Emerging Trend of Bio-plastics and its Impact on Society

Abstract

Plastics have been extensively used by humans since antiquity as a prime component of almost all the materials used in day to day life. Traditional plastics prepared from petroleum, coal and natural gas are non-biodegradable causing serious impact on the environment. The increasing global concerns for adverse impacts of traditional plastics have led to move towards the use of bio-plastics. There are a number of different types of bio-plastics available in the market derived from natural polymers like starch, cellulose, chitin etc. This mini-review discusses about different types of bio-plastics, their utility in different sectors and their fate in future emphasising on their applications and economics.

Keywords: Bio-plastics; Biodegradable plastics; starch; cellulose; protein; lipid; green polyethylene; polyhydroxyalkanoates; polylactic acid.

1. Introduction

Conventional plastics prepared from non-renewable petroleum oil not only take several decades for decomposition, but are also responsible for production of toxins during degradation **(Saharan et al., 2012**). With the growing human population, there is heavy accumulation of solid non-decomposable stuffs on the earth, of which, superfluous accumulation of plastics has become a major concern globally (**Gross and Kalra, 2002).** Considering ill-effects of traditional plastics, it is being realized to search innovative technologies to produce plastics from the bio-materials capable of degradation in the environment.

According to a report of the United Nations Environment Program, our oceans have become dump yards for non-degradable materials and presence of about 46000 bits of plastics/ square mile area has been speculated. In 1988, National Ocean and Atmospheric Administration declared the presence of huge scrap dump yards in pacific oceans which are of the sizes ranging from 0.7 million to 15 million square kilometres. These are the sizes equivalent to total sizes of many cities and also of countries (**Day et al., 1988**). Most of the marine debris deposited so far comprises of non-biodegradable plastics which further break down into smaller pieces. Long term durability, low cost, and malleability has encouraged the use of plastics for more and more consumers and industrial products (**Brassey and Charlotte, 2017**). According to reports, if plastic production and use grows at the current rate, then by 2030, the greenhouse gas emissions will reach to an alarming level up to the extent of total emissions by nearly 300 coal based power plants. With traditional non-degradable plastics, there may be emission of nearly 3 x 10^9 tons of CO_2 in the atmosphere after 30 years. It is equivalent to emissions by nearly 600 coal plants of 500 megawatts capacity (https://www.ciel.org/wp-content/uploads/2019/05/Plastic-and-Climate-Executive-Summary-2019.pdf).

Bio-plastics are made from bio-based materials like polysaccharides, lipids and also proteins. Alternatively, bio-plastics can be derived from natural biopolymers which are synthesized and catabolised by various microorganisms (**Braunegg et al., 1998**). But one of the major challenges faced by these polymers is to hold the strength and other properties as of petroleum based plastics in addition to have the capability to degrade in a shorter time and non-toxic to humans Currently, bio-plastics represent only one percent of the 335 million tons of plastic produced annually. According to reports, the global bio-plastics production capacity is set to increase up to nearly 2.6 mega tons by 2023 (**European Bio-plastics Report, 2018**). Several multinational companies have already begun using bio-plastics. There are reports that sneakers and bricks are being manufactured/ planned using corn stuff and sugar-cane by Reebok and Lego, respectively. Similarly, bio-plastic bottles are also being used by renowned soft drink companies. The need of the hour is to switch towards eco-friendly manufacturing and utilization of plastics for a greener and healthier future. Assessing the need of bio-plastics, work is in progress in our laboratory on isolation of polyhydroxyalkanoates producing bacteria. In the present review, an attempt has been made to describe the research work being carried out for different types of bio-plastics, their utility/applications in various sectors and economics involved. Besides, a comparative account of traditional plastics and bio-plastics and the present status of commercial production of various types of bio-plastics have been discussed

2. Types of bio-plastics

In 1850, a British chemist created plastic using cellulose derived by wood pulp which was termed as bio-plastic. In the later years, plastics produced from soybean were tested as an alternative to fossil based plastics **(Reddy et al., 2013).** Since then, much interest is being exhibited for manufacturing of plastics from plant derived materials owing to rising environmental concerns on the pollution caused by plastics. The European Bio-plastics Organisation has classified plastics into different families as outlined in Fig. 1. Bio-plastics can be defined as a family of materials with varying properties chiefly derived from bio-based materials and must get degraded fully into CO_2, H_2O and other inorganic substances (**Song et al 2009**). Demand for pro-nature materials is increasing day by day and an annual growth rate of 10 to 20% is being expected (**Kumar and Thakur, 2017**). Bio-plastics derived from biodegradable polymers are broadly either plant based polymers viz. protein, cellulose, starch and chitin, or microbes derived polyesters like polyhydroxyalkanoates

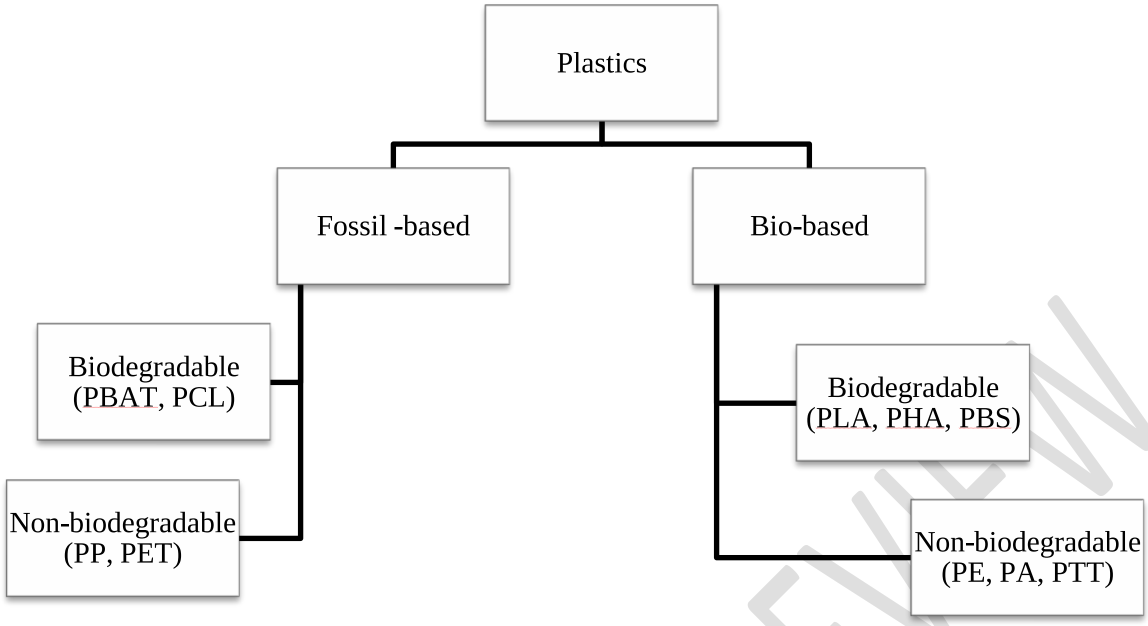

Fig. 1: Classification of plastics based on their composition and degradation. PBAT-polybutylene adipate terephthalate; PCL- polycaprolactone; PLA-polylactic acid; PHA-polyhydroxyalkanoates; PBS-polybutylene succinate; PP-polypropylene; PET-polyethylene terephthalate; PE-polyethylene; PA-polyamide; PTT-polytrimethylene terephthalate.

2.1 Starch-based bio-plastics

In recent times, thermoplastic starch has become one of the most widely used bio-plastic covering nearly 50 percent of the bio-plastics market (**Gadhave et al., 2018**). Starch is one of the abundant polysaccharide present on earth synthesized by plants as an energy storage material. Corn is the main cash crop enriched in starch and grown globally (**Asaf, 2008**). Pure starch has ability to absorb humidity promoting its use for producing drug capsules in the pharmaceutical industry. Moreover, flexibilisers and plasticisers such as sorbitol and glycerol can be easily added to starch to create a diverse range of products having varying characteristics (**Reddy et al., 2013**).

In the present trend, blending of starch is done with other bio-polymers like polylactic acid, polycaprolactone or polybutyleneadipate-co-terephthalate to prepare bio-plastics (**Khalid et al, 2017**). The plasticware are being manufactured on the commercial scale out of these starchy blends and the same have been found to be degradable. **Saraswat et al (2014)** reviewed the status of bio-plastics derived from starch. **Gadhave et al (2018)** discussed starch based bio-plastics and their importance in sustainable packaging.

2.2 Cellulose-based plastics

Cellulose is known to be one of the most abundantly available natural polymer and is obtained from wood pulp or cotton linters by delignification. For preparing cellulose bio-plastics, cellulose esters like cellulose acetate, nitrocellulose and their derivatives, and celluloid are mostly used (**Hossain et al, 2016; Mostafa et al, 2018**). Some of the cellulosic derivatives like hydroxypropyl cellulose, hydroxypropyl methylcellulose and carboxymethyl cellulose are used to form films or edible coatings (**Majid et al, 2018**).

2.3 Chitosan-based plastics

Chitin is a polysaccharide having N-acetyl glucosaminyl moieties linked through β-1, 4 linkages. It occurs mainly in skeletons of invertebrates like arthropods and has also been reported in the cell wall of various fungi including yeast. At commercial level, it is extracted from prawns and crabs wastes using chemical methods. Chitosan obtained from deacetylation of chitin can form films without addition of any additive, which exhibit good carbon dioxide and oxygen permeability, as well as have excellent mechanical properties (**Thakur et al, 2016**).

2.4 Protein-based plastics

Bio-plastics can be made from proteins like gluten, zein, soy protein, keratin and gelatin etc. isolated from different sources. Most of the proteins derived from different sources like wheat gluten and milk casein are shown to be good candidates for the manufacture of degradable plastics (**Song et al, 2009**). Proteins can serve as potential candidates for producing bio-plastics due to their renewable nature, biodegradability and excellent gas barrier properties. However, the hydrophilic character of proteins restricts their use for commercialization. Therefore, blending of these proteins with other biodegradable polymers is recommended or changes in the physical properties of these proteins must be carried out using either chemical or microbial method(s) (**Majid et al, 2018**).

2.5 Polyhydroxyalkanoates (PHAs) based bio-plastics

The aliphatic bio-polyesters which have been used for manufacture of bio-plastics are poly-3-hydroxy butyrate (PHB), polyhydroxyvalerate (PHV) and polyhydroxylhexanoate (PHH). These polyesters belong to the group, polyhydroxylalkanoates (PHAs). Many researchers including our laboratory are engaged in carrying out research on the microbes producing these PHAs.

The PHAs are linear polyesters which are produced by bacteria as a result of fermentation of sugars or lipids. These PHAs act as a source of energy and carbon for the bacteria. In PHAs, many different monomer units may be present and depending on the monomer units, these polyesters exhibit different characteristics. The PHAs derived plastics have been found to be more ductile and lesser elastic compared to other plastics. These bio-plastics have also been found to be bio-degradable. The PHAs derived plastics have found their place in pharmaceutical industries.

Current research activities are dedicated towards making PHA biopolyesters marketable. In recent researches, emphasis is on searching new microbes capable of producing PHAs and their manipulation/ exploitation for better yield and also production of highly efficient biomaterials from advanced manufacturing techniques (**Koller, 2020**)

The commonly used PHA for bio-plastics is PHB which is produced by specific bacteria using corn starch, glucose or wastewater. The PHB derived plastic exhibits properties similar to petroleum oil derived plastic having polypropylene. The PHB- bio-plastic may be exploited for manufacturing transparent film having melting point nearly 130^{o}C and is bio-degradable. In developed countries, sugar based industries have come forward to manufacture PHB on an industrial scale.

2.6 Polylactic acid (PLA) derived bio-plastic

The PLA derived bio-plastic is transparent and it also exhibits properties similar to petroleum oil derived plastics like Polyethylene terephthalate (PET) plastic, polystyrene plastic (PS) and polyethylene (PE) plastic. In addition to PLA derived bio-plastic, PLA blends plastics are also available in the market in the form of granules having different properties. These PLA and PLA blends bio-plastics have been used for the manufacture of fibres, films, cups, bottles etc. The PLA derived bio-plastic is also available as plastic filaments.

2.7 Polyamide (PA) derived bio-plastic

The polyamide (PA) is also a biopolymer produced from natural oil. However, it is not bio-degradable. The PA derived bio-plastic has more thermal resistance and has been used in the manufacture of various items like sports shoes, electronic device components, flexible oil and gas pipes, anti-termite sheathing, automobile fuel lines, pneumatic airbrake tubing etc.

A specific polyamide called as polyamide 410 has been derived from castor oil which has high melting point (more than $200^{o}C$), low moisture absorption and much higher resistance to chemical substances **(Chen et al, 2012)**

2.8 Green Polyethylene (PE) derived bio-plastic

The polyethylene has ethylene moieties in its structure. Petroleum based polyethylene is used since long time. Nowadays, green PE is also available. For green PE, ethylene is derived from ethanol and ethanol is produced mostly by using ligno-cellulosic biomass (second generation bio-fuel). Green PE is similar in properties to chemically derived PE. Similarly, like chemically produced PE, green PE is also not biodegradable but is recyclable. It has been found that in production of green PE, there is much decrease in greenhouse gas emissions. Green PE derived bio-plastic can be used for packaging, closures, bags etc.

2.9 Genetically modified bio-plastics producing bacteria

To the best of authors' knowledge, at present, no genetically modified bacteria is used for production of bio-plastic. However, much work is in progress where people expect to exploit genetically modified crops or bacteria for production of bio-plastic. **Carroll et al (2018)** reviewed strategies of genetic modification in *Cyanobacteria* to enhance PHB production.

2.10 Lipid derived bio-plastic

A number of polymers like polyurethanes, polyesters, epoxy- resins have been prepared using fats and oils isolated from plants as well as animals. These polymers are used for manufacture of bio-plastics. These polymers are also prepared using petroleum oil. Both types of polymers have comparatively similar type of properties. Therefore, there is emphasis on plants and animals derived polymers (**Meier et al, 2007, Pillai et al, 2017; Can et al, 2001, Stemmelen et al, 2011).** A metathesis approach for preparation of polymers from plant oils is considered to be important for bio-plastic production. On the other hand, recent advances in microalgae production enriched with oil may be exploited for bio-production of polymers used in bio-plastic preparation (**Meier et al, 2009**, **Mata et al, 2010**).

2.11 Seaweed polysaccharide based bio-plastics

In recent years, polysaccharides such as alginate and carrageenan derived from marine algal species like *Macrocystis, Laminaria, Chondrus, Mastocarpus* are considered as potential candidates for bio-plastic production. Alginate is an un-branched polysaccharide having mannuronyl and guluronyl moieties joined through β-1,4 glycosidic bonds. It. is widely used in biomedical applications. The blend of calcium alginate and polyacrylamide has been reported to exhibit strength, and therefore is capable to serve as an environment friendly packaging material in future. Another seaweed polysaccharide, carrageenan is also a good raw material for bio-plastic. It is made of β-1.4 glycosyl bonds linked disaccharide units having α-D-galactopyranosyl and β-D- galactopyranosyl moieties. Carrageenan has double helical coil in its structure which shares anion-hosting position and facilitates rigidity in bio-plastic formation. The bio-plastics from this seaweed polysaccharide can be considered as good edible packaging material and serve as excellent food coating material in the future market **(Zhang et al, 2019).**

3. Current utility of bio-plastics

3.1 Packaging

The packaging industry is one of the biggest marketing segments of bio-plastics accounting for 53% of the annual production. In recent years, manufacturers of various agriculture related materials like plantlets, manures, agricultural foils and horticultures; cosmetics; toys; alcoholic drinks; and clothing use bio-plastics derived packaging materials. Alternatively, they are used for packing of disposable utensils including cutlery, cups and plates etc. Besides, they are also being used for wrapping material in food industry **(Ashter 2016).** Numerous multinational companies manufacturing soft drinks, ketchups and mineral water have started using polyethylene terephthalate derived bio-plastic bottles. Various fast moving consumer goods (FMCG) companies like Johnson & Johnson and Procter & Gamble have started using bio-based PE for packaging of cosmetic products. Several studies have reported that use of PLA for food packaging is found to be more efficient than conventional PET plastics as there is minimal change in food coloration, ascorbic acid degradation with reduced limonene scalping **(Koide and Shi, 2007, Almenar et al., 2010).** Currently, McDonald's, Frito-lay, Mont Blanc Primeurs, McCain are using PLA based plastics for packaging food materials.

3.2 Bags

As per estimate, there is an annual use of about five million tons polybutylene succinate for manufacturing shopping bags worldwide. On an average, sixty thousands polybutylene succinate is used every five seconds **(Sabbah and Porta, 2017)**. With increasing awareness about the cons of single-use high density plastic bags, biodegradable or compostable shopping bags are turning out as a superior substitute being environment friendly. These bags are usually made of resins composed of starch, polyethylene and heavy metals or starch combined with biodegradable polymers such as PLA. Another category of bags are oxo-biodegradable containing totally degradable plastics additives (TDPA). These additives are known to speed up the biodegradation process by oxidation. Companies like PepsiCo, Snyder's of Hanover, Delhaize now use PLA based bags instead of conventional bags.

3.3 Disposable houseware

Biodegradable plastics have been used in manufacturing of disposable houseware including items used in washroom such as buckets, mugs, soap holder, bottle containers for shampoos, moisturizer, conditioners, shower gels etc, utensils like knives, forks, spoons, bowls etc, hangers etc. Fantastic Beach toys are made of Mirel bio-plastic derived from corn manufactured by Zoë b Organic. Cereplast is a biodegradable resin marketed under the brand name Nat-Ur, made from corn and potato starch is used for manufacturing of cutlery (http://www.treehugger.com/clean-technology/compostable-cutlery-made-from-cereplast.html). The company 'NaturBag' sells bio-plastic derived cutlery with a trade name 'Natur-Ware'. (http://www.naturbag.com/biobased-compostable-cutlery). United Colors of Benetton have started using 100% recyclable biodegradable hangers (http://www.ecouterre.com/benetton-gets-greener-withbiodegradable-hangers-organic-cotton-garments/)

3.4 Agricultural applications

Bio-plastics have been used for the production of agricultural mulches, seeding strips, and tapes [**http://en.europeanbioplastics.org/market/applications/agriculturehorticulture**]. The bio-plastic has also been used in the manufacture of seed belts and active component capsulations. Bio-plastic derived foils and nets are also available nowadays which are used to cover mushroom plants, tree and bush-roots. Besides, these nets and bio-based yarns have also been used to avoid erosion of slopes and mounds till roots of the plants grow well.

3.5 Consumer electronics

In electronics market, there are reports that SUPLA has optimized polylactic acid compounds derived from lactides developed by Corbion Purac. The company has attempted to develop world's first bioplastic high gloss touch screen computer made from high heat PLA in collaboration with a Taiwanese Original Equipment Manufacturer (OEM)/original design manufacturer (ODM), Kuender. Besides, PLA blends are also being used for manufacturing of computer monitor screens, ~~computer~~ keyboards, laptops, computer tablets etc and also games consoles, mobile phones and ear phones etc. The use of bio-plastics in the electronic industry has proven to be beneficiary in terms of environmental credentials. Moreover, there became improvement in many properties like gloss finish, impact resistance and precise processing of these electronic products (**http://www.plasticstoday.com/articles/k-2013-pla-bioplastic-debuts-touchscreen-computer-housing**).

3.6 Medical Devices

Bio-plastics derived from PLA and PEG have found their uses in many biomedical fields like manufacture of orthopedic devices, wound filling, drug delivery, tissue engineering, manufacture of porous and fibrous scaffolds. These bio-plastics have proved to be better due to better storage modulus, bio-resorbable property, crystalline nature and transition temperature **(Bano et al., 2017)**. Nontoxic biodegradable polymers are also being used in sutures, implants, dental devices, screws, staples, pins, tacks etc. It has been shown that these bio-plastic based sutures stay intact upto the completion of healing of tissues, get dissolved and also get completely metabolized inside the body. TYRX is a biodegradable tyrosine-derived polyarylate marketed by TyRx Pharma, Inc. and is used in a hernia repair device. It acts as an absorbable antibacterial envelope. ParietexProGrip™ is a first bio-component mesh used for laparoscopic self-fixation that facilitates tension-free repair **(Ashter, 2016).**

4. Commercial production of bio-plastics

The speed of change in the production of bio-plastics space for utility in various disposable or non-disposable items revealed that there is not much difference between the costs of petroleum derived plastics and bio-based plastics. The higher cost of the latter is attributable to requirement of lower temperature in processing bio-plastics and constant supply of biomass. Production of biopolymers is gaining impetus nowadays because of their sustainability quotient and industries are trying to utilize waste materials as a source for production of bio-based plastics. This accounts for a revolutionary move, synergizing environment conservation and economic benefits. Further it can help in reducing current oil consumption, as plastic production leads to 4% consumption of the worldwide oil reserves every year. Moreover, increasing oil scarcity is contributing to a sharp increase in prices of petroleum based materials. Thus, it is inevitable that large-scale industrial production of bio-plastics will take over the conventional plastics in time to come. An account of various bio-plastics with cost of production has been given in Table 1.

Company	**Origin**	**Type of Bio-plastic**	**Cost (Eur/kg)**	**Applications**
Novamont	Italy	Mater-Bi starch based resins	3.4-5.1	Filming, Thermoforming, Fillers
Arkema	France	PA10, PA11	2.5-6.9	Thermoforming, Bottle blow molding, Injection molding
Yield10 Bioscience	USA	PHA, PHB		Water treatment
Neste	Germany	Bio-based polyethylene and Bio-based polypropylene		Food packaging materials
NatureWorks	Thailand	PLA	1.5-2.0	Extrusion, Thermoforming, Injection Molding, Films, Cards
Natur-Tec	USA	PLA		Extrusion, Injection Molding, Films, Apparel Packaging

Table 1: Various bio-plastics being manufactured commercially along with their applications (Source: OECD (2014-09-29), “Biobased Chemicals and Bioplastics: Finding the Right Policy

Balance", OECD Science, Technology and Industry Policy Papers, No. 17, OECD Publishing, Paris. http://dx.doi.org/10.1787/5jxwwfjx0djf-en)

5. Bio-plastics versus traditional plastics

Traditional plastics have become a menace for the society due to their ill-effects exhibited on the environment and ecosystem. Due to harmful effects and alarming environmental pollution, many countries like Tunisia, China, Korea, Bangladesh, India etc. have taken the lead to put a ban on single-use plastics. It is expected that more countries will come forward in putting the ban on single-use plastics. As a result of new rules and legislations, the role of environmentally and economically viable bio-plastics has become important. Considering the market demand, it is being speculated that more industries will come forward for manufacturing biodegradable plastics/ bio-plastics.

Conventional plastics are dependent on fossil fuel as a key raw material. The price of petroleum oil has been tremendously increased in recent years and the available stock is likely to exhaust in the near future. In addition, these plastics require comparatively higher energy during the development process as compared to bio-plastics. Studies have reported that typical petroleum based plastic shows much higher carbon dioxide emissions compared to PLA derived bio-plastic **(Reddy et al, 2013)**. On the other hand, bio-plastics which are prepared from sustainable raw materials like ligno-cellulosic biomass and vegetable oils have been globally accepted as a greener alternative for replacing petroleum based plastics **(Gill, 2014).** With equivalent strength and versatility as that of traditional plastics, bio-plastics have made a mark in various sectors like packaging, wrapping, medicines, textiles, agriculture etc. In USA, McDonald Group has started manufacturing biodegradable containers for their fast foods. Similarly other companies such as Bayer, DuPont, Dow Cargill and Nike have also started producing biodegradable packaging materials. Likewise in India, various companies like Envigreen, Ecolife, Plastobags, Earthsoul India and Truegreen have ventured in manufacturing a variety of bio-plastics.

Evolution of bio-plastics across the world in past few years has brought a positive change in environment conservation and is the first step towards a greener environment. Although the potential of bio-plastics is still not fully explored, but looking to the demand of plastics in every sphere of life, it is destined to take over the traditional plastics in future. Various International Committees including Committee of Agricultural Organization in the European Union (COPA) and General Committee for the Agricultural Cooperation in the European Union (COGEGA) have assessed the potential requirement of bio-plastics and it has been predicted that it is increasing year by year. As per a prediction, there will be requirement of nearly six billion tons of bio-plastics by 2021. However it is also important to note that all bio-plastics are not compostable and may require industrial treatment while the recycling treatment of bio-plastics must be separated from the conventional plastics which could otherwise lead to environmental hazards **(Arikan and Ozsoy, 2015).**

6. Conclusion

Increasing environmental pollution and its consequences by way of carbon foot-prints, continuous depletion of petroleum oils on earth, non-biodegradability of traditional plastics has imposed serious threat to the planet. Single-use petroleum based plastic is being banned in various countries and it is the right time for bio-plastics to emerge as a substitute thereof. Considering the requirements, present industrial production of bio-plastics and awareness in the society, it can be said that there is a vacuum which must be filled by promoting the commercial production.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that no competing interests exist. The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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