doi:10.22100/ijhs.v11i4.1291
Original Article

SJMS 2025;11(4):57-67
sjms.shmu.ac.ir
SJMS
Shahroud Journal of Medical Sciences

Confronting the Environmental Fallout due to Polyurethane Waste and Microplastic Pollution: Mini-review

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Received: 30 June 2025
Accepted: 4 October 2025

Abstract

Background: *Polyurethane plays a crucial role in waste management due to its wide range of applications and unique properties. Polyurethane waste is produced in large quantities, creating challenges for proper disposal. Inadequate disposal practices contribute to the release of polyurethane-derived microplastics through production, degradation, and wear processes, posing risks to soil, water, and air quality, as well as to ecological and human health. Despite increasing research, the environmental consequences of polyurethane waste and microplastic formation remain insufficiently synthesized, and existing management strategies are fragmented.*
Methods: *This mini-review systematically examines the environmental impacts of polyurethane waste and microplastic pollution by analyzing studies published up to January 2024 in international and Iranian databases. Emphasis is placed on identifying current management approaches, their effectiveness, and gaps in knowledge.*
Results: *Findings indicate that polyurethane wastes are highly persistent, amplifying their ecological footprint over time, and that recycling and recovery technologies remain limited in scope and efficiency. Few studies provide comprehensive evaluations of polyurethane-derived microplastic concentrations or their long-term hazards. The synthesis highlights the importance of innovative recycling methods, preventive measures, and public awareness initiatives as key strategies to mitigate impacts.*
Conclusion: *The recognition of the importance of polyurethane in waste management shows the need for concerted efforts to effectively address its environmental consequences. By clarifying existing knowledge gaps and future research priorities, this study provides a focused perspective for advancing sustainable alternatives and reducing the environmental burden of polyurethane.*

Keywords: PU, MPs, Recycle, Plastic management, Environment, Energy recovery.
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Please cite this paper as: Jonidi Jafari A, Tangestani M, Zarezadeh E. Confronting the Environmental Fallout due to Polyurethane Waste and Microplastic Pollution: Mini-review. Shahroud Journal of Medical Sciences 2025;11(4):57-67.

Introduction

Polyurethane is a widely used polymer synthesized from polyol and diisocyanate. It is widely used in various products, from clothing and furniture to adhesives, insulation, and automobiles, whose versatility has led to a significant increase in its production and use [1, 2]. The increasing demand has led to substantial growth in polyurethane production; in 2015, global polyurethane production reached approximately 30 million metric tons [3, 4]. Polyurethane relies heavily on non-renewable carbon sources such as crude oil and natural gas. While there are efforts to explore renewable alternatives such as polyols from vegetable oils and biomass, their high cost and limited functional properties hinder their widespread adoption [5].

However, polyurethane has toxic compounds and additives that cause various harmful environmental effects on soil and aquatic environments. The introduction of different compounds into water and soil has caused people to come into indirect contact with different compounds of polyurethanes, which leads to different health effects. Among the effects caused by contact with plastics and polyurethane products, we can refer to cancer, birth defects, reproductive and endocrine disorders. Therefore, the increase in population has caused the production of a large amount of plastic waste, with health and environmental issues [6, 7].

Polyurethanes produced from polyether polyols are one of the common sources of manufacturing plastic products. In case of inappropriate disposal of these compounds in the environment, they are decomposed through various mechanical, physical, and chemical processes and degraded into smaller pieces of plastic, which are known as microplastics (<5 mm) (Figure 1). Today, it has been observed that microplastics presence in different ecosystems has caused it to become part of the human food chain [8-10]. Microplastics produced from the discarded products of polyurethanes have been found in various environments such as oceans, seabed, and beaches [11]. Nowadays, approximately 5 to 13 million tons of plastic waste, such as polyurethane products, enter the oceans from the land due to existing mismanagement to properly dispose of plastic waste [12]. So, Polyurethane waste poses environmental challenges, and most of it ends up in landfills.

Currently, one of the common methods available to manage polyurethane waste disposal is recycling. Recycling includes Mechanical, chemical, and biological methods [2, 13, 14]. Mechanical recycling, the dominant method, produces low-value products due to the thermosetting nature of polyurethane. Chemical recycling, with the aim of cleaving urethane bonds to produce recycled polyol (repolyol), offers a more promising way. However, existing methods, such as aminolysis, hydrolysis, glycolysis, face safety, environmental, and efficiency concerns [15].

This mini-review aims to systematically examine the environmental effects of polyurethane waste and microplastic formation, evaluate the advantages and limitations of current recycling methods, and identify knowledge gaps and future research priorities.

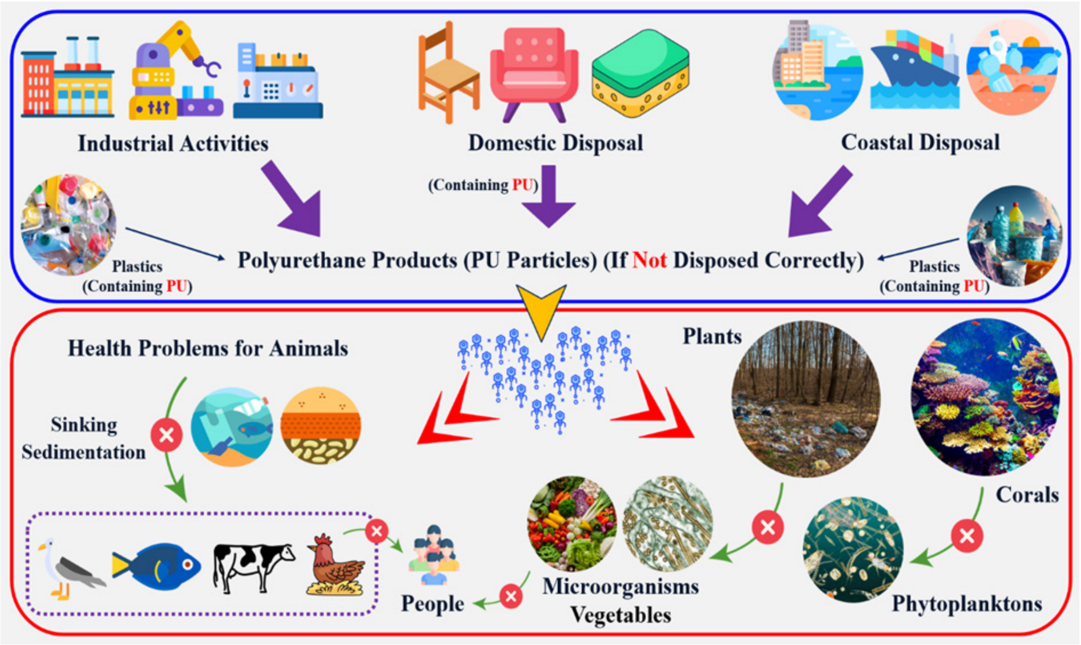

Figure 1. Lifecycle of polyurethane waste: from improper disposal to microplastic formation and entry into the food chain

Materials and Methods

This systematic review followed PRISMA. A comprehensive search was conducted up to January 2024 across major international (Web of Science, PubMed, Scopus, Google Scholar) and Iranian databases (SID, Magiran, IranMedex, IranDoc, Thesis) using keywords related to "Polyurethane wastes" and microplastics. Of the 112 identified articles, 13 met eligibility criteria. Data extraction was independently performed by two reviewers.

The search strategy included the following keywords: "Polyurethane waste" OR "PU waste", "Polyurethane microplastics" OR "PU microplastics", "Recycling of polyurethane", and "Polyurethane environmental impact".

Full-text articles published in English that investigate polyurethane wastes and their role in microplastic formation were included. Studies published up to January 2024 were included to ensure timely coverage of recent literature. Future updates will incorporate studies published after this date. Studies such as review articles, book chapters, conference letters, non-English papers, and those with incomplete data were excluded.

Initial screening was performed by two independent reviewers based on titles and abstracts. Full-text articles were then assessed for eligibility by the same reviewers. Discrepancies were resolved by discussion and consensus with a third reviewer. Data included study design, sample type, polyurethane waste type, microplastic assessment, and recycling approaches were extracted. Data extraction was independently performed by two reviewers.

Results

Out of 112 articles identified, 13 studies met the inclusion criteria. A PRISMA flow diagram summarizes the number of records screened, assessed for eligibility, and included in the review (to be included as Figure 2).

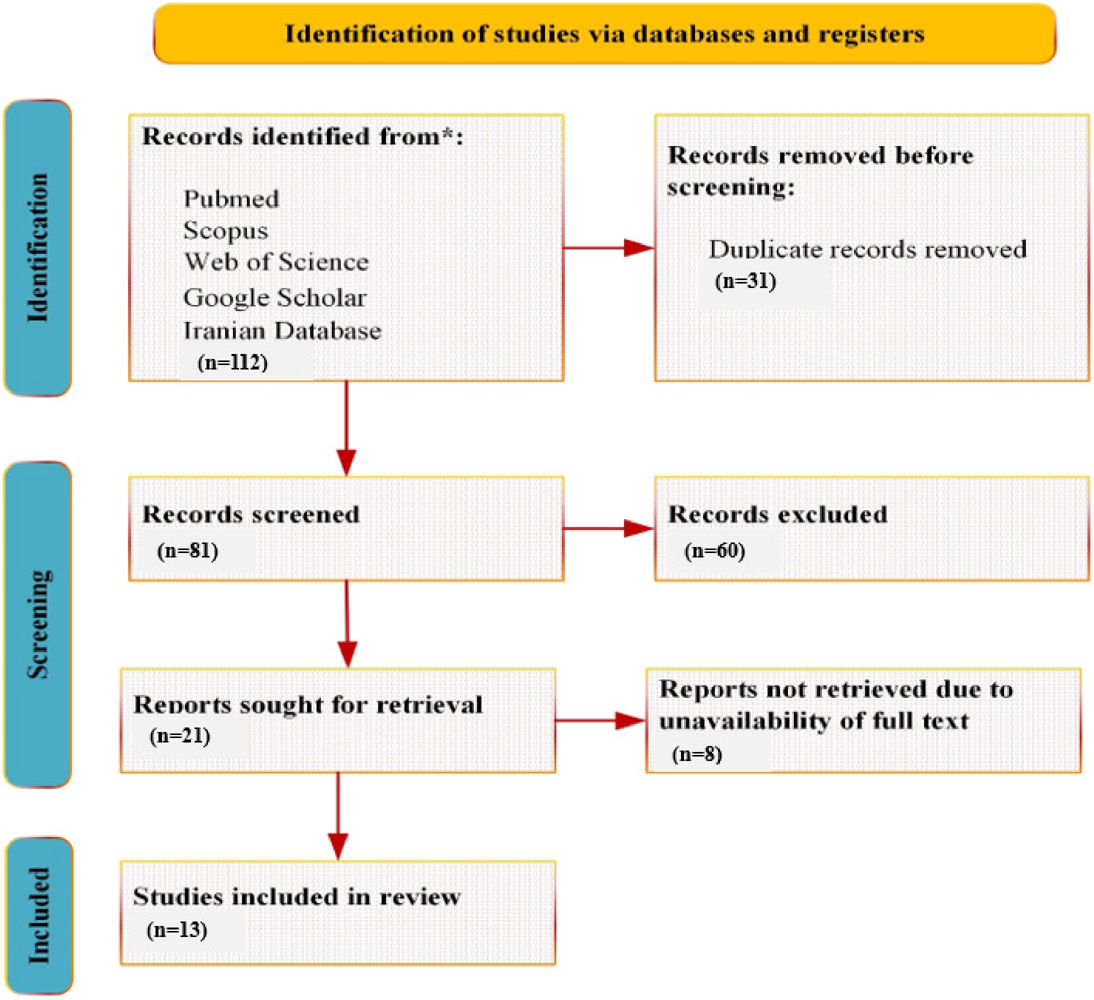

Figure 2. PRISMA diagram

A total of studies reviewed in this systematic mini-review focused on the environmental impacts of polyurethane waste and the performance of different recycling methods. The included works addressed the generation of polyurethane-derived microplastics (Table 1), their presence across environmental compartments (Table 2), and the effectiveness of recycling and disposal strategies.

Table 1. Summary of key findings on polyurethane microplastics

Aspect	Summary	Quantitative data	Reference
PAH accumulation in polyurethane microplastics in contaminated soil	Biodegradable polyurethane microplastics strongly accumulate polycyclic aromatic hydrocarbons (PAHs) within 7 days, with concentrations increasing over 28 days. Conventional polyurethane showed lower PAH sorption. Aging did not affect sorption behavior. Sorption is driven by polymer network flexibility.	Biodegradable polyurethane microplastics had significantly higher PAH accumulation over time; sorption up to 3.6x soil concentration for conventional polyurethane.	16
Toxicity in Aquatic Organisms	Polyurethane microplastics cause toxic effects including oxidative stress, genotoxicity, physical injury in zebrafish; toxicity depends on particle size and concentration.	Grade 3-4 tissue damage at 1000 µg/L exposure; accumulation seen in gills, digestive system after 10 days	17
Chemical Additives Hazard	Polyurethane contains high chemical additive loads (e.g., tris(chloropropyl)phosphate) significantly contributing to toxicity effects.	28-day exposure shows growth inhibition and additive bioaccumulation	18

Formation in Polyurethane-Coated Polyester	Photodegradation of Polyurethane-coated polyester releases nano- and microplastics and dissolved chemicals.	8.5% carbon release in TPU_Ether; 3.7% in TPU_Ester	19
Photodegradation of PU-Coated Polyester Fabrics	PET base fabrics coated with PU show delayed but significant photodegradation compared to pure PET; generate microplastic fibers (MPFs) and particles (MPPs).	After 360 hours UV: 9.32×10^7 MPs/g microplastics, 2.7×10^11 NPs/g nanoplastics released	20
Effects of Polyurethane Microplastics and Cd on Maize	Effects of Polyurethane Microplastics and Cd on Maize	Effects of Polyurethane Microplastics and Cd on Maize	21
Structure and Sorption of Agricultural MPs (Polyurethane)	Structure and Sorption of Agricultural MPs (Polyurethane)	Structure and Sorption of Agricultural MPs (Polyurethane)	22

Table 2. Summary of included studies on environmental impacts and recycling of polyurethane waste

Subject	Study design / context	Focus area	Key findings	Reference
Various environmental monitoring studies	Observational	polyurethane waste in aquatic ecosystems	Leaching of isocyanates and flame retardants disrupts coral reefs and threatens aquatic life.	6, 7, 19, 23
Toxicological and soil studies	Laboratory & field	Soil contamination from polyurethane	Release of isocyanates/flame retardants negatively impacts plants and animals.	5, 7
Air quality studies	Experimental & modeling	Burning of polyurethane	Emission of VOCs and isocyanates linked to respiratory diseases and contribution to climate change.	1, 5
Ecotoxicological assessments	Food chain analysis	Bioaccumulation of polyurethane compounds	polyurethane accumulation in animals disrupts ecosystems and poses risks (respiratory issues, cancer) to humans.	3, 4
Degradation and manufacturing process analyses	Mechanistic	polyurethane-derived microplastics	Both production and degradation processes contribute to microplastic formation, threatening ecosystems and human health.	14, 19
Recycling performance studies (physical recycling)	Experimental	Material property preservation	Advantages: retention of properties, energy efficiency, versatility. Limitations: reduced material strength, complex processing.	1, 3
Recycling performance studies (chemical recycling)	Experimental	Resource recovery	Enables high-purity recycling and resource efficiency. Drawback: need for specialized processes, possible impurities.	15, 24
Solvent-based recycling investigations	Pilot & lab studies	Non-recyclable PU compounds	Innovative technology for hard-to-recycle polyurethane promotes resource conservation.	3, 6, 13
Pyrolysis studies	Energy & chemical recovery	polyurethane foams	Produces useful chemicals/energy; challenges include cost and emission control.	1, 3, 4
Energy recovery methods	Waste-to-energy assessments	polyurethane waste valorization	Maximizes resource use, reduces waste, generates renewable energy, but raises environmental impact concerns.	3, 5

The reviewed studies consistently highlight that improper disposal of polyurethane waste poses severe risks to water, soil, air quality, and human health, largely through the release of toxic compounds and generation of microplastics. Recycling emerges as the most effective strategy to mitigate these impacts, with different approaches offering distinct benefits and drawbacks. Physical recycling preserves material properties but struggles with mechanical strength. Chemical recycling enables high-purity output yet requires specialized technology. Solvent-based recycling represents a promising innovation for otherwise non-recyclable polyurethane waste. Pyrolysis and energy recovery provide dual benefits of waste reduction and energy generation but demand strict environmental management. Overall, advancing recycling technologies through continuous research and collaboration is crucial to support a circular economy and reduce polyurethane-related environmental burdens.

Discussion

The role of polyurethane foams in the production of microplastics: Due to their remarkable physical and chemical properties, plastics have become a major commodity worldwide and have numerous applications in commercial and industrial products. Due to the high demand of society, the large-scale production of fibers and resins has increased worldwide [25]. Packaging is one of the most important and widely used uses of plastic materials. About 40% of plastic materials worldwide are used to store and package final products from various factories. Plastics have made a significant contribution to creating a sustainable, convenient, hygienic, cost-effective, low-consumption, and environmentally friendly packaging system that can keep the environment clean [26]. The versatility of plastics is proof of efficiency for hygienic and cost-effective packaging of food products such as bread, rice, snacks, fruit juices, spices, milk, edible oil, wheat flour, confectioneries, and all kinds of pharmaceutical products. Due to many applications, these products create a lot of waste after use on the environment. Plastics are of various types, including polyvinyl chloride (PVC-U), polystyrene or styrofoam (PS), polypropylene (PP), high density polyethylene (HDPE), polyethylene terephthalate (PETE), etc. [27]. Thermosetting or thermoset plastics are synthetic materials that pass through a series of physicochemical transformation processes under different heat treatments, assisting the creation of a three-dimensional linkage. This transformation is not a reversible process. After heating treatment, these thermoset molecules cannot be reformed or remolten. Thermosets physical state can be changed from liquid with a low degree of viscosity to solid with a high melting point; this shows that different materials with some specific chemical and physical characteristics can be formed from thermosets. In general, thermosetting subunits or monomers have low viscosity, which allows them to be modified and makes them easy for the consumer; different additives are used on thermosets to maximize and optimize the performance of thermosets and will enable them to be applied in different specific uses like others [28].

Polyurethanes refers to a polymer made by polymerizing organic monomers known as urethane, commercially named a carbamate. Many polyurethanes are thermoset and are also called thermoplastic polyurethanes [29]. Physical and chemical properties of polyurethane, like its versatility, allow these polymers to be widely used in different applications such as coatings, foams, adhesives, paints, upholstery, and insulators. Like other polymers, polyurethanes also depend on petrochemicals as a basic material or subunits in their main constituents [1].

Polyurethane foams, commonly found in products like furniture cushions, mattresses, and insulation, can contribute to the generation of microplastics through various processes. Microplastics are tiny plastic particles measuring less than 5 millimeters in size, often invisible to the naked eye [30]. These particles can originate from any plastic source, including bottles, bags, and packaging, as well as synthetic textiles, tire wear, and microbeads from personal care products [31]. The methods that lead to the production of microplastics from polyurethane include (Figure 3):

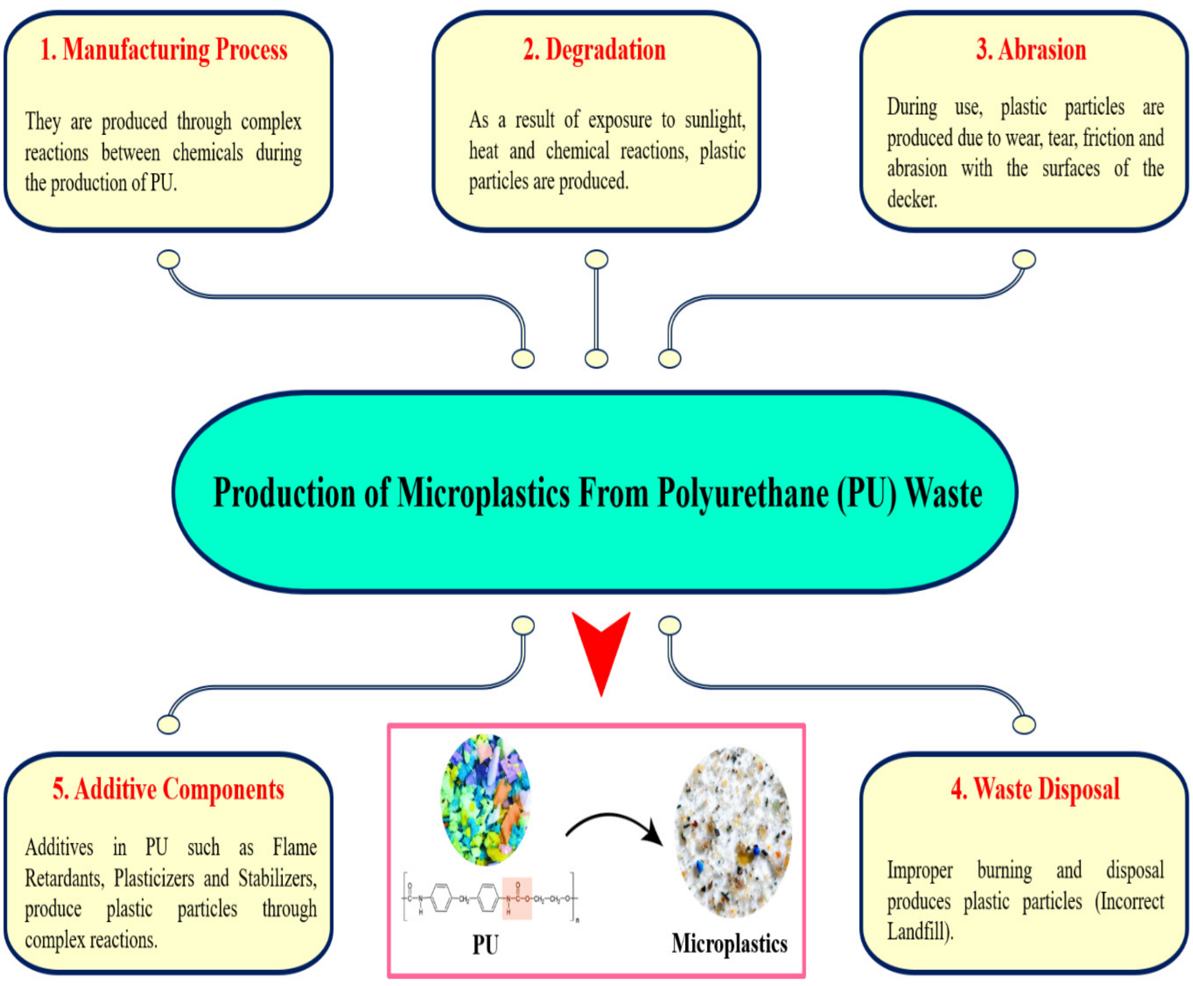

Figure 3. Different methods of producing microplastics from polyurethane waste

Degradation: Over time, polyurethane foams can degrade due to exposure to sunlight (UV radiation), heat, mechanical stress, and chemical reactions. This degradation process can lead to the formation of smaller plastic particles, including microplastics.

Abrasion: Polyurethane foam products undergo wear and tear during use. Friction and abrasion against other surfaces can cause the foam to shed tiny plastic particles, contributing to microplastic pollution [32].

Waste Disposal: Improper disposal of polyurethane foam products is a significant concern. When these products end up in landfills or are incinerated, they can release microplastics into the environment. Burning polyurethane foam releases toxic gases and particulate matter, including microplastics, into air [2].

Manufacturing Process: The production of polyurethane foams involves the use of various chemicals, some of which can be released into the environment during manufacturing processes. These chemicals may contribute to the formation of microplastics through complex reactions [33].

Additives: Polyurethane foams often contain additives such as flame retardants, plasticizers, and stabilizers to enhance their properties. These additives can leach out over time, contributing to the generation of microplastics [30].

Once released into the environment, microplastics can have detrimental effects on ecosystems and human health. They can be ingested by aquatic organisms, potentially entering the food chain and posing risks to human health. Additionally, microplastics can absorb toxic chemicals, further increasing their potential harm [34].

Efforts to mitigate the generation of microplastics from polyurethane foams include improving waste management practices, promoting recycling and circular economy principles, and developing alternative materials with reduced environmental impact [8, 35].

Environmental Consequences of Improper Disposal of Polyurethane Waste: Polyurethane, a versatile and widely used synthetic polymer, has become an integral part of modern society due to its diverse applications in industries [2]. However, improper disposal of polyurethane waste poses significant environmental challenges and has far-reaching consequences for ecosystems and human health. In recent years, the proliferation of polyurethane waste has emphasized the urgent need to address its environmental impacts [36]. The environmental consequences of burying and burning polyurethane waste can be significant.

Water pollution: Improperly managed polyurethane waste, when disposed of in oceans or other water bodies, poses a significant threat to marine habitats and ecosystems. The chemicals present in polyurethane waste, such as isocyanates, can react with seawater, leading to water acidification and harming marine life, especially crustaceans and organisms with calcium carbonate skeletons like corals, oysters, and certain plankton species [37]. This pollution can adversely affect coral reef ecosystems, which serve as crucial habitats for a wide range of marine species. The destruction of coral reefs can disrupt marine food chains and lead to changes in the behavior and reproductive patterns of marine animals, including sea turtles and seabirds. Most of the substances found in everyday products used by humans contain hazardous elements [6]. For example, the composition of polyurethane spray contains a combination of harmful chemicals. Many of these chemicals pose risks to environmental organisms. In case of contact with water, this chemical mixture can negatively affect aquatic life [6]. When the foam solidifies, the chemicals are usually trapped in the solid structure and retain their toxicity. In addition, debris and dust particles generated from foams during handling release excess chemicals directly into the environment, exacerbating harmful effects. Over time, these chemicals find their way to water bodies and different aquatic ecosystems, so that they exhibit bioaccumulative properties in the bodies of organisms [6]. In a study conducted by Rutkowska M, changes in weight, tensile strength, and morphology of polyurethane samples were investigated over time in an aqueous environment. The findings showed that the degree of degradation of polyurethanes in seawater is influenced by the degree of crosslinking. In addition, the complex nature of the marine environment, including microorganisms, animals, salt, sunlight, water fluctuations, and rain, contributes to the degradation process [23].

In a study by Albergamo V, et al., the interaction between polyurethane (PUR) materials and microplastic pollution was investigated, focusing specifically on the effects of solar radiation on different types of polyurethane microplastics. They exposed polyether (TPU_Ether) and polyester (TPU_Ester) thermoplastic polyurethanes, as well as heat-hardened polyurethane (PU_Hardened), to simulated sunlight to simulate the degradation process that occurs in the ocean over time. The results showed that polyurethane microplastics degrade through UV light oxidation mechanisms when exposed to sunlight, leading to the release of dissolved organic carbon (DOC) into the surrounding aquatic environment. This study shows that polymer chemistry affects how microplastics break down. Understanding the fate of released DOC is important for assessing the environmental effects of plastic pollution and can help design materials and regulatory efforts to reduce microplastic pollution. In addition, the findings have potential implications for the design of new materials and regulatory efforts aimed at mitigating microplastics. They show microplastic pollution [19].

Soil pollution: Polyurethanes have positive and negative effects on soil environments. While they can improve soil quality, concerns arise from pollutants released during production. The goal of international regulations is to reduce these risks. Polyurethane, especially when combined with natural fibers, improves soil strength and reduces weak points. However, landfilling polyurethane waste can lead to soil contamination [38]. Some harmful chemicals in polyurethane, such as isocyanates, flame retardants, and plasticizers, can penetrate the soil and groundwater and cause hazards to plants, animals, and humans. Microplastic pollution caused by using polyurethane creates environmental challenges [39]. slow down. Efforts are ongoing to evaluate the biodegradability of polyurethane and minimize the environmental impact.

Polyurethanes can be degraded in soil through microbial action, and fungi play an important role. Techniques such as biostimulation and biofortification enhance polyurethane degradation [40]. Despite their resistance, polyurethanes can be broken down into smaller compounds under the right conditions. Fungi, including Aspergillus tubingensis, show promise in polyurethane degradation, contributing to environmental sustainability and bioremediation efforts [41].

Air Pollution: Burning polyurethane releases harmful pollutants into the air, contributing to air pollution. When polyurethane is burned, it emits various toxic substances such as isocyanates, carbon monoxide, hydrogen cyanide, and volatile organic compounds (VOCs) [42]. These pollutants can have serious health effects on both humans and the environment. Isocyanates, for example, can cause respiratory issues and are known to be respiratory sensitisers, meaning they can trigger asthma and other respiratory conditions. Carbon monoxide is a poisonous gas that can lead to headaches, dizziness, and even death in high concentrations. Hydrogen cyanide is extremely toxic and can cause respiratory failure and death. VOCs contribute to the formation of ground-level ozone and smog, which can irritate the respiratory system, exacerbate asthma, and cause other health problems [43]. In addition to harming human health, these pollutants can also have environmental impacts. They contribute to the formation of smog and acid rain, degrade air quality, and harm ecosystems. Furthermore, burning polyurethane releases greenhouse gases such as carbon dioxide and methane, which contribute to climate change and global warming.

Overall, burning polyurethane contributes to air pollution, which poses significant risks to human health and the environment. Therefore, proper disposal and recycling of polyurethane materials are essential to mitigate these harmful effects [44]. Coralli et al. have evaluated the contribution of polyurethanes (PUR) to microplastic pollution. By investigating the thermal degradation products of PUR using gas chromatography-mass spectrometry (Py-GC/MS) and thermocomulolysis, they sought to understand the presence of PUR-derived microplastics in environmental samples. Their work involved analysis of PUR subclasses, particularly those synthesized with methylene diphenyl diisocyanate (MDI) and toluene diisocyanate (TDI), which are commonly used in various products. Through this analysis, they identified PUR-specific indicators and assessed their occurrence in environmental samples such as road dust and cobwebs collected from urban areas, including those collected near plastic processing plants. This research provided valuable insights into the spread and environmental impacts of microplastics derived from polyurethanes [45].

Health Hazards: Some studies have shown that some polyurethane components, such as flame retardants, can accumulate in animals when they enter waterways. These anti-flame substances, such as tris(1-chloro-2-propyl) phosphate and hexabromocyclododecane, accumulate in the fatty tissues and liver of aquatic organisms and finally enter the human diet through the consumption of damaged organisms such as cod fish [46]. These flame retardants not only affect the reproductive health and survival of aquatic organisms but also plant life and organisms such as worms and daphnids [18]. They disrupt the hormonal balance of the fish and can alter the activity of salmon liver enzymes [18]. Furthermore, these chemicals can persist in the environment for long periods of time, with reported half-lives in aquatic environments exceeding 182 days, indicating their significant environmental impact. Exposure to chemicals released during the burial or incineration of polyurethane waste can pose serious risks to human health and wildlife. Inhalation or ingestion of toxic substances can lead to respiratory problems, neurological problems, reproductive disorders, and even cancer [47]. Among the various health risks associated with polyurethane consumption for humans, we can mention birth defects, cancers, immunodeficiency, reproductive and developmental effects, endocrine and metabolic heart disorders [48]. In addition, a wide range of health issues from exposure to toxic chemicals such as plastic and microplastics, including respiratory problems, skin diseases, are of concern [45, 48].

The ingestion of food items tainted with polyurethanes and microplastics, encompassing vegetables, dairy, meat, and seafood, can yield diverse health ramifications for individuals. The consumption of such contaminated products can lead to adverse effects such as obesity, cancer, alterations in gene expression, recurrent miscarriages, and infertility. Various research endeavors have indicated that the utilization of food packaging containing polyurethane under elevated temperature conditions can instigate disruptions in disparate hormonal systems, expedited onset of puberty, metabolic dysfunctions, immune system alterations, diminished sperm production, and cardiovascular irregularities [45, 48].

Common methods of recycling polyurethane

Physical recycling: Physical recycling, an efficient and cost-effective method, involves crushing polyurethane waste into small particles for reuse. These particles can be used as fillers in various products such as flooring and engine compartments. While suitable for thermoplastic polymers, this method does not apply to heat-resistant thermoset polymers [49]. Techniques such as rebonding, adhesive pressing, and compression molding are common in mechanical recycling [50]. Press glue involves sorting and cleaning recycled polyurethane foams, then pressing them with glue to create new products such as furniture and mattress components. Hot press molding melts scrap polyurethane foam into items such as insulation boards [51]. It is practical to use polyurethane foam waste as a filler or filling material for applications such as cushions and acoustic panels. Extrusion and injection molding processes combine polyurethane with other plastics to create products such as automotive components [52]. Regrinding involves grinding scrap polyurethane foam into powder for re-foaming, while compression molding shapes polyurethane particles under heat and pressure to form new adhesive-free foams. These physical recycling methods provide cost-effective solutions for the reuse of polyurethane waste, although there are some limitations in terms of material strength and product performance [52, 53].

In summary, physical or mechanical recycling methods offer numerous advantages for polyurethane recycling, including the preservation of material properties, energy efficiency, process simplicity, versatility, and reduced environmental impact. These benefits underscore the importance of incorporating physical recycling techniques into comprehensive waste management strategies to promote sustainability and circularity in the polyurethane industry [49].

Chemical Recycling: Chemical recycling offers an effective solution to recycle polyurethane foams by breaking them down into their constituent molecules to produce reusable products [2, 54]. This method is beneficial for extracting pure raw materials and producing high-quality recycled polyurethane and overcomes the challenges in mechanical recycling [55, 56]. Chemical techniques include polymerization of polyurethane foams through various methods such as alcohol, hydrolysis [57, 58], methanolysis [59], aminolysis [50], acidolysis [24, 60], phosphorolysis [50], and glycolysis [24, 54]. Alcoholysis uses polyols to break urethane bonds and produces high-quality polyols for reuse in polyurethane production. Hydrolysis involves breaking urethane bonds using steam or water, and methanolysis targets urethane bonds using methanol to produce polyol and methyl isocyanate compounds [58]. Aminolysis disrupts urethane bonds using nitrogen-containing amines and produces polyols and isocyanates for reuse. Ammonolysis uses ammonia to extract valuable components from polyurethane and offers the potential for further refining. Glycolysis breaks down polyurethane using glycols and produces polyols to produce new foam, while hydroglycolysis combines water with glycolysis to produce complex polyols [61, 62]. Acidolysis uses zinc and acetate ions to break down polyurethane and produce recycled polyols suitable for industry standards [2, 63].

Solvent-based Recycling: Solvent-based recycling is a method used for recycling polyurethane materials. This process involves dissolving polyurethane waste in a suitable solvent, leading to the separation of its constituent components [64]. After dissolution, purification techniques are applied to isolate and extract reusable materials from the solvent solution. This method allows for the breakdown of complex polyurethane structures into simpler forms, facilitating the recovery of valuable resources for reuse in manufacturing processes [64]. Solvent-based recycling contributes to sustainability efforts by promoting resource efficiency and reducing waste in the polyurethane industry [65]. Overcoming challenges is crucial for advancing solvent-based recycling technologies and maximizing their potential for polyurethane waste management. Research and development efforts focused on solvent selection, process optimization, and sustainability are essential for overcoming these limitations and promoting the widespread adoption of solvent-based recycling methods [65].

Pyrolysis: Pyrolysis is a process used in polyurethane recycling in which polyurethane waste is exposed to high temperatures, typically from 300°C to 800°C, in the absence of oxygen. This lack of oxygen prevents combustion and allows materials to thermally decompose [66]. As a result, the polyurethane breaks down into its constituents, primarily isocyanates and polyols. These components can then be collected and used as raw materials for the production of new products or as raw materials for other chemical processes. Pyrolysis offers several advantages in polyurethane recycling, including the ability to handle different forms of polyurethane waste, such as flexible foams, rigid foams, and elastomers, and the potential to recover valuable chemicals from the degradation process. In addition, pyrolysis can help reduce the environmental impact of polyurethane waste by diverting it from landfill and incineration [43]. These methods have some challenges which require concerted efforts from researchers, industry stakeholders, policymakers, and the public. Innovations in pyrolysis technology, process optimization, and product development can improve the efficiency and environmental performance of polyurethane recycling via pyrolysis. These advantages highlight the potential of pyrolysis as an effective and sustainable solution for addressing the challenges of polyurethane foam waste management and promoting a circular economy [66].

Furthermore, supportive policies, financial incentives, and public awareness campaigns are essential for fostering the growth of pyrolysis as a sustainable solution for polyurethane waste management. By overcoming these challenges collectively, pyrolysis can play a significant role in advancing the circular economy and reducing the environmental footprint of polyurethane materials.

Energy Recovery: Energy recovery is a method utilized in polyurethane recycling, aiming to extract energy from polyurethane waste through various processes. One common approach involves the thermal treatment of polyurethane waste in facilities equipped with specialized furnaces or reactors. During thermal treatment, polyurethane waste is subjected to high temperatures, typically ranging from 800°C to 1000°C, in the presence of oxygen or steam [67]. This process, known as incineration or combustion, breaks down polyurethane waste into its constituent components, releasing heat energy in the form of steam or hot gases. The heat energy generated can then be captured and used to generate electricity or heat buildings, providing a sustainable energy source [67].

Each of these recycling methods has its advantages and limitations, and the choice of method depends on factors such as the type of polyurethane waste, its condition, and the desired end products. By implementing these recycling techniques, we can reduce the environmental impact of polyurethane waste and promote a circular economic approach to materials management.

Also, in addressing these challenges, ongoing research and development efforts are essential to enhance the efficiency, environmental performance, and cost-effectiveness of energy recovery technologies for polyurethane waste (Table 3). Moreover, fostering public awareness and engagement is crucial for promoting acceptance and understanding of sustainable waste management practices. Through collaborative efforts and innovation, the potential of energy recovery methods in mitigating polyurethane waste can be realized while addressing the associated challenges.

Table 3. Advantages/disadvantages and challenges of different polyurethane recycling methods

No.	Process	% Of studies	Advantage	Disadvantage	Challenge

1	Physical/mechanical recycling	Physical: 40%	Preservation of material properties Energy efficiency Simplified process Versatility and flexibility	Technical constraints Complexity in processing Environmental impact	Limitations in strength and performance Market limitations
2	Chemical recycling	Chemical: 35%	High-Purity recycling Enhanced material recovery Versatility in feedstock Potential for Closed-Loop Systems	Complexity of processes Impurities and by-products Cost-effectiveness Environmental impact	Energy and resource-intensive
3	Solvent-based recycling	20%	Recycling Non-Recyclable Compounds Breakthrough in recycling technology Environmental sustainability Resource conservation Versatile applications	Impurity Removal	Solvent selection Solvent recovery Energy consumption Scale-Up Challenges (Technical constraints)
4	Pyrolysis	15–20%	Resource recovery Energy generation Waste minimization Versatility	Environmental and health risks Product contamination Equipment corrosion	Thermal degradation Energy intensive Technical and economic challenges (process efficiency, maintaining product quality, and managing waste streams effectively) Residue Management
5	Energy recovery	15–20%	Resource utilization Renewable energy generation Waste reduction Cost-effectiveness Circular Economy	Environmental impact Waste stream composition	Energy recovery rates Regulatory compliance Public perception

Conclusion: Improper disposal of polyurethane waste is a significant environmental threat and affects water, soil, air quality, and human health. Chemicals that leach into water bodies from polyurethane waste disrupt marine ecosystems, especially coral reefs, and endanger aquatic life. Soil pollution occurs through the release of harmful substances such as isocyanates and flame retardants, which affect plant and animal life. Burning polyurethane exacerbates air pollution, releasing toxins such as isocyanates and VOCs and contributing to health issues and climate change. In addition, the accumulation of polyurethane components in animals disrupts the ecosystem and poses risks to humans through the food chain, including respiratory problems and cancer. Addressing these challenges requires proper disposal, recycling, and the development of alternative materials. Polyurethane, derived from polyols and diisocyanates, is widely used in industry, but its reliance on non-renewable resources and toxic compounds poses environmental and health risks. Improper disposal leads to the production of microplastics, which are a threat to the ecosystem and human health. Various factors, including degradation and manufacturing processes, contribute to the production of microplastics from polyurethane foams. Among the different methods of polyurethane waste disposal, the recycling method is the most effective. Physical recycling methods offer advantages such as preservation of material properties, energy efficiency, and versatility, but face challenges related to material strength and processing complexity. Chemical recycling methods enable high-purity recycling and resource recovery, although they require specialized processes and may introduce impurities. Solvent-based recycling offers innovative technology to recycle non-recyclable compounds, promoting resource conservation and environmental sustainability. Pyrolysis facilitates resource recovery, energy production, and chemical recycling of polyurethane foam, while energy recovery methods maximize resource use, generate renewable energy, and help reduce waste. Despite their advantages, each method faces challenges such as technical limitations, environmental impacts, and affordability. Overcoming these challenges requires continuous research, innovation, and collaboration to advance polyurethane recycling technologies and promote a circular economy approach to waste management and the development of alternative materials.

Ethical Considerations

This systematic review adhered to PRISMA guidelines, ensuring transparency and integrity. No human or animal subjects were involved, as the study analyzed existing literature from international and Iranian databases, requiring no ethical approval. Data extraction was independently conducted by two reviewers to minimize bias.

Acknowledgment

The present project was supported by Research Center for Environmental Health Technology, Iran University of Medical Sciences [Grant number: 1402-4-61-28100].

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This study was funded by the Research Center for Environmental Health Technology, Iran University of Medical Sciences [Grant number: 1402-4-61-28100].

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