Journal of Experimental Biology and Agricultural Sciences, June - 2022; Volume – 10(3) page 456 – 473

Journal of Experimental Biology and Agricultural Sciences

http://www.jebas.org

ISSN No. 2320 – 8694

Plastic Waste in India: overview, impact, and measures to mitigate: Review

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Received – May 07, 2022; Revision – June 14, 2022; Accepted – June 22, 2022
Available Online – June 26, 2022

DOI: http://dx.doi.org/10.18006/2022.10(3).456.473

KEYWORDS

Plastic waste

Waste recycling

Waste processing

Bioplastics

EPR

ABSTRACT

India is one of the world's large and fastest-growing economies. With the expanding development, the usage of plastic for anthropogenic activities has expanded many folds and India alone generated around 3.3 million metric tonnes of plastic in the financial year 2019. 79 percent of the plastic generated worldwide enters our land, water, and environment as waste; part of it also enters our bodies through the food chain. The industry in India states that 60 percent of what is generated is recycled and we had assumed that we had solved the problem of plastic waste by recycling, or burying it in landfills. But we were incorrect. Plastic garbage is omnipresent today. It is filling up our oceans and harming marine life and affecting all organisms in the food chain. With the development of economic growth of the country per capita consumption of plastic will only increase in the coming years and we will end up generating more plastic waste The review paper aimed to examine the major impact of plastic waste in India and how to reduce plastic consumption, considering measures such as phasing out or banning multilayered plastics that cannot be recycled, contemplating renewable raw materials, promoting the use of bioplastics, incentivizing the recycling business, and making the rules and guidelines for Extended Producer Responsibility (EPR) simple and enforceable.

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Peer review under responsibility of Journal of Experimental Biology and Agricultural Sciences.

Production and Hosting by Horizon Publisher India [HPI] (http://www.horizonpublisherindia.in/).

1 Introduction

As per the annual report of the Central Pollution Control Board (CPCB) for the year 2018-19, India produced over 3.3 million metric tonnes of plastic, an increase of over more than 1 million metric tonnes compared to 2017-18; the major generation came from Maharashtra (12 percent), Tamil Nadu (12 percent), Gujarat (11 percent), West Bengal (9 percent), Uttar Pradesh (8 percent), Karnataka (8 percent) and Delhi (7 percent). The 4,773 registered plastic recycling units, including 7 biodegradable facilities, and 1,084 unregistered plastic recycling enterprises, were employed to manage such a massive amount of plastic rubbish (CPCB 2019). 60 percent of all manufactured plastic is recycled. The remaining 40 percent of plastic becomes waste if it is not cleaned and segregated, and it is either landfilled or pollutes streams or groundwater resources. India, a rapidly rising non-industrial country with a population of 137 billion people, ranks twelfth in the world economy in terms of GDP (Gross Domestic Product). Furthermore, it is ranked third in the world in terms of PPP (purchase power product) (US EPA 2015). Industrialization and urbanization are exploding, resulting in the massive production of plastic waste products (Chauhan et al. 2021). Due to its lightweight, water-resistant, and flexible characteristics (Millet et al., 2018), plastic is now a common component of human life for carrying various types of items. These factors have piqued the public's interest in using plastics. However, people often overlook the fact that it is more toxic and harmful to both humans and the environment because it is non-biodegradable (Phanisankar et al. 2020). Plastics have grown at a rate unparalleled by any other material used in packaging (Schwarz et al. 2019) or building (Mansour and Ali 2015), these are the two crucial areas where plastics are frequently used. The expected increase in future plastic use will be accompanied by an increase in post-consumer plastic trash (Lebreton and Andrady 2019).

Plastics are classified as thermoplastics or thermosetting plastics based on how their physical and chemical properties change before and after heat treatment (Schimpf et al. 2017; Trotta et al. 2019). Thermoplastics are heat-susceptible plastics such as polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), polycarbonate (PC), and polytetrafluoroethylene (PTFE) (Dhanumalayan and Joshi 2018; Koomson et al. 2018; Xu et al. 2019; Huang et al. 2019) can be softened or melted into any shape under heating conditions and solidified when cooled, which can be repeatedly deformed with typical plasticity (Ning et al. 2015). Thermosetting plastics such as epoxy resin, phenolic resin, urea-formaldehyde resin, and organo silicon resin do not undergo plastic deformation when heated; instead, they would decompose when the temperature continues to rise between 250-300 ºC (Chen et al. 2019). Thermoplastics account for up to 80 percent of all plastics produced worldwide, while thermosets account for the remaining 20 percent. Thermoplastics are easily recyclable and pose no risk, whereas thermoset plastics such as epoxy resin and polyurethanes are not (Phanisankar et al. 2020). Clear polyethylene terephthalate (PET) bottles and natural high-density polyethylene (HDPE) bottles can be recycled successfully (Velzen et al. 2020), while PVC, PS, and PP are not routinely recycled from post-consumer waste (Joseph et al. 2021). Approximately 50 percent of plastics are used for single-use disposable applications, such as packaging, agricultural films, and disposable consumer items (Fasake et al. 2021), and between 20 and 25 percent for long-term infrastructures, such as pipes, cable coatings, and structural materials, and the remainder for durable consumer applications with intermediate lifespan, such as electronic goods, furniture, vehicles, and so on, and are made of PVC, PS, or PP, which have low recycling rates (Di et al. 2021) and thus are not suitable for reuse; thus contributing significantly to plastic waste (Hopewell et al. 2009).

2 Environmental impact of plastic waste in India

India is a major producer and consumer of numerous types of plastic. However, the waste management situation in India is abysmal, with minimal source segregation, limited recovery, and a large proportion of garbage ending up in dump yards and random littering. India's plastic waste processing capability is only 15 percent of the total waste generated, and because it is a land-scarce country with a high population density, dump yards, and landfill sites are overburdened (Dhanshyam and Srivastava 2021). Even in the most developed metropolitan areas or super urban areas, trash collection, separation, and treatment facilities are inadequate and ineffective (Dharwal et al. 2022). Plastic debris thrown ashore primarily enters civic seepage lines, suffocating them and contributing to floods in major Indian cities. (Mayur et al. 2021). Plastic packets, diapers, tires, and water bottles including building debris have all been blamed for the flooding of several towns in metropolitan India (Pathak and Nichter 2021). Plastic garbage, according to environmental experts, not only clogs drainage lines but also poses a greater risk because it is non-biodegradable and eventually converts to microplastic (tiny microscopic particles less than 5 mm), which clogs pipelines, becomes poisonous, and harms soil layers (Karthik et al. 2018; Vaid et al. 2021). Furthermore, a large number of vertebrates, birds, reptiles, and fish have been identified as being at risk of injury or death as a result of the damage caused by plastics (microplastics). Plastics or microplastics generally have an impact on marine life by trapping or causing them to ingest (Vaid et al. 2021). As a result of these factors, every one of the world's seven turtle species is in jeopardy or under threat as a result of plastic pollution (Chauhan et al. 2021). The toxicity of harmful chemicals absorbed from adjacent water bodies, as well as microplastic contamination, is a growing concern (Yuan et al. 2019). Following ingestion, microplastics may act as vectors for dangerous compounds to spread to other living things, such as invertebrates, plants, and animals, resulting in physio-chemical impacts and a risk to human health (Wang et al. 2018; Vethaak and Legler 2021). The first report of microplastics in Vembanad Lake in Kerala, India was reported by Sruthy and Ramasamy (2017).

The inability of waste plastic to biodegrade in the atmosphere has created various challenges for both urban and rural India (Adeyanju et al. 2021). Drain clogging, water stagnation, and harmful gas leakage during open incineration are all common concerns linked with waste plastic generation (Gangwar and Tiwari 2021). As plastic is resilient, non-reactive, and mainly non-biodegradable, it stays in landfills for prolonged periods, posing a risk because harmful chemicals are drained out and contaminate underground water bodies (Singh et al. 2008; Devi et al. 2019). Overall, solid waste from most cities is collected and stored in landfills, where it attracts flying creatures, rodents, and bugs, resulting in unsanitary conditions (Alam and Ahmade 2013). The contamination of solid waste results in the release of CO_2, CH_4, and other gases. Furthermore, open dumpsites affect the quality of drinking water and contribute to illnesses such as cholera (Chaturvedi and Singh 2021).

Despite their low cost, plastics are highly engineered materials with exact physical qualities (LaPensee et al. 2010). Rotation, injection, extrusion, compression, blowing, and thermoforming can all be used to mold them into practically any shape. Their material properties are changed before and after synthesis to achieve the appropriate strength, permeability, porosity, opacity, and color (Ali et al. 2020). Plastic shoes (primarily flip-flops) are one such commodity, accounting for up to 6 tonnes of the total waste collected and removed from Aldabra Atoll in Seychelles [in the Southwest Indian Ocean, home to the last remaining population of the Indian Ocean giant tortoises (*Aldabrachelys gigantea*) and the largest nesting sites for endangered green turtles (*Chelonia mydas*) in the western Indian Ocean]. Flip-flops are the most popular shoe among Indians, and they're largely made of plastic foam, and they're stacking up on beaches and in the oceans (Burt et al. 2020). They take decades or centuries to decompose naturally. In 2020, a cleanup initiative resulted in the recovery of almost 60,000 individual flip-flops from a beach in Mumbai, India. (Pathak 2020).

India is confronting a significant waste management crisis as a result of rising urbanization (Srivastav and Kumar 2021). Over 377 million people live in 7,935 cities, producing 62 million tonnes of municipal solid trash each year. Only 43 million tonnes of garbage are collected, 11.9 million tonnes are treated, and 31 million tonnes are thrown in landfills. Solid waste management (SWM) is one of the most important services given by municipal society in the country to maintain metropolitan areas clean. Almost all municipal authorities, on the other hand, indiscriminately discharge solid trash at a dump yard within or outside cities (Kumar et al. 2021). According to experts, India's trash disposal and management system is flawed. Even the most developed metropolitan areas and super urban areas in India lack efficient and effective trash collection, separation, and treatment facilities (Chauhan et al. 2021). The key to effective waste management is to make sure proper waste segregation at the source (Rakib et al. 2021) and that the garbage passes through various recycling and resource recovery channels. Unsegregated municipal solid trash has become a difficult problem for India, as well as other emerging countries (Shukla et al. 2021). The MSWM (municipal solid waste management) system has several issues with waste treatment options such as composting, recycling, and energy generation (Joshi and Ahmed 2016). If the existing MSWM system does not offer the solution to these problems, the entire municipal mixed waste will end up at dumpsites and therefore causing the MSWM system to be dependent upon landfill sites (Ahluwalia and Patel 2018). A huge amount of dumped municipal solid waste (MSW) is becoming the main reason for groundwater pollution, soil contamination, and environmental pollution (Kanhai et al. 2021). The MSW typically includes domestic and commercial wastes generated in municipalities or notified areas either in solid or semi-solid form (Nanda and Berruti 2020). Metro cities are the major contributor to the process of waste generation and due to continuous infrastructure development the production of waste; the amount of waste is also higher than in other regions. About 80 percent of the total generated waste is being collected by various means while the rest 20 percent is again mixed up and lost in the urban environment. About half of the total trash generated is sorted at the source and is amenable to further processing. As a result, approximately 40 percent of the total generated trash is treated in the existing MSWM system, with the remainder deposited into landfill sites (Shukla et al. 2021). The majority of the time, garbage sorting is done by the unorganized sector (Kumar and Agrawal 2020). The segregation and sorting process is carried out in extremely hazardous and unsafe conditions, and the effectiveness of segregation is logically low because the unorganized sector segregates only the most important disposed of constituents from the waste stream, which can offer them a higher monetary return in the reusing market (Agrawal and Anupama 2020; Shukla et al. 2021). Due to a lack of space for inventory, many waste processing industries are utilizing the waste from the dumpsite, which essentially contains mixed waste. This leads to an increase in the cost of waste processing and poor quality of recyclable materials and compost (Rawat et al. 2013).

During the COVID-19 pandemic, a variety of plastic-based personal protective equipment (PPE) played a critical role in keeping people safe (Lockhart et al. 2020). Since the coronavirus pandemic began, there has been an unusual surge of single-use plastics, such as gloves, protective medical suits, masks, hand sanitizer bottles, takeaway plastics, food, and polymer products packages, and medical test kits. The management of waste generated by single-use plastics is a concerning side effect of the COVID-19 pandemic, which has wreaked havoc on global healthcare systems and damaged national economies (Das et al. 2021; Leal-Filho et al. 2021; Patrício Silva et al. 2021). Since the SARS-CoV-2 outbreak, there has been a significant increase in the number of discarded single-use surgical and face masks, as well as latex gloves, found littering the streets, roads, medical institutions, and parking lots, dumpsites, beaches, gutters, and shopping carts. The COVID-19 pandemic has exacerbated the plastic pollution problem by reviving consumer demand for single-use products and materials for health and safety concerns (Benson et al. 2021; Vanapalli et al. 2021; Parashar and Hait 2021; Nghiem et al. 2021). Inadequate management of bio-medical waste (BMW) leads to many issues, including the spread of infectious diseases and various forms of environmental pollution (Rai et al. 2020). It has been determined that 10–25 percent of BMW is hazardous, and research suggests that the COVID-19 virus is highly contagious and can survive for several days on plastic surfaces. As a result, it has created many challenges for current BMW legislation and management practices around the world (Goswami et al. 2021). During the COVID-19 outbreak in Wuhan, China, healthcare waste generation increased by 600 percent (Lan et al. 2022). To prevent the virus from spreading, recycling restrictions, increased production, and incorrect treatment have created an unsettling situation. Several studies have cited the handling of BMW during this pandemic as a major source of concern since it can enhance the risk of further spread of the corona virus (Goswami et al. 2021).

3 Mitigation Strategies

Plastic is ubiquitous, it's visibly the backbone of globalization. However, like in any other country, plastic waste management is a pressing issue in India, especially with the unceasing growth of consumerism throughout the nation. Only 60 percent of the total plastic generated is recycled, the majority of which escapes into the environment. Eliminating the total of it is quite difficult; however, the majority of the nations are trying to encounter this threat with reasonable and pragmatic solutions (Santhosh and Shrivastav 2019). At this juncture, India needs robust and stringent waste management measures (Figure 1) to substantially improve the situation and for an effective nationwide waste management performance, it is imperative for the government, local bodies, and civilians to achieve a common target of zero plastic waste (Plastic Waste Is India's and the World's Most Formidable Environmental Challenge Today, and the COVID-19 Pandemic Has Made Matters Worse: CSE, 2020).

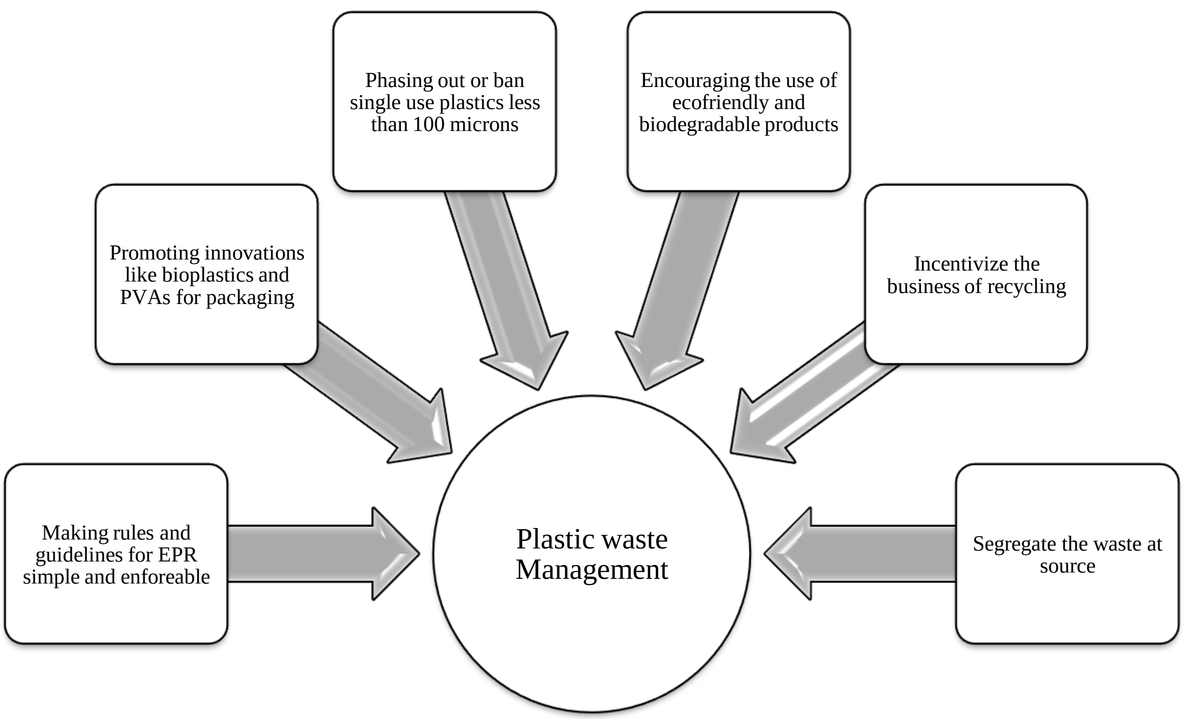

Figure 1 Plastic waste mitigation strategies.

3.1 Reused plastic wastes in construction purposes

In India, the problem of plastic waste is not a recent phenomenon. The entire amount of waste plastic available is enormous. The waste plastic material is either buried or disposed of on land (Jha and Kannan 2021). Plastic waste is combined with municipal solid refuse and spread out across a large area. Both humans and animals have suffered as a result of improper plastic garbage disposal (Bhardwaj et al. 2020). Plastic is harmful and is found in numerous forms (Bahij et al. 2020). The problem of plastic waste can be solved in two ways: first, by substituting other materials for the plastic, and second, by collecting and recycling the plastic garbage (Trimbakwala 2017). A noteworthy technique to exploit or repurpose the plastics is the construction of roads with that plastic waste (Biswas et al. 2020). Plastic is robust and deteriorates extremely slowly. The chemical connections are so strong that they make plastic robust making it resistant to degradation (Trimbakwala 2017; Biswas et al. 2020; Kokare et al. 2021). Road construction from plastic waste isn't new. The director of the Central Road Research Institute (CRRI), in India noted that "bitumen, when blended with rubber or plastic, enhances the life of roads and the quality of roads" although polymers when mixed with bitumen increased the building cost up to six percent but enhanced the longevity of roads manifold (Gunjan et al. 2021). Bitumen is hydrophobic by nature, and plastic is also hydrophobic by nature. When hydrophobic materials are added to bitumen, the strength of the combination rises substantially, and it becomes more water resistant. Plastic carry bags, polyethylene packets, and discarded PET bottles are added to the bitumen mixture at a high temperature to make an aggregate that can be laid like a standard bituminous road (Bhardwaj et al. 2020; Kokare et al. 2021). Mostly shredded plastics are poured over the heated aggregates, thus generating plastic coated aggregates, which are then mixed with hot bitumen to make a plastic coated aggregate bitumen mixture for laying roads (Figure 2). This helps to have better binding of bitumen with the plastic-waste coated aggregate due to higher bonding and greater area of contact between polymer and bitumen, thus preventing moisture absorption and oxidation of bitumen by entrapped air (Yadav et al. 2017).

Since 2001, the plastic man of India, R. Vasudevan, Dean, Thiagarajar College of Engineering, Madurai, and his team at the Centre for Studies on Solid Waste Management (CSSWM), have been researching the possibility of employing plastics in the construction of roadways (Vasudevan 2010). The trend of employing plastics for road building gained momentum in 2015 when the Indian government announced suggestions on plastic use with hot mixes for bitumen roads around urban areas.

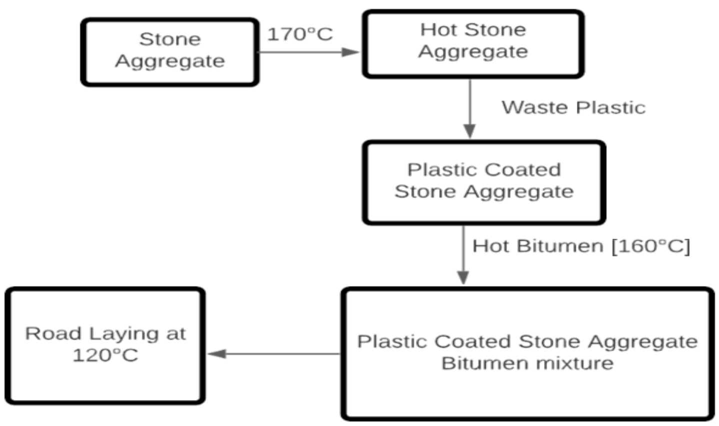

Figure 2 Flow chart for construction of plastic-aggregated coated roads (Yadav et al. 2017).


Figure 3 A road made of waste plastic in Madurai, India (Vasudevan 2010).

Subsequently, India has developed one hundred thousand kilometers of roads in at least 11 states by utilizing waste plastic (Figure 3). The front runners have been the following cities: Chennai, Pune, Surat, and Indore. As of July 2021, 703 kilometers of national highways have been developed using waste plastic in the form of a wearing coat of flexible pavement (Team Prakati 2021). The implementation of such revolutionary technology will not only reinforce road construction but will also increase road life as well as aid to improve the environment by giving a solution to get rid of plastic waste.

3.2 Recycling of PET bottles into textile fibers

PET plastic bottles are considered a major fraction of the plastic waste that is deposited in landfills every year and takes at least 500 years to decompose (Lundell and Thomas 2020). The alarming rate at which the number of used plastic bottles is accumulating in landfills poses considerable damage to the ecosystem. Thus, it seems that recycling PET plastic bottles has a vital function in making the environment friendlier (Jafari 2021). Many companies globally are now coming forward to recycle waste PET bottles to create jobs and to maintain the environmental sustainability. Not just entrepreneurs, but fashion designers are also coming out to join their hands in supporting the environment. With the help of advanced technology, PET bottles are melted, extruded, and spun into polyester yarn, called recycled polyester (rPET). Fabrics can then be woven directly from rPET. This rPET is considered to be eco-friendly, cost-effective, safe and also consumes 30 percent less energy than garments that are made from conventionally manufactured polyester (Mukherjee 2017). With development in recycling technology, plastic PET bottles can now be turned into light, soft and breathable textiles that are not only trendy and fashionable but will help maintain sustainability by minimizing plastic waste generated. Such eco-conscious effort will undoubtedly witness rise in the usage of recycled plastic fibers for daily necessities.

3.3 Biodegradable Leaf plates as an alternative to disposable plastic plates

Plastics such as polyester PE, PP, PET, PS, PC, epoxy resins, polysulfone, PVC, polyvinylidene chloride, and melamine formaldehyde are used to make disposable plates, cups, bowls, tumblers, spoons, bags, covers, sheets, and films (Hanga 2015). During use, these plastics can emit hazardous substances such as bisphenol A, melamine, vinyl chloride, phthalates, and other chemicals into the food they contain (Notardonato et al. 2019). Over the last few decades, an increase in ecological consciousness has encouraged various experts and researchers to work on sustainable and environmentally friendly materials that could partly or substitute synthetic non-biodegradable polymeric materials in all-around applications (Korbelyiova et al. 2021). Currently, substantial interest has been shown in the development of biodegradable products made from non-food materials for usage in various industries (Pandey et al. 2021). The influence of throwaway plastic ware consumption in our day-to-day has led to a quest for alternate renewable resources, i.e., the use of plant leaves as dining plates and food wrappers, a traditional practice in India (Kora 2019). The long-standing tradition has its own cultural, religious, medical, and social relevance in India (Balkrishna et al. 2021). The leaves are one of the non-timber forest products (NTFP) and are harvested from the forests by the tribal people of India. The leaf plates are environment-beneficial, biodegradable, suitable for extended-duration storage, and may be readily thrown off. They are inexpensive and don't require cleaning with phosphate-rich soaps and detergents, a time-consuming and labor-intensive operation. Among the many natural fibers available, areca sheath fibers have enormous potential to be used directly or as a filler material in composites, resulting in the production of bio-degradable, eco-friendly materials (Nayak et al. 2021). The normal procedures involved in leaf plate manufacture include leaf harvesting, leaf drying, hand or machine stitching into plates, and bundling for shipping. Usually, the leaf harvest from neighboring

Figure 4 Compostable and biodegradable machine compressed dining plates made from leaf sheath of Areca palm and Sal leaves (Kora 2019).

forests is done by women and a distant distance by males. But the stitching labor is carried out largely by women at home. The plates are created on a small scale by cottage enterprises. The single-layered hand and sewing machine sewn plates, called Khali, are directly utilized by the consumers for eating purposes or further pressed into thick plates by heat pressing machines, which are procured by the commission agents, dealers, and traders. Among the locally available resources, leaves from sal, areca palm, and palasa are acceptable for commercial leaf plate production (Figure 4) (Kora 2019).

3.4 Bamboo as an alternative to plastic bottles

Molded fiber and its products have garnered considerable attention as a green and sustainable packaging material because of its renewability, recyclability, sustainability, and biodegradability (Didone and Tosello 2019). Molded fiber products (MFPs) are regularly made by some renewable and biodegradable lignocellulosic fibers defined as molded fiber or pulp under a series of processes, such as pulp preparation, forming, pressing, and drying in the mold to form different sorts of three-dimensional fiber products. The MFPs have been commercially used in several packaging markets, like food-related (egg and fruit trays), industrial packing (electronics and car parts), throwaway products (bedpans and urine bottles), and horticulture trays/pots (Didone et al. 2017). This has led to the increase in the popularity of bamboo bottles in various places, in which *Bambusa balcooa Roxb.* (Poaceae: *Bambusoideae*) is utilized (Tewari et al. 2014). *B. balcooa* is a perennial, drought-resistant bamboo species (Kaushal et al. 2021) that is indigenous to north-east India and also known as "poor man’s lumber". It is the fastest growing plant and plays a key role in the food and nutritional security of the tribal-dominated northeastern districts of India (Kikon 2021; Behera and Balaji 2021). Eco-friendly bamboo bottles produced from various bamboo varieties (Figure 5) have been found all around the country; this sustainable project has not only restricted the use of plastic but also provided a source of work for many. In 2018, the Indian government revised the National Bamboo Mission to assist the growth of the bamboo sector and help with its marketing (Adil 2021). Lachen, a small hamlet of Sikkim, India, arguably the first to entirely ban plastic drinking water bottles, is proposing bamboo bottles as an alternative. The plastic bottles left behind by tourists spurred the local community to introduce the ban (Senger 2020).

3.5 PVA as an alternative to plastic packaging

Packaging is a vital step in the food industry since it is used to avoid spoilage, improve shelf-life, and offer an appealing presentation of the food product (Soltani-Firouz et al. 2021). Plastic packaging is utilized throughout the world, and its production is expanding year after year. It comes in a range of colors and styles. However, it has generated major environmental difficulties, notably for the ocean, which has become a home for discarded plastic packets (Lombardi et al. 2021; Walker et al. 2021). To solve this issue, biodegradable packaging was designed to replace the use of plastic packaging because it helps to reduce environmental impact and waste management costs (Shaikh et al. 2021). Biodegradable packaging is also known as ecologically friendly packaging since it may be degraded into carbon dioxide, water, inorganic chemicals, and biomass by microbes, algae, fungus, as well as enzyme catalysts. To create biodegradable packaging, biocomposite films like polyvinyl alcohol (PVA) are necessary (Yazik and Tukiran 2021). It is a synthetic water-soluble polymer that is both colorless, odorless, and with a backbone consisting exclusively of carbon atoms and is biodegradable under both aerobic and anaerobic conditions by microorganisms and their PVA degrading enzymes, especially PVA oxidases and hydrolases (Halima 2016). It originally garnered prominence in 1989 (Thyagarajan and Janarthanan 1989) when PVA film was used to package pesticides in unit-dose, water-soluble pouches that protected farmers from accidental chemical exposure (Youssef et al. 2019). This invention then changed the cleaning business, where single-use laundry and dishwasher detergent packs and tablets provided consumers with dramatically better

Figure 5 Eco-friendly and sustainable bamboo bottles found in Indian markets.

convenience, safety, and sustainability (Sultana et al. 2021). PVA is safe and environmentally friendly (Asthana et al. 2021). Beyond the popular laundry and detergent packets, it is used in many households, biomedical (Bialik-Wąs et al. 2021; Kamoun et al. 2021), personal care, and industrial electronic applications (Hashim 2020), including food packaging (Amin et al. 2020), textile yarns (Jhang et al. 2021), paper products (Islam 2020), unit-dose pharmaceuticals (Nemati et al. 2021), water treatment chemicals (Rolsky and Kelkar 2021), "artificial tears" used to treat dry eyes, contact lens lubricants (Yu et al. 2020), transfer printing, agrochemicals, embroidery, and dust abatement (Islam 2020). Food-grade versions of the film are used to deliver pre-measured quantities of grains, pasta, chocolate flavoring, and nutritional supplements (Polyvinyl Alcohol (PVOH, PVA, or PVAl) 2021)

3.6 Role of bioplastics

Bioplastics are polyesters manufactured by a range of microorganisms cultivated under varying nutrient and environmental conditions. These polymers are mainly lipid-based and are collected as storage resources (in the form of mobile, amorphous, liquid granules), facilitating microbial survival in stressful situations (Luengo et al. 2003). Among the many biopolymers, polyhydroxyalkanoates (PHAs) have received interest for industrial-scale manufacturing not only due to their biodegradability and compostable features but also due to their facile conversion to diverse forms, possessing required characteristics as plastic materials (Sirohi et al. 2020). PHA is the only bioplastic that is entirely produced by microorganisms, with more than 30 percent produced by soil-inhabiting bacteria. Many microorganisms in activated sludge (Jayakrishnan et al. 2021), on high seas (Stanley et al. 2021), and in the harsh cold environment are also capable of generating PHA (Prudnikova et al. 2021). In the last 10 years, PHA has been developed fast enough to find applications in numerous fields (Chen 2010). Best researched microorganisms include *Ralstonia*, *Pseudomonas*, *Halomonas*, *Burkholderia*, *Rhodospirillum*, etc. able to utilize a variety of carbon sources and create different forms of PHA. Even though PHA has various uses and is employed in surgical implants, sutures, artificial blood vessels, tissue engineering, scaffolds, controlled drug administration, etc. (Murab et al. 2021). Despite having the potential to replace conventional plastic (Ganesh Saratale et al. 2021), PHA manufacture is relatively expensive in contrast with petroleum polymers, restricting industrial scale usage. The elevated cost is attributable to the expensive feedstock, synthesis methods, and downstream processes (Bhatia et al. 2021). Consequently, great effort has been directed to minimize the production cost of PHA by enhancing bacterial strain, efficient fermentation, and recovery method (Al-Battashi et al. 2020; Yadav et al. 2020). The stressed environment of salinity off the Gujarat coast, India in which the cyanobacteria *Spirulina subsalsa* thrives nearly overrides the contamination problem and can minimize the sterility requirements of a production facility, thus, decreasing the investment cost. The possible use of these microalgae for PHA generation from sludge, industrial effluent, or other wastewater which has a high salt content can be the way forward (Tharani and Anantha subramanian 2020). The capacity of *Spirulina subsalsa* to flourish in salinity makes them ideal for industrial and bioremediation applications (Shrivastav et al. 2010). The Indian bioplastics industry is improving rapidly and several firms have engaged in the sphere of making bio-based plastic products. In cooperation with Earthsoul, The J & K Agro Industries Development Corporation Ltd. established India's first bioplastics manufacturing facility with an overall production capacity of 960 metric tonnes per year. The key players in bioplastics in India are Truegreen in Ahmedabad, Biotec Bags in Tamil Nadu, Ravi Industries in Maharashtra, and Ecolife in Chennai. Truegreen has an established capability of manufacturing roughly 5,000 tonnes per year of bioplastics products (Rafey and Siddiqui 2021).

4 Plastic recycling targets set by Government of India

As of 2019, India generates approximately 660,787.85 tonnes of plastic garbage per year, 43 percent of which is packaging material, most are single-use plastic, and approximately 60 percent of which is recycled (Wang et al. 2021). The Environment Ministry in India has announced proposed rules that force makers of plastic packaging materials to collect all of their produce by 2024 and ensure that a minimum percentage of it is recycled as well as used in the supply. It has also outlined a system whereby makers and users of plastic packaging can accumulate certifications termed Extended Producer Responsibility (EPR) certificates and trade them in (The Hindu 2021). Only a fraction of plastic that cannot be recycled such as multi-layered will be eligible to be sent for end-of-life disposal, such as road construction, waste to energy, and waste to oil and cement kilns, and here too, only methods prescribed by the CPCB will be permitted for their disposal. Plastic packaging, as per the laws made public on October 6, 2021, falls into three categories i.e. category 1 is "rigid" plastic; category 2 is "flexible plastic" packaging of a single layer or multilayer (more than one layer with different types of plastic), plastic sheets and covers made of plastic, carry bags (including carrying bags made of compostable plastics), plastic sachets or pouches; and category 3 is called "multi-layered plastic packaging", which has at least one layer of plastic and at least one layer of material other than plastic. Producers of plastic will be compelled to submit to the government, via a centralized website, how much plastic they make annually. Companies will be required to collect at least 35 percent of the target in 2021–22, 70 percent by 2022–23, and 100 percent by 2024. In 2024, at least 50 percent of their rigid plastic (category 1) will have to be recycled, as will 30 percent of their category 2 and 3 plastics. Every year, the targets will be raised, and by 2026–27, 80 percent of their category 1 waste and 60 percent of their other two waste categories will have to be recycled. From July 1, 2022, the manufacture of a range of plastic products will be outlawed. These include earbuds with plastic sticks, plastic sticks for balloons, plastic flags, candy sticks, ice-cream sticks, polystyrene for decoration, plates, cups, glasses, cutlery such as forks, spoons, knives, straws, trays, wrapping or packing films around sweet boxes, invitation cards, and cigarette packets, plastic or PVC banners less than 100 microns, and stirrers (Sharma and Mallubhotla 2019; Kapur-Bakshi et al. 2021; The Hindu 2021).

5 Challenges and Future Perspectives

In the recent decade, plastic pollution has emerged as a major global concern in public discourse (Pathak 2020). Packaging currently accounts for the highest consumption of plastics in India, at 24 percent of overall consumption and most of which are single-use plastics. These end up cluttering the environment in part due to reckless individual behavior. Bad waste management systems also play a major role. Governments must recognize the importance of waste management services for a sustainable future. To prevent plastic pollution, measures should be made in line with the waste management hierarchy. The drive to eliminate plastic needs to focus on getting rid of it at the source as the only way to prevent it from getting into the environment (Kim et al. 2022). The adoption of PHA as an alternative to synthetic plastics can be the future way ahead. Not only they are biocompatible and biodegradable, but they can also be made from diverse biowastes such as lignocellulosic biomass, municipal waste, garbage cooking oils, biodiesel industry waste, and syngas. Despite the efforts, PHA manufacturing cost is greater compared to synthetic plastic. In 1998, Bipol a commercially generated PHA was 17 times costlier as compared to the price of synthetic plastic, and with the advancements in science, this price is recently lowered to 5 euro/kg PHA in comparison to 0.8–1.5 euro/kg synthetic plastic. The high cost of PHA is mainly due to the slow development of microorganisms, low conversion of raw material into PHA, high energy requirements in sterilizing and aeration, and expensive downstream processing (Bhatia et al. 2021). Future research activity should be focused on overcoming all these abovementioned challenges.

Despite increasing the efficiency of solid waste management in India, there are large quantities of nonbiodegradable garbage that are left untreated or deposited into landfills. In developing countries like India, as landfill has been the major option for disposing of solid waste (Nanda and Berruti 2020), there would be an ever-increasing landfill in the future, which might put constraints on finding land for further dumping of garbage, unless there is a way to reuse those solid wastes that have significant potential to be utilized again for other purposes. Fortunately, several environmentalists and academics have come up with innovative methods of utilizing these wastes in the construction of buildings (Dadzie et al. 2020) and roads (Vasudevan 2010). Discarded plastic bottles are currently being used for the construction of dwelling units in the form of building blocks, replacing conventional bricks and concrete, decreasing the overall cost of construction considerably, at least 20 to 40 percent as compared to the conventional way of construction (Saji et al. 2019; Obiadi 2020). Roads laid using the plastic waste mix are found to be superior to the regular ones. The binding property of plastic makes the road last longer by supplying increased strength to bear heavier weights. While a standard 'highway quality' road lasts four to five years it is claimed that plastic-bitumen roads can last up to 10 years (Trimbakwala 2017). However, the cost of roads produced out of plastic wastes is slightly higher compared to the usual approach, this should not hinder the adoption of the technology as the benefits are far larger than the cost. Plastic roads would be a benefit for India’s hot and extremely humid climate, where temperatures routinely reach 50°C and torrential rains create chaos, leaving most of the roads with giant potholes (Trimbakwala 2017; Bansal et al. 2017; Mulyono et al. 2021).

SWM has emerged as one of the most enormous development concerns in metropolitan India. Numerous studies demonstrate that the unsafe disposal of trash generates toxic gases and leachates, due to microbial decomposition, climate conditions, refuse characteristics, and land-filling processes (Ray et al. 2021). According to the 12th Schedule of the 74th Constitution Amendment Act of 1992, urban local bodies (ULBs) are responsible for maintaining cities and towns clean. However, most ULBs lack suitable infrastructure and confront several strategic and institutional shortcomings, such as poor institutional capability, financial limits, and a lack of political will (Ghatak 2021). Various legislations have been created for regulating the manner of trash disposal. The Ministry of Environment, Forest and Climate Change (MoEFCC) and the Ministry of Housing and Urban Affairs (MoHUA) have collaboratively carried out policies and programs to address these concerns. However, most of these have failed to fulfill their aims due to a lack of clarity and understanding amongst the stakeholders, and insufficient enforcement by the regulators (Joshi and Ahmed 2016). One crucial feature of efficient SWM is “waste segregation”. It is now necessary for garbage generators to put their rubbish in color-coded bins. This lessens the impact of SWM on ULBs greatly. Segregation can substantially lessen the strain of transportation of trash as well as lower leachate and greenhouse gas (GHG) emissions (Ravichandran and Venkatesan 2021). Currently, the standards for trash segregation and recycling are poorly administered, and many cities have failed to incorporate door-to-door collection into the informal sector. Further, the restrictions do not address the difficulties generated by the “not-in-my-backyard (NIMBY) syndrome” (Massoud et al. 2021). According to the guidance note on MSWM, compliance with the SWM standards demands that adequate systems and infrastructural facilities be put in place to undertake the scientific collection, management, processing, and disposal of SWM. The 2016 Rules have recommended the formation of a Central Monitoring Committee under the chairmanship of the Secretary of the MoEFCC. This committee will be responsible for overseeing the overall implementation of the 2016 SWM Rules. The COVID-19 pandemic has presented a new set of obstacles in the SWM system in India: preserving social distances at the treatment plants and amongst the collecting workers, and a shortage of PPE gears for conservancy staff (Ganguly and Chakraborty 2021). These concerns weaken the safety of SWM employees, waste treatment regulations, and other operations. There is a lack of effective planning and indigenization of advanced waste process facilities, as well as the provision of regular training to garbage collectors. To boost the effectiveness of SWM in India, citizen participation should be promoted, especially in source segregation and treatment processes (Prajapati et al., 2021). The policy agenda for sustainable SWM must stimulate behavior change amongst individuals, elected representatives, and decision-makers, to limit wastage and littering and boost reuse and recycling. Community awareness and a shift in people’s attitudes about solid waste and its disposal can go a long way in enhancing India’s SWM system (Singh 2020). Viable decentralized composting plants should be established to minimize the load on ULBs for collection and transportation of MSW, which ultimately culminates in a reduction of the strain, put on the landfills. Characterization of garbage during collection and also at disposal site should be made and be available in the public domain. Government should take initiative to encourage Universities, and technical Institutions to take up waste management in its curriculum. The assistance of academic institutions should be asked in the characterization of waste in their proximity. Thereby most parts of India would be covered and location-specific relevant solutions for waste management can be devised (Joshi and Ahmed 2016). Future studies should focus on eliminating the negative effect of waste-to-energy technology as well as the obstacles that waste-to-energy initiatives confront. Future trends and technologies such as microbial fuel cell technology, an eco-friendly strategy that converts municipal solid waste into high energy yield, and hydrogen gas should be advocated (Prajapati et al. 2021).

The recent Indian EPR framework was built by relying upon successes and failure studies from other nations, previous Indian waste management experience, and opinions from diverse stakeholders. Considering the vastness of the problem, significant socio-economic and cultural diversity, demographic complexity, and the predicted implementation challenges, the Indian EPR framework is substantially different in approach compared to EPR approaches of advanced nations. India being a rising economy and a non-OECD country, its EPR framework has emerged not mainly from international commitment but through the voluntary proactiveness of domestic stakeholders. The Indian EPR method is a break from the typical legislative strategy of ‘command and control’ (Pani and Pathak 2021). It is non-directive in character and inclusive of a wide range of stakeholders from both the organized and unorganized sectors. It allows many models to co-develop and coexist at the same time, and it will have a huge impact on producers and manufacturers across sectors and industries (MoEFCC 2020). Analyzing the development, application, and ramifications of this EPR strategy, therefore, is of utmost importance to policy makers, environmentalists, industrial stakeholders, and academia.

With its "people first" orientation, Indian government initiatives such as the Swachh Bharat Mission (SBM), formally started on October 2, 2014, have reached all corners of the country and impacted the lives of countless inhabitants. The Mission changed the sanitation paradigm in the country by providing 100 percent access to sanitation facilities in urban India (Ghosh et al. 2021). Now, building on the SBM achievements, the focus of SBM-U 2.0, launched on October 2, 2021, for the next five years will be on sustaining the sanitation and SWM outcomes achieved and accelerating the momentum generated, bringing Urban India to the next level of "Swachhata”. The sustainable SWM program will place a stronger emphasis on source segregation with a focus on phasing out single-use plastic, material recovery facilities, and waste processing.

Conclusion

India being a developing country, it is apparent that sustainable development plays a vital role at every step of its development process. One such crucial component that aids in its development sustainably is the efficient handling of plastic garbage in the nation. This review study indicates that dependability and economics are the two driving variables that drive the increase in plastic usage as part of industrialization which eventually also increases the waste output from plastic. Few states in India make more plastic garbage that can be regulated. Hence, novel techniques become important to handle the excessive waste generation from plastic and improve the health and environmental quality of society. People need to be supplied with adequate alternatives that are conveniently available and cheap. It is necessary to encourage and promote the usage of Areca palm and Sal leaves to produce plates and containers. They're not only biodegradable, but they'll also help our fledgling cottage sector develop. Bamboo toothbrushes and bottles, for example, can help us reduce a lot of plastic waste. Algae-based flip flops which are biodegradable can help us eliminate plastic flip flops which a huge percentage of the Indian people wear, therefore reducing plastic flip flops from accumulating in landfills which ordinarily would take hundreds or thousands of years to biodegrade. Through recent technology advancements, the development of such innovative products employing renewable raw materials would help reduce plastic usage and promote a sustainable environment. As a result, it is up to us to demand biodegradable products from corporations. Companies will not contemplate making such things if we do not demand from them and will continue to supply us with plastic commodities. In this regard, central ministries of the government of India, such as the Ministry of Environment, Forest and Climate Change (MoEFCC), can jointly frame a strategy and action plan to work with the state ministries to build their capacity to implement conventional plastic waste processing and bioplastic production projects. They should collaborate closely to provide the financial and economic incentives required to simultaneously boost the processing of plastic wastes. Such an effort would enhance further research which will lead to new solutions and innovations for better utilization and disposal of plastic garbage.

Disclosure statement

No potential conflict of interest was reported by the authors.

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