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Review

Overview of Bioplastic Introduction and Its Applications in Product Packaging

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Abstract: Each year, more than 330 million tons of plastic are produced worldwide. The main consumers of plastics are the packaging (40%), building (20%) and automotive (8%) industries, as well as for the manufacture of household appliances. The vast majority of industrial plastics are not biodegradable and, therefore, create environmental problems due to the increase in the amount of solid waste. Studies have been conducted to produce biodegradable materials such as bioplastics to overcome this environmental problem. Bioplastics are defined as materials that are bio-based, biodegradable, or both; they can provide excellent biodegradability and can be used to help alleviate environmental problems. Therefore, this article presents an overview of the introduction of bioplastic materials and classifications, and a comprehensive review of their drawbacks and areas of importance, including basic and applied research, as well as biopolymer mixtures and biocomposites developed in the last decade. At the same time, this article provides insights into the development of bioplastics research to meet the needs of many industries, especially in the packaging industry in Malaysia. This review paper also focuses generally on bioplastic packaging applications such as food and beverage, healthcare, cosmetics, etc.

Keywords: bioplastic; plastic; packaging; biodegradable; biocomposite

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1. Introduction

Plastics are a wide class of polymer composites that use polymers as a major ingredient. The class of synthetic polymers includes polyethylene (PE) (used in plastic bags), polystyrofoam (PS) (used in styrofoam cups), polypropylene (PP) (used in fiber and bottle), polyvinyl chloride (PVC), and polytetrafluoroethylene or Teflon (PET) (used in food packages, bottles and drain pipes) [1]. Meanwhile, semi-synthetic polymers are obtained from natural polymers by subjecting them to a chemical process; this includes natural materials which have been modified and combined with other materials. An example of this is cellulose acetate, a reaction product between cellulose and acetic anhydride used to make films [2]. The plastics are made of carbon and hydrogen. In addition, the plastics can contain other elements, such as sulfur, silicon, chloride, fluorine and phosphorus. Plastic is manufactured in various forms and is a material that can be adapted for many different applications. In addition to the cheap production process, this suitability, combined with a variety of beneficial properties such as light, durability and flexibility has led to widespread use in today's society. As far as product packaging is concerned, packaging plays a role in product holdings and food safety for the food industry [3].

All plastics can be divided into two main categories, thermosetting and thermoplastics, according to their reactions to heating [4]. Thermoplastics are plastics that can be melted and molded by heating, and when cooled, take the shape in which they were formed. If the formed thermoplastic is reheated, it softens and melts again. Known thermoplastics are polyacrylates, polyesters, polyolefins, polyamides, etc. These polymer materials are used to produce packaging, disposable utensils, carpets, laboratory instruments, clothing and other goods. In contrast to thermoplastics, thermosetting plastics are irreversibly hardened by curing from soft solid or liquid resins. Curing is induced by heat or radiation and may be promoted with the addition of catalysts (hardener). Heat does not need to be applied externally, because it is often generated by the reaction of the resin with hardener. Curing results in chemical reactions that create cross-linking between polymer chains to produce an infusible and insoluble network. If the cross-linked thermosetting plastics are reheated, they will not soften or melt, but will remain in the form in which they were formed. Typical examples of thermosetting resins are liquid polyesters used in fiberglass products and melamine-formaldehyde resins used in Formica-based kitchen worktops [2].

Most modern plastics are synthesized from fossil petrochemicals such as natural gas or oil. However, such plastics are resistant to biodegradation and, therefore, their widespread use leads to the accumulation of a huge amount of plastic waste. According to a 2016 plastic industry report [5], global plastic manufacture has expanded by 8.6 percent each year since 1950, from 1.5 million tonnes to more than 330 million tonnes. Non-decomposed plastic enters our ecosystem and pollutes the environment, reduces soil fertility and leads to the death of millions of animals [6].

Recently, the industry has started using natural and renewable materials such as fats and vegetable oils, gluten [7], egg white protein [8] and sago starch [9,10] in the manufacture of plastic to produce bioplastic. Bioplastics are defined as materials that are bio-based, biodegradable, or both. This approach substantially decreases the total carbon dioxide balance as the CO_2 emitted during the processing, usage and recycling of plastics is balanced by the CO_2 absorbed during the plant growth cycle. Moreover, petroleum, at a continuously increasing price, being substituted by renewable raw materials from agriculture, is very economical [11]. Bioplastics can also be generated using bacterial micro-organisms and often nanometer-sized particles, particularly carbohydrate chains (polysaccharides) [12]. Bioplastics are an important necessity now in many industrial applications, including food processing, agriculture, compost bags and sanitation. However, bioplastics have poorer values, unlike their synthetic counterparts. Therefore, much research is being carried out on exploring new green polymer materials to fulfil the increasing market for bio-based and biodegradable polymers.

At present, many scientists and engineers worldwide are very interested in bioplastics because of their vulnerability and water exposure, lack of good relation, a low melting point relative to plastic petroleum [13]. However, the development of bioplastics is hampered by higher costs of production compared to traditional plastics [11]. They cost two to three times as much as conventional plastics, and their manufacture is plagued by low yields and high costs. Some bioplastics have a shorter lifetime than oil-based plastics due to poorer mechanical features, such as more water vapour permeability than conventional plastic, being easy to rip like tissue paper, being very brittle, and having poor mechanical and barrier capabilities [14]. Thus, the production of additives, such as polymer and composite mixtures, to enhance biodegradability is typically explored in order to make bioplastics sustainable and to boost their properties. Where polymer composites or biocomposites are used, different forms of fillers are also researched, including inorganic fillers (e.g., calcium carbonate and nanoclay) and natural fibers (wood and plant fibres) [15]. Currently, numerous studies use plant waste as a biofiller. Bashir and Manusamy [16], for example, utilized widely available sugarcane bagasse fibre as a biofiller to improve the mechanical characteristics of recycled poly(ethylene terephthalate) (PETr). Furthermore, nanomaterials such as nanoclay have been employed to improve the thermal stability of starch-based bioplastics [17]. According to Harunsyah et al. [18], a bioplastic made from cassava starch, clay nanoparticles, and the plasticizer glycerin exhibited intriguing mechanical features such as transparency, clarity, homogeneity, flexibility, and ease of handling. Furthermore, the interfacial bonding between the biofiller and polymer matrix influences the polymer matrix's characteristics. It has been discovered that biofiller-reinforced polymer composites have greater mechanical characteristics than unfilled polymer [19]. Therefore, this paper provides some insights on various approaches for the study of bioplastics and biocomposites, especially in food packaging applications. This review article also focuses primarily on exploring all possible uses of natural fibers with a view towards implementation in the bioplastic industry through sustainable engineering technology.

2. Description on Bioplastic—Definition, Biodegradability and Classification

Most researchers classify a material as a bioplastic if it is bio-based, biodegradable, or both [12]. In addition, there is also a definition of bioplastics as polymers that can be decomposed into CO_2, H_2O and inorganic compounds or bio-mass, mainly through the enzymatic effects of microorganisms. Actually, the term bio-based refers to products that are derived from biological material made from biomass. This means that the phrase "bio-based" refers to materials or products that are made entirely or partially from renewable resources (biomass); for example, in common plastics, the petrochemical resin is replaced by animal or vegetable polymers, and compounds such as glass or carbon fiber are replaced by natural fibers such as wood fibers, hemp, flax, sisal, and jute [15].

According to Geueke [20], polymers are extracted directly from biomass (e.g., starch and cellulose) or generated by microorganisms in fermentative processes (e.g., polyhydroxyalkanoates (PHA)) using an appropriate carbon source. Plant biomass can also be transformed chemically or biocatalytically into building blocks for other polymers (e.g., polylactide (PLA) and polyolefins), as shown in Figure 1. Biobased products, on the other hand, do not have to be made entirely of renewable sources; they can also incorporate fossil fuel-based raw materials. Carbohydrate-rich food crops, such as corn or sugar cane, are widely used to make biobased polymers. Non-food crops, such as lignocellulosic material, can be converted into chemical building blocks that can be used to make a range of bioplastics. Currently, this technique is not economically viable, but it could be a beneficial solution in the future. Bioplastics have also been made from animal biomass (e.g., whey and chitosan) as well as protein- or oil-rich plant biomass (e.g., soy protein isolate and castor oil).

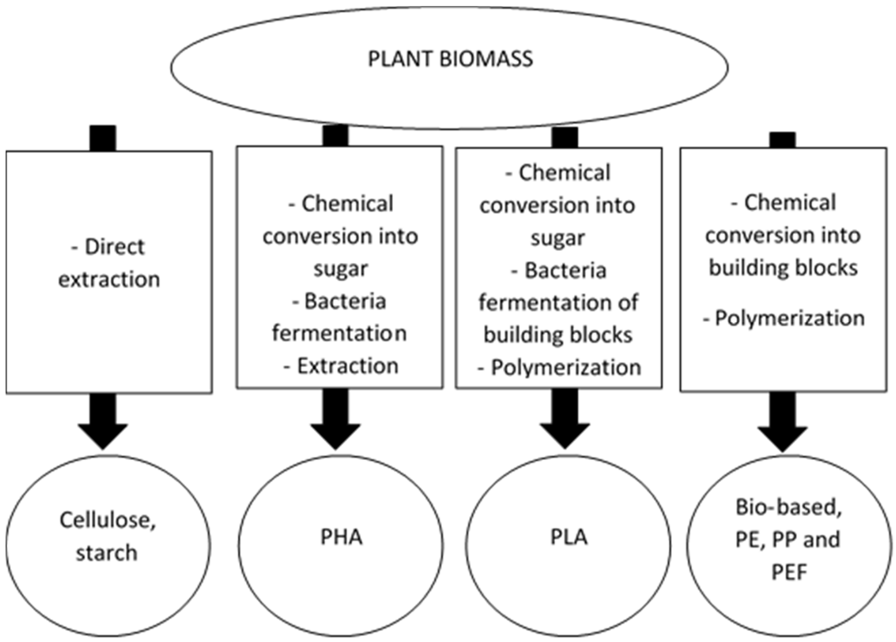

Figure 1. Bioplastic processing routes dependent on plant biomass. Data adapted from [20].

Therefore, bioplastics refer to innovative bio-based plastic polymers such as PLA (polylactic acid), PHA (polyhydroxyalkanoates), PHB (polyhydroxybutyrate), and starch blends, as well as microbial polymers such as polynucleotides, polypeptides, and polysaccharides. The majority of bioplastic products on the market today are made from first-generation feedstocks such as corn, sugar cane, castor oil plant, potato, or wheat. The technical maturity of these feedstocks is very high [21]. Feedstocks that are not suitable for food or animal feed are included in the second generation. These can be non-food crops (for example, cellulose) or byproducts of first-generation feedstocks such as corn stover or sugarcane bagasse. The usage of second-generation feedstocks is still in its early stages of commercialization. This is because the conversion of these feedstocks is relatively expensive. The current most innovative feedstocks, which are still in the early stages of development, are included in the third generation. It is made up of algae biomass as well as industrial or municipal waste [22].

Meanwhile, biodegradability is caused by biological processes during composting and yields carbon dioxide, water, inorganic compounds, and biomass at a rate similar to that of other known, compostable materials, and leaves no other recognizable or hazardous residue [23]. Similarly, compostable plastic is biodegraded in industrial composting facilities and must meet strict standards [24]. Most of the bioplastics are renewable materials. Therefore, bio-plastics are bio-based materials. Non-bioplastics are known to be petroleum-driven plastics [25]. Bioplastic materials can have a wide range of biodegradability percentages and can be obtained from a wide range of renewable and non-renewable sources; hence, numerous classification systems based on different criteria have been developed to separate them.

Some plastics can be made with the same polymer chains using renewable resources. The terms of renewable resources are resources that can be used multiple times when they are replaced naturally. For example, using agricultural products and microorganisms, fermentative biotechnological processes can produce polyhydroxyalkanoates (PHA) and lactic acid (raw materials for PLA) [26]. Then, PHB is a natural polymer produced by many bacteria as a means of storing carbon and energy. Because it can be synthesized from renewable low-cost feedstocks and the polymerizations are carried out under mild process conditions with minimal environmental impact, this polymer has piqued the interest of researchers and businesses all over the world [27]. In addition, other resources are considered renewable, but time or commitment is required to renew them (e.g., wood, oxygen, leather, and fish). Many useful metals may also be renewed. In essence, renewable resources have infinite reserves, such as solar energy, wind energy, and geothermal pressure. A nonrenewable resource is a substance that is depleted faster than it can be replaced. It has a limited quantity. Most fossil fuels, minerals, and metal ores are nonrenewable resources. Even if precious metals are not naturally substituted, they can be recycled because they are not destroyed during their extraction and use [28]. Instead, metal oxide-based nanoparticles, such as calcium carbonate, have typical metal resistance characteristics. In recent years, researchers have opted to combine the flexibility of plastic with the mechanical strength of inorganic oxide to create a material that is extremely adaptable and suited to forming various forms of packaging [29]. The bioplastics that arise are chemically identical to their fossil counterparts. PET, for example, short for polyethylene terephthalate, which is used to make most bottles, can be manufactured from fossil fuels or plants such as sugarcane. The final substance is the same [30]. The European EN 13432 standard is one of the most well-known standards of biodegradability [31]. As shown in Figure 2, if the product meets the standards, it will be labelled as a compostable product.

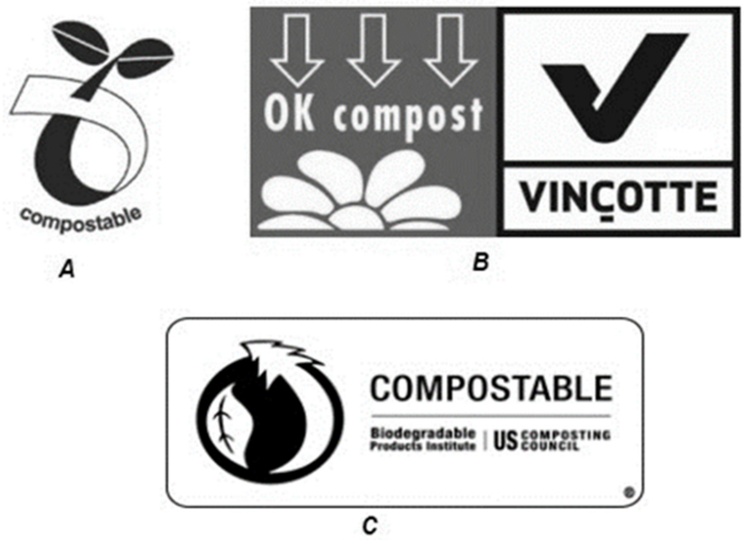

Figure 2. Examples of Logos certifying a material's compostability in EU countries: The (**A**) "Seedling" and (**B**) "OK compost" logos are issued by DIN CERTCO and Vincontte, and (**C**) the "compostable" logo is issued by the Biodegradable Plastic Institute in the U.S. Sources: [21].

It can be inferred from the study that bioplastics made from bio-based polymers can be categorized under two terms, either biodegradable according to the existing standard rules and referred to as compostable material, or another class of biodegradable bioplastic that does not conform to the established standards and is labelled as non-compostable material. However, there is another degradation process that is known as oxo-degradation. These oxo-biodegradable products do not degrade under the aforementioned standards and are not actually biodegradable or compostable (Figure 3). For example, polyolefins such as polyethylene (PE) and polypropylene (PP) are the major components of oxo-biodegradable plastics, which also contain chemical additives to speed up degradation, where the above-established standards do not apply to oxo-biodegradable polymers [32]. The polyolefin degradation process is separated into two stages. The first stage involves the reaction of oxygen in the air with the polymer. The polymer's carbon backbone is oxidized, resulting in the creation of smaller molecular fragments. Abiotic processes are used in this initial stage of oxo-degradation. In this stage of oxo-biodegradation, the oxidative degradation of the polymer can be accelerated by ultraviolet (UV) light (photodegradation) or by thermal degradation using heat over time. The second stage involves the biodegradation of oxidation products by microorganisms (bacteria, fungus, and algae) that devour the oxidized carbon backbone fragments to produce CO_2, H_2O, and biomass [33].

In Malaysia, the standards used for plastic biodegradability are obtained through the SIRIM eco-labelling scheme, and they include the ECO 001/2016, ECO 001/2018, and ECO 009/2016 labels. These products are certified by the Standard and Industrial Research Institute of Malaysia's SIRIM. The criteria of SIRIM ECO 001:2016 refer to all plastic sheets and films in the form of sacks or packing materials, while the criteria of SIRIM ECO 009:2016 apply to biodegradable and compostable biomass-based items used for food serving and packaging purposes [34]. However, the majority of traders in Kuala Lumpur still continue to use oxo-biodegradable bags because they are cheaper; only a small percentage of stalls and sundry shops in the city have switched to fully biodegradable plastic bags. In addition, there are also some traders who have also opted for cheaper photo-degradable plastics rather than oxo-biodegradable plastic bags. Photo-degradable plastics can be disintegrated into smaller pieces when exposed to sunlight, while oxo-biodegradables fragment into smaller pieces and contribute to microplastic pollution [35].

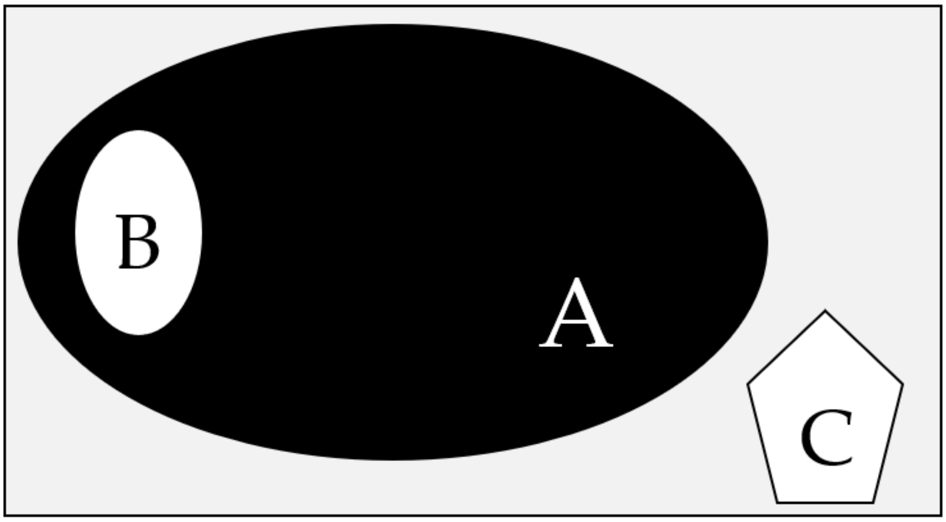

Figure 3. Chart on biodegradable vs. compostable vs. oxo-degradable plastic categories: (**A**) biodegradable, (**B**) compostable and (**C**) oxo-degradable. Data adapted from [36].

The disparity between biodegradability, compostability and oxo-degradability is a key cause of uncertainty. Although often interchangeable, these words are not synonymous. Confusion in popular bioplastic terms such as these can have catastrophic implications, particularly when it comes to the disposal of bioplastic goods. To sell their goods correctly and fairly, businesses must consider the differences between each category. To make informed purchase decisions and to dispose properly of bioplastic goods at the end of use, consumers must consider these conditions [36]. Therefore, it is necessary, first of all, to clearly understand the three keywords used in the definition of bioplastics (e.g., biodegradability, compostability, and oxodegradability). Table 1 shows the compostability and biodegradability of some of the most common bioplastics in different environments. The biodegradation capacity of bioplastics is influenced by the physical and chemical structure of the bioplastic, for example, polymer chain length, crystallinity and polymer formula complexity [37]. According to Emadian [38], polymers with shorter chains, lower crystallinity and less complex formulations are usually more susceptible to biodegradation. Furthermore, pH, temperature, humidity and oxygen are essential factors in environmental degradation, including polymer degradation.

As reported by Zhao [37], bioplastics are, so far, relying on their end uses for their longevity in food packaging. As an example, for foods with shorter shelf-life (less than six months), bioplastics with high biodegradability, including starch and cellulose bioplastics, can be used, whereas for foods with a longer lifespan, lower biodegradable plastics, such as PHA, can be used (approximately 1 year), and bioplastics that take a long time to biodegrade and are recyclable, such as PLA, can be used in long shelf-life foods (up to five years). However, PLA is not suited for the packaging of water-sensitive products that will be stored for prolonged periods of time without the inclusion of extra barrier materials. It is possible to produce materials with good barrier qualities for a wide range of applications (including crisps and coffee) while keeping compostability when PLA films are utilized in laminates with barrier materials or when SiO_x or AlO_x technologies are used. While PLA film has been used in fresh food packaging for years, this is the first time it has been utilized in the packaging of longer-lasting items (long shelf-life), which are increasingly wrapped in flat, stand-up, or squared-bottom pouches [39]. Further, starch-based plastics are utilized in biodegradable applications such as agricultural products (mulching films), service ware, green waste rubbish bags, and carry bags. The benefit is that these goods can be composted alongside organic garbage. Then, according to Novamont, [40], starch-based films can be translucent (not transparent) and are utilized as monolayers and laminates in packaging materials (for example, barrier films in combination with cellulose). They are used in situations where there is no need for transparency. When starch films contain flexible polyesters such as PBAT, they can be extremely flexible. These materials are appropriate for packaging potatoes and carrots (shorter shelf-life), as well as grocery bags. Starch-based films replace (perforated) PE in certain applications, and barrier qualities are unimportant [39].

Table 1. Biodegradability of bioplastics in different environments. Data adapted from [37].

Bioplastic	Environment	Condition	Biodegradability (%)	Method	Testing Period (Days)	Ref
PLA	Compost	58 °C, 60% RH	60–70	CO_2 produced	30	[38]
	Soil	10–25 °C	0	CO_2 produced	120	[41]
	Simulated marine environment	25 °C	3–4	CO_2 produced	180	[42]
PHB	Compost	55 °C, 70% RH	80	CO_2 produced	28	[38]
	Soil	20 °C, 60% RH	48.5	CO_2 produced	280	[38]
	Simulated marine environment	25 °C	38–45	CO_2 produced	180	[43]
Starch-based	Compost (starch thermoplastic)	58 °C	73.1	CO_2 produced	56	[44]
	Soil (wheat starch-derived plastic)	20 °C, 60% RH	14.2	CO_2 produced	110	[38]
	Marine (neat starch)	26 °C	100	Weight loss	50	[45]
Cellulose-based	Compost (cellulose acetate)	53 °C	100	CO_2 produced	18	[46]
	Soil (bacterial and vegetable cellulose)	25 °C	100	Weight loss	180	[47]
	Simulated marine environment (neat cellulose)	Room temperature	75	Oxygen consumed	150	[48]
PBAT	Compost	58 °C	34–67	CO_2 produced	45	[49]
	Soil	10–25 °C	6.6	Organic carbon content	120	[41]
	Simulated marine environment	29 °C	1–1.4	Biological oxygen demand	28	[50]
PBS	Compost	65 °C, 50–55% RH	90	CO_2 produced	160	[51]
	Soil	20 °C, 60% RH	1 (film), 16.8 (power)	Weight loss	28	[38]
	Simulated marine environment	27 °C	1	Biological oxygen demand	28	[51]

Composting is a process of enhanced biodegradation under controlled environmental conditions, such as temperature, humidity and the presence of microorganisms. It is also referred to as aerobic biodegradation [52]. Bioplastics degrade at different rates in anaerobic digestion and composting (aerobic composting), owing to the presence of aerobic microorganisms, which are plentiful and active in composting but not in anaerobic fermentation. This is because some bioplastic such as PCL is degraded by fungi and not by bacteria, and so cannot be degraded by AD [53]. However, as reported by Ruggero [54], significantly less research has been conducted on anaerobic biodegradation of bioplastic than on composting, and further research is required.

3. Types of Bioplastic

Bioplastic types have been categorised according to their backbone chemical composition. It is also easier to divide bioplastics into two broad types, namely biodegradable and non-biodegradable bioplastics. Bioplastic is made of naturally based plants, animals or microorganisms. Bioplastics are mostly, or sometimes totally, renewable resources [54].

Therefore, bioplastics are bio-based. Biodegradable yet petroleum-based plastics are not regarded as bioplastics, as stated earlier. Table 2 indicates the key divisions in which bioplastic forms are distinguished. This is not supposed to be a complete or full collection. Many bioplastics such as PLA, PBS, PTT, etc. may be derived from bio-based (non-biodegradable) materials. PLA can be synthesised from fossil fuels, but also can mainly be produced by fermentation of renewable materials such as starch and sugarcane, and is also known as bioplastic. The bio-based plastics studied so far can be classified into three major classes, as seen in Table 2 below [55]. The classification is based on plastic type (bio-based, fossil fuel-based, or their mix) and biodegradability.

Table 2. Types of bio-based plastics and fossil-fuel-based plastics.

Types	**Bio-Based**		
	Plant	**Microorganism**	**Animal**
BIODEGRADABLE (bio-based plastic)	Cellulose and its derivatives (polysaccharide) Lignin Starch and its derivates (monosaccharide) Alginate (polysaccharide) Lipids (triglycerides) Wheat, corn, pea, potato, soy, potato (protein) Gums (e.g., cis-1,4-polyisoprene) Carrageenan PLA (from starch or sugarcane)	PHAs (e.g., P4HB, PHB, PHBH, PHBHx, PHBV) PHF Bacterial cellulose Hyaluronan (polysaccharide) Xanthan (polysaccharide) Curdlan (polysaccharide) Pullulan (polysaccharide) Silk (protein) gellan	Chitin (polysaccharide) Chitosan (polysaccharide) Hyaluronan (polysaccharide) Casein (protein) Whey (protein) Collagen (protein) Albumin (protein) Keratin, PFF (protein) Leather (protein)
-	Bio-based		
NON-BIODEGRADABLE (bio-based/fossil-fuel based plastic)	PE (LDPE, HDPE), PP, PVC PET, PPT PU PC Poly(ether-ester)s Polyamides (PA 11, PA 410, PA 610, PA 1010, PA 1012) Polyester amides Unsaturated polyesters Epoxy Phenolic resins		
-	Fossil-based		
BIODEGRADABLE (fossil-fuel based plastic)	Poly(alkylene dicarboxylate)s (e.g., PBA, PBS, PBSA, PBSE, PEA, PES, PESE, PESA, PPF, PPS, PTA, PTMS, PTSE, PTT) PGA PCL PVOH POE Polyanhydrides PPHOS		

Based on Table 2, it can be concluded that the biodegradable bioplastics that are dependent on natural materials are starch plastics, cellulose polymers, sugars, lignin and chitosan plastics, polylactic acids (PLA), and polyhydroxy alkanoates (PHAs), but also polyhydroxybutyrates (PHBs), polyhydroxyvalerates (PHV) and their copolymers in different percentages (PHBV) [56]. In detail, starch-based polymers are typically biodegradable polysaccharide polymers, an alternative to polystyrene (PS) materials, and are used in food processing, disposable tableware and cutlery, coffee machine capsules, and bottles. Starch is a cheap, renewable, and widely available biopolymer, but intermolecular tensions and hydrogen bonding prevent it from being treated as a thermoplastic material. Therefore, a plasticizer (urea, glycerol, sorbitol, or glycerin) is needed in addition to water to generate thermoplastic starch (TPS), a deformable thermoplastic polymer [57]. Because of its cost-effectiveness and abundance, TPS can be employed in the food packaging sector as a viable choice by increasing its qualities. TPS can be mixed with a variety of polymers, each with its own range of attributes and applications.

Meanwhile, cellulose-based polymers are the next biodegradable polysaccharides. However, their disadvantages include the small vapour water block, poor mechanical characteristics, poor processing, and weakness (pure cellulose polymer). Even so, compost-coated cellulose film can be used in packaging for bread, meat, beef, dried goods, etc. Polylactide (PLA) is also known as one of the thermoplastic forms of biodegradable polyester. It consists of alternatives to polyethylene (LDPE and HDPE), polystyrene (PS) and polythylated poly (PET) of low and high density and is extensively used in the manufacturing of translucent, rigid containers, bags, jars and films [32]. In addition, polyhydroxyalkanoates (PHA) are also referred to as polyester degraded polymers. Chemically, polymers of this sort are distinct. Moreover, brittleness, rigidity and thermal volatility are also intrinsic.

Furthermore, polypropylene biobasis (PP) and polyethylene (PE) are non-biodegradable vinyl polymers. They are mainly produced from sugarcane and have similar physico-chemical properties. Other than that, biobased polyethylene furanoate (PEF) is also a non-biodegradable polyester based on five heteroaromatic ring structures. It also acts as a stronger buffer than PET. It is arguably a 100% raw material that is biobased and can be used in bottles, fabrics and films in the future. Polyamides (PA) are another example of non-biodegradable polymers. They are not widely found in food contact materials (FCMs), and are used in high-performance polymers [32]. Equally important are the biodegradable plastics from fossil fuels such as polycaprolactone (PCL) and (PVOH). PCL is a biodegradable polyester made by ring-opening ε-caprolactone polymerization. This is a non-renewable resource. Because of its low melting temperature and biodegradability, for the most part, pure PCL is employed in medical applications. The low melting point (62 °C) makes it ideal for blending with other biopolymers (e.g., starch). PCL blends are also used as food contact materials (FCMs). Meanwhile, PVOH is a biodegradable vinyl polymer and is used for coatings and adhesives, and as an additive in the production of paper and boards. Another type of bioplastic is in the biocomposite category, as mentioned in the next section, where bioplastic is reinforced with natural fibers, such as sisal, flax, cotton, jute, banana, wood and various grasses, and/or fillers and additives. A biodegradable matrix resin reinforced with natural fibers is the basis of innovative biocomposites [30].

4. Bioplastic and Biocomposite

Biocomposites from local and sustainable sources (natural composites) provide substantial sustainability; the production of next-generation materials, goods, and processes is driven by industrial ecology, environmental quality and green chemistry [58]. Biocomposites are classified as composites that are biocompatible or environmentally friendly. These comprise many organic and/or inorganic materials, including polymers, polysaccharides, proteins, sugars, metals and nanocarbon, naturally and synthetically. Different types of biocomposites, such as films, membranes, moulds, layered fabrics, particles, fibres and moulds, are present [59]. Meanwhile, these biocomposites are made from agricultural and forestry feedstock that is renewable, recyclable, and sustainable. In other terms, according to Pilla [15], biocomposites are green composites made from bioplastic and natural fibers such as hemp, wood, kenaf, coir, sisal, grasses, and so on. They are 100% bio-based and have biodegradability and/or compostability as end-of-life alternatives. Biocomposites, in general, are commonly used in different industries including aircraft, vehicle, manufacturing, maritime, consumer goods and electronic parts, etc. Researchers use terms such as bio-nano-composites, composite bioplastics, nano-biocomposites, green biocomposites, and others to describe biocomposite materials. For example, Energy et al. [60] stated that biocomposite material from polymer/clay mixtures, known as nano biocomposite, is one of the new advances in food packaging technology.

In 2012, a paper from Pilla [15] reported that the production of composites using fiber-reinforced polymers (FRP) is a long-established area of research that begun with the impregnation of fibreglass in synthesised plastics after 1908. In 1941, Henry Ford introduced biocomposites from plastics based on flax, sisal and cellulose. Since then, many biocomposites were investigated, and there has been a great deal of progress in extending their use in different industries, as previously stated. Science and technology specialists worldwide are now focusing on bio-based goods that combine bioplastics and synthetic plastics with natural/synthetic fibres. Composites produced from bio-plastics and plastics impregnated with natural or synthetic fibers, or both, are also called biocomposites (see Figure 4). Biocomposites manufactured from bioplastics and natural fibers are also often referred to as "eco composites" and are more environmentally sustainable than those made from conventional plastics and/or fillers.

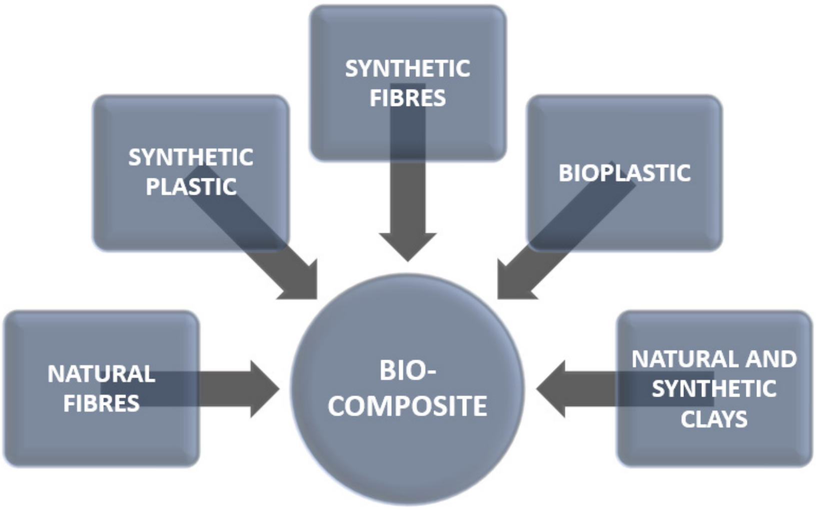

Figure 4. Variety of biocomposite processing pathways. Data adapted from [13].

For example, by adding microcrystalline cellulose as a filler, starch-based bioplastics can be used as a food box with improved mechanical barrier qualities (water and oxygen content decreases as cellulose content increases) [61]. This is because, according to Jiang et al. [62], the incorporation of cellulose and macro/nanocrystalline cellulose or nanofibril into starch-based bioplastics improves processes and increases the mechanical properties of the film. Because all of the ingredients are taken from food sources, it is acceptable for both food packaging and food.

Furthermore, clay is a naturally occurring mineral that is suitable for food packaging applications, as well as being cost-effective and commercially available. Bionanocomposite material, which consists of biopolymer and nano clay, is one of them [63]. Furthermore, when effectively dispersed in the biopolymer matrix, nanoclay has the ability to improve the mechanical, thermal, and barrier properties of food packaging by generating an exfoliated structure [64]. Montmorillonite nanoclay (MMT) [65] and halloysite nanotubes (HNTs) [66] are two forms of nanoclay that can be used to make bionanocomposite materials for food packaging applications. As reported by Jin and Zhong 2012 [65], nanocomposites, which are made up of uniformly dispersed nanoscale fillers in a polymer matrix, have the potential to improve the mechanical, barrier, and thermoresistance properties of natural biopolymer-based packaging films. Because of its low cost, abundance, vast surface area, and enormous specific aspect ratios (reported to be about 50–1000), montmorillonite nanoclays (MMT) are one of the most common layered silicates in the production of biopolymer-based nanocomposites. In addition, because of their unique features, HNTs are the most promising among them. HNTs are non-toxic, biocompatible, and have high dispersion properties (De) [66,67]. As an additional case, PLA blends with halloysite nanotubes, as defined by Risyon et al. [63] have the potential to increase the shelf life of tomatoes, leading to improved mechanical, thermal and even barrier properties. Furthermore, HNTs are a promising candidate for supporting biopolymer matrixes such as PLA. PLA/HNTs bionanocomposite films will be created when HNTs are integrated into PLA biopolymer films. HNTs also disperse well in the PLA matrix, which is an important characteristic for improving the characteristics of PLA/HNT bionanocomposite films [68].

Other than that, the Food and Drug Administration (FDA) has now recognized PLA as typically safe for food and beverage packaging [69]. This is because when the PLA is applied to the nanocomposite magnesium (MgO) bacteria, approximately 44% die after 24 h, and it is ideal for food embalming [70]. With the inclusion of 2% MgO nanocomposite, the plastic characteristics were increased by nearly 146%. Marra et al. [71] reported, however, that added PLA polymers of zinc oxide (ZnO) showed approximately a 99.99% decrease in *E. coli* after 24 h.

In short, advancements in biodegradable polymer nanocomposites have been made, with a particular focus on developing cost-effective bio-based packaging material. The nanofiller is added to improve the mechanical properties and barrier properties of the polymer biocomposite. Another aspect of this progress is a decrease in the environmental carbon footprint of biocomposites consisting of conventional plastics impregnated with natural fibers or bioplastics filled with synthetic fibers [15].

5. Bioplastic in Packaging Application—Global and Malaysian Perspectives

The use of bioplastics varies from packaging, food, consumer electronics, cosmetic, vehicles, agriculture/horticulture and toys to textiles and a host of other segments in growing markets. At present, rigid packaging and consumer products, predominantly biobased PET and PUR, dominate the bioplastics market. Bioplastic products have proven to be the main sector for packaging, commanding a share of more than 53% of the global bioplastic industry (1.14 million tonnes) by 2019 [55]. The world production capacity for bioplastics was projected to be 880,000 tonnes in 2017. In 2022, bioplastics are forecast to generate 1–8 million tonnes. Bioplastics are increasingly being employed in a wide range of industries, from packaging and consumer goods to electronics, automotive, and textiles. Packaging continues to be the largest market for bioplastics as of 2020, accounting for 47 percent (0.99 million tonnes) of the entire bioplastics market [72]. Percentages regarding application within the bioplastic industry in recent years, as of 2020, can be seen in Figure 5. The figure shows that the bioplastic materials used in packaging applications are supposed to work by protecting products from the environment and preserving the quality of products [73]. In bioplastic packaging applications such as food and beverage, healthcare, cosmetics, etc., most packaging is produced by the food processing sector. Food packaging is a combination of the art, science and technology of containment of a commodity in order to ensure the secure and low-cost transport and the supply of the products to customers in good condition [74].

Furthermore, one of the bioplastic potentials for cosmetics and healthcare use is the packaging. Cosmetics are highly valuable, but they are easily damaged. Cosmetic packaging demands sustainable solutions in this environment, and research is focused on modifying bio-based and biodegradable polymers to meet the rigorous requirements for cosmetic preservation while maintaining sustainability and biodegradability [75]. Several bio-based and biodegradable polymers such as poly (lactic acid), polyhydroxyalkanoates, polysaccharides, etc. are already on the market and some early solutions are now being explored and optimized for rigid and flexible packaging. In several scientific trials, bioplastic in nanoparticles or bio nanocomposite application has increasingly been used in plastic materials to improve their barrier properties. For example, the use of polylactide (PLA) nanocomposites (which integrate organically modified clays (organoclays) into polymers) in cosmetics packaging could provide a biodegradable alternative [76]. Besides bioplastic packaging, the uses of nanocellulose itself, specifically in cellulose nano fibril application, in cosmetics and healthcare have expanded rapidly over the last several years due to its anti-ageing effect, good coating agents, as well as improving the wet compatibility of hair. A study conducted by Ioelovich and Figovsky [77] also shows that nano-cellulose has promising bio-carrier characteristics. The nano-sized particles can clean the skin's pores by penetrating through the lipid layer and epidermis within the skin's strata. This fact shows that nano-cellulose is extremely suitable for gentle skincare, as well as higher effectiveness towards skin treatment.

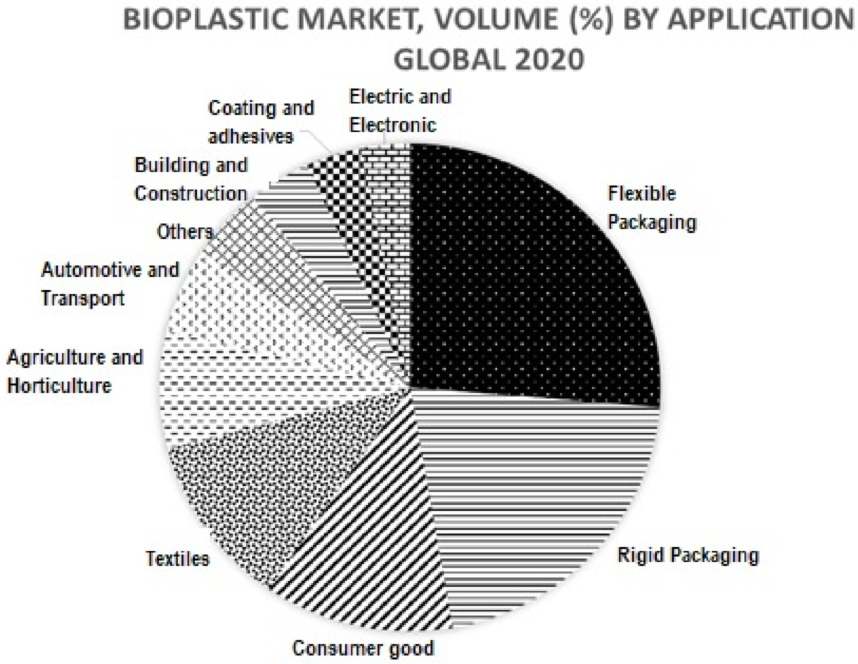

Figure 5. Composition of bioplastic market worldwide, 2020. Data adapted from [72].

Equally important, some cosmetics require a combination of qualities, such as biodegradability or recyclability, as well as enhanced packaging functionality for specific purposes; for example, PLA-based packaging has gained attention recently due to its good rigidity and mechanical resistance for cosmetic packaging [78]. In addition, PHAs are also important as a packaging material for their high perishability in various situations. Despite the lower production rate of PHA than PLA, which makes it more expensive than PLA, it has several properties that make PHAs more useful for cosmetic packaging, such as the fact that it has no harmful effect when it is applied in contact with skin, it emits less greenhouse gases, and has very high biodegradability as well as excellent biocompatibility in different environments [79]. Some market penetration has been obtained in the production of PHA-based packaging, coatings, and hygiene goods [80]. Further, starch and cellulose by-products are also the most used poly saccharides in the field of cosmetic packaging. Chitosan and chitin have recently been employed as active packaging due to their antibacterial qualities. Cosmetics packaged with chitosan and chitin boost their antibacterial and skin regenerative properties while also increasing their shelf life [81].

In the food industry, bioplastic in the nanocellulose application has shown rapid growth for the past several years and is expected to grow more in the near future. It is especially noticeable with the increased rate of research on food applications, especially in the food packaging sector. Due to the growing economic and sustainability concerns in the food industry, this application has been taken into consideration to help in solving the unsustainability, costs, and disposal issues that the food industry faces. Some of the properties of bioplastics in nanocellulose applications, such as edibility, flexibility, biodegradability, and anti-microbial properties, are some of the promising factors that have attracted researchers. Lu et al. 2020 [82] used nanocellulose as a colorimetric indication for food freshness in intelligent food packaging in their latest research. The color of the hydrogel will change according to the freshness of the chicken used in the experiment. It was reported that the nanocelullose used in the experiment has a quick response towards the chicken spoilage which increases the valuability of intelligent packaging.

In other cases, one of the packaging applications often consists of polymers that degrade or decompose when exposed to air, water or sunlight. Currently, CU Dining

Services encourages the use of biodegradable shopping bags. There are three major types of the biodegradable bag [75]:

(A) The original biodegradable sacks still used today are constructed from starch-containing resins, polyethylene, and heavy metals such as cadmium, lead, and beryllium, as well as commonly known as plastics based on petroleum.
(B) A second form of starch, mixed with biodegradable polymers such as PLA or BASFEcoFlex, also known as bioplastics, has been patented. These bags comply with ASTM compostable requirements, while the standard does not comply with other bag types (types A and C).
(C) To promote the breakdown of polymers, oxo-biodegradable bags use Totally Degradable Plastics Additives (TDPAt) to speed up the biodegradation process of traditional plastics, as seen in Figure 3 above.

Bioplastics minimise petroleum fuel consumption and are favoured worldwide by customers. These environmental issues are a key driver of this industry's progress [83]. However, as has previously been stated in Malaysia, because they are cheaper, most traders continue to use oxo-biodegradable bags. There are already very few buyers for these plastics and suppliers are hesitant to create the replacements in significant numbers, even though they will help to minimise the prices. Since biodegradable plastic bags were made available in 2017, only a small percentage of the stalls in the city have turned out only use biodegradable plastic bags, comprising around 60% of restaurants and 80% of shopping areas. The people who have not made the shift are mostly small traders in the wet, night and food markets [35].

The Malaysian plastic industry is divided into seven major sectors: packaging, electrical and electronics, building and construction, automative and transportation, furniture and bedding, and other subsectors such as medical devices [84]. According to Figure 6, packaging is the most common end-use for Malaysian plastic, following global trends. Improving wear and chemical resistance, ease of moulding, recyclability, puncture resistance and high mechanical toughness are all key factors for the increasing use of plastics in packaging. However, the key driving forces, according to market research, are environmental factors that help to bring about a paradigm change, as well as the rising demand for flexible packaging in the form of bioplastics. In the future, substitutes for petroleum-based plastics and regulatory restrictions on traditional plastic products could be possibilities [85].

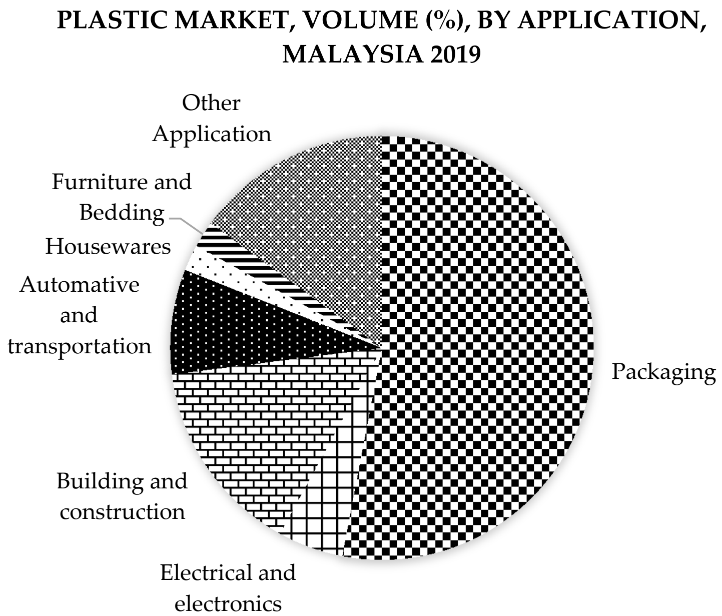

Figure 6. Composition of plastic market in Malaysia, 2019. Data adapted from [85].

6. Advantages and Disadvantages of Bioplastic and Its Modification in Packaging Applications

The packaging industry is the biggest and largest user of synthetic plastics derived from fossil fuels. As discussed, as a substitute for petrolic synthetic polymers, bioplastic has great appeal. For example, poly (lactic) acid (PLA) is a biodegradable aliphatic polyester that can be produced by fermentation of renewable resources such as rice, cassava, potatoes and sugar cane [69]. As mentioned earlier, PLA has paid great attention to applications for food packaging with films and coatings. Because of its transparency and relatively good mechanical characteristics, it is already in use in some markets. PLA is, thus, a strong environmentally friendly competitor in the product packaging industry since it addresses all environmental issues [60,86]. The characteristics of bioplastics (PLA and PHAs) compared to other common polymers used in food packaging are shown in Table 3. In this report, PHAs and PLA-based green composites, natural fillers and agro waste fibers can be explored for use as sustainable packaging. Moreover, other alternative packaging materials, obtained from renewable resources, such as poly (hydroxyalkanoates) (PHAs), starch or proteins, have also been proposed as alternatives to replace non-biodegradable polymers in product packaging applications.

Table 3. Comparison of bioplastics' (PLA and PHAs) properties to other common polymers used in product packaging. Data adapted from [37,87,88].

Property/Polymer	PLA	PHAs	LDPE	PET	PP	PS
Strength (MPa)	37–66	20–40	10–12	55–79	15–27	24–60
Elongation at break (%)	0.5–9.2	1.4–5.5	300–500	15–165	100–600	1.6–2.5
Oxygen barrier (permeation at 30 °C ($\times 10^{-10}$ cm^3(STP)·cm/cm^2·S·cm Hg))	3.3	2–16.5	6.9	0.04	1.5	2.6
Moisture vapour transmission rate (g-mil/10in.2/24 h)	18–22	2.36	1.0–1.5	2	0.5	10
Water absorbance (%)	3.1	0.7	0.005–0.015	0.1–0.2	0.01–0.1	0.01–0.4
Thermal properties (Glass Transition Temperature-Tg (°C))	55	−9–9	−110	73	−20	90
Transparency (Clarity)	High	High	High	Excellent	Poor	Excellent
Carbon dioxide barrier (permeation)	10.2	3	28	0.2	5.3	10.5
Chemical resistance	Poor	Poor	Good	Good	Good	Good

However, the development of some of these materials (i.e., PLA, PHAs) for rigid containers is one of the key features in the still incipient commercial use of bioplastics in food packaging [89]. Bioplastics can have a much higher permeability to water vapour than normal plastics. In certain cases, such as sandwich packing, this could be a downside, but in the case of freshly baked bread, a bioplastic container may have a considerable benefit in releasing excess vapour or steam. Moreover, bioplastic can feel more soft and tactile. This can be a significant market advantage for applications such as cosmetics packaging [90]. According to Rhim et al. [91], the properties of some bioplastics, such as thermal instability, difficult heat saleability, brittleness, low melt strength, high water vapour and PLA oxygen permeability, restrict their use as a film in food packaging applications.

This discussion seeks to provide an overview and draw reasonable conclusions. For example, the challenges that need to be tackled successfully in the coming years and decades are the lower material performance of certain biopolymers, their relatively high production and processing costs, and the need to reduce agricultural land and forest use, thus preventing competition in the area of food production, and adverse effects on biodiversity as well as other environmental impacts [89]. Some researchers stated that bioplastic production is not cheap compared to traditional packaging, and the usage of land for the manufacture of bioplastics is also a big barrier to the success of bioplastic functionality [91]. In addition, due to its hydrophilic nature, other materials such as starch and cellulose-based packaging materials have a low water vapour barrier, which is responsible for poor processability, brittleness, susceptibility to degradation, reduced long-term stability and poor mechanical properties [92] such as elongation and tensile strength [93], and their low melting point makes the use of cellulose reinforced fibre composites more desirable for bioplastics [13]. Moreover, in the case of PHA/PHB hardness, brittleness (due to high glass transfer and melting temperatures), thermal instability and low impact resistance also limit their use in food packaging [12].

Thus, the drawbacks, as stated, open a research portal to enhance the functionality of bioplastics. Bioplastic also needs to contain additives, such as plasticisers [90], and several different methods have been used to improve its properties, in particular by improving the gas and water barrier properties, such as coating, mixing, addition of nanoparticles, addition of cellulose, chemical/physical modification, etc., which give the product the required characteristics [12]. Oxygen and humidity represent two factors affecting the shelf-life of food. The lack of oxygen is required to ensure food quality during storage in many cases for microbial growth or biochemical deteriorating reactions [94]. Bioplastics have several potential advantages in finding new material opportunities and keeping an eye on the goal of sustainable development and usage. For instance, the use of natural biodegradable polymers and their blends to synthesize the polymer-based material for packaging provides a sustainable alternative to enhance and produce new sets of bioplastic materials with desired properties due to the many advantages of this bioplastic including the low cost, accessibility, biodegradability and flexible processability [87].

Many attempts were made to market new bioplastics, with improved characteristics and new features, for the packaging of films and coatings. For example, the addition of zein and PHAs, according to Fabra [95], would increase the barrier to oxygen for food packaging films. PHAs are viewed as a promising food packaging material to compete with traditional plastics because of their hydrophobic qualities and the flexibility of the mechanical properties board. In other polymers including PLA, PBS, polycaprolactone etc., PHAs can be used raw, blended or as an added agent. The biopolymer must be removed, washed and compounded from the bacterial cell content in order to manufacture bioplastics made of PHAs [96]. The properties of the gas barrier can also be exploited in the preparation of PHA-coated paper and film, which can be used for the production of cartons for milk packaging [97].

Similarly, PLA is one of the biopolymers which, due to its economic and business viability, has become very important during processing in recent years [98]. PLA's high molecular weight, water solubility, good processing capability and, e.g., biodegradability, are properties that make PLA a good material in food packaging [99]. Although PLA seems to be a possible biodegradable polymer for use in the packaging of different food items, it has unmodified constraints, namely that it is brittle and degrades more easily with a large temperature increase [98]. Table 4 provides the list of patents for the biopolymers based on starch and PLA.

Table 4. List of patents for the biopolymers based on starch and PLA. Data adapted from [98].

Patent No.	Topic	References
EP 2712889 A1	Starch-based biodegradable material	[100]
US 8188185 B2	Biodegradable packaging film made from TPS/PLA blend	[101]
US 8133558 B2	Poly lactic acid blown film and method of manufacturing	[102]
US 20110135912 A1	Biodegradable packaging materials with enhanced oxygen barrier performance	[103]
US 8263197 B2	Poly lactic acid shrink films and methods of casting same	[104]
US 6987138 B2	Biodegradable poly lactide resin composition	[105]
WO 2007/063361 Al	Bio-based biodegradable polymer compositions and use of same	[106]
EP 2 432 830 B1	Bioplastics	[107]
WO 2013/042083 Al	Biodegradable films obtained from cassava starch and their manufacture process	[108]
WO 2019122308 A1	Novel proteases and uses thereof	[109]

Furthermore, cellulose is a subunit of β-D-glucose and is one of the most commonly used biopolymers for alternative natural packaging materials. However, cellulose, in its original form, has very low solubility in water and is thus a relatively unsuitable packaging material. Its polymer can be derived from plant material [80]. However, cellulose can be modified with a plasticizer to provide the raw material for the production of packaging films [110]. In addition, it can also be improved by surface modification or by coating and blending in order to be soluble in water. Nanocellulose fibres have high mechanical stability and transparency. Films and composites can be made from fibres as thick as 15–20 nm [111]. Acid hydrolysis or mechanical grinding may be used for the formation of nanocellulose fibres from cellulose [112]. Nanocellulose fibers may be used in composites to avoid the use of inorganic fillers [113,114]. The insertion of nanofibers into the polymer matrix will increase the poor moisture barrier to cellulose without impacting biodegradability [111]. Equally important, Ana et al. [115] reported that the addition of ZnO and casein to PCL would minimize the permeability of water vapour and would be ideal for food packaging. However, cellulose clay-hybrid films showed thermal stability, proper gas permeability, and antimicrobial activity, suitable for food packaging applications [116]. They also demonstrate improvements in mechanical properties and improve the antimicrobial activity of film development. PCL is ideal for food packaging with an additional small amount of silver kaolinite for long-term antibacterial films [117] where the addition of 4 per cent kaolinite nano clay to PCL improves the properties of the gas barrier, as well as improving processability and thermal stability [118]. In addition, de Andrade et al. [119] found that adding ZnO to PCL reduced the degradation temperature by roughly 50–70 °C, and that the films are thermally stable up to 200 °C, making them appropriate for packaging hot grilled chicken.

Because of the variety of raw materials available and the potential elements supplied by bioplastics, the usage of bioplastics will undoubtedly be priced, particularly for packaging. With the right technique and material, bio-plastic qualities can complement regular plastics and provide a number of benefits. Natural fibres and/or inorganic fillers can increase the barrier, thermal, optical, and mechanical properties of bioplastics. These biocomposite could overcome the limitation of the bioplastic use for packaging.

7. Bioplastic Industry Overview

Business analysts have predicted global growth in bioplastic demand from about 2.05 million tonnes worldwide in 2017 to around 2.44 million tonnes in 2022 [55]. The sector is increasing gradually. In principle, any disposable product made of plastic, such as cutlery or packaging and straws, should be replaced with bioplastics. In Europe, bioplastics account for around 1% of the 320 million tonnes of plastic manufactured per year, despite increasing commodity requirements. It has been demonstrated that the bioplastic industry is a young and innovative sector [83]. The same is true in Malaysia, which is still far behind. According to a 2016 survey, the study in the field of market research forecasts a rise from 1743.9 million m^2 in 2016 to 2427.1 million m^2 in 2021, for mono films used in flexible packaging, in Europe [80,120]. The rise in the usage of biopolymer-based films is projected to occur, in particular, in the category "Other food products, including drinks," with an approximate increase of 161 per cent over five years (2016 to 2021) [120].

Figure 7 below shows, the global production capacities of bioplastic materials in 2020 and forecasts for the next 5 years (2025). This derives from the growing awareness of the environmental impact and of the need to reducing fossil resource dependency as well as the constant advancement and innovation of new materials with better quality and new functions in the bioplastic industry. The data report that polylactic acid (PLA), starch blends and polyhydroxyalcanoates (PHA) are the major products used for manufacturing in the bioplastic industry. This polymer is 100% biodegradable and biological in nature, and its structure has several mechanical and physical characteristics. More than 55.5% (over 1 million tonnes) of global bioplastic manufacturing capacity comprised total biodegradable plastics, including PLA, PHA, starch mixtures, etc. Bioplastic demand is projected, due in particular to the significant PHA growth rate, to rise to 1.33 million by 2024 [55].

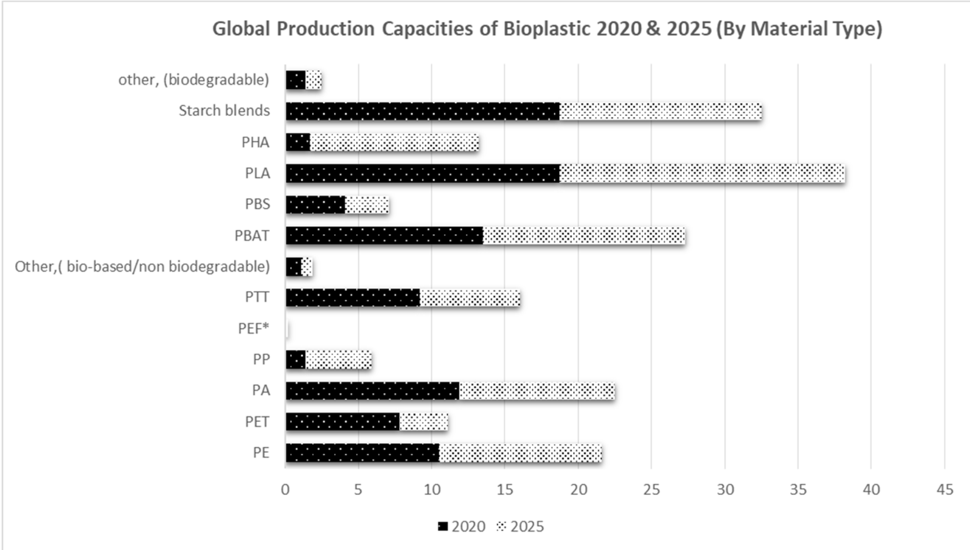

Figure 7. The worldwide production of bioplastic types by material: 2020 and 2025 [72].

Thus, it can be said that the key drivers for growth in biobased biodegradable plastics are innovative biopolymers such as PLA and PHAs. PHAs are an important polymer family that has been in research for some time and is now commercially available, with production capacity expected to increase in the next five years [121] as shown in Figure 7. Meanwhile, PLA is a very adaptable polymer with good barrier qualities that can be used to replace PS (polystyrene), PP (polypropylene), and ABS (acrylonitrile butadiene styrene) in more demanding applications, especially in packaging. Indeed, PLA, PHA, and starch-based plastics were large volumes of production in bioplastic. PLA, PHA, starch blends, and other biodegradable polymers account for more than 58% (over 1 million tonnes) of global bioplastics manufacturing capacity. Bio-based, non-biodegradable plastics, which include drop-in solutions such as bio-based PE (polyethylene) and bio-based PET (polyethylene terephthalate), as well as bio-based PA (polyamides), account for over 42% (almost 1 million tonnes) of global bioplastics production capabilities. However, plans to boost bio-based PET production capacity have been not realized at the rate expected in past years. The PET rate, for example, fell from 9.8% in 2019 [55] to 7.8% in 2020 [72]. The focus has switched to the development of PEF (polyethylene furanoate), a novel polymer set to hit the market in 2023 [55]. PEF is similar to PET but is entirely bio-based. It is also believed to have an extra barrier and thermal qualities, making it an appropriate material for beverage, food, and non-food packaging. As a result, PEF will soon be able to replace growing amounts of PET.

As well as according to reports, the packaging sector is the largest business segment that generates profits from the bioplastic industry [72]. Bioplastics can be used to replace practically any traditional plastic material and its application. Within the next five years, as more bioplastics materials become commercially available, such as polyethylenefuranoate (PEF), bio-based polypropylene (PP), polyhydroxyalkanoates (PHAs), and polylactic acid (PLA), production capacities will continue to grow and diversify. According to the recent industry data gathered by European Bioplastics, the global capacity for bioplastics production is expected to rise from around 2.11 million tonnes in 2020 to over 2.87 million tonnes in 2025 [72]. However, Asia is now projected, accounting for 56 % of global industrial output, to be the world's largest manufacturer of bioplastics. The current manufacturing potential of Europe is 18%, and 16% is reflected in North America [83]. Although the global biodegradable plastics industry accounts for less than 1% of the overall bioplastic market, in the next 5 years bioplastic can expand quickly. In order to solve industrial applications, bioplastics research should be transformed through industrial/academic partnerships. The transition from petroleum-based plastics to bioplastics requires sustainable supplies of bioplastic raw materials and appropriate recycling/recollection options [122]. The explanation is that the growth of the industry is driven by continuous research and development programmes, improved environmental consciousness and stringent environmental legislation.

8. Conclusions

Given all that has been mentioned so far, one may suppose that bioplastics are a well-known example of biomass green materials with a rising ability to replace fossil fuels based plastics. However, in terms of non-competitive prices, bioplastics face big obstacles. At the same time, drop-in plastics are also a market leader, reducing carbon footprint while also voicing biodegradable concerns, particularly in the packaging industry, as compared to most plastic products. Nonetheless, in terms of the future, bioplastics are becoming a possible alternative to fossil-based plastics, especially in the context of increasingly tight global oil supplies. Thus, the whole world, and Malaysia in particular, are evolving and eager to take advantage of the opportunity to expand the industry by investing in R&D to ensure that bioplastic or bio-based goods fulfil the needs of the global market. Studies indicate that PLAs are bio-based and biodegradable plastics, with a renewable and rising demand, whereas PHAs are scalable solutions that can be obtained from a range of biomass sources and are projected to expand production potential in the years ahead. Meanwhile, the most extensively used biopolymer matrices for the manufacturing of bioplastics are starch and cellulose. In 2020, starch-based plastics was found are expected to account for the majority of production capacity (1.3 Mt), with the remainder based on polylactic acid (PLA), polyhydroxyalkanoates (PHA), bio-based polyethylene, and other materials [116]. The enormous market share of starch-based plastics can be attributed to various factors, including high availability, low cost, and renewability.

The existing potential of bioplastics for short- and long-term packaging, as well as items that do not require outstanding oxygen or water barrier qualities, necessitates the commercialization of these bio-based packaging materials. However, innovation has contributed to the use for packaging of foodstuffs requiring better packaging. Clearly, bio-based packaging materials provide a multi-faceted opportunity in the packing industry, but storage studies need to be conducted on packaging equipment to validate the industrial use of these packaging films. Therefore, to provide access to the versatility of bio-based packaging materials, a crucial assessment is needed before being introduced on the market as a single substitute for traditional packaging materials. Finally, the concepts of sustainability, industrial ecology, eco performance, green chemistry and engineering have all been implemented into the production of materials, goods and processes for future generations through bio-based materials and natural fibers, bioplastics and biocomposites.

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