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REVIEW ARTICLE

Challenges and possible solutions to mitigate the problems of single-use plastics used for packaging food items: a review

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Abstract Single-use plastic (SUP) being a versatile material, is adopted as an alternate to traditional materials specifically for the use in food packaging due to its inherent characteristics like high durability, inertness, and protecting ability but has become a curse for living being today due to its random usage and unplanned rejection to nature. Mostly plastics used in packaging of beverages, fresh meats, fruits and vegetables are under concern today. Single-use packages result in generation of several billion tons of garbage till date, which pollutes the environment. At the immediate past, it has come to light that micro plastics obtained due to slow degradation of SUP present in oceans, are also being consumed by marine organisms such as fishes and shellfish species which disturbs the marine life extensively. Hence, finding right strategy to mitigate the plastic waste related issues has becoming inevitable today. This review paper briefs various strategies undertaken worldwide to mitigate the pollution due to generation of plastic waste. Various notable impact of adopted strategies and recent innovations to replace the SUP products are also discussed and in view of this a roadmap is also suggested which can be used to achieve the milestone of Zero Plastic Waste.

Keywords Single-use plastic · Pollution · Recycles · Biopolymers · Edible plastic · Roadmap

Introduction

In a very short period of time, plastic has earned popularity in various aspects of packaging and other many engineering applications (Ebnesajjad 2012). Utility of single-use plastic (SUP) in packaging has emerged due to its excellent preservation capabilities, protection abilities and low prices (Mangaraj et al. 2009; Gahleitner and Paulik 2017). It is a unique solution provided to the mankind which replaced almost all form of natural resources based materials especially paper for the application in packaging food items to maintain the freshness of the food items. The production of paper not only requires enormous destruction of trees but also the time required to produce packages are also high. Development of the paper based packages slowly reduces the greenery of the planet. It has been reported by Capital Solutions, UK that “Out of the 17 billion cubic feet of trees deforested each year, over 60% are used to make paper.” (Capital Documents Solutions 2018). Similar causes of deforsestation are also stated by N. McCubbin in his review articles. (McCubbin 1983). The plastic like PVC, PS, Celluloid were discovered in the nineteenth century (Risch 2009) and later on PE, PP were commercialized. From the beginning of twentieth century, it readily replaced the other packaging materials made of glass or paper due to its synthetic nature, high production rate, excellent barrier properties, high mechanical durability and versatility. Year wise intervention of various plastic packages up to the year of 2019 is highlighted in the Table 1 (American Chemistry Council 2018). In the subsequent years, the research in packaging has turned into active and smart packaging solution, bio-degradable packaging and most recently edible film is introduced as a packaging solution. Beside this, the nutraceuticals, iron, vitamins are also incorporated in to packaging materials or

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Table 1 Year wise intervention of various plastic packages up to the year of 2019 [American Chemistry Council 2018]

Year	Packaging material	Unveiled by
1862	Cellophene	Alexander Parkes
Early 1900	Cellophane as the first fully flexible, water impermeable wrap	Dr. Jacques Edwin Brandenberger
1930	Scotch® Cellulose Tape	Richard Drew
1933	Saran™ (polyvinylidene chloride)	Ralph Wiley
1946	Tupperware®	Earl Silas Tupper
1946	"Stopette"	Dr. Jules Montenier
1949	Saran film (Cling wrap)	Dow Chemical
1950	"Black or green plastic garbage bag" (made from polyethylene)	Harry Wasylyk and Larry Hansen
1954	"Zipper Storage Bags"	Robert W. Vergobbi
1959	The "first licensed character lunch box" with a plastic handle	Geuder, Paeschke and Frey
1960	Entire lunch box made of plastic	Geuder, Paeschke and Frey
1971	Active packaging	First nag of microwave popkorn
1978	Clamshell, a type of plastic blister packaging	Tomas jake lunsford
1986	"Aluminum trays" made of plastic, "microwavable trays"	–
1996	"Salad-in-a-bag packaging" by "Metallocene-catalyzedpolyolefins"	–
1998	Dean's milk chug	Dean foods
2000	Flexible plastic tubes for yogurt	–
2000	Polylactic acid as bio-based plastic	–
2005	Bio-switch (Active packaging)	A. R. De Jong, H. Boumans, T. Slaghek, J. Van Veen, R. Rijk, M. Van Zandvoort
2006	Intelligent packaging systems exist to monitor certain aspects of a food product and report information to the consumer	G. L. Robertson
2007	"Two litres plastic beverage bottle" and "one gallon plastic milk jug"	–
2008	Recycling of plastic bottles are endorsed effectively (27% recycling rate)	–
2010	Heinz® dip and squeeze™	–
2012	55% growth in recycling of plastic bags and flexible product wraps since 2005	U.S
2012	Edible packaging	Harvard bioengineer david edwards launched wikifoods
2014	Ompostable waste bags for food waste collection, agricultural mulch film	Bioplas, Sydney
2014	A technology called "100BIO" developed that is used to create a biodegradable styrofoam	TAG packaging
2015	Conversion of plastic bags into things like ski jackets and eco-friendly solvents	Bio cellection
2016	Dessert spoons and small glasses that are made entirely of 100% natural cane sugar	Candy Cutlery
2017	Recup	Smart planet technologies
2017	Self-heating food packaging	Chengdu weilan enterprise marketing, China
2018	Compostable coffee capsule	European food packager and Nature Works
2019	Zero Waste Packaging	Universal Biopack
2019	Skin pack	Advanta, a global packaging supplier
2019	Self-chilling can	The joseph company
2019	Patented intelligent pigments and inks that will change colors depending on the temperatures of CO_2 levels in the product (An indicator for freshness of food)	Insignia technologies

edible films which can be used to cure certain diseases like anemia, vitamin deficiencies through encapsulated or ion fortified edible materials.

Low density polyethylene, linear low density polyethylene, polypropylene, cellophene, polyvinyl chloride, poly(vinilidene chloride), are few examples of SUP which are completely non-biodegradable and remains as it is in the nature for more than 450 years (Hahladakis 2020). Plastic bags can be categorized into two types based on their degradation times: $10-20$ years or $500-1000$ year as reported by Chamas et al. (2020). Single used plastics are mostly used as packaging materials for short term use. Then it is disposed directly to the nature by the most of its users. It is defined as the product whose life cycle is less than few hours, non-biodegradable under domestic composting or landfill conditions, non-retrievable and which loses more than 95% of its economic value after single use. Huge amount of plastic waste is generated due to our “throw away culture” (Maguire et al. 2019). Most of the plastic waste goes to either landfill or various water bodies like ocean, river, lake, pond etc. According to the prediction of Lebreton et al. (2018), “at least 79 (45–129) thousand tonnes of ocean plastic are floating inside an area of 1.6 million km^2”. This directly affects the marine life as well as raises the pollution in nature. T. D. Nelsen et al. (2020), stated that “An estimated 8.3 billion tons of virgin plastics have been produced to date, of which 4.9 billion tons have ended up in landfills or natural environment” (Nelsen et al. 2020). In Europe, “25 million tonnes of post-consumer plastic waste is generated every year” as reported by Horodytska et al. (2018). In order to find effective remedy to mitigate the ever increasing pollution anti-single-use plastic movement has been initiated all over the world. According to Maguire et al. (2019), 2018 is the year which is marked as turning point in the history of “plastic pollution”. In this year, U.S.A., The European Commission, The UK, Chile, banned the use of SUP products (Cristi et al. 2020; Godfrey 2019). With the immediate effect, supermarkets and many companies phased out light weight plastic bags. Many transnational companies have restricted plastic straws and replaced it with paper based straws. But the fact is SUP has become a part of fabric in our life today and it is very difficult to find a suitable replacement of it.

Rather than replacing it, a solution or strategy or a roadmap to mitigate the hazards of plastic waste is required to control the pollution generated from plastic waste. In view of the recent literatures, it is found that biopolymers, bio-based polymers, edible polymers are under focus in recent days but its many drawback limits its usage. Prime limitations include: (i) high process cost, (ii) low production rate, (iii) brittle characteristics and (iv) inferior barrier characteristics. Recycling is another thought to control the plastic pollution through converting the waste into meaningful products which are also drawing attention of the researchers as an effective solution to the plastic waste.

Consequences of the ban imposed by government bring about development of several products by simply mixing the non-biodegradable plastics with biodegradable plastics by industries. Mixing or blending processes limits its recyclability and exhibits partial degradation. Even after degradation, the non-biodegradable part is fragmented into microplastics which have notable ecological impact. It has come to light that micro plastics present in oceans are also being consumed by marine organisms such as fishes and shellfish species which disturbs the marine life extensively. Hence, finding right strategy to mitigate the plastic waste related issues has becoming inevitable today. This review focuses on current impact of single-use plastics on nature, future of it and possible strategies adopted to remediate the pollution due to the use of SUP packages. In addition, an attempt is made to create a possible roadmap in view of the recent literatures, which may enlighten the way to mitigate the problem discussed here.

Impact of single-use plastics

SUP as carry bag has become an “iconic product in debate” in the area of packaging technology. Its excellent strength to weight ratio, good barrier properties, and its comparatively low production cost has made it an excellent choice as packaging materials (Lewis et al. 2010). Polyethylene and polypropylene are largely used as SUP in packaging. According the data published in the year of 2018, polyethylene (mostly LDPE, HDPE and LLDPE) are now an industry of nearly “100 million tons with a value of \$183bn” (Hutley and Ouederni 2016). Over 31% of the global plastic market is captured by polyethylene whereas the polypropylene captures 27% of the global plastic market (Hutley and Ouederni 2016). Poly 4-methyl pent-1-ene is marketed by Mitsui with a trade name “Opulent$^{\text{TM}}$” which is of very low surface energy and excellent optical as well as acoustic properties. Polybutene and polycyclopentadiene are some other polyolefines which have become popular at the immediate past in the packaging industries. Respective advantages are shown in the Table 2 (Paine 1991; Hutley and Ouederni 2016).

In spite of so many advantages, the material lacks in biodegradability which makes it sustained in nature without major loss in weight of it. Sometimes it is laminated or blended or coated with biodegradable polymers, which leads to partial breakdown of the product.

It is also evidenced that weathering and UV radiations lead to slow biodegradation and breakdown of large plastic particles into small size, low density particles. The low degradation rates pose long-term hazards to the environment. One study is reported in the journal of Environmental Science and Pollution Research where presence of microplastics is evidenced in the River Kelvin sediment. 80% of the microplastic is colored and 20% is colorless as reported by Blair et al. (2019). Airborne microplastics can

Table 2 Advantages of various single use plastics used today

Polyolefin	Advantages for the use in packaging applications	References
Polyethylene	1. Low cost compared to the paper of similar load bearing capacity 2. High tear resistance 3. Good resistance to crack propagation from accidentally created holes 4. Excellent impact resistance 5. Heat Seal ability 6. Low permeation of gasses 7. Hydrophobic 8. Recyclable	Paine 1991; Abdel-Bary 2003
Polypropylene	1.Mechanically durable 2. Good impact property 3. Resistance to fatigue 4. Hydrophobic 5. low permeation to gasses	Paine, 1991
Polyvinyl chloride (Plasticized)	1. Soft and flexible 2. easy to heat seal 3. Excellent self-cling 4. Good toughness property 5. High resilience 6. Good clarity 7. High permeability compared to polyethylenes, paper etc	Abdel-Bary 2003
Opulent^{TM}	1. very low surface energy 2. Excellent optical characteristics 3. Good acoustic properties	Hutley and Ouederni 2016
Polybutene	1. Excellent retention of strength at high temperature 2. Ability to form "two-phase structure" when blended with polyethylene which is used in developing "Seal Peel Technology (easy-opening flexible packaging)"	Hutley and Ouederni 2016
Polycyclopentadiene	1. Good chemical resistance 2. Outstanding optical properties 3. Low moistureabsorption	Hutley and Ouederni 2016

directly be inhaled by humans, especially workers in plastic industries, due to their small sizes and thus pose hazardous impact on human health. Reduced growth rates, inflammation, reproductive complications, oxidative stress and others are caused due to the ingestion of plastics (Chae and An 2018).

Small size microplastics and microbeads present in air get directly inhaled by humans. Various biological processes such as lymphatic transport, mucociliary esclator and mechanical methods (sneezing) prevent them from entering into human body (Prata 2018). However, some of these microplastics are not removed biologically thus they get deposited into human lungs. These micro plastics cause inflammation resulting from release of intracellular messengers, reactive oxygen species and proteases (Gasperi et al. 2018). Dust overload, cytotoxicity, translocation and oxidative stress also occur when the clearance mechanism of human body fails. All of these problems caused due to particle toxicity lead to inflammation among humans (Prata 2018).The measure and action of many anti-oxidant enzymes in human body such as catalase (CAT), total glutathione (GSH), superoxide dismutase (SOD) and glutathione peroxidises (GPx) rise up, thus protecting human organs from harmful effects.

Awareness of the waste problem and degradation of plastics initiated as early as in 1990s. Scientists have reported that plastic fibers tend to persist at a stretch of 180 days in an extracellular lung fluid without any changes in surface area (Law et al. 1990). Single use plastic waste in food packaging in hospitals through instantly usable formula bottles for infants show that around 40% of the plastic debris generated by these bottles, including its packaging, is without the recycling code which makes it difficult for the everyday user to manage these bottles properly (Leissner and Ryan-Fogarty 2019). Majority of plastic waste goes into ocean waters which has been the primary and crucial reason of environmental pollution at global level.

The massive increase in pollution caused by plastic waste affected the micro algal growth, which are primary producers at the basis of food chain. It has been observed that the growth of micro algae, also a vital source of oxygen, was affected up to 45% in a negative way by its exposure to uncharged particles of polystyrene at higher concentration while no effect was observed on the photosynthesis of microalgae (Sjollema et al. 2016). Effect of different types of single-use polyethylene (PE) bags on larvae and embryo of *clam Meretrix meretrix* show that the plastic leachates have no effect on the fertilization of embryo but the survival, shell height and deformity of the D-velinger larvae are severely affected by leachates from all types of bags. It is found that the toxicity observed is mainly due to the compounds leaching from plastic bags (Ke et al. 2019).

Single-use plastics (SUPs) also including microbeads are considerable sources of marine pollution. Microbeads from cosmetics can also pose a major threat to the environment when they are eluted into water bodies as they are only partially blocked by the waste water treatment plants. Micro plastics get transported with phytoplankton aggregates from surface to deeper ocean layers. It has been found that though the exposure of micro plastics did not produce any adverse effects to phytoplanktons and marine aggregates can prove to be effective for micro plastic sink by influencing their vertical distribution in the water column (Long et al. 2015).

It is evidenced that plastics is affected by both the salty ocean waters and fresh water ecosystems. This damage brings about excessive plastic pollution in water bodies (Sanchez et al. 2014; Fu and Wang 2019). The existence of microplastics is found in “digestive tracts of gudgeons” collected from French freshwater river (Sanchez et al. 2014). This study shows that freshwater fishes are also found contaminated with ingested microplastics which confirms the contamination of freshwater ecosystems (Sanchez et al. 2014). Concentration of microplastics in freshwater Asian bivalve clams is reported to be 0.2–4.9 particles g^{-1} w.w. Detected microplastics in freshwater fishes in China ranges between 0.33 and 18 particles $ind.^{-1}$ (Fu and Wang 2019). Microplastics are a potential source of bisphenol A and analogous compounds among fishes in North East Atlantic Ocean. Liver has higher levels of bisphenols than muscles and other organs of fishes with maximal concentrations of 302 and 272 ng/g dry weight respectively (Barboza et al. 2020).

Beside this, migration of toxic components from SUPs to food has also become a concern for the use as food contact materials. Many literatures have reported the migration chances of toxic contaminants like heavy metal elements, organic additives and reaction or breakdown product that can contaminate the packaged food items. Migration of toxic contaminants from SUPs has become the cause of many health hazards. Hence, it is one of the major concerns today for the use of SUPs as food contact materials.

Steps taken to reduce the use of single-use plastic

SUPs have become major sources of land and marine pollution due to unplanned rejection of used non-biodegradable packaging materials. However, this can be prevented either by legislative or non-legislative practices. Jambeck et al. (2015) reported that plastic waste accumulated in natural environment till 2015 was about 79% of the total 6300 metric tons generated (Jambeck et al. 2015). Among the rest, 12% of this plastic waste was incinerated and 9% had already been recycled. It was also reported that developing countries, especially those having coastal boundaries, discharge largest quantities of plastic waste into world’s ocean.

It is observed that the bans on plastics in its early stage were not effective because the charges levied on plastic bags were not applied on customers directly and rather they were borne by retailers only. This step was insufficient in triggering a change in behaviour of customers. The EU (2015) directive took a step by mandating the charges on plastic bags for customers after December 2018 and thus removing the customer’s apathy towards plastics (Schnurr et al. 2018).

India, a developing country with coastal boundaries, has already imposed a ban on plastic bags with less than 20 µm thickness as early in 2002. In 2005, legislation was passed banning less than 50 µm thick plastic bags. A complete ban on plastic bags was introduced in the state of Karnataka in the year 2016. Imposition of these bans in India was done to prevent the clogging of the municipal drainage systems especially in the season of monsoon. These bans also helped in preventing the sacred cows ingesting plastics bags while eating their food, thus resulting in their deaths (Macintosh et al. 2020). According to Macintosh et al. (2020), country like Sri Lanka in September, 2017 also banned the use as well as manufacture of SUP bags having thickness less than 20 µm. Nepal also introduced a ban on production, distribution and sale of plastic bags having thickness less than 30 µm in the month of July 2016 (Macintosh et al. 2020).

To mitigate the problem of plastic pollution, one of the common steps taken by various governments of different countries worldwide is to impose a ban on shopping bags manufactured from SUP. Macintosh et al. (2020) presents the results of sustainability of bans on SUPs in 2011 in Australia (Macintosh et al. 2020). In seven year period from 2011 to 2018, a reduction in consumption of polyethylene bags by approximately 2600 ton is observed due to the bans imposed. It is reported by Macintosh et al. (2020) that from the initiation of the ban, 58% of population of Australia supported the policy, which has increased to 68% of population by 2018. Yet the net reduction in consumption of plastics in the study period is 275 ton which is relatively low (Macintosh et al. 2020).

Figure 1a (Xanthos and Walker 2017) shows a chronology of plastic bans in last three decades in the form of a bar diagram and it is evident from the figure that number of countries taking actions and maintaining policy frameworks on plastic bags have increased tremendously (Up to 2015) in each decade with Germany being the first one to take a step by levying taxes on plastics in 1991 (Xanthos and Walker 2017). Figure 1b shows country wise number of interventions since 2017. (Schnurr et al. 2018).

With reference to the Fig. 1b, it is evident that the awareness among countries has constantly been arising in terms of reduction of production and sale of SUPs. However, it is difficult to acknowledge the effectiveness of the implemented policy frameworks in all these regions. Therefore, further stringent steps are needed to be taken collectively by all governments to reduce SUPs. Studies show that there is an acute necessity for development of an alternative material. Governments need to finance researches for the development of substitute materials and workout campaigns for raising awareness among consumers.

In order to combat with the potential health hazards of toxic contaminants migrated from food contact materials, several regulations are employed in different countries like EU10/2011, EU10/2016, FSSAI Regulations 2018, FSSAI regulations 2020, IS9845 etc. Different regulations are employed to ensure that the extent of migration stays below the specified limit for food contact materials. EU10/2011 and FSSAI regulations 2018 are the two regulations are in use for SUPs. Few examples are given in the Table 3.

Beside this many additives are in use for specific purposes which are not found in EU regulation. Ibarra et al. (2018) reported about many additives which are in use as intentionally added substances (IAS) and are prone to migrate; such migration results in contamination of the food items packed in it (Table 4). One non-intentionally added substance (NIAS) is also noteworthy to mention here as potential toxic contaminant which is obtained as byproduct of the antioxidant.

Strategies to remediate the pollution

SUP has small life cycle (few hours to months), non-biodegradable under domestic composting or landfill conditions, non-retrievable and it loses more than 95% of its economic value after single use. Some of them are of complex structure and non-recyclable. Few examples of these kind of products are bi-phasic polymers, multi-layered co-extruded film, polystyrene, flexible PVC, polyurethane, bubble wraps, blister packs and films which come in contact with the food items, body fluid, household chemical products. These materials have no viable recycling options. Such plastics stay in the nature year after

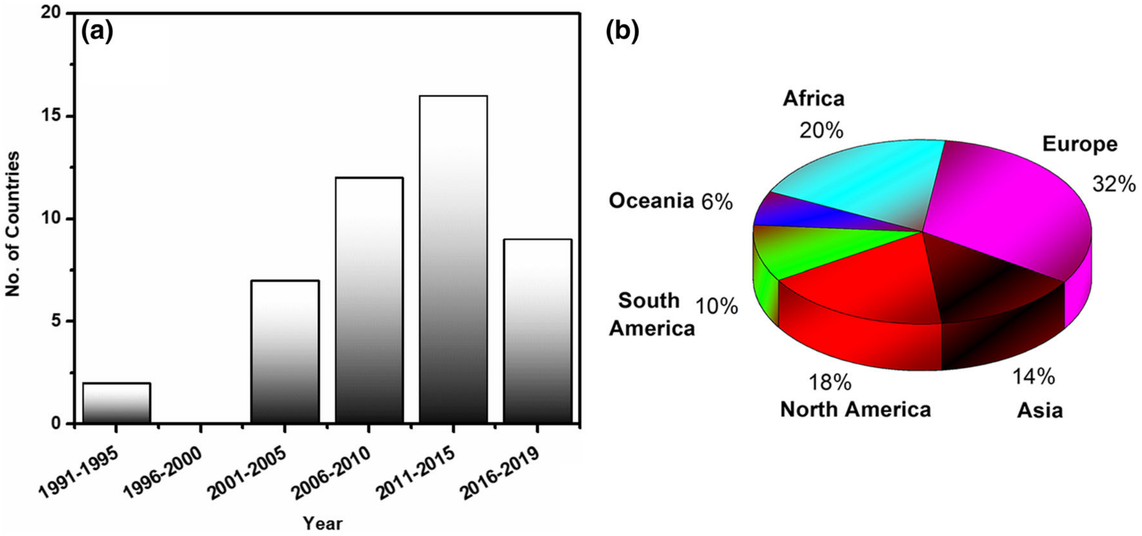

Fig. 1 **a** Bar diagram indicating number of countries banning plastic bags for the span of five years (Xanthos and Walker 2017), **b** Pie chart of Legislative interventions of various countries since 2017 (Schnurr et al. 2018)

Table 3 List of packaging materials and possible contaminants migrated from the packaging materials to food

Package type	Name of the packaging materials	Name of Contaminant	Use of contaminant	SML** (mg/kg)	Ref
Bottles, baby feeding bottles	Polycarbonate	Bisphenol A	Monomer	0.6	Bhunia et al. 2013
Styrofoam, rigid containers	Polystyrene	Styrene	Monomer	NA	Cruz et al. 2019
Packaging materials	Plastics	Lead, Neonate (Organo lead species)	Catalyst	0.01	Standard, 2004
		Ba	Additives	1.0	FSSAI 2018
		Co		0.05	
		Cu		5	
		Fe		48	
		Li		0.6	
		Mn		0.6	
		Zn		25	
		Sb		0.04	FSSAI 2020
		Phthalic acid, bis(2-ethylhexyl)ester (DEHP)		1.5	
Aluminium/SUP laminates or any SUP	Laminates	Aluminium	Found in aluminium alloy	1.0	EC 2016
		Lithium		0.6	
		Barium		1.0	
		Iron		48.0	
		Copper		5.0	
		Cobalt		0.05	
		Zinc		5.0	
		Manganese		0.6	
		Benzophenone	A photoinitiator for inks and varnishes/lacquers treated with UV radiation, wetting agent for pigment	0.6	Silano et al. 2017

#*NA* Not available in view of our literature survey

***SML* Specific Migration Limit

year. Government of many countries banned the use of SUP and tried to endorse the use of biodegradable packaging solutions in replace of it. Such biodegradable packaging solutions includes paper, biodegradable polymers and edible materials. Papers and edible materials are incapable in providing durability and protection to the packaged items. Various attempts were reported like laminates, blending with other non-biodegradable materials and coating which are used to increase the applicability of such materials for the developing durable and effective packaging solutions. However, such products have limited biodegradability and are difficult to recycle. It is noteworthy to mention here about edible materials which can be moulded in the form of plate, spoon so that it can be used during consumption of food as well as it can be used as “ready to eat” food product (Siracusa et al. 2008). In India, Bakey’s Pvt Ltd. founded by Narayana Peesapathy in Hyderabad attempts to provide spoons that can be eaten instead of the SUP spoons (Sun and Lin 2019). The edible spoon in India are generally made of millet (Jowar) blended with other grains. These ‘Millet Spoons’ are also available in various flavors, like plain, sweet and spicy as well as in different taste like ginger-cinnamon, ginger-garlic, celery, black pepper, cumin, mint-ginger, and carrot-beetroot.

Bio-based polymers like polysaccharides, celluloses, starch, proteins are another thought which can be a replacement of SUP. But main problem is associated with

Table 4 list of few examples of IAS and NIAS (Ibarra et al. 2018)

Sl. No	Compounds	Level of toxicity (TC)	Type	No. of samples	Applications	Limit as per EU regulations (mg/kg)
1	Octocrylene	III	IAS	6	Adhesive/Coating	0.05
2	cis-11-eicosenamide	III	IAS	1		NS
3	Erucamide	III	IAS	10	Slip Agent	NS
4	Oleamide	III	IAS	4	Slip Agent	NS
5	Hexadecanamide	III	IAS	13	Slip agent for printing inks, processed plastics, coatings, and films	NL
6	Tert-butyl-1-oxaspiro(4,5)deca-6–9-diene-2,8-dione	III	NIAS	15	A byproduct of the antioxidant Irganox 1010	NL
7	Isopropyl myristate	I	IAS	5	Plasticizer for cellulosic, pigment dispersant, binder	NL
8	1-hexadecanol	III	IAS	13	adhesive in food packaging	NL
9	Octadecanoic acid	I	IAS	1	PVC lubricant/heat costabilizer, adhesive in food packaging, lubricant in food contact coatings	NS
10	Glyceryl stearate	I	IAS	3	Plasticizer for cellulose nitrate, lubricant in plastics, processing aid for plastics	NL
11	Tributyl aconitate	I	IAS	5	Light and heat stabilizer for PVC	NL
12	Tributyl phosphate	III	IAS	18	Plasticizer in nitrocellulose, plastics, and vinyl resins	NL
13	Phthalates (DEP, DIBP, DBP, and DEHP)	I	IAS	86	Plasticizers	–
14	Acetyl tributyl citrate (ATBC)	I	IAS	33	Plasticizer	–

NL Not listed; *NS* Not specified

its lacunas like poor moisture tolerance, brittleness, and low resistance to permeation which need improvements. Review of Saxon et al. (Saxon et al. 2020) describes the various methods to synthesize bio-based polyesters from biomass. According to Saxon et al. (2020), “Isosorbide, 2,4:3,5-di-O-methylene-d-mannitol, bicyclic diacetalyzedgalactaric acid, 2,5-furandicarboxylic acid, citric, 2,3-O-methylene L-threitol, dimethyl 2,3-O-methylene L-threarate, betulin, dihydrocarvone, decalactone, pimaric acid, ricinoleic acid and sebacic acid” are the monomers derived from biomass (Saxon et al. 2020). These monomers are used for the production of polyester which can replace the petrochemical based polyesters. Trees and crops, feed crop residue, aquatic plants, agricultural food, wood and wood residue, animal wastes and other waste materials are used as biomass (Ohara 2003). Diols developed from biomass are used to synthesize bio-based polyesters. Some biopolyesters are also reported which are poly(3-hydroxybutyrate) (PHB), poly(3-hydroxyhexanoate) (PHH)and poly(3-hydroxyvalerate) (PHV) which finds use as packaging materials. Various types of bio-based polyester are given in Table 5 (Caretto et al. 2018; Lavilla et al. 2012, 2013; Papageorgiou et al. 2015).

It is still under debate that which way can be taken to reduce the pollution due to the plastic waste. It is not possible to completely replace or ban the SUP as no suitable replacement solution is available till date. Recycle-Reuse-Reprocess can be effective strategy to deal with the problem. Along with that biopolymers also can be potential candidate in packaging industry if recollected properly after use. These are discussed in subsequent sections.

Recycle or reprocess ability

Recycling is one of the major process that are found suitable for reduction of plastic waste, but it is estimated that out of the total plastics produced (6300 Mt) only 4900 Mt have been thrown away either in landfills or they remain littered in the environment and only 9% (567 Mt) have been recycled (Geyer et al. 2017). Furthermore, recyclability of the product is significantly reduced due to the use of lamination, metals, inks, adhesives, pigments, blending, additives and printing on waste plastic (Hopewell et al. 2009). It is noteworthy to mention here that several advancements in recycling technique are also taking place

Table 5 Sources, characteristics and applications of various bio-based polyesters

Polyester	Monomer derived from biomass	Nature	Application	T_g	Ref
Isosorbide based polyesters	Sugar derived isosorbide, isomannide and isoidide as monomeric diols	Highly rigid and non-toxic	used in physiological environment as ecological or stable iomaterials	30 (Max)	Caretto et al. 2018
Mannitol based polyesters	2,4:3,5-di-O-methylene-d-manni	High thermal stability (up to 370 °C)	Used as a novel renewable resources based polyesters	55–137	Lavilla et al. 2012; Lavilla et al. 2013
Galactaric acid based polyesters	Bicyclic diacetalyzedgalactaric acid (Galx) and galactitol	flexible	used in polyesters synthesis	Below room temperature	Papageorgiou et al. 2015
Furan based polyesters	5-Hydroxy methylfurfural (HMF)		Most capable monomer used in polyesters synthesis	~ 7	Papageorgiou et al. 2015

to meet up the challenges in reducing the plastic waste from the environment.

The definition of recycling can be summarized as, it takes post-consumer plastic waste or PCPW (that would be land filled, or otherwise disposed) out of the waste stream and transforms it into a secondary material that can be put back into the system, in order to make similar or novel materials and products, with similar or lower functionality; hence "closing the loop". This facilitates in achieving "Circular economy (CE)", which really brings uplift in the economy and benefits the society (Hahladakis and Iacovidou 2019).

Hahladakis and Iacovidou described CE as " a system that has the ability to restore, retain and redistribute materials, components and products (MCPs) in the best possible way and for as long as it is environmentally, technically, socially and economically feasible" (Hahladakis and Iacovidou 2019). CE employs moving away from conventional system of "take-make-consume-discard" to a system where materials are repeatedly reused and recycled and hence forms a closed loop. Globally it has become a huge thrust to achieve CE in order to manage the problems created by excessive amount of single-used plastic waste generated and also to increase the economy. But attainment of complete recovery of the waste material is not always possible, as some products (mostly biphasic systems, coated materials, laminates) are difficult to recycle. Hereby, closing the loop requires further modifications. One way to close the loop can be proposed as shown in the Fig. 2. Different types of recycling techniques are established by different research groups to properly handle the plastic waste. These techniques are discussed in the subsequent section.

Plastic recycling can be categorized into four main types, which are (i) Primary recycling (re-extrusion); (ii) Secondary recycling; (iii) Tertiary recycling (chemical or feedstock recycling); and (iv) Quaternary recycling (energy recovery).

Primary recycling process

Primary recycling involves the reuse of clean or semi-clean (after sorting out the unclean parts) single type of waste plastics (having properties comparable to the indigenous products) into the extrusion cycle, mainly applied within the processing line. It is also known as re-extrusion or closed loop processing, primarily needed for the treatment of post-industrial (pre-consumer) waste. Municipal solid waste contains large amount of contaminants which makes it unsuitable to be recycled using this technique (Singh et al. 2017). Many plastic packaging faces excessive problem when they are recycled using this method, as it involves the usage of different materials like metals, inks, adhesives, pigments and paper (Hopewell et al. 2009). The packaging waste materials which can be readily recycled using this must possess the criteria like, (1) they can be very easily cleaned from the origin of their contamination and (2) have good thermal stability such that it does not undergo degradation when they are reprocessed and later used.

This method of recycling was carried out at the University of Leuven during the recycling of back covers of the flat screen television set which was made of acrylonitrile butadiene styrene and polycarbonate blend incorporated with flame retardant (Ignatyev et al. 2014). The back covers were successfully recycled into testing bars and new back covers. The pre-consumer (industrial) plastics are subjected to primary recycling routes as high level of homogeneity is required. Nearly 95% of total plastic scrap was reported to be primarily recycled in the UK (Al-Salem et al. 2010). However, post-consumer plastic waste are also primary recycled. Household plastic items are the main source of such post-consumer plastic waste.

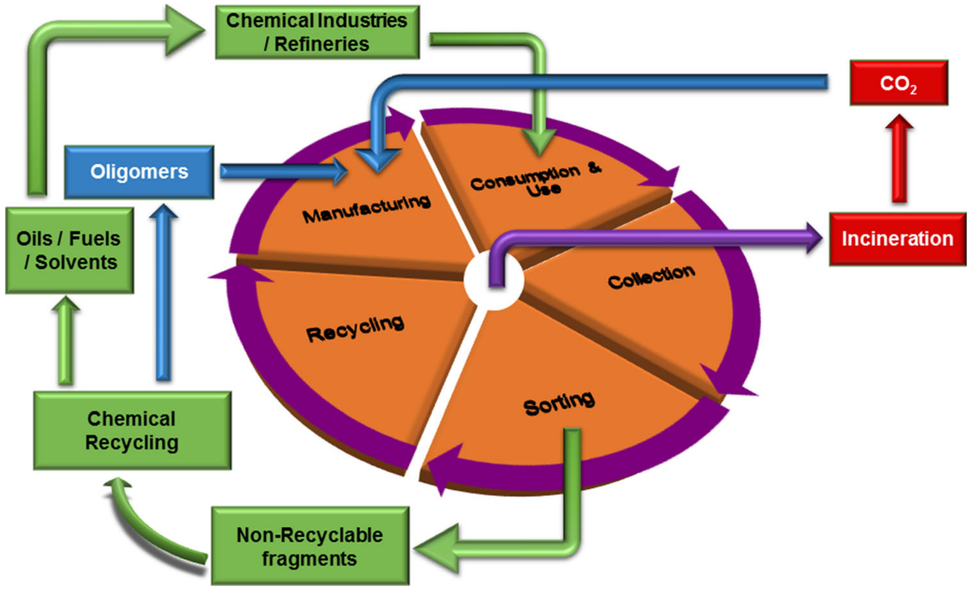

Fig. 2 Schematics of the proposed way to close the loop to bring about circular economy

Secondary recycling process

Secondary recycling is also known as "mechanical recycling or plastics reprocessing". This process is classified into two types:

(a) Closed loop or Upcycling –This process involves the mechanical recycling of plastic waste into materials having properties similar to the original product. The recycled materials are used further to develop similar products as before (e.g. PET bottles gets recycled to form fresh PET bottles).

(b) Open loop or Down cycling- This process involves the recycling of solid plastic waste into resources where the properties of the resultant recycled material may be poorer than the original product, mainly caused by loss of plastic properties. This make the application of the material different than the original one, e.g., Recycled PET bottles used along with concrete (Albano et al. 2009).

Collection, sorting, cutting/shredding, decontamination, granules formation and processing are the processes which are followed during secondary recycling of PCPW. Various processing techniques like, injection moulding, blow moulding and screw extrusion moulding are used to process the granules to develop final product.

Various thermoplastics are subjected to the secondary recycling process in order to convert it in granular form. These granules are then further used to obtain less valuable products. Prakash et al. described secondary recycling process using single screw extruder. Here, the plastic granules were fed in to the hopper of the extruder. At least 500 psi pressure is required for the materials to come out from the extruder (Prakash et al. 2020). Another notable example is recycling of post-consumer PU foam which involves secondary recycling technique. In this case the post- consumer PU foam was crushed to form pellets which was then remoulded to form a new product (Ignatyev et al. 2014). Another example of such recycling process is the reuse of automotive shredder residue obtained by shredding of car components. The recycled products can be used as parts of a new car in the form of composites (Sakai et al. 2014). Vartiainen et al. (2018) reported a study on mechanical recycling of LDPE film. According to their report, both virgin and recycled LDPE possess excellent transparency (Nearly the same). However, a reduction in oxygen transmission rate was reported for LDPE. The tensile strength and young modulus were reduced by 15.3 MPa and 303 MPa respectively due to the secondary recycling process used by Vartiainen and coworkers (Vartiainen et al. 2018). Jiun et al. (2016) reported that young modulus was found to increase upto third cycle of recycling. Increase in crystallinity can be the reason of such variation. However, chain scissoring or thermal degradation was noted as a consequence of several number of recycling (i.e. greater than 3) which resulted in deterioration of young modulus for thermoplastics. Whereas, the mechanical properties of thermoplastic elastomers were found to be remained unaffected when recycled for several times (Jiun et al. 2016).

Tertiary recycling process

Primary and secondary recycling process faces lots of problems for some type of plastic solid waste (PSW) as highlighted in the Table 6. In tertiary recycling (also

Table 6 Summary of the advantages and disadvantages of different recycling processes (Al-Salem et al. 2009; Singh et al. 2017; Passamonti and Sedran 2012; Bhadra et al. 2017; Sharobem 2010; Hahladakis and Iacovidou 2018)

Recycling process	Advantages	Problems faced
Primary and secondary recycling	Technique is simple and cost effective	Some polymer waste like Municipal solid waste (MSW) is difficult to clean as it made of mostly heterogeneous component Plastic waste especially plastic based packaging is made of different components like inks, adhesives, pigments, paper, and coatings. These components (chemicals used during manufacturing of plastic) affect the quality of the product after recycling. The chemicals can remain during the recycling and hence bear the chance of being present in the recycled product with increase in chance of migration The discarded plastic packaging must be properly sorted according to their type. Polymers (having different melting temperature) when mixed together and recycled some polymer may remain unmelted while other may burn, which affects the appearance and performance of feedstock (raw material) and it constrains its application further for product formation. It is also reported that PET flakes when contaminated with PVC after recycling gave brittle and yellow colour PET bottles which are undesirable and had to be discarded. Plastic waste must be decontaminated before recycling, but unfortunately many people do not have the proper knowledge and hence sometimes the impurities may have the risk of getting diffused into the polymer bulk as they are permeable in nature. This influences their recyclability Product properties like mechanical (impact strength, elongation) declines, brittleness increases with every processing cycle due to decrease in molecular weight resulting from chain scission reactions that occurs in presence of impurities like moisture and small amount of acid (during processing). Polymers with poor thermal stability, thermosetting polymers (do not flow when melted), polymer blends, composites, polymer which show high melt viscosity for e.g., fluoropolymers
Tertiary recycling	The pyrolysis of plastics leads to breaking of chain forming monomers which is used formation of new product or useful low molecular weight fractions like oils, oligomers, chars or gases useful in petrochemical industry	Expensive process Catalyst used during pyrolysis is expensive and cannot be restored
Quarternary recycling	The thermal energy generated by incineration of plastic waste can further be harnessed to generate electricity through turbine generators and the remaining thermal energy is utilized for heating houses and industrial buildings	Incineration of PSW leads to emission of harmful, toxic gases like dioxins (for polymers containing chlorine groups) and smoke and ashes, which are not desirable “Zero emission” during incineration of plastic waste is not possible

known as chemical or feedstock recycling), the various chemical process like pyrolysis, cracking, gasification and chemolysis helps to convert the plastic to its original raw materials or sometimes into valuable smaller molecules (oligomers, liquids like gasoline, kerosene, diesel oil etc. or gases, sometimes solids or waxes) by depolymerisation, which further acts as raw material or feed stock for the formation of novel plastics and petrochemicals. It is denoted as first step to close the loop of circular economy. It contributes to sustainability in energy which is not met up during primary and secondary recycling (Kumar et al. 2011). Two examples are noteworthy to mention here, which are BP’s PET depolymerization plant in the USA and Eastman’s investment into methanolysis of PET (Lee and Liew 2020). Recently, microbes are used to accelerate the degradation process for degradable plastics like polylactic acid, polycaprolactone etc. Beside this, three other bacteria strains namely *Kocuria palustris* M16, *Bacillus pumilus* M27, and *Bacillus subtilis* H1584, were isolated from the Arabian Sea. These bacteria were evidenced to cause notable weight loss in PE films. High hydrophobicity and chemical inertness makes PE and PP more resistant towards degradation. A recent study reported that abiotic treatment can accelerate the degradation process. One such example is *Brevibacillus borstelensis* strain 707 which assisted degradation of 11% UV treated LDPE in 30 days at 50 °C. Hydrolytic enzyme like cutinase was reported to degrade the PET completely into trephthalic acid and ethylene glycols (Monomers) in 24 h at 50 °C and pH 8 (Sulaiman et al. 2012). Lipase is also reported to be used for degradation of polycaprolactone. The depolymerisation reaction of polycaprolactone was found to complete in 24 h at 70 °C (Feghali et al. 2020).

Quaternary recycling process

This method of recycling is applied when sorting and separation of PSW is difficult or costly, or the plastic solid waste is poisonous and is very dangerous to handle. It is the process of incineration which helps to convert the chemical energy stored in the PSW into thermal energy giving side products like carbon dioxide and water. The thermal energy can further be harnessed to generate electricity through turbine generators and the remaining thermal energy is utilized for heating houses and industrial buildings. Thane Municipal Corporation (TMC) has a daily generation of plastic waste of 60–70 MT. Quazi et al. showed the recycling of the plastic waste generated daily in Thane Municipal Corporation (TMC) was efficiently carried out by pyrolysis of the plastic waste (Mulyani et al. 2017).

Plastic used in the field of agriculture possess many impurities like dust, mud etc. which pose difficulties in their primary and secondary recycling process. Such plastics especially which are pulled from the "raised beds", contains high level of contaminants (4–66%). The agricultural plastic films were also observed to contain impurities up to 50% by its weight. Presence of impurities (like non-plastic materials) in a high concentration makes their reprocessing difficult by primary and secondary recycling techniques (Lawrence 2017). It was reported that quaternary recycling is very effective technique for disposing the agricultural plastics waste by incineration. As the calorific value of thermoplastics is very high, such plastics are excellent choice as alternative "Energy producing materials". The plastics on burning produced superheated steam which can be used in the production of electrical energy (Kumar 2020). However, such incineration process leads to pollution which can be serious threat to environment. Al-Salem et al. (2010) mentioned few case studies in his review. In one case, emission of both nitrous and nitric oxide was observed when high nitrogen fuels like PU foam, nylon, urea–formaldehyde resin were subjected to a combustion at 750–950 °C in 93%N_2/7% O_2. In another case, polyolefins based plastic solid waste was used as a feed in a blast furnace unit which produced reducer gas (CO and H_2). The reducer gas then reacted with the iron ore to form pig iron. The gas after the reaction was recovered from the top of blast furnace. Use of waste plastic as supplementary fuel with coal has become popular since it is environmentally less hazardous (Kumar 2020).

Challenges faced by different recycling process

Recycling is the main need today to manage the disaster caused by use and discard of single use plastic products. But it faces various constraints due to which it has become difficult to recycle (Hahladakis and Iacovidou 2018).

Solis and Silveira (2020) showed that tertiary recycling (chemical recycling) is better technique for properly utilizing the plastic waste than the other three process. The problems faced during recycling are listed in the Table 6 (Al-Salem et al. 2009; Singh et al. 2017; Passamonti and Sedran 2012; Bhadra et al. 2017; Sharobem 2010). Beside this, migration related issues can be aggravated as the polymer materials were subjected to recycling or reprocessing. During every recycling cycle, degradation occurs due to exposure to high processing temperature. Such degradation leads to molecular breakdown to oligomers and monomers which has a high chance to migrate to the packaged food items. Various non-intentional added substances including reaction and breakdown products, impurities have a high chance to migrate from recycled packages to food items. The use of recycled plastic is regulated by Plastics Recycling Regulation (EC 282/2008) and in US, safety of using recycle paperboard is ensured by the regulation, 21 CFR 176.260, which restricts the use of waste paper that contains any form of toxic molecules or deleterious substances (Geueke et al. 2018). But in Europe no regulation is used for the waste paper. On the other hand, Switzerland banned the use of recycled plastic as food contact materials. In the current scenario, specific regulation for the use of recycled packages as food contact materials has become essential due to increase in contamination possibilities from the recycled items in order to ensure safety for the human health. In majority of the cases, proper scientific method for sorting-reprocessing-recycling are not properly followed especially in underdeveloped countries. This may result in migration of several potentially toxic substances like toxic metals, brominated flame retardants, persistent organic pollutants such as dioxins and polycyclic aromatic hydrocarbons into packaged food items (Hahladakis et al. 2018). Whitt et al. (2015) reported results indicating greater tendency for migrating chromium from R-PET. However, the extent of migration of lead and chromium is very low and is under tolerable limit for R-PET (Whitt et al. 2015). So it is not a concern for food packaging under ambient conditions. But microwaving leads to higher chances of migration from R-PET as compared to its conventional usage which may be a concern for packaging of ready to eat products. However, another report revealed that specific migration of chromium and nickel from microwaved R-PETs are 0.08 ppb and 0.07 ppb respectively which can be considered as safe (Whitt et al. 2015). Mineral oil aromatic hydrocarbons (MOAH), mineral oil saturated hydrocarbons (MOSH), polyolefin oligomeric saturated hydrocarbons (POSH) are the few contaminants which are reported to migrate from recycled paper board, PE, PP, BOPP, PP/Acrlate film and PET/PE film. The migration of MOSH was found to increase significantly after 9 months from recycled paperboard. As high as 52 mg/kg of MOSH migration from recycled paperboard items to oatmeal food items was reported (Biedermann et al. 2013). According to Song et al. (2019), a higher amount of styrene is detected for recycled expanded polystyrene cups. The maximum styrene concentration was detected in the 3% acetic acid simulant which is 176.78 µg/kg for recycled material which complies with the European Regulation No.10/2011 for food contact materials (Song et al. 2019). Styrene can affect the organoleptic properties of the packaged food items and hence organoleptic study was recommended by Song et al. (2019) to certify the compliance according to European regulation. However, such studies are scanty and require more investigation to determine the effect of recycling on the migration for all types of packages used in food packaging.

Overcoming the recycling challenges and moving towards circular economy-recent innovations

Wu et. al. (2019) reported a novel strategy recently to segregate various packaging materials using near infrared spectral information of various plastics like PP, ABS, PS using the method "linear discriminant analysis combined with principal component analysis" which make recycling easier and fruitful (Wu et al. 2019).

Another type of sorting technology have been developed by TOMRA sorting recycling, where with the help of sorter equipped with spectrometer camera that operates in visible range (RGBVIS). This helps to detect coloured and opaque contaminants if they are present with plastic which are to be recycled. It also detects different polymers as well as metal types if mixed together. (WMW 2016). Brooks et al. (2019) discussed various types of sorting processes that can be used to sort various types of waste plastic materials. The technology of separation is based on few tests: (i) magnetic tests, (ii) file test, (iii) knife test and (iv) acid test (Brooks et al. 2019). But mostly it is useful for metal scrap recycling plants. Recycling of plastics requires further work to develop technologies for effective sorting of the materials. Moreover, black plastic poses significant challenges in recycling the waste plastic as it remains undetectable by most of the sorting instrument (Mohan Raj 2019). Prime source of black plastic is the 'Plusticulture' (A form of agricultural use of plastic). Here field of crop is wrapped in plastic film to retain more water in soil (the process is known as Mulching). These materials are difficult to process. In addition, the degradation poses another challenge for the reprocessing of the plastic materials like PET, PVC etc. These materials degrade upon heat application which results in deterioration in mechanical properties of the polymers. These materials are now is in use in developing furniture, fencing etc. Plaswood is an example which is prepared by using a blend of several post-consumer polymers. It is used to develop benches, picnic tables, fencing, decking and bollards. These materials do not require varnishing. They are durable, excellent UV stability, anti-termite and remain unaffected against adverse environmental conditions.

Biopolymers-probable potential candidate for replacing single-use plastic

Biopolymers are naturally occurring polymers derived from natural sources. They are biodegradable, environment friendly, made from renewable feedstock and in the last two decade research are being carried out to see whether they can be used in place of conventional plastic.

Yadav et al. stated that biopolymers have the potential to be used as solution in order to mitigate the problems caused by plastics, since they undergo degradation easily in the environment. They also mimic some properties of polymers derived from petrochemicals (Yadav et al. 2018). Aloui et al. (2011), revealed that biopolymers have the capability to replace present synthetic-based plastics (Aloui et al. 2011). The use of biopolymers in the area of food packaging is an alternative to the SUP. The use of active and intelligent packaging has escalated to satisfy the ever increasing demand of consumers for fresh ready to eat, packaged foods (milk, chicken, vegetables). Intelligent packaging was synthesized to sense/monitor the quality of products inside the packaging and active packaging involves in improvement of the properties of packaging by interacting with the food by releasing the "active components" to elevate the shelf life of the food. Many biopolymers have been used in developing intelligent packaging and active packaging. Though the biopolymer shows good film forming properties, they lack behind in the mechanical, barrier characteristics, and antimicrobial activities, hence many researchers have been working on the development of techniques to improve the lacunas present in different biopolymers by modifying it with necessary biopolymers, nano materials and antimicrobial agents (Qin et al. 2019). The necessity of this was to fabricate a suitable biodegradable packaging which could work as intelligent and active packaging having the efficiency to replace single use plastic. Marichelvam et al. (2019), revealed that out of different biopolymers, 50% of them that are used commercially are manufactured from starch (Marichelvam et al. 2019). Starch derived from different sources like rice, potato, corn, cassava and tapioca have been extensively used to synthesize biopolymers (Ezeoha and Ezenwanne 2013). Starch based films modified with silver nanoparticles (Abreu et al. 2015), zinc nano particles (Jayakumar et al. 2019) have been synthesized to offer good antibacterial and barrier property, making it a probable candidate for being used in active packaging. Besides carbohydrates based packaging materials, films made from different proteins e.g. plant derived protein (soy protein, wheat gluten and zein), milk protein (whey protein and casein), animal derived protein (collagen and gelatin) are also used widely in food packaging (Gómez-Estaca et al. 2016).

PLA has been found to be most useful among other biopolymers owing to some special properties which it possess, like they are recyclable, can be thermoformed, biocompatible, biodegradable, their monomers are renewable and their production involves consumption of carbon dioxide. It has also been termed as, "green food packaging polymer". But main challenge is to maintain the flexibility and mechanical durability of the PLA film when incorporating additives in PLA to improve the aforesaid properties. (Zhou et al. 2019) In this contest few works are noteworthy to mention here among which one is the incorporation of graphene oxide and carbon nano tubes in PLA (Kim et al. 2020).This report provides the evidence for significant rise in both mechanical and barrier characteristics of the PLA film. The thermoformed products from PLAfinds use in containing food items like vegetables, fruits and salad (Sengupta et al. 2020). The PLA-PHB-Fennel film possessed good antimicrobial property additionally it also showed greater oxygen barrier property than PLA-PHB film (not containing Fennel oil) (Miao et al. 2019; Sengupta et al. 2020). Hence, the film prolonged the lifetime of oysters when it was packed with it, Many scientists have incorporated different antimicrobial agents in the PLA-matrix like silver nanoparticles (Fortunati et al. 2012; Gan and Chow 2018), chitosan (Bonilla et al. 2013), zinc oxide nanoparticles (Zhang et al. 2017). Polyhydroxy alkanoate (PHA) is another popular biopolymer which is developed by using microorganism, emerge as important material for the use in mainly food packaging applications. These polymers are biodegradable in nature. PHAs also exhibit the characteristics like printability, heat sealability, thermal stability, flavor and odor barrier, low moisture barrier properties, grease and oil resistance, which makes it ideal candidate in developing packages for the food items (Zhao et al. 2020). Synthesis of more than 150 number of different polyhydroxy alkanoates are reported which can be used in food packaging applications. Main lacuna of this polymer is its inferior thermo-mechanical characteristics. Blending with polbutyl succinate (PBS), polybutyrate adipate terephthalate is used to improve the thermo-mechanical characteristics to make it suitable for film or bag formation (Meraldo 2016). Use of nisin activated PHB/polycaprolactone blend is found to be effective against spoilage bacteria (L. plantarum CRL691) to protect the processed meat (Correa et al. 2017).

"Tea fungus" which is by-product made of cellulose and some organic acids generally prepared by incubating Kombucha tea for 12–15 days at 20–26 °C. This type of microbial cellulose has several advantages like "chemical purity, nanoscale fibrous network, high water-holding capacity, hydrophilicity, high degree of polymerization and crystallinity index, good chemical stability, transparency, biocompatibility, renewability, biodegradability, and superior mechanical strength" (Cohen et al. 2019). There are other sources of bacterial cellulose which are strains of Gluconacetobacter, Komagataeibacter. Such type of cellulosic fibers is evidenced to have width in nanometric dimension (As low as 3.5 nm) and high elastic modulus (Nechita and Roman (Iana-Roman) 2020). Ramírez Tapias et al. (2020) developed thin film using by-product obtained during fermentation of Kombucha Tea which possess tensile strength of 25 MPa when unplasticized with glycerol as well as the antioxidant characteristics (Ramírez Tapias et al. 2020).

A category of biopolymer is edible polymers. It can be an alternative to SUPs in the area of food packaging. But, it is must for them to cover all properties of safe-food ingredients according to (FDA) Food and Drug Administration and have Generally Recognized as Safe (GRAS) status (Erkmen and Barazi 2018). The edible polymers are produced exclusively from renewable sources, and edible ingredients such as hydrocolloids, polypeptides and lipids. They are highly biodegradable, non-toxic and biologically absorbable (Ramos et al. 2012).

Food items are coated by dipping, spraying, electrostatic, panning, foaming, and fluidized-bed coating methods or wrapped by thin edible films. The ever growing plastic waste garbage can be reduced due to the development of an edible packaging system (Shit and Shah 2014).

Many scientists have been working on edible films/coatings materials.

The first ever development of grafted chitosan based edible films was reported by Singh and Ray (1998) in India (Singh and Ray 1998). Dhumal et al. (2019), prepared the sago starch and guar gum based composite edible films incorporated with essential oils carvacrol and citral. Also, composite edible films were developed using the biopolymers whey protein isolate, sago starch, and guar gum loaded with carvacrol and citral (Dhumal et al. 2019). Liu et al. (2020), blended soluble soyabean polysaccharide and gelatin to form an edible film. The synthesized film showed improved heat seal strength, good mechanical properties (tensile strength and stretchability), and high barrier against UV radiation and good optical transparency making it an ideal material for the use in food packaging. (Liu et al. 2020) Chitosan films incorporated with bees wax showed good antimicrobial, barrier and mechanical property which are also noteworthy to mention here in order to increase the longevity of the stored fruits (Velickova et al. 2013). These films could be used for the primary food packaging as an alternate solution to single used plastics.

Roadmap to replace SUP

Possible roadmap to success in dealing with the pollution is very difficult to draw as diversification in opinions exists in this context. Reduction of pollution can only be attained by reducing the plastic waste disposed in the nature. Many solutions are proposed by different research groups in order to reduce the plastic waste. Most popular methods accepted in the recent scenario are–(i) Anti-single-use plastic movement, (ii) Replace it with agro-based plastics, (iii) Use of biopolymers like polylactic acid, PHA etc. (iv) Use of edible polymers in developing packaging, (v) increase in recycling of plastics and (vi) Recollect-Reuse-Reprocess strategy. Directly ban in using SUP in packaging is not a viable option as no suitable replacement solution is available till date. The products that are under consideration has many limitations for the use as packaging materials like inferior protection ability, high wetting, low wet strength, low antifungal characteristics. Industries are looking for suitable solution to improve its applicability as packaging materials through lamination, blending and coating with synthetic materials. Many of them are marketed under the tag “Eco-friendly product”, “Bio-degradable” etc. But it is a myth. Bio-degradable products are only becomes degradable under specific compostable conditions. Paper can be a popular choice but its production results in deforestation which again harms the nature. It is also cannot be single choice because of its low availability compared to the synthetic plastics. Moreover, such materials required special attention as they become non-recyclable. Such non-recyclable products act as double edged sword as users discard them directly to the nature by considering it as an eco-friendly material which may increase in non-recyclable, non-reusable waste rapidly in nature. These may promote more severe pollution in nature. Beside this, use of multi-component materials also increase the chances of contamination to the food items if it is used as food contact materials. In place of banning the products, effective strategies are required to recollect-reuse-reprocess the materials after use. In place of banning the whole SUP it may be more effective if it is banned from directly rejecting to nature and if its use is reduced. In addition, more emphasizing on the use of single plastic based product in packaging will increase the recyclability of the materials. The process to analyze recyclability of the product is not also available at present. Moreover, rules can be implemented to promote recyclable, reusable and retrievable products which can be available for daily purpose use. In view of the literatures one possible road map is suggested to mitigate the plastic waste issues. Schematic presentation of the roadmap is shown in the Fig. 3.

Conclusion

Anti-Single-Use Plastic Movement cannot be an effective strategy for controlling the pollution arising from plastic waste when the applicability of other solutions is questionable. However, it can be proposed that replacing non-recyclable SUP and controlling the misuse of single use packaging materials are able to bring positive changes in this context. In spite of many attempts to create a replacement of SUP in the last decade, it still remains as a problem. Development of biopolymer based edible packaging system is one of such alternative to SUPs. Biopolymers may help in reduction of dependence on conventional plastic made from petrochemicals, minimizing the global pollution caused by use of non-biodegradable SUPs, thus helping in moving towards green economy. But the myth of bio-degradation of such materials in nature poses a great challenge in dealing with the pollution by plastic waste. Edible materials on the other hand come with a great potential to be used as packaging materials. Use of many biopolymers is highly efficient in reducing global plastic debris because of its biodegradability, palatability and environmental friendliness. At the same time, partially biodegradable polymers are equally dangerous as it forms microplastics which indirectly affect human health due to its deposition in various organs. Hence, it may be beneficial to use plastics which are either 100% recyclable or completely edible. Blend, lamination and incorporation of many toxic ingredients not only reduces the recyclability of

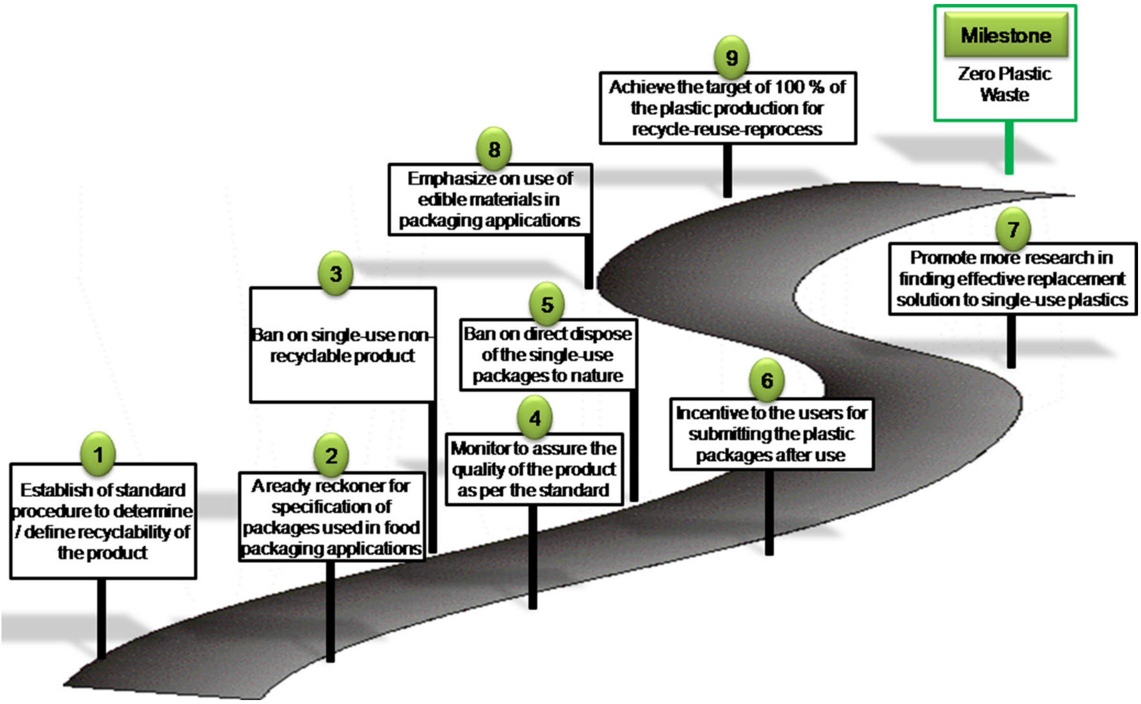

Fig. 3 Possible road map to mitigate the plastic waste issues

the product but at the same time contributes toxic chemicals as a migrant when used as food contact materials. Biopolymers can be one of the best alternative for developing packaging materials, cup, water bottles, spoons, and edible circuits etc. but has their own limitations. The mechanical durability and barrier properties of biopolymers still requires further investigation to make it more suitable material that can replace non-biodegradable SUP. Moreover, it is required to search for other resources to combat with the scarcity in availability for biopolymers.

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