-	Polystyrene (PS)	[20]
Recyclable but show to degrade, potential for ingestion via bottled water and textiles.	Transparent, moisture-resistant, recyclable. Used in beverage bottles, textiles.	(--OC—C_6H_4—$COOCH_2CH_2O$--)—n--	Polyethylene Terephthalate (PET)	[20]
Contains partially biodegradable amide bonds but still contributes to micro/ nanoplastics load.	Strong, flexible, elastic. Used in fabrics, mechanical gears.	Contains amide linkages	Nylon (Polyamide)	[20]
Impact-resistant but prone to UV breakdown, bisphenol A (BPA) release is a known endocrine disruptor.	Transparent, impact-resistant. Used in eyewear, optical discs, electronics.	Contains carbonate linkage	Polycarbonate (PC)	[53]

In modern industry, medicine, and energy the Plastic polymers represent one of the most transformative classes of structure of materials. Their exceptional versatility arises from their underlying chemical structures, which determine key properties like, mechanical strength, thermal resistance, biodegradability, and recyclability. Yet their degradation into nanoplastics particles < 100 nm raises growing interests for human health ,and animal. The widespread use of plastic materials by Yemen citizens such as agriculture, industry, and households create multiple exposure routes. Understanding the chemical structures is essential to assessing their environmental persistence and potential biological impact [14].

3. Influence of Chemical Structure on Biodegradability

Plastic polymers can be biodegraded, and the capacity to be biodegraded is directly related to its chemical structure. One of the most important factors is the present formaltation of chemical bonds. Popular plastics such as polyethylene (PE) and polypropylene (PP) also have solid, powerful carboncarbon connections, and this property renders them very inaccessible to microbial degradation. Conversely, polymers having ester (-COO) or amide (-CONH) bond such as PLA and nylon are more vulnerable to enzymatic degradation and hydrolysis [21].
The presence of polar or hydrophilic functional groups is also the other significant factor. Plastics with hydroxyl (-OH), carboxyl (-COOH) or amine (-NH2) functional groups are more susceptible to microbial enzymes and water which boosts their degradation.
The level of crystallization is also a major factor. The disordered structure of amorphous polymers permits more readily of penetration of water and enzymes, leading to quicker degradation. Crystalline polymers, on the other hand are densely packed and resistant to breakdown [17].
Lastly, environmental behavior of a certain polymer can also be largely affected by the application of degradable additives or catalysts. An example is the incorporation of plastics with starch, enzymes, or photodegradable agents in plastics which causes degradation of the plastics under certain conditions including light, heat or moisture exposure [22].

3.1. Examples of Biodegradable Plastics

A number of biodegradable plastics have gained interests because of their environmental friendliness. Polylactic acid (PLA) is an ester bond material making it easily degraded in wet conditions or by composting conditions in industries. Polycaprolactone (PCL) is a flexible polyester, which inhibits the rate of biodegradation; however, it can be used in long-term applications. Conversely, Polyhydroxybutyrate (PHB), the type of polymer that is normally formed by fermentation of bacteria, is easily broken down in the soil and in water.

4. Plastic Usage in the Yemeni Market and Local Context

Information regarding plastic waste in Yemen is unavailable, one study [55] evaluation that plastic waste generation was rang about (0.6-0.35/kg /person/day), amounting to approximately 3.8 million tons per year. The same study reported that between 2012-2016 the plastic made up within the waste stream was 6.23% equating to about 50000 tons of plastic annually. By 2014, plastic risen to 10% of waste materials [56]. As well as, the daily consumption of plastic bags in Sana'a city alone reached one million[57].
In Yemen, several types of plastic are widely used across various sectors:

- Low-Density Polyethylene (LDPE): founded in plastic bags, agricultural films, and shopping bags.
- High-Density Polyethylene (HDPE): Used in production water bottles, sewage pipes, and chemical containers.
- Polypropylene (PP): Applied in household utensils, packing crates, lids, and heat-sealed packaging.
- Polyvinyl Chloride (PVC): Utilizing in water and electrical piping systems, in addition plastic doors and windows.
- Polystyrene (PS): Common used in foam packaging and insulating wraps [23].

4.1. The key Manufacturers of Plastic in Yemen

The Yemen Plastic Manufacturing Company (YPMC) in Taiz: Producing containers, pipes, and various household plastic items.

- Yemeni Plastic Industries Company in Taiz: Producing plastics for pipes, hoses, and packaging tools [24].
- The Factory of Al-Irtika Industrial Plastics in Sana'a: Supplies agricultural and domestic plastic needs.

The volumes producing from these factories aren't publicly disclosed their output contributes directly to the local plastic stream. In the absence of formal waste management, increasing environmental pollution by this material.

Without formal production statistics, the magnitude of plastic discharging into the Yemen environment can be measured by the type of waste generation. When a traditional per capita rate of plastic waste production using techniques in international analyses [3] is applied to the Yemeni population of about 34 million people, one can expect to estimate plastic waste of more than 75,000 metric tons/per year. It is this waste both locally manufactured and imported that acts as the major source of the formation of the secondary (MPs) and (NPs).

Thus, in Yemen the available plastic stock results from a mix of local production and continued imports of finished plastic goods, which ultimately contribute to the national waste stream.

4.2. Applications of Plastics in Yemen

Plastics plays a vital role across multiple sectors in Yemen. For example, in agriculture, the generally used are Plastic tunnels, irrigation hoses, soil covers. Household: Kitchenware, containers, furniture.

- Industry: Pipes, chemical containers, packaging tools.
- Healthcare: Medicine bottles, basic medical instruments [25].

This reliance on (PVC pipes), coupled with a lack of recycling, suggests a direct pathway for plasticizer (phthalate) contamination into water supplies a risk factor compounded by Yemen's ongoing water crisis. This connects local practice to scientific risk.

5. Nanoplastics: From Source to Organism

5.1. Size and Source

Microplastics(MPs) are defined as plastic particles ranging from 1 micrometer to 5 mm (1 µm – 5 mm). (NPs) are particles smaller than 100 nm (down to 1 nm) (<100 nm or 1-100 nm) arising from the continued fragmentation of microplastics or secondary microplastics. And nanoplastics is the breakdown process is not likely to stop at the micro level but will instead continue until the microplastic become small, nano sized plastic particle. (NPs; size range 1 nm–1 m) are emerging plastics-related environmental pollutants [26]. Their detection is highly challenging due to their minute size and chemical similarity to organic matter [27] see Table 2

Table 2. comparison of the properties of microplastics and nanoplastics

Property	Nanoplastic (NPs)	Microplastics (MPs)
Size range	< 100nm	1µm- 5mm
Primary risk	Cellular penetration translocation across biological barriers (blood-brain, placental	Physical blockage , chemical leaching.
Environmental detection	Extremely challenging, often requiring specialized spectroscopy.	Challenging but established
Toxicological concern	Sub-cellular interaction, oxidative stress, genotoxicity.	Organ level inflammation, carrier of pollutants.

5.2. Environmental Dispersion

Plastic waste entering marine ecosystems is forecast to reach 100–250 million tons by 2025 [28]. Studies have demonstrated the release of nanoparticles up to 30 nm in size was recorded after being exposed to the outdoor aquatic microcosm of from PP, PS, and PE pellets in aquatic environments [29,30], with particles <10 µm showing greater toxicological effects on aquatic life [30].

6. How do nanoplastics Reach Humans?

1. Ingestion: The primary exposure route, through bottled water, seafood, salt, tea, beverages, and ready meals. Humans are estimated to ingest tens of thousands of microplastic particles annually from these sources [31,32].
2. Inhalation: Airborne micro- and nanoplastics can be inhaled, particularly in polluted areas or near industrial sources [33].
3. Dermal Absorption: A less common but possible route for some associated chemicals[49].

Once inside the body, these particles can translocate via the bloodstream and accumulate in various organs [52]. They have been detected in:

- The Gastrointestinal Tract: Feces, with associations to inflammatory bowel disease [34].
- The Liver: Liver tissue in cirrhotic patients [35].
- The Lungs: Due to inhalation.
- The Placenta and Blood: Indicating their ability to cross biological barriers and affect fetuses [9,36].

7. Health Impacts: From Molecule to Disease

Plastic-associated chemicals (e.g., BPA, DEHP, PBDEs) are linked to a wide array of adverse health outcomes [37, 38]. Mechanisms and health effects include:

- Oxidative Stress and Inflammation: A primary cellular response to foreign particles.
- Cellular Damage and Toxicity Accumulation: nanoplastics can interfere with cellular functions and act as carriers for toxic chemicals into the body.
- Endocrine Disruption: Chemicals like BPA and phthalates mimic or interfere with natural hormones, affecting growth, puberty, and fertility [39].
- Neurotoxicity: Potential association with IQ loss in children from prenatal PBDE exposure [40].
- Increased Disease Risk: Linked to numerous chronic conditions including cardiovascular disease [41], asthma, immune disorders, and certain cancers [42].

8. Biocontrol: The Role of Microorganisms

Microorganisms hold potential for the biological degradation of polymers in natural environments. In recent years several experimental studies using model polystyrene nanoparticles have emphasized that various . Studies show organisms like zooplankton and mussels can ingest or adsorb nanoplastics particles [43,44,45,46]. Research has focused on specific fungi and bacteria with plastic-degrading capabilities:

- Fungi: Fungi from Ascomycota (Dothideomycetes, Eurotiomycetes, Leotiomycetes, Saccharomycetes, and Sordariomycetes),, Basidiomycota (Agari comycetes, Microbotryomycetes, Tremellomycetes, Tritirachiomycetes, and Ustilaginomy-cetes),, and Mucoromycota (Mucoromycetes). The taxonomic placement of plastic-degrading fungal taxa is briefly discussed. The Eurotiomycetes include the largest number of phyla have been recorded degrading plastic. Strains of Aspergillus niger and A. japonicus showed 8-12% degradation of polyethylene bags over one month [7,47].
- Bacteria: Bacteria from genera like Bacillus are involved in degradation processes. Efficiency can be improved by optimizing environmental factors [48].

However, these methods remain largely experimental and face challenges in large-scale application within the complex, open environments characteristic of Yemen's pollution scenario. While these laboratory findings are promising, their application in Yemen faces significant hurdles. These are they require bioremediation control facilities, and the quantity of waste being produced to the low degradation rates in comparison to the volume of waste produced to the basic collection of waste over an advanced treatment technology. To that end, biocontrol is still a promising line of study and not a solution yet, which underlines the significance of the preventative policy of waste management.

9. Discussion

It is known that the widespread presence of plastic and its progressive breakdown into microplastics (MPs) and nanoplastics (NPs) is considered a critical and escalating environmental and public health concern worldwide including Yemen. This paper provides evidence that plastic pollution is complex and serious threat that affects ecosystems, food chains, and human biology. Statistically, the production of plastics nowadays exceeds 400 million tons per year. accompanied with inadequate recycling infrastructure. Approximately 14% of plastics waste is recycled. This results in continuous and ongoing environmental challenge. A significant amount of this waste degrades into persistent microplastics and nanoplastics which turn into contaminants, spread from the deepest ocean trenches to the mountain peaks. The human body is not an exception. The situation in Yemen represents the challenges encountered by countries with insufficient waste management systems. The widespread use of plastics in many fields such as households, agriculture, manufacturing and healthcare brings out permanent sources of primary and secondary plastic pollution. The dominance of non-biodegradable polymers such as LDPE, HDPE, PP, and PVC in Yemen, leads to long-term environmental persistence and continuous generation of microscopic plastic fragments.

A shift towards the nanoplastics (NPs) that are less than 100 nm in diameter is a significant escalation of the risk because these plastics are more bioavailable and capable of penetrating cellular barriers. As is well familiar, NPs elude the traditional detection methods and are transported with great efficiency via air, water and food chain [50]. The literature reviewed proves the fact that exposure of human to pollutants through ingestion and inhalation leads to the accumulation of plastic particles in the tissue, including blood, lungs, liver and placenta. The health consequences which come with it are dramatic and extensive. The endocrine disruptors, carcinogens and neurotoxic agents enter the body through the leaching of plastic-associated chemicals of these particles. Such particles are phthalates (DEHP), flame retardants containing brominated dibenzenedicarboxyl (PBDEs) and bisphenol A (BPA). The exposure is associated with various bad consequences such as inflammatory conditions such as inflammatory bowel disease, developmental disabilities, reproductive toxicity, cardiovascular and possible causing cancer.

The chemical structure of polymers has a significant contribution to both the environmental fate as well as the toxicological profile. Polyolefins (PE) and polypropylene (PP) have strong carbon-carbon backbones that are resistant to biodegradation which results in centuries of environmental interference and disintegration into NPs. PET or Nylon polymers with amide or ester linkages are to a certain degree more prone to degradation but still not enough to avoid accumulation. Polyvinyl chloride (PVC) is an especially worrying substance to Yemen due to its broad application in water pipes since degradation may cause the release of chlorine-based substances.

The biological control methods have been made more promising by the use of certain fungi strains, including *Aspergillus* spp, and bacteria strains, including *Bacillus* spp. Nevertheless, their use in a practical and large scale setting as in the case of Yemen is faced with significant challenge. Their viability as an independent solution is highly constrained by a number of factors that include: slow rates of degradation as compared to plastic input, the requirement of controlled environments and the complexity of mixed plastic waste streams. In its turn, the plastic issue in Yemen must be considered as a multifaceted socio-ecological phenomenon that overlaps with environmental regulation, economic limitations, national healthcare system and the general trends in global plastic manufacturing. The lack of an effective waste collection and recycling and regulatory systems intensifies the weakness of the country.

10. Conclusions and Recommendations:

Considering the situation in Yemen, plastic waste buildup and its subsequent breakdown into micro- and nano-plastics are a critical and growing eco- and health-related threat. The mass utilisation (PVC pipe) without proper recycling, implies that there is a direct route of contaminated plasticizer (phthalate) into water resources that is a risk factor that is compounded by the current water problem facing Yemen. This connects local practice with scientific risk. The reliance of the country on non-biodegradable plastics in all leading sectors, lasting and persistent, and that an insufficient waste management capacity leads to the situation in the country predisposing to massive contamination of nano-plastics by virtue of their small size and high mobility which constitute the most common type of this pollution which can penetrate and accumulate well in the biological tissues. The extensive exposure of humans to such particles and the toxic chemicals that accompany it is an obvious manifestation where there are recorded routes through diet, water and air. The health sequel is expected to be severe affecting multiple organ systems and contribute to chronic diseases. The strategies of bioremediation by using microorganisms offer a glimmer of hope for long-term mitigation, however, they are not a panacea.

The research lacks localized, quantitative data on plastic leakage, accumulation of micro-plastic, and nano-plastic presence in air, water, soil and food. The need for operational laboratories, severe shortage of research funding and difficulty conducting field studies due to security and access issues as well as the absence of advanced analytical equipment, for nanoparticle detection, are other challenges.

Addressing this crisis in Yemen demands a multi- faceted, urgent and sustainable strategy as follows:

1. With regard to policy and regulation, there is an absence of specific laws or enforcement mechanisms targeting plastic production use or pollution and no extended producer responsibility (EPR) schemes in place. It’s essential to develop and enforce robust policies for plastic waste management, promote (EPR) and phase out the most hazardous single use plastics .
2. Regarding public awareness, there is overdependence on single use plastics (bags, water sachets) driven by cost and convenience, coupled with low public awareness of health and environmental risks accompanied with nanoplastics. There is an immense need for comprehensive public education to enhance their awareness.
3. With reference to waste management placement, formal collection and disposal systems are fragmented or non-existent in many areas. The situation is building capacity for improved waste collection, segregation, and recycling infrastructure to reduce environmental leakage.
4. Regarding research and monitoring, there is a need to establish local research initiatives to quantify the scale of nano-plastics pollution in Yemeni environment, i.e. air, water, food, and monitor biomarkers of human exposure. In addition, international academic partnerships must be fostered to support training and remote data analysis.
5. Finally, other alternatives such as supporting the development and adoption of viable, environmentally benign alternatives to conventional plastics should be supported wherever feasible.

Ultimately, for future generations mitigating of plastic and nanoplastics crisis is imperative for safeguarding the health of Yemen's population and ecosystems. Action coordination is required at local, national and international levels. Besides, definition of plastic pollution as a transboundary challenge that mirrors the global nature of its production and distribution has to be clearly stated.

11. Acknowledgments

The authors thankfully to professor Mohamed Alansi and professor Saleh Sharkhah from English department, Albaydha University, for providing English proofing and correction.

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Journal of Basrah Researches (Sciences) **52**(1), 97 (2026)
DOI: https://DOI.org/10.56714/bjrs.52.1.8

مشكلة البلاستيك في اليمن، وتأثير النانو بلاستيك على الانسان والحيوان والبيئة

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معلومات البحث

الاستلام 13 كانون ثاني 2026
المراجعة 21 شباط 2026
القبول 02 اذار 2026
النشر 30 حزيران 2026

الكلمات المفتاحية

نانو بلاستيك، بلاستيك، صحة الانسان، النظام البيئي، البيئة، البيئة المائية

Citation: H. M. Al-gabr et al., J. Basrah Res. (Sci.) **52**(1), 97 (2026). DOI:https://DOI.org/10.56714/bjrs.52.1.8

الملخص

يمثل التلوث البلاستيكي أزمة بيئية عالمية خطيرة، حيث يشكل تحللها إلى جسيمات بلاستيكية دقيقة ونانوية (NPs) تهديداً شديداً للنظم البيئية وصحة الإنسان. هدفت هذه الورقة الى استعراض المشكلة المتصاعدة مع تركيز خاص على اليمن، الدولة التي تعاني من تلوث بلاستيكي كبير تفاقم بسبب محدودية البنية التحتية لإدارة النفايات. تشرح الورقة بالتفصيل الاعتماد الواسع النطاق على البوليمرات غير القابلة للتحلل الحيوي بما في ذلك البولي إيثيلين (PE) والبولي بروبيلين (PP) وكلوريد البولي فينيل (PVC) عبر القطاعات الزراعية والصناعية والمنزلية في اليمن، مما يشكل مصادر مستمرة للتلوث البيئي. يتم تسليط الضوء على تفتت النفايات البلاستيكية إلى جسيمات نانوية الحجم (<100 نانومتر) باعتباره الشاغل الرئيسي نظراً لقدرتها العالية على الانتشار والتوافر الحيوي وقدرتها على التسلل إلى الأنسجة البيولوجية. تؤكد الأدلة الحالية أن التعرض البشري للجسيمات النانوية يحدث في المقام الأول عن طريق تناول الطعام والماء الملوثين واستنشاق الهواء الملوث. فيؤدي هذا التعرض إلى تراكم الجسيمات البلاستيكية والمواد الكيميائية السامة المرتبطة بها (مثل بيسفينول أ، الفثالات) في الأعضاء الحيوية، بما في ذلك الرئتين ومجرى الدم والمشيمة، والآثار الصحية الناتجة عميقة، وتشمل الأمراض الالتهابية، واختلال الغدد الصماء، والسمية الإنجابية، وزيادة مخاطر الإصابة بأمراض مزمنة مثل أمراض القلب والأوعية الدموية. بينما تقدم استراتيجيات المعالجة الحيوية التي تستخدم الفطريات والبكتيريا تخفيفاً محتملاً على المدى الطويل، إلا أنها غير كافية لمواجهة النطاق الحالي للتلوث. وخلصت الدراسة إلى أن معالجة أزمة النانو بلاستيك في اليمن تتطلب استراتيجية عاجلة ومتعددة الجوانب تشمل تعزيز السياسات واللوائح، وحملات التوعية العامة، والاستثمار في أنظمة إدارة النفايات، والبحث المحلي المستهدف. هذا النهج الشامل أمر لا غنى عنه لحماية الصحة العامة والاستدامة البيئية من هذا التهديد المنتشر والدائم.

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ISSN: 1817-2695 (Print); 2411-524X (Online)
Online at: https://jou.jobrs.edu.iq