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Review article

A comprehensive review on Single-Use Plastics (SUPs): Challenges and sustainable solutions

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ABSTRACT

This review compiles recent studies on single-use plastics (SUPs), including their widespread use, environmental impacts, and management techniques. Plastic, sometimes referred to as "the material with 1,000 uses," is so versatile that SUPs are essential to modern life because of their low production cost, flexibility, durability, and light weight. However, SUPs contribute to pollution from plastic waste, which may harms ecosystems, wildlife, and increases greenhouse gas emissions during its burning, therefore SUP's have emerged as a major global environmental problem. SUP waste management is difficult, and existing methods such as recycling and disposal have serious drawbacks. This paper critically evaluates conventional waste management strategies and identifies new, more sustainable alternatives such as chemical recycling and circular economy models. Plastic bags, recycling initiatives and promotion of biodegradable materials are important strategies to tackle SUP waste. To reduce the environmental impact of SUP, legislative changes and public awareness are considered crucial. Further studies are recommended to focus on developing recycling technology, strengthening international regulations and promoting sustainable consumer habits. This article provides an in-depth analysis of SUP waste management, emphasizing the need for creative approaches and concerted efforts to solve this persistent environmental issue.

1. Introduction

The production and consumption of SUP is expanding quickly, raising serious environmental issues in the twenty-first century. Straws, silverware, bags, and packaging are among the items that contain these single-use polymers. Because of their accessibility, robustness, and convenience of use, they are widely employed in modern culture, yet this extensive use has a detrimental effect on the environment. The Table.1 summarizes the major events in the history of plastics, ranging from early inventions such as Bakelite to the development of development of most recent biodegradable polymers. It also highlights the growing awareness of plastic pollution, biodegradable plastics, and the discovery of the Great Pacific Garbage Patch (Pilapitiya and Ratnayake, 2024). SUP packaging has proliferated globally, improving people's lives in a number of ways. However, this characteristic has caused immense harm to the natural world. The world plastic production has grown from 2 million metric tons in 1950 to an estimated 413.8 million metric tons in 2023 (Statista, 2023). About 79% of it ends up in landfills or the environment, spreading pollution far and wide. It is estimated that eight million tons of plastic enter the ocean each year (Ritchie et al., 2024). Plastics break down into tiny particles that can enter the food chain, endangering human health in addition to damaging marine ecosystems (Gallo et al., 2020). By 2025, it is estimated that annually 46 million metric tons plastic waste released into lakes, rivers and the ocean while the amount released into terrestrial habitats will reach nearly 50 million metric tons over the same time (Borrelle et al., 2020; MacLeod et al., 2021). SUPs have an impact on the environment that goes beyond pollution. Climate change has been exacerbated by the production and disposal of plastics, which contributes

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significantly to greenhouse gas emissions. 2.8 kg of CO_2 is released into the environment while burning 1 kg of plastic (Janaswamy et al., 2022). This number is expected to increase as plastic production increases. Handling of SUP waste comes with many difficulties, First, there is a huge output of waste beyond the infrastructure for waste management, which already exists, especially in developing countries. Second, only 9% of all plastic manufactured is recycled, indicating that the plastic recycling rate is still low (Geyer et al., 2017). This is partly because recycling contaminated or mixed plastic waste presents both technical and financial difficulties (Juan et al., 2021). The management of plastic waste has been further complicated by the absence of norms and regulations worldwide that effectively limit the use and improper disposal of SUPs (Vanapalli et al., 2021). Various approaches have been put forward and put into practice in response to these difficulties to reduce the impact of SUP on the environment.

Table 1 A chronological overview of the evolution of plastic (Pilapitiya and Ratnayake, 2024)

Year	Information
1862	Parkesine was introduced by Alexander Parkes,it was the first man made plastic
1907	Bakelite (One of the oldest polymers) was introduced by Leo Baekeland, first fully synthetic plastic.
1920’s -30’s	Polyvinyl chloride (PVC) and polystyrene (PS) was developed, they are inexpensive and durable
1933	Polyethylene(PE) , most commonly used plastic was invented by accident
1940’s	Early single use plastic phase, production of disposable cups and plates was high.
1959	Single use plastic became more common with rise of cellophane wrap and plastic lined carton
1960	Single use plastic began replacing paper bags
1990’s	Environmental impact of single use plastic became evident ,especially marine pollution and landfill concerns
2000s-2020s	Efforts to reduce single use plastic intensified, especially banning of plastic cutlery straw and bags Innovation of biodegradable plastics

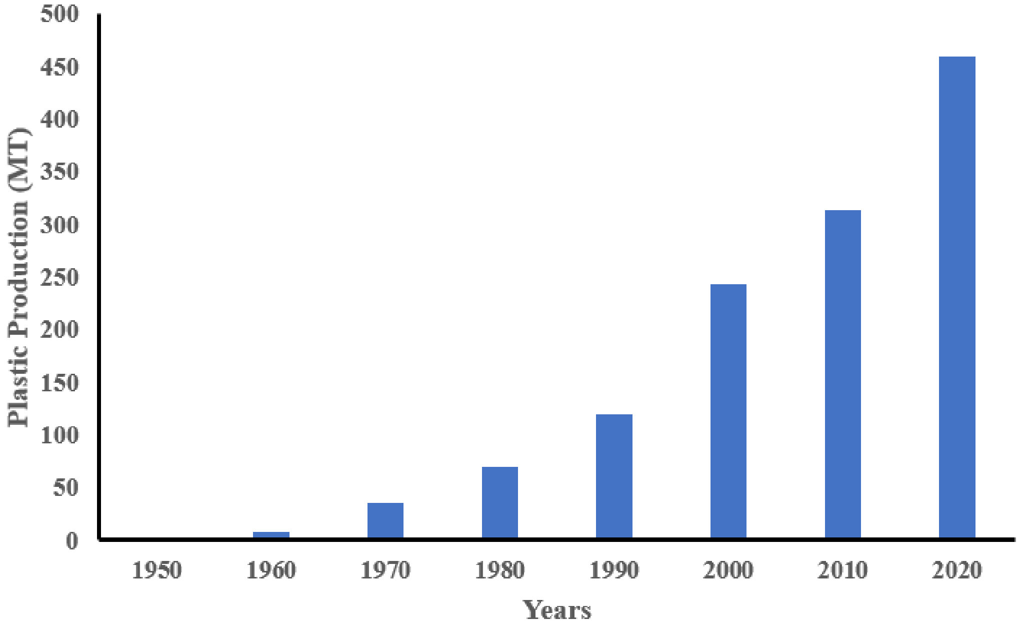

Fig. 1 Graphical representation of plastic production in Million Tonns (MT) over a decade

These include the creation of compostable and biodegradable alternatives, taxing or banning special SUPS, and encouraging recycling programs (Nanda et al., 2022). Additionally, cutting-edge strategies such as the implementation of circular economy models, which keep materials in use for as long as possible, and chemical recycling SUP present intriguing answers to the waste issue (Juan et al., 2021). The goal of this review is to present an in-depth analysis of SUP waste management as it stands today, looking at the issues, solutions, and potential paths in this important area. The report aims to identify shortcomings in current technologies and provide ideas for more sustainable management of SUP waste by summarizing the previously published literature.

2. Environmental impacts of single use plastics (SUPs):

SUPs have a variety of negative effects on the environment, including pollution, harm to animals, and accelerating climate change. The ubiquitous and enduring character of plastics in the environment, poses serious risks to ecosystems and human health.

2.1 Pollution

Pollution is one of the most pronounced and dangerous effects of SUPs on the environment. SUPs are easily dispersed by wind and water due to their lightweight and robust design, and they often wind up in rivers, oceans, and other natural surroundings. SUPs are a significant contributor to the 8 million metric tons of plastic waste that is believed to enter the ocean annually (Ritchie et al., 2021). Large garbage patches, like millions of square kilometres of Great Pacific Garbage Patch, form when this plastic waste builds up in marine ecosystems (Lebreton et al., 2018). A major problem is the persistence of plastic in the environment. Plastics don't biodegrade like organic matter; instead, they break down into tiny pieces called microplastics, which are plastic particles with a diameter of less than 5 mm (Sobhani et al., 2020). Since they have been discovered in a variety of ecosystems, including deep-sea sediments and Arctic ice, microplastics are ubiquitous in the environment (Obbard et al., 2014). These particles act as carriers of harmful compounds in both marine and terrestrial food webs because they have the ability to absorb and transfer contaminants, including persistent organic pollutants (POPs) (Rochman et al., 2013).

2.2. Effect on wildlife

Wildlife is severely threatened by SUPs in particular in marine habitats. Animals often confuse plastic waste for food, which can result in ingestion and physical injury, digestive tract obstruction, malnutrition, and even death. According to the study by Trivail et al. (2015) seabirds, fish, and marine mammals are among the nearly 700 species of marine animals that are affected by plastic waste. For example, seabirds like albatrosses often consume plastic items because they mistake them for fish or squid, which can lead to damage, famine, or even death (Wilcox et al., 2015). Another serious problem is animals like seals, whales and sea turtles getting entangled in plastic waste. Fishing nets, plastic rings and packaging are among the items that can entangle animals, causing damage, impaired movement, drowning, or even death (Gregory, 2009). Plastic pollution affects animals in a way that goes beyond individual species and can have wide-ranging ecological impacts, such as population reduction and changes in eating habbits (Horton et al., 2020).

2.3 Climate change

Climate change has been made worse by the creation, use and disposal of SUPs, which may involve increasing greenhouse gas (GHG’s) emissions. Plastics are produced using a lot of energy and mainly fossil fuels, especially oil and natural gas. The production and burning of plastics are believed to have contributed 1.8 billion metric tons of CO_2 equivalent to the environment in 2015 (Janaswami et al., 2022). This number is expected to rise exponentially, with the plastics sector contributing perhaps 15% of the world's carbon budget by 2050 (Shen et al., 2020). In addition, the open burning of plastic debris – which is widespread in developing countries due to the lack of infrastructure for waste management which releases dangerous pollutants including carbon dioxide, methane and black carbon, which are strong greenhouse gases that increases air pollution (Kida et al., 2021). In addition to contributing to global warming, these emissions have a direct negative influence on local health of local communities, including respiratory disorders and other ailments (Stockwell et al., 2020).

2.4 Human health implications

Through multiple channels, the impact of SUP on the environment also affects the human health. Concerns have been raised over the potential health effects of microplastics on people due to their detection in food items, drinking water and even air (Cox et al., 2019). There is growing evidence that ingestion or inhalation of microplastics can cause inflammation, oxidative stress, and other harmful health effects, even though the full scope of these effects is still unknown (Wright and Kelly, 2017). In addition, endocrine disruptors such as phthalates and bisphenol A (BPA) used in the manufacture of plastics have been shown to contaminate food and beverages stored in plastic containers, further threatening human health (Ramadan et al., 2020). The fact that plastic particles are present in the environment both physically and chemically shows widespread and complex the environmental consequences of SUP’s.

3. Current strategies for SUP’s waste management

Managing waste of SUP’s has emerged as an important environmental issue, driving the creation and application of many solutions worldwide. The strategy focuses on passing laws to cut plastic use, improve recycling processes, support substitute ingredients, and reduce the negative environmental impacts of SUP.

3.1 Reduction and prevention initiatives

Cutting manufacturing and consumption of these products is an important part of limiting SUP waste. Policies aimed at reducing dependence on SUPs are being adopted more frequently by governments, organizations, and consumers. For example, some countries have imposed tariffs or restrictions on specific SUPs such as plastic straws and bags. The efficacy of such economic means was demonstrated by the introduction of the plastic bag charge in 2002 of the Ireland, resulting in a 90% reduction in the consumption of plastic bags in just one year (Convery et al., 2007). In addition to legal restrictions, public awareness initiatives are crucial to reduce SUP consumption. Initiatives such as the UK's "Plastic Free July" promote a sustainable culture by encouraging people and companies to use less single-use plastics (Poortinga et al., 2016). Educational initiatives that educate the public about the negative impacts of plastics on the environment and the benefits of sustainable alternatives often help these campaigns. Corporate activities play an important role in reducing SUP. Businesses are devoting more and more time to improving their products, getting rid of unnecessary packaging, and spending money on more eco-friendly materials in an effort to reduce their plastic footprint. For example, unilever, a british based consumer goods company, has pledged to cut virgin plastic use by 50% by 2025 as part of a larger initiative to move the world economy towards a circular (Arijeniwa et al., 2024) .

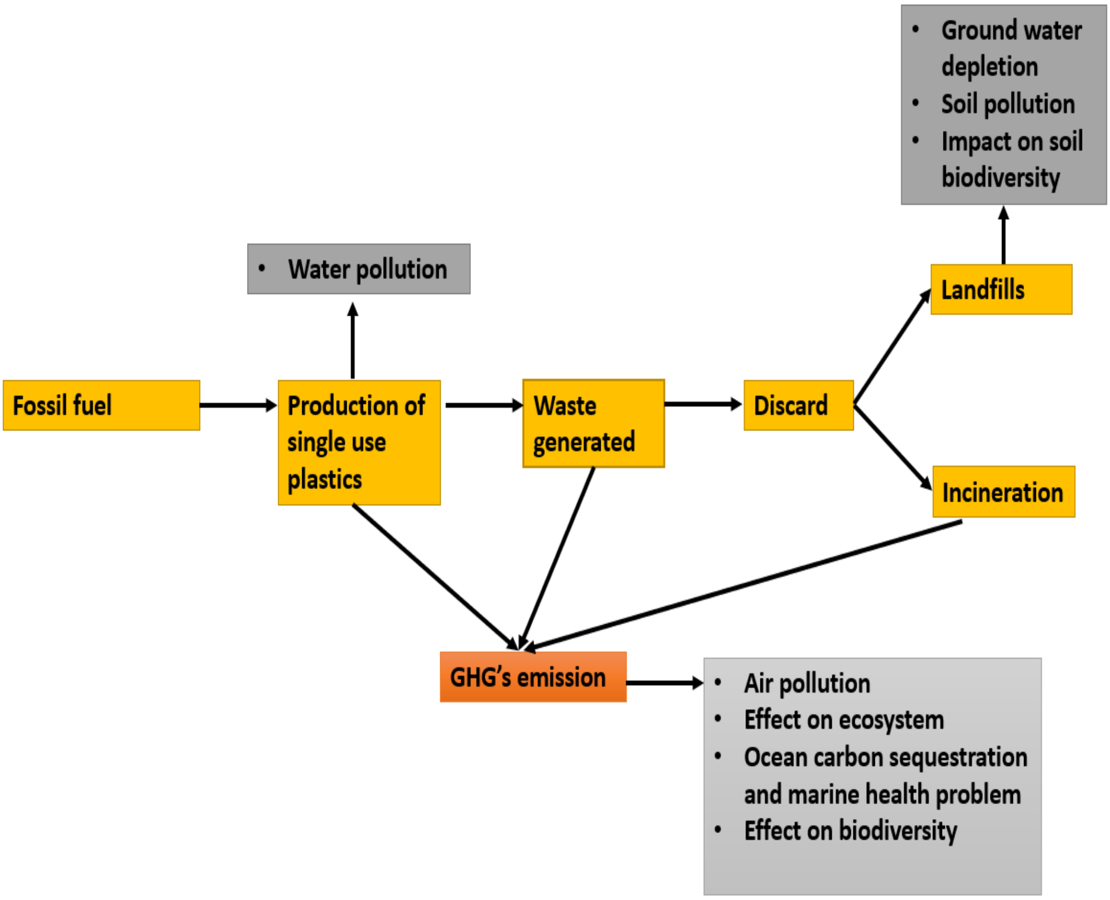

Fig. 2 Graphical representation on overall Environmental impact of single use plastic during its Life Period

3.2 Recycling and waste management programs

Despite the difficulties posed by the complexity of plastic waste streams, recycling is a key component of SUP waste management. To increase rates of recovery of plastic items, many nations are modernizing their recycling processes and infrastructure. Recycling rates have increased dramatically in Germany as a result of the Green Dot scheme, which mandates manufacturers to pay for the recycling of their packaging (Dahlen and Lagerkvist, 2010). There are new options for handling SUP waste thanks to advanced recycling techniques, including chemical recycling. Chemical recycling is the process of separating this technology is especially helpful for the recycling of dirty or mixed polymers that are challenging to handle using more traditional mechanical recycling techniques (Van Waeyenberg et al., 2024). Schemes for EPR are becoming more popular as a means of enhancing SUP waste management. By shifting the burden of waste management from governments to producers, EPR encourages manufacturers to consider the impact of their products at the end of their lives. It has been demonstrated that these programs reduce waste and boost recycling rates, especially in countries with strong EPR regulations (Brown et al., 2023).

3.3 Policy and legislative measures

To address SUP waste, governments around the world are implementing different laws and policy measures. These include everything from outright bans on particular SUP goods to comprehensive waste management laws that address plastics throughout their lifecycle. One landmark law that aims to reduce SUPs in member states is the Single-Use Plastics Directive, which was enacted by the European Union in 2019, aimed at reducing the use of other plastic goods. The rule forbids the use of certain SUPs, including straws and plastic cutlery. In addition, it is mandatory that by 2030, at least 30% of plastic bottles made in the EU must have recycled content (Kahlert et al., 2022). For the purpose of controlling SUP waste globally, international agreements are necessary in addition to regional and national legislation. It was updated in 2019 to cover plastic waste. This amendment seeks to reduce the impact of plastic waste on a large scale on the world, especially in developing countries that often suffer from the worst effects of plastic pollution (Raubenheimer and Mcilgorm, 2018).

3.4 Promotion of alternative materials

To reduce SUP waste, alternative materials to replace conventional plastics should be developed and adopted. One of the most promising options that can reduce the environmental impact of plastic items is biodegradable and compostable plastics. These materials have been engineered to decompose faster than conventional plastics, both in industrial composting settings and natural conditions (Ramadan et al., 2020). However, appropriate waste management techniques, such as access to industrial composting facilities, are critical to the efficacy of biodegradable plastics. High production costs and the need for clear labelling to avoid contamination with conventional plastics are additional barriers to the widespread adoption of these materials (Dilkes-Hoffman et al., 2019). New advances in materials science are opening up intriguing opportunities for the continued advancement of research into novel materials. For example, to create sustainable, biodegradable plastic alternatives, researchers are looking at the use of fungi, algae, and other natural resources. These materials have the potential to provide the resilience and adaptability of plastics without causing the same environmental damage (Lambert et al., 2017).

3.5 International collaboration and multilateral initiatives

Solving the global SUP waste issue requires coordinated actions around the world. Diverse global institutions and programs are striving to foster collaboration and exchange optimal approaches to plastic waste management. One such project is the New Plastics Economy Global Commitment, which is being led by UNEP and the Ellen MacArthur Foundation. It brings together companies, governments and organizations around the world to create a circular economy for plastic waste managerment and do away with unnecessary plastic packaging. In some places, regional initiatives such as the ASEAN Regional Action Plan for Marine Debris Resemblance are important in reducing plastic pollution. In order to reduce plastic waste, enhance waste management infrastructure and advance sustainable production and consumption methods, member countries are encouraged to collaborate under this scheme (Campitelli et al., 2024).

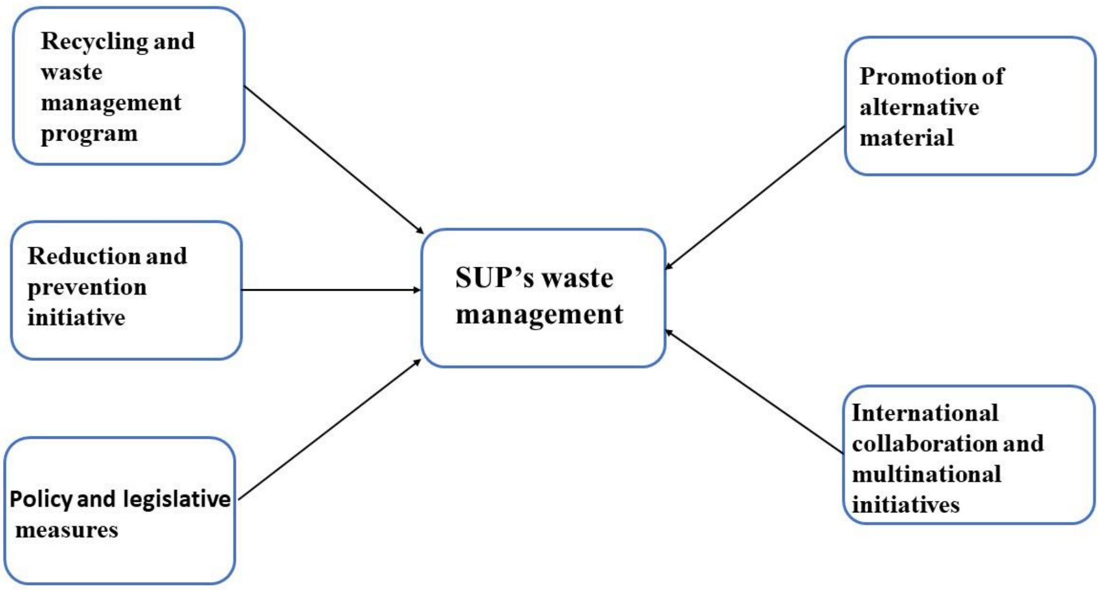

Fig. 3 Flow chart showing Waste management For SUP's

4. Innovative approaches in SUP's waste management

New solutions to the shortcomings of traditional waste management techniques are being developed as the problem of handling single-use plastic (SUP) waste becomes more complex. These inventive approaches include new materials, inventive policy frameworks, and technology developments. This section examines several innovative approaches to SUP waste management and emphasizing their potential applications.

4.1 Advanced recycling technologies

Considering the shortcomings of traditional mechanical and advanced recycling techniques presents encouraging options for handling SUP waste. Enzymatic degradation and chemical recycling are two notable technologies. Chemical recycling involves separating plastics into their basic chemical components that is opposed to mechanical recycling, which physically breaks down the plastics. Mixed and contaminated polymers that are difficult for mechanical recycling can be controlled by chemical and mechanical recycling. Techniques used in chemical recycling include pyrolysis, which involves heating plastics without oxygen to make liquid fuels and chemicals. Depolymerization involves changing the polymerization process to recover monomers (Van Waeyenberg et al., 2024). These technologies are now more economically viable and efficient than before, making them a good addition to traditional recycling methods. Specific enzymes are used in enzymatic degradation to reduce polymers into smaller, easier-to-manage components. Research has found that polyethylene terephthalate (PET), a key plastic used in bottles and packaging, can be broken down by enzymes such as PETase and MHETase (Yoshida et al., 2016). This approach is being expanded for use in industrial applications after demonstrating promise in laboratory settings. Management of plastic waste can be significantly improved by manufacturing modified enzymes with better breakdown capabilities.

4.2 Biodegradable and compostable plastics

The manufacture and use of compostable and biodegradable polymers is significant progress in an effort to reduce the environmental impact of SUP. As Compared to conventional plastics, these materials are made to decompose more quickly and safely. Under certain environmental conditions, these plastics are intended to break down into elements found in nature, such as water, carbon dioxide and biomass. Often, renewable materials such as sugar cane or maize starch are used to make them. Biodegradable plastics can reduce amount of waste , there effectiveness depends on how well they are managed. Establishing guidelines and accreditation for biodegradable plastics is essential to guarantee their proper application and ecological benefits. Plastics that are meant to decompose in compost are made to do so in commercial composting facilities. To guarantee total degradation for this method, certain parameters, including humidity and temperature, must be considered (Dilkes-Hoffman et al., 2019). Applications of compostable plastics includes making utensils and food packaging material can be made. To avoid contamination with conventional plastics, the effectiveness of this approach is contingent on the availability of appropriate composting infrastructure and clear labelling.

4.3 Plastic waste-to-energy technologies

Plastic waste can be converted into fuel, heat or electricity, which is called plastic waste-to-energy. Using these technologies, the amount of plastic waste generation can be reduced and a landfill option can also be offered. To produce energy, plastic waste is burned at high temperatures using contemporary incinerator that are equipped with sophisticated filtration mechanisms to minimize particulate matter emissions and maximize energy extraction. This process can generate energy and reduce waste, but it needs to be carefully managed to deal with pollutants and leftovers (Cheng and Hu, 2010). Thermal processes called gasification and pyrolysis turn waste plastics into fuel-producing gases or liquids. Syngas, a combination of hydrogen and carbon monoxide, is created during the gasification process that is produced due to reaction between plastic waste and oxygen at high temperature. In contrast, pyrolysis is the process of heating plastics without the presence of oxygen to form liquid chemicals and fuels. Although these methods have the potential to recover valuable materials and energy from plastic waste, more research and development is needed to increase their effectiveness and reduce their prices (Jha et al., 2019).

4.4 Circular economy models

The goal of the circular economy model is to establish a closed-loop system that continuously recycles, reduses and reuses the plastic resources. This strategy is in opposition to the traditional linear economy, which discards goods after only being used once. An essential component of the circular economy is product design that considers recycling. This includes using recycled materials, creating designs that are easy to disassemble, and avoiding the use of challenging and multiple to distinguish plastic types. To improve recycling and cut waste, businesses like Unilever and Coca-Cola are implementing circular economy concepts in the design of their products. The reverse logistics and take-back initiative involve collecting discarded goods and packaging from customers for recycling or other uses. These programs, which aim to close loops in the product life cycle, can be put in place by retailers or producers. In a good example of applying circular economy principles, Nike's "Reuse-a-Shoe" program collects athletic shoes used for recycling into new items.

4.5 Policy innovations and market-based instruments

Systemic change in SUP waste management can be facilitated by creative policies and tools based on the market. These strategies may be used for granting financial incentives and legal restrictions to support sustainable activities and waste reduction. Businesses and consumers can be incentivized to use less plastic by implementing taxes or other price mechanisms on plastic products. The usefulness of such policies in changing behaviour and reducing plastic waste is demonstrated by their success, such as Ireland's plastic bag fee (Convery et al., 2007). To reduce consumption, governments are considering similar policies for another SUP. EPR regulations state that manufacturers handle end-of-life care of their goods (Lorang et al., 2022). This may include certain duties related to disposal, recycling, and collection. Manufacturers can be encouraged by the EPR initiative to invest in waste management infrastructure and design products with recycling in mind. Due to recent reforms, EPR frameworks are becoming more comprehensive and effective.

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5. Challenges in managing SUP's waste

SUP's waste management is fraught with difficulties due to the sheer volume of waste generated, the intensification of recycling processes, financial constraints, and inadequate legislative framework. These problems make waste more difficult to manage effectively resulting deteriorating the environment and making the world's worst plastic pollution problem.

5.1 High volume of waste

Over the past few decades, the manufacture of plastics has increased significantly worldwide, accounting for a large portion of this production. Global plastics manufacturing reached 407 million tons in 2015, with a significant portion coming from food containers, plastic bags and packaging materials such as SUPs (Geyer et al., 2017). Due to the short lifespan and high turnover of the SUP, waste management systems are unable to handle the huge volumes of waste produced, especially in poor countries. The infrastructure for garbage collection, sorting, and disposal is inadequate to handle the large volumes of plastic waste produced in many parts of the world. Because informal waste management systems are prevalent in low- and middle-income countries, there is a substantial amount of mismanaged plastic waste due to this inadequacy (Kaza et al., 2018). Poor management often leads to open burning, dumping, or leakage into the environment, increasing pollution and endangering people's health.

Table 2 Advantages and disadvantages of biodegradable polymers that are currently being used

S.N.	Biodegradable polymer	Application	Advantages	Disadvantages	References
1.	Polyhydroxyalkanoates	Biodegradable packaging Wastewater treatment and Agriculture- coating	Biodegradability Versatility Low carbon footprint	High production cost, Energy intensive production	Raza et al. (2018)
2.	Polylactic acid (PLA)	Food packaging, Medical applications, Surgical implant- temporary implants like screw and Drug delivery system 3D printing	Biodegradability, Renewable resource based, Reduce carbon footprint, Recyclability and Low energy processing	High production cost , Low thermal resistance, Limited degradation in landfills and Environmental concerns	Li et al. (2020)
3.	Polyglycolic acid (PGA)	Medical applications Surgical sutures wound closures. Tissue engineering Drug delivery system and Surgical meshe , Industrial applications, Biodegradable plastics and Compostable agriculture products	Biodegrability Biocompatibility and Thermal stability	High production cost , Rapid degradation Brittleness, Recycling challenges and Environmental conditions needed for degradation	Samantaray et al. (2020)
4.	Polycaprolactam (PCL)	Textile industry, Engineering plastics ,Automotive components, Electrical applications, Medical application and Prosthetics and orthotics	Biodegradability , Biocompatibility, Low melting temperature - around 60°C, Excellent flexibility and toughness	Slow degradation rate , Poor thermal stability, High water absorption Poor ,resistance to UV light and oxygen	Nandakumar et al. (2013)
5.	Poly lactic-co-glycolic acid (PLGA)	Medical and pharmaceutical applications, Drug delivery system, Surgical implants, Microparticles for vaccines, Environmental applications, Agriculture biodegradable, Cosmetics and personal care , 3D printing and additive manufacturing	Biodegradability, Tunable degradation rate and Minimal inflammatory response	High cost, Variability in degradation rate , Poor mechanical properties, Hydraulic degradation challenge and Limited shelf life	Idumah et al. (2022)

5.2 Complex rrecycling pprocesses

Recycling is one of the main ways to handle plastic waste, but there are many obstacles in the way of its success. A primary concern is the variety of plastic types seen in SUP. Different polymers, each with unique characteristics, melting points, and recycling requirements, are combined to form plastics. This variability complicates the sorting and recycling process, which makes it challenging to effectively recycle mixed plastic waste streams (Juan et al., 2021). Contamination is yet another major issue, SUPs are often contaminated with organic matter or other non-plastic contaminants, which can disrupt the recycling process. This is especially true for food packaging.

Recycling is more expensive and difficult when dealing with contaminated plastics because they require special cleaning and processing (Kibria et al., 2021). To make matters worse, due to their low material value and processing challenges, many SUPs such as thin plastic films and multi-layered packaging cannot be profitably recycled (Juan et al., 2021). In addition, inefficiencies in the recycling system arise from the lack of uniform and standardized recycling processes in different countries and regions. Technically plastics for recycling often wind up in landfills or incinerators as a result of inadequate recycling infrastructure or a lack of technically recycled plastics often wind up in landfills or incinerators as a result of inadequate recycling infrastructure or a lack of consumer demand for recycled goods technically recycled plastics often wind up in landfills or incinerators as a result of inadequate recycling infrastructure or a lack of consumer demand for recycled goods. Technically recycled plastics often wind up in landfills or incinerators as a result of inadequate recycling infrastructure or a lack of consumer demand for recycled goods.

5.3 Economic barriers

One of the biggest barriers to managing SUP waste is the cost of plastic recycling. The expenses associated with collecting, classifying, and handling plastic waste often exceed the market value of the reclaimed material. Therefore, recycling activities are sometimes not lucrative, especially in areas where waste management systems are not adequately funded or where there is no financial motivation to recycle (Mwanza and Mbohwa, 2017). The economics of plastic recycling is also affected by the volatility of oil prices around the world. Because of its petrochemical origins, virgin plastic could be less expensive than recycled plastics due to changes in oil prices, which would reduce the market for recycled materials and make recycling initiatives further more challenging. (Geyer et al., 2017). Especially in underdeveloped countries where informal waste collection methods are common, the absence of funds and investment in recycling infrastructure exacerbates this economic hardship. In addition, local governments and communities are responsible for handling plastic waste in many places due to the lack of EPR policies, rather than companies that profit from SUPs and make profits. EPR programs, which make manufacturers responsible for managing the end of life of their products, have been demonstrated to increase recycling rates and reduce waste, although their adoption is still quite low (Brown et al., 2023).

5.4 Inadequate policy and regulation

Strong policy frameworks for governing the manufacture, use, and disposal of plastics are essential for effective management of SUP waste. Nonetheless, the current regulatory environment is uncoordinated and unequal, with considerable regional and national differences in the laws governing the disposal of plastic waste. Risks to the public's health and the environment are often caused by inadequate or badly enforced regulations (Borg et al., 2022). Some SUPs such as plastic straws and bags are subject to levies or restrictions in some countries, but these policies are often narrowly concentrated and do not address the larger problem of plastic pollution. Efforts to regulate SUP waste globally are made more difficult by the lack of International legislation or agreements that explicitly tackle plastic pollution. Despite the existence of measures such as the Basel Convention, which govern the transboundary flow of hazardous waste, there is currently no legally enforceable international framework that fully handles the life cycle of plastics from construction to disposal (Raubenheimer and Mcilgorm, 2018). This regulatory gap can cause SUPs to continue to proliferate, disrupting coordinated response around the world.

5.5 Public awareness and behaviour

For managing SUP waste, customer behaviour and public awareness are essential. SUPs are still popular among customers because of their affordability and ease of use, even despite the growing awareness of the negative environmental impacts of plastics. It is difficult to change consumer behaviour, especially in cultures where plastic use is a daily necessity (Arjeniwa et al., 2024). The lack of knowledge about the negative impacts of plastics on the environment and human health, as well as the cultural and economic variables that influence consumer choice, often hinder efforts to reduce plastic waste through education and awareness campaigns. Furthermore, even if customers are determined to cut down on their use of plastic, doing so in many areas can be challenging because of lack of readily available and reasonably priced alternatives of SUPs (Heidbreder et al., 2019).

6. Future directions and recommendations for SUP's waste management

The global problem of SUP's waste is still evolving, so future waste management approaches need to close current gaps and leverage new technology. A comprehensive strategy that includes policy reform, technology innovation, and active stakeholder participation will be essential for effective management of SUP's. Key tips and future pathways to improve SUP waste management are outlined in this section.

6.1 Enhancing recycling technologies

To manage complex and polluting plastic waste, future efforts should focus on developing enzymatic degradation and chemical recycling methods. For these technologies to be widely used, they must be more scalable and efficient. These techniques can be made even more effective by researching novel catalytic processes and enzyme engineering (Al-Salem et al., 2009; Yoshida et al., 2016). For these technologies to be incorporated into current waste management systems, pilot projects need funding and expansion of innovative technologies. State-of-the-art recycling technology can be integrated into circular economy models to create closed-loop systems that continuously recycle and reuse plastic. This integration can be facilitated in product development by emphasizing design for disassembly and recycling. Regulations should encourage businesses to apply the principles of the circular economy, such as using recycled materials and making goods that are simple to discard.

6.2 Promoting sustainable alternatives

It is imperative that more research is done on substitute materials for conventional plastics. Novel materials that originate from organic materials, such as fungi or algae, may offer more environmentally friendly alternatives. To accelerate the commercialization and adoption of these materials, both the public and private sectors must fund research and development initiatives.

6.3 Strengthening policy frameworks

Regulations aimed at SUPs should be strengthened and expanded by policy makers. This includes tightening regulations for plastic packaging and expanding prohibitions and borders for a wide variety of plastic products. Encouraging companies to use less plastic and adopting sustainable practices should also be the main objective of the policy. Successful implementation and enforcement of policies is essential. To ensure that regulations are followed, governments must invest in systems for enforcement and monitoring. According to Scharff. (2017) openness in public reporting and policy execution can also promote adherence and accountability. Addressing plastic waste requires coordinated global action and international cooperation. Global efforts to control SUP waste can be improved by enhancing international agreements and frameworks to fight plastic pollution, such as changes made to the Basel Convention. International organizations, NGOs, and nations can work together to coordinate efforts and exchange best practices (Raubenheimer and Mcilgorm, 2018).

6.4 Fostering public engagement and education

Expanding public awareness efforts to reach out to diverse groups and encourage sustainable practices should be a part of future plans. Consumer education campaigns should be the main goal of the campaigns about the benefits of reducing plastic use and the effects of plastic waste on the environment. Involving communities in local activities and educational initiatives can help promote behaviour change (Poortinga et al., 2016). Incorporating sustainability education into community and school programs can help children develop environmentally conscious behaviours at an early age. To provide students with a full understanding of the problem, educational programs should cover the entire lifetime of plastics, including their manufacture, use, and disposal. Businesses should be encouraged to implement CSR initiatives that prioritize reducing plastic waste and the advancement of sustainable alternatives. Corporate sustainability activities can have a greater impact if they are transparent and work closely with NGOs and government organizations (Moghaddam and Crowther, 2020).

6.5 Investing in infrastructure and innovation

To increase recycling rates and manage different types of plastic waste streams, investments in recycling infrastructure, including buildings and technologies, are crucial. To enable sophisticated recycling technologies and circular economy models, governments and private sector players must work together to create and enhance recycling infrastructure. It is essential to fund research and development for state-of-the-art waste management systems and environmentally friendly products.

7. Conclusion

The worldwide problem of SUP’s waste requires a multi-pronged strategy that includes public participation, innovation and legislation. SUPs contribute to pollution, biodiversity loss and climate change, all of which have adverse effects on the environment. Current management technologies such as mechanical and chemical recycling and biodegradable alternatives have potential, but their successful use within a circular economy framework is essential. It is important to address issues such as behavioural resistance and inadequate recycling infrastructure. To reduce plastic use and improve recycling, legislative action is necessary, including tariffs, bans and EPR programmes, as well as public awareness campaigns. Developing recycling technology, promoting sustainable materials, enforcing laws and encouraging public participation should be the main priorities. Governments, corporations and society must work together on an international level to reduce generation of SUP’s waste and move towards a more sustainable future with less impact on the environment.

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Conflict of Interests

The author have no conflict of interest with respect to this publication.

Authors' Contributions

This project was conceptualized by Shashikant Kumar, who also prepared the manuscript and conducted the literature review. The manuscript was revised and refined under the guidance of Dr. Jiwan Singh, who provided critical evaluation and intellectual direction. Acknowledgments are also extended to Roshni Bajaj for her assistance in editing the manuscript. The final version of the manuscript has been read and approved by all authors.

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