Compostable Plastic
– On the Cusp of a Grand Arrival

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Out of 8,300 million tons of plastic produced globally between 1950 and 2015 only 2,600 million tons is still in use today including the 100 million tons of recycled plastics[1]. Out of 5,800 million tons of plastic used only once (most of it in packaging applications) 4,600 million tons was discarded and went straight to landfills and 700 million tons was incinerated. This represents 64% of the plastics produced between 1950 and 2015. India generates 25,940 tons of plastic waste every day, however more than 40% of it remains uncollected causing choking of drainage and river systems, littering of the marine ecosystem, soil and water pollution, ingestion by stray animals, and open air burning leading to adverse impact on human health and environment[2].

Seeking to make India single-use plastic-free by next year, the central government has proposed a ban on use of such items in two phases beginning January 1, 2022. In order to deal with the menace of huge uncollected plastic waste across the country, the government has also decided to increase thickness of polythene bags from 50 microns to 120 microns from September 30 this year. Manufacture, import, stocking, distribution, sale and use of all single-use plastic commodities will be prohibited under amended rules ahead of the celebration of 75 years of India's independence on August 15 next year.

Compostable plastics represent one of the environmentally friendly alternatives to replace single use plastics. ASTM defines those polymers as compostable that undergo degradation by biological processes (biodegradation) under certain conditions to yield CO_2, water, inorganic compounds and biomass at a rate consistent with other compostable materials (e.g. lignin-cellulose) and leaves no toxic residue. Compostable plastics are biodegradable, with an added benefit - they break down, to release valuable nutrients into the soil (compost), aiding the growth of trees and plants. All compostable plastics are biodegradable, but all biodegradable plastics need not be compostable. Certain biodegradable products can take several years to break down and, in some cases, even leave toxic waste behind.

The only sustainable solution is phase-out of petrochemical based single use plastics. The phase-out must be in conjunction with availability of alternative eco-friendly materials. The top of the list eco-friendly materials are bio-degradable & compostable plastic materials that can replace single use plastics from petroleum sources. These materials include starch-based plastics and other special grades of compostable plastics like PBAT, PLA, PBS, PCL, PHAs etc. Some of these biodegradable plastics are produced from biological sources like Starch, PLA and PHAs. Some like PBAT, PBS & PCL are produced from petrochemical sources but are completely biodegradable and compostable.

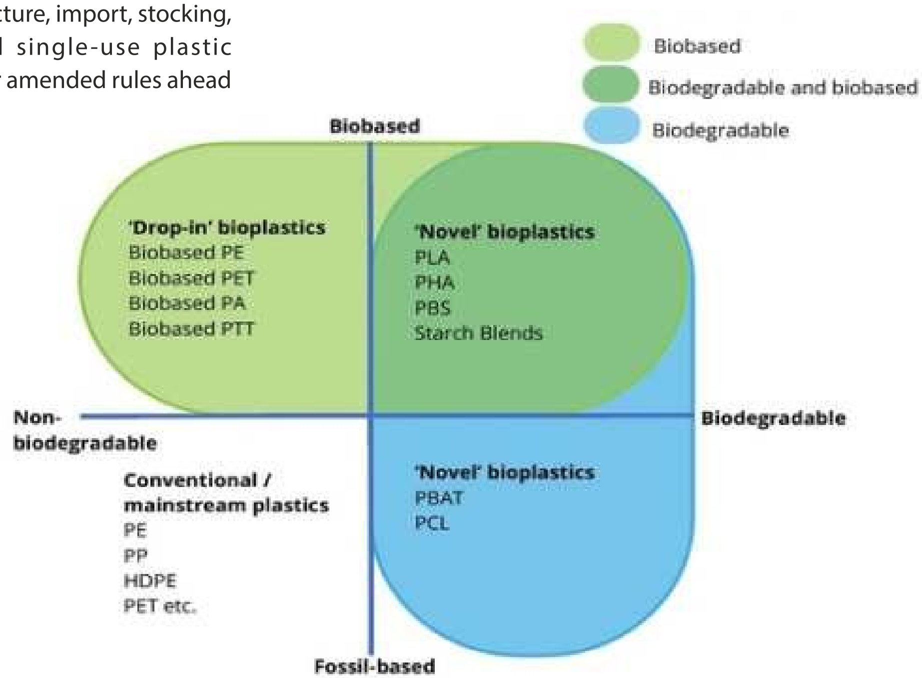

Figure 1: Conventional, Biodegradable and Bio-based plastics

Thermoplastic Starch (TPS) is produced from renewable agricultural products like corn starch and other variants like potato / cassava / tapioca starch --- non staple foods. TPS is a low-cost polymer and is blended with other compostable polymers to reduce cost, improve biodegradability & increase biobased content. Starch is made up of polysaccharides (linear & branched sugar molecules) that are readily attacked by microbes to provide a faster rate of compostability. TPS is blended with PBAT and PLA to produce compounds for end products like carry bags, shopping bags, garbage bags, packing of fruits & vegetables, packing of consumer products, agricultural mulch films.

PBAT or polybutylene adipate co-terephthalate is a biodegradable co-polyester produced by the random co-polymerization of 1,4-butanediol, adipic acid and terephthalic acid monomers. PBAT is a fully biodegradable & compostable alternative to LDPE, having similar properties including high flexibility and toughness, allowing it to be used for various packaging applications.

PLA or Polylactide (also known as Polylactic Acid) is a versatile biodegradable & compostable thermoplastic based on lactic acid that is produced from 100% renewable resources like corn, sugar cane, sugar beets etc. PLA can replace conventional petroleum-based thermoplastics like PE / PP / PS, due to the excellent combination of properties it possesses. PLA is blended with other bio-degradable plastics (like PBAT, TPC, PBS & PHA's) to improve its properties while keeping the blend completely compostable. PCL or Polycaprolactone is a completely biodegradable & compostable polymer produced by ring opening polymerization of caprolactone, a cyclic ester.

PHAs (Poly-Hydroxy-Alkanoates or polyhydroxy fatty acids) is a family of biobased polyesters that are suitable for even the most challenging convenience food applications. PHAs are biodegradable, readily compostable thermoplastics, produced by microbial fermentation of carbon-based feedstocks. The properties of PHA polymers are customizable to the application, depending on the specific combinations of different monomers incorporated into the polymer chain. PHAs can be produced from low cost industrial by-products like molasses / whey / raw glycerol and organic waste feedstocks like ligno-cellulosic crop by-products (rice husk, bagasse, rice bran etc.), vegetable waste (e.g. potato skin peels), vegetable oils / waste cooking oil and various other organic sources.

Depending on the type of PHA, they can be used for applications in films and rigid packaging, biomedical applications, automotive, consumer electronics, appliances, toys, glues, adhesives, paints, coatings etc. Beverage applications require polymers that maintain their properties when in contact with liquids up to 100 °C that PHA copolymers can easily sustain.

PBS or Polybutylene Succinate is a biodegradable and compostable polyester, which is produced from succinic acid, 1,4-butanediol and sometimes a third monomer which is an organic di-acid. New biotechnological routes now allow the production of succinic acid based on renewable feedstocks, such as glucose, sucrose and biobased glycerol. PBS is a crystalline polyester with a melting temperature exceeding 100°C, which is important for applications that require a high temperature range. Copolymers of PBS like PBST or Poly (butylene succinate - terephthalate) and PBSA or Poly (butylene succinate - adipate terephthalate) possess good biodegradability along with desirable physical properties.

For manufacturing & selling compostable plastic products one has to obtain a registration certificate / number from Central Pollution Control Board. The product must meet the BIS standard IS / ISO 17088 – 'testing standard for industrially compostable plastics' to obtain registration from CPCB. One of the main requirements of the test standard is that the plastic product should demonstrate satisfactory rate and level of biodegradation when tested in accordance with ISO 14855-1, ISO 14855-2 or ASTM D 5338 i.e. at least 90% of organic carbon in the polymer should be converted into CO_2 within 180 days. There are various other requirements under the standard. The other global standards for testing of compostable products are ASTM D6400 in North America and EN13432 in Europe. All these standards are similar in nature and practice.

Thermoplastic Starch, TPS / PCL & PHAs undergo biodegradation under all conditions (see Fig. 2) i.e. at

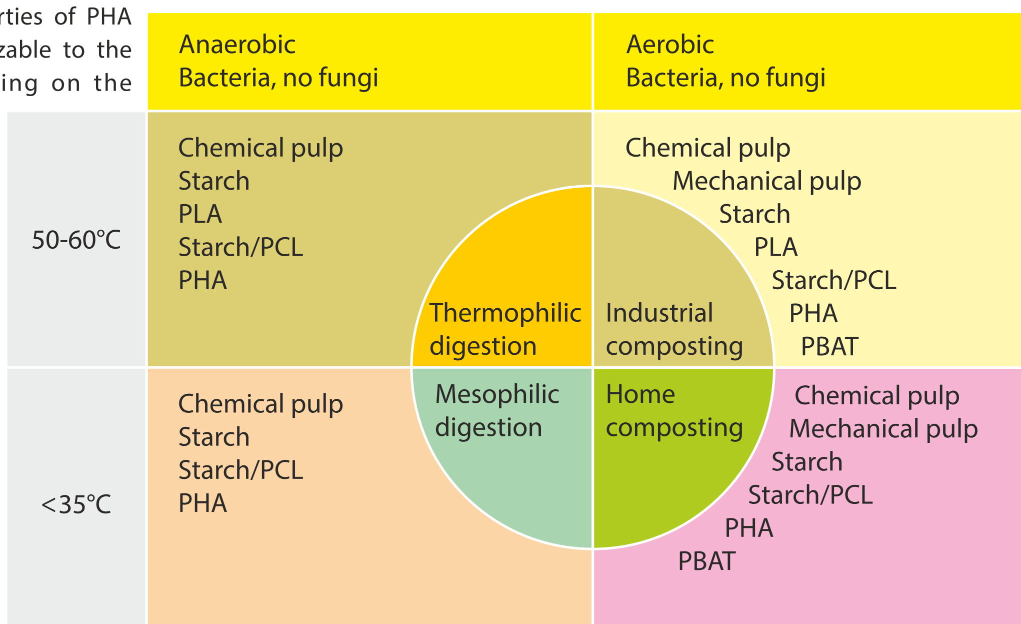

Fig. 2: Types of biological waste treatment of biodegradable polymers[3]

REVIEW WILEYONLINELIBRARY.COM/APP **Applied Polymer**

Polymer category	Polymer	Tensile strength (MPa)	Young's modulus (GPa)	Strain at break (%)	References
Polyesters	PCL	19-21	0.21-0.33	300-897	4,50
	PBAT	>84	0.04	>200	102
	PBSA (Bionolle)	20	0.44	20	106
	PLA	21	0.35	3	4
	PHBV	40	3.5	5	4
Protein	Wheat gluten[a]	1.86	0.004	58	103
Polysaccharides	Starch	5	0.13	31	4
	Cellulose	12-13	1.41-1.50	4-5	104
	Chitosan[b]	27-39	-	11-33	105

[a] Measured at 25°C and 70% RH.
[b] Measured at 25°C and 50% RH.

ambient temperature with or without oxygen and at elevated temperature again with or without presence of oxygen. However, some of the polymers like PLA & PBAT are mainly industrially compostable (aerobic at 50 – 60° C). Figure 3 provides comparative mechanical properties of the various biodegradable plastics. Some of the polymers like PBAT have very high flexibility whereas some like PLA have very high stiffness. Biodegradable polymer blends provide the best balance of mechanical properties – strength, flexibility & stiffness besides cost optimization suited for the end application.

<u>Market Scenario</u>

No reliable data is available regarding consumption of compostable plastic consumption in India. However, as per market sources the consumption of compostable plastic compound in 2019 was around 5,000 to 6,000 MT. This is expected to increase to 25,000 to 40,000 MT by 2025 depending on the implementation efficacy of the single use plastics ban as well as 120 micron thickness plastic film use in carry bags and packaging.

Bio-degradable / Compostable Plastics – Market Segments

<u>Market Segment 1 – Extrusion Blown Films</u>

- Largest in volume and sales
- Compound blends used – (i) PBAT + PLA, (ii) PBAT + PLA + Mineral Filler, (iii) PBAT + TPS, (iv) PBAT + PLA + TPS etc.
- Conventional uses - Carry bags, Shopping bags, Grocery bags, Apparel packing, Fruit & vegetable packing, Garbage bags, Agricultural film
- Specialized uses – Consumer goods / FMCG / Hardware / Electronics / Industrial packaging (all non-food)
- Other Specialized uses – e.g. PLA + PHA - metallized packaging for potato chips
- New materials – PHAs, PBS, PCL, PBSA, PBST (low availability and high cost)

<u>Market Segment 2 – Extruded products</u>

- Emerging market in India (will expand rapidly due to single use plastics ban)
- Materials – PLA blends with PBS / PCL / TPS / PBSA / PBST / PHAs etc.
- Extruded Sheet (0.3 to 1.0 mm thickness) for thermoformed products like plates, thalis, bowls, cups, glass etc.
- Extruded Drinking Straws
- Extrusion lamination on paperboard for disposable cups, plates, bowls, glass etc.
- High temperature resistant compound for hot beverage glass, hot food plates & bowls
- 3D printing filament compound
- PLA fiber and non-woven fabrics, cigarette filter buts

<u>Market Segment 3 – Injection Moulded products</u>

- Niche but growing market in India
- Materials – PLA compounds and blends with other bio-degradable plastics
- Injection moulded cutlery (fork, spoon, knife), small containers / bottles (toiletries)
- Injection moulded small containers / bottles for pharmaceutical usage

<u>New developments carried out:</u> Many have produced Thermoplastic Starch (TPS) on an industrial scale first time in India. TPS has been produced in bulk quantities and blended with PBAT & PLA to produce compounds for extrusion blowing of films. Due to the high cost and global shortage of PBAT / PLA, blending of TPS with these polymers presents an excellent opportunity to reduce cost, increase rate of compostability as well as increase the biobased content of the compound. One might argue that adding mineral fillers like talc / $CaCO_3$ to PLA / PBAT compounds can also reduce cost, but this will neither increase rate of compostability nor increase biobased content of the compound. Mineral fillers added to the compound do not produce compost. Mechanical properties of the blown film have been quite good for the various end applications. (see some examples of mechanical properties in Fig. 5).

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Property	PBAT 70% + TPS 30%	PBAT 60% + TPS 40%	PBAT 52% + TPS 48%
Tensile Strength (MD)	25 MPa	19 MPa	14 MPa
Elongation at Break (MD)	350%	200%	300%
Density	1.3 g / cm^3	1.26 g / cm^3	1.3 g / cm^3
MFI (190 °C at 2.16 kg)	9.0 g / 10 min	8.0 g / 10 min	18.0 g / 10 min
Melting Temperature (DSC)	119 °C & 126 °C	111 °C & 120 °C	117 °C

Figure 5: Extrusion Blown film from compound based on PBAT & TPS blend

Figure 6: TPS pellets

Figure 7: TPS + PBAT compound pellets

We have produced various types of compostable compound blends for the extrusion blowing of films. Some examples are PBAT + TPS compound, PBAT + PLA + TPS compound, PBAT + PLA + Mineral Fillers, PBS + TPS compound etc. We have also produced TPS + Polyvinyl Alcohol blend compound pellets and extrusion blown film on an industrial scale. The film is soluble in ambient and hot water and such bags / pouches can be used for dosing of detergents and chemicals. The TPS + PVOH blend film is biodegradable under action of certain microbes when dissolved in water.

We have produced PLA / PBAT blend compound with additives for extrusion coating on paperboard for making disposable tableware like plates, cups, glass, bowls etc. The lamination has excellent adhesion to paper / paperboard. We have also produced blend compounds for extrusion of rigid sheet (0.30 to 1.0 mm thick) for producing thermoformed articles like plates, cups, bowls, trays etc. These compound blends are made from PLA / PBAT and PLA / TPS with additives & fillers and are completely compostable. We have also produced filler masterbatch based on TPS & talc. We have recently produced 3 layer ABA type blown film with core layer blend compound rich in TPS and skin layer blend compound rich in PBAT. We have recently carried out trials to produce LDPE / TPS blend compounds that are partly compostable with excellent mechanical properties.

Figure 8: PBAT + TPS blown film

Figure 9: TPS + PVOH compound pellets

Figure 10: Examples of Laminated paper cups & thermoformed articles

Figure 11: Examples of thermoformed trays

Conclusion: As mentioned phase-out of petrochemical based single use plastics must be in conjunction with availability of alternative eco-friendly materials like compostable plastics / paper / cotton textile packaging materials. Within the alternative eco-friendly materials, compostable plastics provide wide range of end use applications whether flexible or rigid usage, water & moisture resistance, strength & tear resistance etc. Availability & cost of compostable polymer resin is an issue. However, with increasing global production capacity and start of local production these issues can be mitigated to a great extent. Another issue is the low number of industrial composting facilities in India. Local municipal corporations have been mandated to set-up & run industrial composting facilities. Perhaps private companies can also venture into industrial composting with tie ups with large users like quick format restaurants. In the end all stakeholders (consumers, brand owners, manufacturers, waste segregators, NGOs, composting facilities) have to join hands to make the ban on single use plastics a success.