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Comprehensive 3R's method's approaches to mitigate plastic pollution and its indirect role in reduction of greenhouse gas emissions: a review

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Abstract

Plastic pollution has become an extreme global issue, destroying ecosystems and human health. This comprehensive review investigates the multifaceted challenges posed by plastic waste, ranging from the low recycling rates and mismanagement. Projections of a stunning 12 billion Mt (million metric tons) of plastic waste by 2050 emphasize the urgent effective involvement. The 3R's approach, surrounding Reduce, Reuse, and Recycle, appears as a vigorous strategy to hold this crisis. Under the "Reduce" banner, bioplastics are the best sustainable alternatives, offering eco-friendly attributes, reduced reliance on non-renewable energy, and reduced greenhouse gas emissions. Other policy tools like single-use plastic restrictions/bans, excessive packaging regulations, and extended producer responsibility also help to reduce plastic waste accumulation in the environment. Transitioning to the "Reuse" model highlights the extension of plastic lifespans through reusable containers and bags, influences industries to prioritize product redesign for durability, implementation of closed-loop system, and supply chain integrations at the industrial level, and advances sustainable initiatives like plastic banks for effective waste management. The "Recycle" dimension explores mechanical and chemical recycling methods, explaining their respective advantages and drawbacks. Importantly, the review underlines the 3R's indirect role in reducing greenhouse gas emissions, revealing how strategies like minimizing plastic waste and reusable alternatives contribute to a reduced need for production and landfill space. In conclusion, the 3R's method emerges as a pivotal and comprehensive strategy to combat plastic pollution, requiring widespread adoption across individual, industrial, and policy domains to ensure a sustainable and healthier future for our planet and its inhabitants.

Keywords Plastic pollution · 3R's approach · Bioplastics · Greenhouse gas emissions · Sustainable alternatives

1. Introduction

Plastic pollution now has become very dangerous and fast-growing issue in the world as it affects every level of organization in the world (Wilson and Velis, 2015), and cause dangerous diseases in humans like silicosis, lung cancer, brain cancer, breast cancer, leukaemia, lymphoma etc (Lin et al., 2023). It effectively causes dangerous problems and diseases in the different ecosystems. Because of its non-biodegradable composition, it is difficult to find a safe way to dispose it off, which leads towards its harm to living ones and environment via poisonous chemical exposes (Ting et al., 2020; Koushal et al., 2024). Although this issue is created by humans but now it is destroying the lives of other organisms, mostly marine life (de Sousa, 2023). Low rate of recycling, mismanagement of waste control, useless increasing demand of plastic products, implementation of wrong policies and lack of guidance in public are the leading causes of plastic pollution (de Sousa, 2023). In 2021, the production of plastic waste was about 380 million metric tons (Mt) and if this rate continues, then in 2050, 12 billion Mt of plastic waste will be produced in the environment (Geyer et al., 2017; Klemes et al., 2021), that will be absolutely terrifying for the lives of living individuals (Fig. 1).

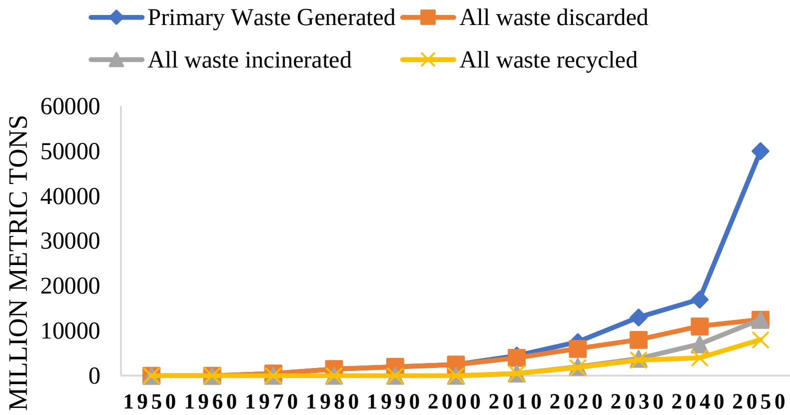

Figure 1: Increasing plastic waste generation and disposal (Geyer et al., 2017)

Plastic was regarded as the wonder of the 20th century but now it has become a critical issue all over the world. Although the world is using different techniques to control such a devastating problem, but 3R's method stands as a best practice to fight against plastic pollution (Steinhorst and Beyerl, 2021; Ahmadi, 2017; Wichai-Utcha and Chavalparit, 2019). 3R stands for 'Reduce, Reuse and Recycle'. It provides a comprehensive tools and ways to minimize the harmful effects of plastic waste (T'ing et al., 2020; Samiha, 2013). This review was conducted to elaborate the techniques and best practices provided by 3R's method like minimizing the production of virgin plastic and reducing in production of waste, necessary volume production, and landfill waste to control over the rapidly increasing dangerous problems caused by plastic waste and its indirect role in reducing greenhouse gas emissions. In 2023, the theme of World Environment Day was "Beat Plastic Pollution". Keeping in view this theme, such type of review is compulsory to give awareness to society for proper use, handling, disposal and destruction of plastic products and waste.

1.1 Reduce

Plastic waste can be reduced by minimizing production of new plastic products by using alternative products (Kumar et al., 2023), use of bioplastics in the packaging sector (Chowdhury et al., 2023), production, and usage of biodegradable products (Ghosal and Ghosh, 2023), minimizing the usage and production of single use plastic products by introducing alternatives in market (Basil et al., 2023).

1.2 Bioplastic

Bioplastic is a best practice to minimize the plastic waste especially in packaging sector because of its biodegradability characteristics (Venkatachalam and Palaniswamy, 2020; Kale et al., 2007). These are considered as best alternative of synthetic plastic as they are more sustainable and reliable than that of synthetic plastics (Benetto et al., 2014). Unique properties of bioplastic like eco-friendly, biodegradable, sustainable, biocompatible, easily recycled through mechanical as well as chemical method, requires less energy on production, and non-toxic to environment and its vast applications in food (Venkatachalam and Palaniswamy, 2020; Jabeen et al., 2015), cosmetics (Matarazzo et al., 2020), electronics (Ravenstijn, 2010), medical (Mukheem et al., 2021), and construction field make them emerging alternatives of synthetic plastic (Jayakumar et al., 2023). The eco-friendly advantages of bioplastic are as follows,

1.2.1 Decreased reliance on non-renewable energy

Bioplastics are made of renewable resources like plants, agriculture by-products and microorganisms. Unlike synthetic plastic that mainly relay on fossil fuels as raw materials, bioplastic use renewable energy resources (Kumar et al., 2024). This moves toward plant-based source for production decrease the demand for fossil fuels for production of plastic products (Benetto et al., 2014). As bioplastics are biodegradable, they can break down naturally after throwing up into the environment, decreases the dependence on fossil fuels-based plastics that persist in the environment for very long periods of time (Zhou et al., 2023).

1.2.2 Reduction in greenhouse gas emissions

Growing plants to produce bioplastics absorbs CO_2 from the atmosphere that ultimately lowers the emissions of greenhouse gases that emit during the production of synthetic plastic (Kumar et al., 2024; Ibrahim et al., 2021; Atiwesh, 2021). Cultivating plants for production of bioplastic can also help to decrease greenhouse gas emissions by storing CO_2 and this ultimately leads to lowering the carbon footprint (Zhou et al., 2023).

1.2.3 Lowers the persistence of plastic waste

Ability to degrade naturally is another advantage of bioplastic as it decreases the persistence of plastic waste into the environment. Its ability to break down naturally aids in the reduction of endurance of plastic waste in environment (Kumar et al., 2024). Furthermore, it is easy to recycle through mechanical as well as chemical method also helps in the reduction of persistence of plastic waste. Polycaprolactone (PCL) is a biodegradable bioplastic that can break down in distinct environment (Casarejos et al., 2018; Brockhaus et al., 2016).

1.2.4 Maintenance of marine ecosystem

The Marine ecosystem is the biggest influencer of plastic pollution (de Sousa, 2023). Regular accumulation of plastic waste into marine ecosystems badly affects the ecosystem and marine life. This marine plastic waste can be reduced by using bioplastic instead of traditional plastic. The harmful effects of plastic waste on marine life can be reduced by bioplastic, which is made in such a way that it is degradable in marine environment and not harmful to marine life (Kumar et al., 2024). Fig. 2 shows the applications and eco-friendly benefits of bioplastics.

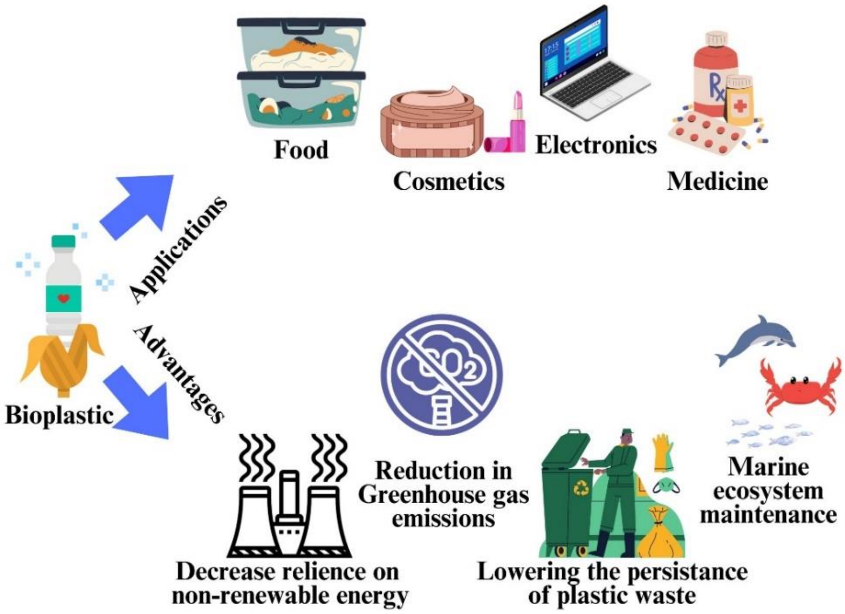

Figure 2. Bioplastic applications and their advantages on environment

1.3 Single-use plastic bans/restrictions

Short lived existence, one-time usage, recycling difficulty (Geyer et al., 2017; Eriksen et al., 2019; Chen et al., 2021) and omnipresence of single-use plastic are the distinct properties that make it a main component of plastic waste (Kiessling et al., 2023). Single-use plastic products like plastic bags, plastic bottles, beverage bottles, and wrappers mostly finish in marine environment as a massive amount of single-use plastic is found in rivers and near the rivers (Morritt et al., 2014, Blettler et al., 2017, Schoneich-Argent et al., 2020, Mitchell et al., 2021). So, the only solution to stop this plastic waste component is implementing the bans, heavy duties, and taxes on its production worldwide and to introduce the alternatives sustainable products so that the public don't go back towards the single-use plastic usage.

1.4 Excessive packaging regulations

Plastic packaging is one of the major sectors of plastic usage in different countries of the world (Jiang et al., 2020). Because of the higher concentration of polymers used in plastic packaging products and high possibility of being contaminated from drinks and food, it is very difficult to recycle the plastic packaging (Zhang et al., 2023). Plastic packaging contributes about 50% of total plastic waste generated globally (Zhang et al., 2023). Redesigned plastic packaging for its sustainable recycling (Steenis et al., 2018), alternative and biodegradable packaging (Nuojua et al., 2024) are some of the packaging regulations that can help us to fight against plastic waste generated due to the global packaging sector.

1.5 Encouragement for alternatives

Alternative products made up of materials other than plastic are another best practice to reduce the plastic waste is domestic life span (Table 1). Introducing the alternatives of synthetic plastics and encouragement for alternative products usage is another helpful way to overcome the plastic waste generated at domestic level. Following is the table of different alternatives of plastic products to reduce the accumulation of plastic waste in the environment.

1.6 Extended Producer Responsibility Policies

Extended Producer Responsibility (EPR) is a principle policy tool that transfers the waste management responsibility of plastic products and their packaging from regional authorities to basic producers as it lay outs some distinct inducements to producers of plastic products to avert from waste generated at initial level, and to diminishes the influx of materials destined for landfills or escaping into the environment by supporting, initiating, or extending infrastructure for recycling after consumer use (Eriksen et al., 2014; Newman et al., 2015; Tibbetts, 2015; Harris et al., 2021). Different European countries, United states and Canada have implemented EPR for reduction of plastic wastes (Filho et al., 2019; Diggle and Walker, 2020; Tumu et al., 2023). EPR policy is mainly used in the packaging industry because it offers a thorough approach to lessening the plastic waste produced at packaging sector as shown in Figure 3. Its implementation in other sectors can also help the producers to mitigate the plastic waste generated at the initial level.

Table 1: Alternative products of different households, kitchen, and other plastic products

Plastic products	Alternative Products	References
Rolls of plastic wrap	Beeswax	(Nadalin, 2022)
Plastic packaging	Silicon food covers and lids	
Plastic straw	Paper or metal straws	
Plastic bags	Paper bags	
Toothpaste tube	Toothpaste tablets	
Plastic toothbrushes	Bamboo toothbrushes	
Soap and detergent bottles	Glass soap and detergent bottles	
Plastic shopping bags	Cotton tote bags	
Plastic packaging	Glass or metal containers	
Single use coffee cups	Reuseable coffee cups	
Cold drink plastic bottles	Reuseable drink bottles	
Shampoo bottles	Shampoo and soap bars	
Plastic cutlery	Bamboo cutlery	
Plastic cups	Paper cups	
Plastic spoons	Bamboo cutlery/spoon	(Lamar, 2022)
Domestic plastic bags	Organic cotton bags	
Plastic teacups	Reuseable tea bags/cups	
Disposable face wipes	Reuseable makeup rounds	
Disposable diapers	Reuseable/washable diapers	
Plastic meal pouches Cling film	Reuseable sandwich and snack bags	
Craft glitter	Biodegradable craft glitter	
Plastic packing/shopping bags	Mesh bags	
Disposable batteries	Rechargeable batteries	
Plastic razor	Bamboo/stainless steel razor	
Disposable face mask	Reuseable face mask	

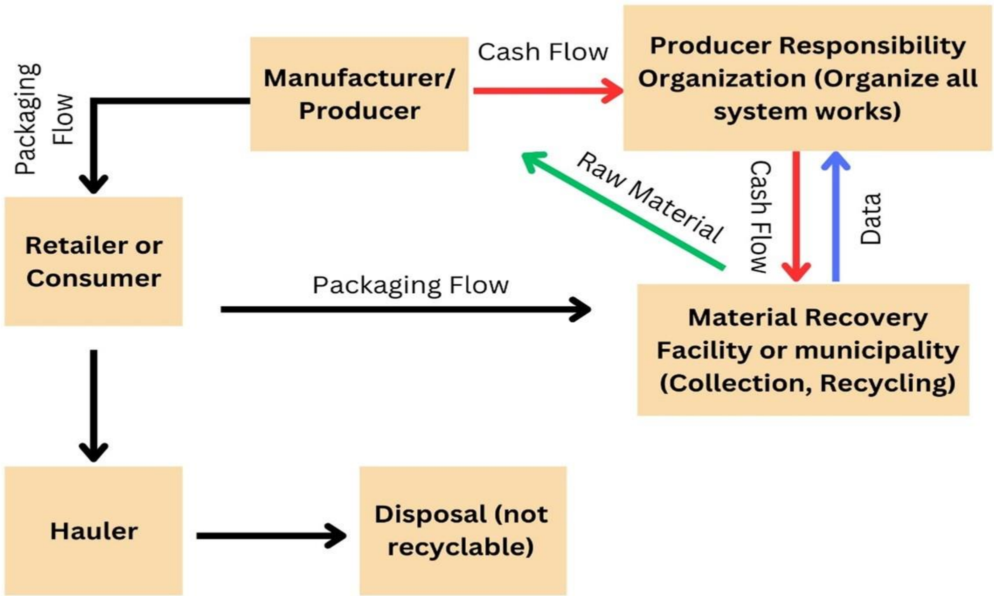

Figure 3: Diagrammatic representation of an Extended Producer Responsibility (EPR) system for packaging materials (Cyclos-GmbH, 2019)

2. Reuse

Reuse of plastic products again and again extends the life span of traditional synthetic pre-existing plastic which results in the decreased demand for production of new plastic. Reusable plastic packaging in food, agricultural, and other sectors (Bradley and Corsini, 2023), usage of reusable plastic containers, plastic straws, plastic bags, reusable bags, and water bottles is another best practice to minimize plastic waste. Refillable plastic packaging usage in the food sector also aids in the reduction of plastic waste (Junior et al., 2019). Refillable containers and bottles for beverage, cleaning products and personal care items are the best practices to minimize the worst impacts of plastic waste (Okada et al., 2021). Reusable alternatives like cloth bags, glass or stainless-steel containers and refillable water bottles reduce the demand for single-use plastic like plastic bags and disposable water bottles (Mansour and Ali, 2014). Industries and manufacturers of plastic products can play pivotal roles to minimize plastic waste by redesigning their plastic products in such a way that they can be easily repairable and durable that have extended life span and decreases the frequency of disposal (Silva et al., 2020). Fig. 4 shows the role of reusable and refillable plastic products in plastic waste management.

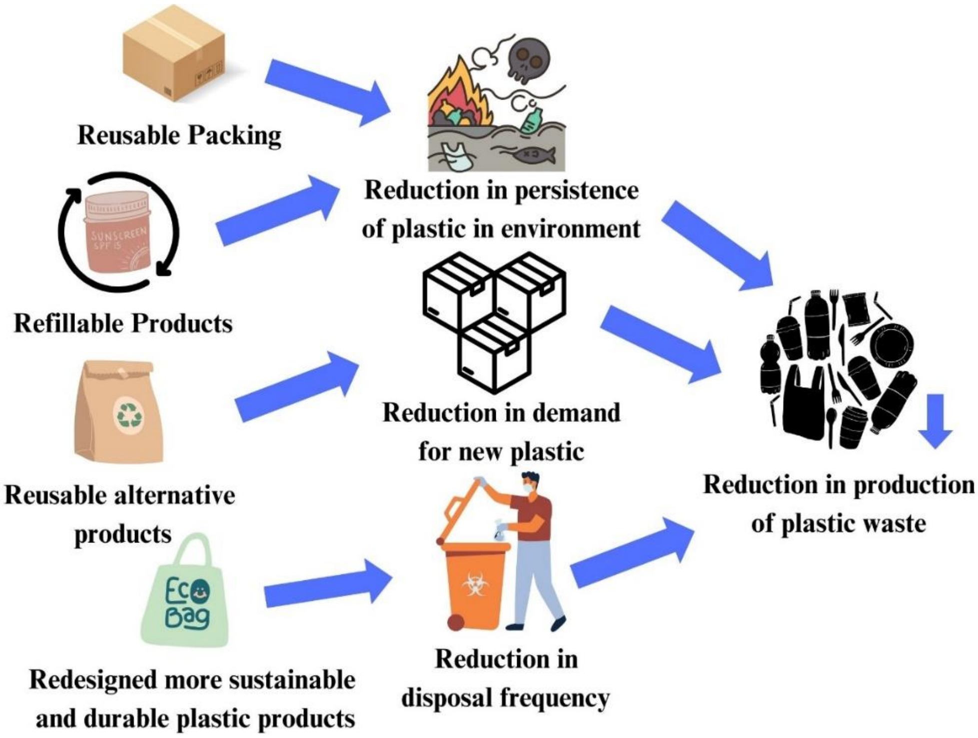

Figure 4: Role of reusable and refillable plastic products in the reduction of plastic waste

2.1 Reuse practices in industries

Implementing diverse practices in industries not only diminishes industrial plastic waste but also yields significant environmental benefits. This multifaceted approach fosters sustainability by efficiently managing resources and minimizing the negative impact of plastic disposal on ecosystems.

2.1.1 Implementation of closed loop system

Implementation of closed loop systems in industries presents a significant approach to address the worst environmental impacts of plastic waste generated at industrial level by focusing on mitigating harsh impact of plastic waste by highlighting their reuse within industrial processes (Yuan et al., 2021). By implementing a closed loop system, industries can effectively lessen their dependence on single use plastics, promoting a more sustainable approach by optimizing production processes to ease significant collection, recycling, and reintroduction of plastic materials in manufacturing cycle (Lonca et al., 2020).

2.1.2 Supply chain integration

By implementing the eco-friendly practices throughout the whole supply chain, from raw materials sourcing to final products production and distribution, industries can significantly minimize their plastic footprint by encouraging collaborations with stakeholders, integrating efficient packaging techniques, and introducing sustainable disposal methods (Gunawan et al., 2024; Noviastuti et al., 2024).

2.1.3 Energy production from plastic waste

Energy production from plastic waste is an important initiative strategy that helps not only to mitigate the plastic waste but also to generate new renewable energy sources (Dhara et al., 2023). This initiative not only helps to maintain the sustainable environment but also minimizes our reliance on fossil fuel for energy production (Doniavi et al., 2023). Gasification and Pyrolysis are the techniques that process all the plastic waste to generate renewable energy by heating plastic waste in oxygen absence to break down the plastic to gas which is then used to generate the heat and electricity (Ismail and Dincer, 2023a; 2023b). Energy production form plastic waste benefices us in many ways as it provides a way for sustainable use of plastic waste, which is biggest problem of modern world, lessens reliance on fossil fuels for energy production, and to help in effective management of plastic waste (Doniavi et al., 2023).

2.2 Reusing the ocean plastic waste

Accumulation of plastic waste in massive quantities at coastal and marine areas now has become a havoc for environment at global scale (Villarrubia-Gómez et al., 2018; Jambeck et al., 2015). The amount of plastic waste accumulated at coastal areas has reached millions of tons and the debris entering marine and coastal areas is 80% accumulated by land (Veettil et al., 2023). The only solutions to mitigate this plastic waste are cleaning up of the oceans and re-utilization of plastic waste in different purposes like recycling, redesigning to reintroduce into market and its utilization for energy production (Giezen and Wiegmans, 2020).

2.3 Plastic banks

Plastic banks are the recent innovative sustainable approaches that help in mitigating the plastic waste by encouraging the people to collect plastic waste from environment and raise awareness among public about harmful impacts of plastic on environment (Kholil et al., 2019). Plastic banks not only play a vital role in waste management but also aids in ocean cleaning, wildlife conservation, and spread awareness among public for sense of responsibility for waste management for a sustainable environment (Katz, 2019).

3. Recycle

Recycling of plastic is divided into four categories: Primary recycling, secondary recycling, tertiary recycling, and quarterly recycling (Chen et al., 2024). Primary recycling refers to a type of recycling in which plastic is reprocessed to obtain the new plastic that have the same application as of virgin plastic, this is also known as close-loop recycling (Chen and Hu, 2023). Primary recycling preserves almost all the properties of original plastic. Secondary recycling collects plastic waste and processes them to obtain new products by melting, however the original properties of plastic lost during melting process as impurities are added that also disrupt the actual structure of plastic (Chen and Hu, 2023). Tertiary recycling is also known as chemical recycling, high value plastic products are recovered from synthetic plastic waste by transforming plastic waste into monomers by chemical processes like pyrolysis (Rahman et al., 2023), carbonization (Chen et al., 2019), depolymerization (Khopade et al., 2023), hydrocracking (Munir et al., 2018), and photocatalysis (Cao et al., 2024). Quarterly recycling is incineration of plastic products to obtain energy and heat (Chen and Hu, 2023). This incineration is not as traditional incineration as energy is obtained for other uses, and it doesn't allow to the material's value loss (Shen et al., 2021). Moreover, mechanical and chemical recycling are two major categories of recycling (Ragaert et al., 2017).

3.1 Mechanical recycling

Conversion of large molecules of plastic into small molecules by breaking it through various processes like crushing, shedding, and peeling off plastic by breakage of carbon chain is referred to as mechanical recycling (Lin et al., 2023). Easy recycling, short-time consumption, low energy usage, and recovery of energy consumed are the basic features of mechanical recycling (Jubinville et al., 2023). However, in mechanical recycling, total degradation can't be done but it is better than thermal recycling because thermal recycling produces harmful toxic gases. Time consumption for processing of mechanical recycling mainly depends on some factors like temperature, amount of energy supplied, plastic type, and microorganisms' strains that help in degradation (Lin et al., 2023).

3.2 Chemical recycling

Chemical recycling refers to the extra chemical's addition (e.g., peroxides and carbonyl) for the breakage of carbon chains, oxidation, polymer's cross-linkage of plastic products for its degradation by lowering the actual weight of plastic and altering its mechanical properties (Lin et al., 2023). Plastic products are broken down into intermediates from that they can either be converted to original same plastic or to any other material (Chen and Hu, 2023). The ability to deal with contaminated, degraded and even more complex plastic which is hardly done by mechanical recycling is distinctive feature of chemical (Chen et al., 2020). Pyrolysis (Peng et al., 2022), gasification (Doniavi et al., 2024), solvolysis and carbonization are the methods used to process the chemical recycling. A comprehensive comparison of mechanical and chemical recycling is presented in table 2.

Table 2. Comparison of Mechanical and Chemical recycling regarding degradation method, advantages, and disadvantages (Lin et al., 2023)

Category	Degradation Method	Advantages	Disadvantages
Mechanical recycling	Thermal and mechanical degradation	Easy to process less time consumption Recovery of consumed energy	Increased burden limited application scope releasing harmful toxic gases difficult to degrade completely
Chemical recycling	Photodegradation	More sustainable way high adaptivity	Not complete degradation more time taking sensitive to environmental factors

3.3 Precious plastic project

Precious plastic project is an advance community-based innovation that encourages the people to establish small scale recycling facilities to recycle their plastic waste into new useful plastic products themselves (Spekkink et al., 2020; 2022). It's small scaled machinery design and easy to use character make it more significant approach for reduction on plastic waste on local level (KAUST, 2023). This initiative not only minimizes the plastic waste but also promotes awareness among public at community level for sustainable approaches.

3.4 Indirect role in reducing greenhouse gas emissions

3R's method has an indirect comprehensive role in reduction of greenhouse gas emissions (Fig 5). Reducing plastic waste by using alternative products, bioplastics and biodegradable products leads toward the reduction of necessary volume production, plastic waste, and landfill waste. Reduction in plastic waste aids in the reduction of fossil fuels used for incineration of plastic waste, reduction in necessary volume production reduces the energy consumption used during production of plastic products, and landfill reduction decreases amount of methane generated at landfills. Reduction in usage of fossil fuels, reduced energy consumption, and lower amount of methane generated at landfills ultimately aids in reduction of greenhouse gas emissions (Liu et al., 2021). Reusage of reusable and refillable products results in the reduction of plastic waste, necessary volume production, and leads toward the production of alternative energy sources which minimize the production of greenhouse gas emissions (Zhang et al., 2022). Usage of bioplastics as an alternative to traditional synthetic plastic also aids in the reduction of greenhouse gas emissions as growing plants as a raw material to produce bioplastic capture the CO_2 from the atmosphere which reduces the amount of greenhouse gas emissions that emit during production of traditional synthetic plastic (Kumar et al., 2024).

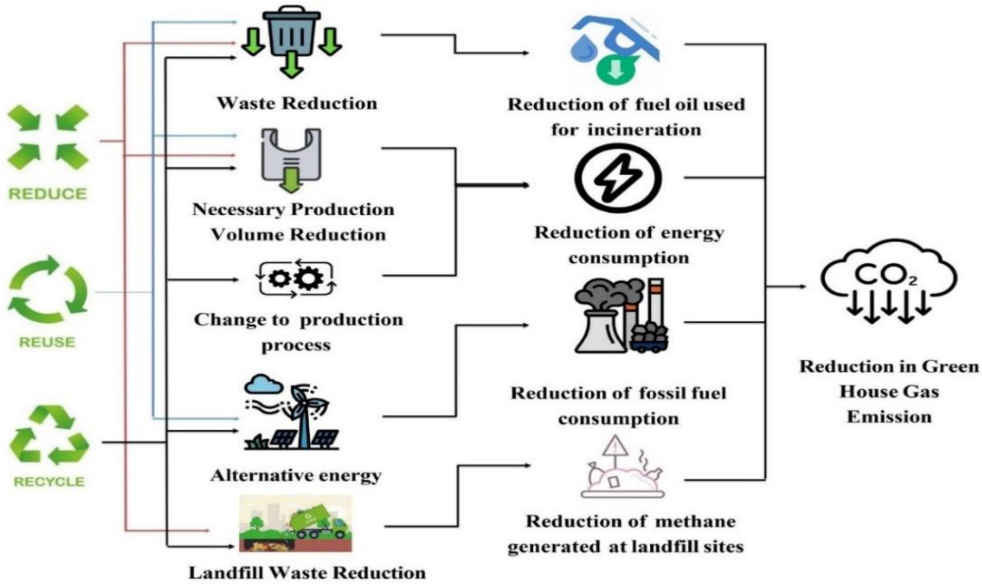

Figure 5: Indirect role of 3R's method in reduction of greenhouse gas emissions

4. Conclusion

This review successfully elaborates on the significant approaches of 3R's method as the dominant strategy to cope with the pressing issue of plastic pollution in the recent era. During the ever-increasing plastic production and its harmful impact on ecosystems, shifting collectively toward sustainable practices is crucial. Implementing alternatives like bioplastics, effective policies, promoting reusable substitutes, and adopting diverse recycling methods can mitigate the impacts of plastic waste generated pollution. Further than the waste management, the 3R's method plays a crucial role in indirectly reducing greenhouse gas emissions and advocating a significant approach for a more sustainable future. It is vital for global communities to unite in executing these principles and practices, transforming the narrative of plastic from a 20th-century marvel to a responsible and eco-conscious legacy.

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