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Design for Sustainability with Biodegradable Composites

Dina Fouad and Mahmoud Farag

Abstract

Many of the petroleum-based materials and products are causing problems with sustainability of resources and disposal at the end of their lives. Such problems can be solved if biodegradable materials from renewable resources are used in product design. For a material to be fully biodegradable, all its constituents must be biodegradable and should come from renewable resources if it is to be sustainable. Starch-plant fiber composites satisfy both conditions. In addition to their environmental benefits, materials from renewable resources can also be economically advantageous in certain applications, such as motorcar and packaging industries. This chapter starts with a review of the characteristics of biodegradable materials and uses case studies to illustrate their use in the design of sustainable products. The concept of design for a life (DFL), in which the material used in making a given product that will biodegrade at the end of its useful life, will also be explored.

Keywords: sustainability, design for a life (DFL), biodegradable composites, natural polymers, natural fibers, degradation, economics of sustainable designs

1. Introduction

Recently, several reviews have been published to report on the advancement in the fabrication and superior properties achieved in biodegradable materials [1–5]. Such growing global notion and urgency toward the need for biodegradable sustainable alternatives to petroleum-based synthetic plastics have stemmed from the increased environmental awareness, depletion of the scarce nonrenewable resources, as well as the implementation of stringent governmental regulations in several countries [5–10]. They mostly emphasized on the suitability of bio-based polymer composites as substitutes for conventional synthetic polymers. The main problem stems from the fact that plastics have become one of the major pollutants of current times. Due to the ubiquity of nondegradable plastics associated with products used in everyday life and the deficiency in creating a proper recycling infrastructure, plastic waste has proliferated over the years and accumulated in landfills and oceans causing severe ecological and environmental problems across the globe [10]. Another concern is the possibility of such waste releasing toxins in landfills and reaching food resources, which has a negative impact on human health [11, 12]. Consequently, a high demand for biodegradable alternatives has arisen in different fields and industries as an attempt to achieve a more environmentally friendly approach in product manufacturing and design [7]. Accordingly, the European bioplastics report published in 2018 has forecasted more than a 20% growth

in the production of bioplastics by the year 2023 [13]. Concurrently, the demand and production of plastics in general continue to rise, where it is expected to reach staggering 540 million tons in 2020, where only 2.2 million tons are estimated to be of bio-based resources [13, 14]. Despite the promising growth rates in the field of bioplastics, comparison demonstrates that the rate of growth is still very small in contrast to that anticipated for traditional plastics. The transition and adaptation of bioplastics is generally impeded by their higher cost of production and lower durability as opposed to their conventional counterparts [8, 9, 15]. Therefore, it is important for the degradable plastic alternatives to be designed so as to offer the same functionality as the original synthetic plastics for the required service life and at a competitive cost [8]. Here, the cost is only justified when the cost of sustainability is taken into consideration and not only that of production [15]. On the other hand, in spite of the challenges faced, several industries such as the packaging, automation, consumer goods, and biomedical fields have shown encouraging implementations of biodegradable alternatives in their plastic-based commodities, taking the necessary preliminary steps towards the commercialization of bio-based and biodegradable plastics [7, 13, 16]. Products that are produced using such materials are designed to biodegrade at the end of their useful life using the design for a life (DFL) approach which is a crucial element in the successful transition to sustainable bioplastics [17]. For instance, a packaging material can start to biodegrade soon after the consumption of its contents with a supplementary benefit of avoiding any harmful contaminants that could have leached to the food content from the synthetic counterparts, which indicates a clear environmental advantage. Ecological and sustainable advantages are also achieved when they are applied for components of automobiles to achieve an eco-friendly design [18]. Thus, in order to achieve a successful implementation of the DFL approach, a thorough understanding of the different biodegradable polymers and composites available is needed along with their properties, methods of production, and degradation to properly evaluate and asses its life cycle and positive impact. This chapter presents an overview on the different types of biodegradable polymers and composites highlighting their main characteristics and advantages. Moreover, the use of the design for a life approach will be elucidated using a case study in the field of automation.

2. Biodegradable polymers: classifications and properties

Biodegradable plastics can be derived from either synthetic or natural resources and are commonly referred to as “biopolymers” [5]. They are defined as polymers

Category	Type	Source	Source type	Method of production	Example
Synthetic	Bio-polyesters	Bio-derived	Renewable	Chemical polymerization of bio-monomers	PLA
		Synthetic monomer	Nonrenewable	Polymerization of lactide	PLA
		Bio-chemosynthetic monomer	Renewable	Biosynthesis of polymers in microorganisms	PHA
		Synthetic monomer	Nonrenewable	Enzymatic catalyzed polymerization	PCL
Natural	Agropolymer	Biomass products	Renewable	Fragmentation of biomass	Starch

Table 1. Classification of biodegradable polymers [7, 19–22].

that naturally degrade and assimilate in the environment into water (H₂O) and carbon dioxide (CO₂) by means of microorganisms [23]. In regard to the bio-polyesters, their hydrolysable ester bonds are what make them biodegradable, while for the natural polymers, the process is usually through hydrolysis [7]. Moreover, the means of fabrication are categorized into three main classes: (1) chemical polymerization of monomers originating from biological processes such as in the case of polylactic acid (PLA), (2) chemosynthesis of the polymers in microorganisms such as polyhydroxyalkanoate (PHA), and (3) modification of natural polymers, i.e., starch [5]. **Table 1** summarizes the different typologies used to categorize the different types along with their source and methods of production. Also, characteristic examples of each type are indicated, and their main features highlighted.

2.1 Bio-polyesters: synthetic polymers

Among the most representative of the synthetic polymers are the aliphatic bio-polyesters (listed in **Table 1**), PLA, PHA, and polycaprolactone (PCL) [18]. Polycondensation of bifunctional monomers and ring-opening polymerization processes are commonly used to yield high molecular weight polymers [7]. A comprehensive overview of the different chemical synthesis methods used to synthesize them is reviewed in [23]. The prime interest in this class of materials is due to the fact that they exhibit mechanical properties equivalent to petroleum-based polymers such polyethylene (PE) and polypropylene (PP) [19]. A summary of the reported mechanical and physical properties of the bio-polyesters and natural biopolymers in comparison to the polyolefin low-density polyethylene (LDPE) is provided in **Table 2**.

2.1.1 Polylactic acid

Polylactic acid is a high molecular weight, crystalline thermoplastic obtained from the ring polymerization of lactide [20]. It was first synthesized in 1931 by a DuPont scientist and was derived from agricultural products such as corn [22]. The typical glass transition temperature (T_g) falls in between 40 and 70°C, while the melting temperature (T_m) is between 130 and 180°C, as referred in **Table 2**. Additionally, it exhibits high strength, where the average tensile strength is 50 MPa compared to 14 MPa of polyolefins such as LDPE.

Table 3 demonstrates the essential differences between the different biopolymers with regard to their cost, mechanical properties, hydrophilicity, and biodegradation rate. PLA is a hydrophobic polymer due to the methane side group present along the chain's backbone. Thus, it is more resistant to hydrolysis than PHAs, and hence, their biodegradation rate is relatively slow [7]. Moreover, the hydrolytic degradation process needs to be catalyzed at high temperatures, normally in the

Polymer	T _g (°C)	T _m (°C)	UTS (MPa)	ε (%)	Degradation time (months)	Reference
LDPE	−100	98–115	8–20	100–1000	NA	[20]
PCL	−60	58–63	4–28	700–1000	>24	[20, 24]
PLA	40–70	130–180	48–53	5–8	12–16	[20, 24]
PHA	−30–10	70–170	18–24	3–25	1–2	[20, 26]
Starch	60–80	—	2.6	47	Bulk	[6, 25]

Table 2.
Physical and mechanical properties of biodegradable polymers compared to non-biodegradable LDPE.

range of 60°C. This means that it is not compostable at home, for instance, and requires a specific compostable environment [22]. Despite its high strength, PLA is limited due to its brittleness thermal instability [20]. Additionally, PLA polymers are derived from nonrenewable resources that make their sustainability a questionable matter. While other semisynthetic variants are fabricated; however, their use would not be favorable due to being partially degradable [7].

2.1.2 Polyhydroxyalkanoate (PHA)

PHA is a microbial polymer which retains close properties to non-biodegradable thermoplastics such as LDPE, as shown in **Table 2** [27]. Its discovery and synthesis began during the early twentieth century [22]. It possesses desirable physical and mechanical characteristics such as high melting temperature; the tensile strength is slightly higher than that of LDPE with an average of 21 MPa. Unlike the aforementioned PLAs, PHAs exhibit good impermeability to water as well as rapid biodegradation properties, as shown in **Table 3**. They are a class of biopolymers which biodegrade by microorganisms. Additionally, they are considered thermoplastic and could be easily processed using existing molding and extrusion technologies known for petrochemical-based polymers [20]. Their rapid degradation under various environments is considered its main attribute in contrast with other alternatives, not to mention that they are considered as a sustainable substitute for being bio-compatible and biorenewable as it originates from plant oils and sugars [27]. However, methods of synthesis are highly costly, and until a cost-effective method is derived, PHA commercialization would be limited and economically unjustified.

2.1.3 Polycaprolactone

PCL is a semicrystalline polymer fabricated by means of ring polymerization of caprolactone in the presence of a catalyst [1, 7]. It is considered a synthetic biopolymer fabricated from a nonrenewable resource, and similar to PLA, PCL is a hydrophobic polymer with a low degradation rate [18]. Additionally, compared to PCL, the average tensile strength is lower, but it is important to note its high elongation at break being comparable to that of LDPE. Nevertheless, its high cost of processing and non-renewability are major drawbacks in the context of sustainable design.

To that end, in spite of the several advantages offered by synthetic polymers such as compatible properties and easy processing, they are considered very expensive to produce [6]. Also, from a sustainability point of view, they offer a weak competition, with some being nonrenewable such as PCL and partially degradable as PLA. This dictates the importance of the agro-/natural polymers that are inherently both biodegradable and biorenewable as well as being cheaper to

Polymer	Cost of processing	Mechanical properties	Impermeability to water	Degradation rate
PCL	High	Moderate	Good	Slow
PLA	High	High and brittle	Good	Slow
PHA	High	Moderate	Good	Rapid
Starch	Low	Poor	Moderate	Fast

Table 3.
Comparison between biodegradable polymers [16, 18, 20, 21].

produce. Owing to their attractive attributes, this category provides a promising sustainable candidate for green product design over their synthetic equivalents.

2.2 Agropolymers: natural polymers

Natural polymers form during the ecological growth cycle of living organisms [7]. They are mainly derived from biomass fragmentation processes, where polysaccharides are classified as the most representative family of natural polymers.

2.2.1 Polysaccharides: starch polymers

The main polysaccharides explored in various applications are starch and cellulose-based derivatives [7]. Owing to being abundant, low in cost, and biodegradable, starch-based polymers are among the most extensively studied biodegradable polymer and are considered one of the most favorable candidates for sustainable materials [2, 6, 7, 14–16, 19, 20, 25, 28, 29]. Starches are hydrophilic carbohydrate materials that are regenerated by photosynthesis from plants such as wheat, corn, rice, and potato [6, 28].

Starch is primarily composed of two glucose homopolymers: (1) linear amylose and (2) highly branched amylopectin [1, 16]. Different sources yield different proportions of the homopolymers in the range of 10–25% amylose and 75–90% amylopectin [6]. This leads to variable properties, where high amylose content in starch leads to an improvement in mechanical properties such strength and elongation [7, 20]. Additionally, the hydroxyl side groups present in the polymeric chain aid in the rapid biodegradation of the biopolymer [6]. The polymer is considered as highly sustainable, where it is worth noting that during the natural assimilation process, starch is hydrolyzed into glucose that is further metabolized into CO₂ and H₂O. Afterwards, an ecological equilibrium is created, whereas aforementioned the starch is regenerated by the natural photosynthesis process of plants as they absorb the processed CO₂ [6, 27]. Nevertheless, it is important to note that native starch by itself cannot be processed and it must undergo a modification process to improve its processability.

2.2.2 Modification of natural starch: gelatinization to form thermoplastic starch (TPS)

The modification process initiates by applying thermomechanical processing to the starch granules mixed with water at temperatures in the range of 90–180°C, which causes expansion and disruption of the granules as a means of transforming the semicrystalline structure into an amorphous thermoplastic starch [28]. This process is referred to as “gelatinization,” and at this stage, the starch is difficult to process, and the addition of a plasticizer such as glycerol or other polyhydroxy compounds is needed to reduce the glass transition temperature (T_g) and improve its flow properties and mechanical properties as reported by Elsayed et al. [28], Ibrahim et al. [29], and Mehanny et al. [30], where optimum conditions were found at glycerin content of 30 wt.%. Additionally, Vroman and Tighzert reported—in their review on biodegradable polymer—an improvement in the flexibility and elongation properties at glycerol contents higher than 20% [7]. Thus, the resultant properties and loss of crystallinity is a function of the type of starch used and supplied water and heat during the gelatinization process [16, 28]. Concurrently, the processing technique plays a vital role in the crystallinity and mechanical properties of TPS, where the shear stresses applied during the extrusion process allows for an efficient transfer of the water into the molecules, and also the use of injection molding leads to a more amorphous structure and ductile properties [16].

Additionally, it is argued that the addition of plasticizers retards the retrograding process that takes place as the polymer recrystallizes and becomes brittle with time [31]. However, the pure thermoplastic starch still acquires properties similar to that of native starch such as poor mechanical properties and high hydrophilicity [2, 20]. This is due to the fact that the plasticizers themselves increase the hydrophilic nature of the polymer and results in higher water permeability [14, 31]. This leads to thermal instability and the loss of mechanical properties [2].

2.3 Modification of thermoplastic starch

2.3.1 Acetylation

To improve the properties of TPS, several methods were devised. The first technique is known as acetylation, where starch acetate is fabricated through the chemical mixture with pyridine and acetic acid [7]. The resultant polymer has a high content of the linear amylose polymer that is less hydrophilic, thus overcoming the permeability issue exhibited by pure TPS [7].

2.3.2 Grafting

Another powerful technique devised is grafting or copolymerization. Examples include grafting synthetic bio-polyesters such as PCL and PLA to the starch by a chemical bond [6]. However, it is argued that the rate of biodegradability is sacrificed under these conditions as the chains *will not* assimilate in nature readily nor easily [7].

2.3.3 Blending

At first, scientists used to blend starch with polyolefin synthetic polymers to achieve desirable superior properties; however these systems are partially biodegradable and thus are regarded unacceptable from a sustainability point of view [32]. Thus, the use of only biodegradable synthetic polymers is restricted while using this technique. A thorough review is provided in [7]. The most common components to blend with starch are the aliphatic bio-polyesters such as PLA, PCL, and PHA [33]. The resultant material achieves improved properties and cost competitiveness. On the other hand, a major shortcoming is reported, where it is outlined that starch and many polymers are immiscible, which, thereafter, causes these blends to become weak and eventually deteriorate [6].

Thereupon, it could be inferred that a large range of properties could be tailored among these polymers for specific applications. However, each of them exhibits a variety of limitations which restricts their use and applicability across many fields, and from a sustainability viewpoint, starch-based polymers still provide the best alternative especially if their shortcomings are overcome. Their main advantageous features rely on being the lowest cost material compared to other biodegradable polymers, which are processed by existent processing techniques used for conventional polymers. Also they are both renewable and biodegradable, where several studies have reported an immense improvement in the mechanical and physical properties of modified TPS. Different techniques such as blending, grafting, and acetylation have been implemented to improve properties; however they affect the biodegradability of TPS which is its key successor that establishes it as the front runner in the race toward achieving sustainable alternative materials [7]. Subsequently, it has been reported in the literature that tailoring starch-based composites that are dependent on natural resources yields optimum results while still preserving the biodegradability nature of the polymer [6]. Given their favorable potential,

the nature of these composites will be discussed in Section 3 along with introducing the different types and characteristics.

3. Biodegradable starch-based composites

A biocomposite polymer is classified as a material which combines a biodegradable polymer as its matrix and a biodegradable filler as the reinforcement [18]. Such composites are also commonly known as “green composites,” and as the focus in this chapter is sustainability, the use of natural fibers as fillers will be the only class investigated [34]. Several researchers have demonstrated a high compatibility between starch- and natural-based fibers such as cellulose derivatives [2, 14, 16, 18, 28, 29, 33]. Considerable improvement in the mechanical properties of starch-based composites coupled with a reduction in water permeability has been reported. Additionally, Reddy et al. has reported the use of nano-fillers specifically cellulose-based in the fabrication of green composites, where significant enhancement in properties is anticipated [35]. The classification of natural fibers is presented in Section 3.1, and an overview of their impact as reinforcements on the TPS matrix is provided in Section 3.2.

3.1 Natural fibers

Fiber fillers are added as the source of reinforcement and load bearing component within the composite matrix. They are of either natural or synthetic origin such as plants and carbon, respectively. However, natural fibers offer several benefits over their synthetic counterparts, one of them being that they are essentially biodegradable which is considered as a merit for the environment [8]. Additionally, high specific properties such as strength and low density along with being renewable and low in cost have led to their emergence as excellent substitutes for the man-made competitors [4, 36]. The fiber strength comes from the strong inter- and intramolecular bonds that make the fiber stiff and rigid developing intertwined threadlike structures [31]. In addition to the strong bonds, the higher the crystallinity of the filler material, the less exposed areas of the matrix that would absorb water and moisture. Each type differs slightly in their characteristics; there are three major classes upon which this family of fibers are classified: (1) plant-based fibers, usually referred to as bast fibers and are extracted from the outer bark of plant stems, such as flax, jute, and hemp; (2) leaf fibers, which are hard and strong fibers obtained from leaf tissues such as in the case of sisal and pineapple; and finally (3) seed fibers such as cotton and coir [4, 16]. Other types are extracted from wood or grass [4]. **Table 4** illustrates the mechanical properties of the characteristic natural fibers commonly used for each category compared to carbon fibers. It can be observed that the plant-based flax fibers exhibit the highest strength with a maximum of 1500 MPa, while that for the remaining bast and leaf fibers is less than 1000 MPa. Nevertheless, they all show high specific strength and specific stiffness properties compared to carbon fibers, where the specific gravity of carbon is much higher than the natural counterparts.

Furthermore, it is important to note that natural fibers have wax on its surfaces and other elements such as lignin and hemicellulose, which leads to difficulty in the adhesion of the matrix to the fibers. Therefore, to improve the poor linkage and adhesion problem, the fibers undergo a surface chemical treatment before synthesis with the matrix, which also aim to reduce the fiber permeability to water [16]. Most treatments work on removing the hydrogen bonds on the surface so as to make it hydrophobic and to improve the surface roughness.

Category	Type	UTS (MPa)	ϵ (%)	E (GPa)	Specific gravity (g/cc)
Bast fibers	Hemp	270–900	1.6	24–90	1.4–1.5
	Flax	345–1500	2.7–3.2	27–100	1.4–1.5
	Jute	393–800	1.16–1.5	13–55	1.3–1.49
Leaf fibers	Sisal	468–700	3–7	9.4–22	1.3
Seed fibers	Coir	131–220	15–40	4–6	1.15–1.46
Synthetic	Carbon	2500	1.4–1.8	425	1.9

Table 4.
Mechanical properties of natural fibers compared to carbon fibers [16, 34].

3.2 Natural fiber-reinforced starch-based composites: performance evaluation

The main goal driving the fabrication of the natural fiber-reinforced starch-based composites is overcoming the limitations of TPS and attaining better mechanical and physical properties while still retaining the biodegradability attribute of natural materials. This section attempts to evaluate the performance of the different variations of the green composite based on the improvements achieved in the mechanical properties, thermal stability, and biodegradation rates compared to that of the starch matrix. **Table 5** summarizes the outcome of the studies performed on different combinations of natural fiber and starch. Key findings and conclusions are drawn from comparing the data tabulated and will be discussed in the following sections, based on which the DFL approach will be highlighted.

3.2.1 Mechanical properties

As observed from **Table 5**, there is a general increasing trend in the tensile strength as the fraction of fiber increases in the composite compared to that of pure thermoplastic starch. This is demonstrated in the case of adding flax fibers to TPS, where the tensile strength increased from 50 to 60 MPa as a function of increasing the fiber content from 40 to 50%, respectively. However, increasing the content beyond certain percentages, the opposite occurs where the properties deteriorate instead of improving. This is slightly observed post increasing the flax fiber content to 80%, where the tensile strength reduced to 55 MPa. However, this phenomenon was clearly observed when using date palm fibers, where increasing the fiber composition from 50 to 80% led to a significant 60% decrease in the tensile strength from 32.7 to 12 MPa, respectively. Moreover, in spite of following similar trends, different fibers possess variable properties which eventually lead to major differences in the properties attained. It could be remarked that flax-based starch composites acquire the highest in tensile properties coupled with the highest ductility among other composites. It is clear that the strong flax fibers have imparted their high strength properties (listed in **Table 4**) to the starch matrix and produces a high strength composite with desirable properties. Additionally, the hybrid between date and flax fibers has led to an increase in the tensile strength equivalent to the average increase attained from each type—at the same composition—separately.

3.2.2 Thermal stability

Another upward trend is attained in the thermal stability which incrementally increases as a function of increasing the fiber content. Due to the organic nature of the biocomposite constituents, heat application is expected to cause changes in their physical and chemical properties [16]. Thus, thermal stability is tested through a

Fiber	Composition (%)	UTS (MPa)	ϵ (%)	E (GPa)	Weight loss (%) / week	Temp. at 10% weight loss (°C)	Reference
TPS	0	3.8	138	0.5	30	192	[28]
Flax	40	50	—	3.5	16	—	[28]
	50	60	5.7	4.3	15.4	229	[2]
	80	55	—	2	5	251	[28]
	50	131	5.8	7.5	15.4	—	[2]
	(unidirectional)						
Palm	50	28.2	1.82	3.85	18.6	—	[2]
Banana	50	25.4	2.03	3.71	20.3	—	[2]
Bagasse	50	29.8	3.27	3.23	20	—	[2]
Date	50	32.7	—	2.8	18	232	[29]
	80	12	—	7	10	250	[29]
Hybrid	25(Date) & 25 (flax)	43	—	—	—	—	[29]
Sisal	20	2.8	2	151	—	—	[38]
Hemp	20	4	3.4	182	—	—	[38]
Short fiber-cellulose	15	15.43	6.08	364.9	—	350	[39]
Jute	12.5	5.5	—	—	—	—	[40]
Lentil flour	0.5	2.1	49	0.86	23.1	—	[14]
	1	6.3	42	4.8	23	—	[14]

Table 5.
Mechanical properties, thermal degradation, and biodegradability of TPS and natural fiber-reinforced TPS.

method known as thermogravimetric analysis (TGA), where one of the test methods evaluates the temperature it takes to cause a 10% weight loss and records the differences among the different composites, with higher values indicating improved stability. Compared to TPS, the temperature at which 10% weight loss occurs increased from 192 to 229°C and 251°C corresponding to a 50 and 80% increase in the flax fiber fraction, respectively.

3.2.3 Biodegradation

Biodegradability is an integral process of biocomposites, which occurs as a result of microbial bacteria or fungi naturally assimilating the material structure and causing its degradation [16]. The main scheme followed to test the biodegradability rate is by measuring the percentage weight loss during a period of time. Generally, the higher the percentage of fibers, the lower the degradability rate due to the lower degradation rate of the fibers than starch-based polymers, as shown in **Table 5**. During the 1-week test period dictated to measure the rate of biodegradability, only 5% weight loss has occurred in the 80% flax fiber-reinforced TPS compared to the loss of 16% in the 40% flax fiber-reinforced TPS and 30% loss in pure TPS.

3.3 Design for a life approach

The design for a life approach assumes that the lifetime of a product can be estimated based on the rate of biodegradation, which depends on the material

composition and service conditions. Data on biodegradation of various materials, such as that in **Table 5**, can be used to select the appropriate material for a given service environment and expected useful life of the product. The different mechanisms associated with the life cycle assessment of polymers is provided in [9], which provides a comprehensive overview of the needed knowledge for the determination of the useful life of the polymer. Moreover, Elsayed et al. presented biodegradation data related to flax fiber-reinforced starch composites, where the weight loss test was applied for long periods of time. The time needed for a 100% loss in weight was determined to be 6 weeks for TPS coinciding with a less than 40% reduction in the composite [28].

Successful application of the DFL approach entails a proper material selection process to be performed along with sufficient knowledge of the physical and chemical reactions associated with the proposed composites. This will provide the framework and foundation needed for choosing the applicable bio-based alternative and eventually help in controlling the service lifetime of the polymer by either accelerating the degradation process or stabilizing it depending on the application. The case study presented in Section 4.1 elaborates further on the use of material selection and substitution processes to aid in making the proper choice for applications in the automotive industry. The case study is adopted from material substitution cases reported by Farag and published in [16, 41].

4. Sustainable product design

4.1 Case study: the use of biodegradable composites in the automotive industry

Material selection processes are considered one of the most vital steps in the engineering and sustainable product design. This has become a necessary activity performed by automotive manufacturers and designers. Driven by the need to improve fuel efficiency, weight reduction has become a prime requirement. Accordingly, the fraction of lighter materials such as aluminum and plastic composites has progressively increased and substituted heavier steel alloys traditionally used. Other factors driving the search for alternatives are price, end-of-life vehicle legislation, and sustainability [16, 36]. Al-Oqla and Sapuan have emphasized on the importance of selecting the proper alternative biocomposite that meets all the requirements needed for environmental sustainability as well as compatibility to performance prerequisites [8]. Also, the authors added that considering the tremendous need and awareness of environmental issues, natural fiber-reinforced composites have become of major interest by researchers. Given their low density, good mechanical properties, renewability, and biodegradability, automotive interiors could be designed with high specific strength and stiffness properties, meeting design requirements while still meeting environmental criteria [37, 42].

4.1.1 Materials and composites for interior panels

Conventionally, polymers such as polyvinyl chloride (PVC) have been used for the interior panel structures [41]. Advantages such as easy processing and low cost have led to its extensive use in a wide variety of applications. However, it is a synthetic polymer with recycling and degradability issues making it an unfavorable choice. Subsequently, alternatives have been proposed in the literature with a recent review summarizing the selection criteria for biocomposites to be used in automotive structures [42]. **Figure 1** illustrates the use of hemp fibers in reinforcing polypropylene composites as a substitute in car doors.

Holbery and Houston have indicated that the use of bast fibers and specifically flax fibers presents a strong competition against E-glass fibers commonly used in composites implemented in automotive applications [43], where the specific strength for flax fiber is 1200 compared to 1275 for E-glass fibers [43]. Other natural fibers suggested for reinforcing plastics are hemp and jute. Their use has been reported in reinforcing PP replacing fiber glass-reinforced plastics in commercial Mercedes-Benz and Ford cars [44]. **Figure 2** demonstrates the use of flax fiber composites in different components of the Mercedes-Benz A-Class vehicle.

However, these composites are argued to be only partially biodegradable due to the synthetic matrices and hence are not an environmentally friendly option. A rather more sustainable option is the use of natural polymers such as starch reinforced by natural fibers. Nevertheless, this option has not been investigated in the literature in applications related to the automotive industry in spite of the benefits these composites offer, which range from the low energy needed for production to being renewable and biodegradable. The case study presented in Section 4.1.2 evaluates the use of natural fiber-reinforced starch as a potential candidate for substitution.

4.1.2 Performance indices and material requirements

For interior panels, the material requirements needed are lightweight and high stiffness. Cost and environmental considerations are other factors considered for the decision-making process. Thus, the material performance index (m) for a stiff light structural member is calculated based on the consideration that a panel is

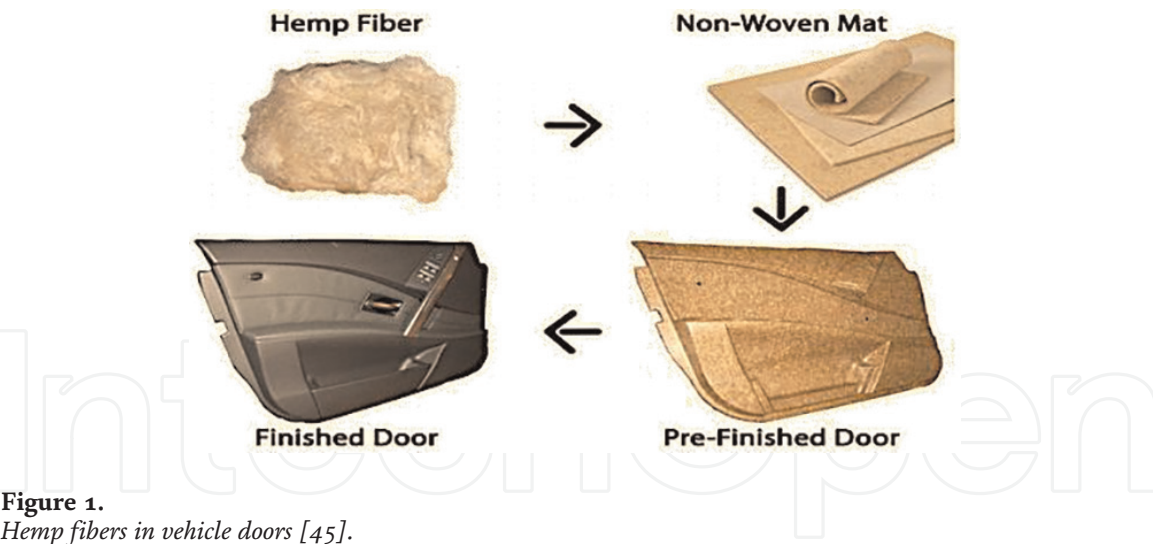


Figure 2. Mercedes-Benz A-Class vehicle components made of flax fiber composites [46].

rectangular of 100 cm in length (l), 50 cm width (b), and thickness (t) 3.7 mm for the PVC conventional material:

$$m = E^{1/3}/\rho \quad (1)$$

The mass (M) of the panel is

$$M = \rho t b l \quad (2)$$

The thickness is given by

$$t_n = t_o (E_o/E_n)^{1/3} \quad (3)$$

where t_n is thickness of alternative material, t_o is thickness of the PVC conventional material, E_o is elastic modulus of alternative material, and E_n is elastic modulus of the PVC conventional material.

Calculations for each performance index are presented in **Table 6** for the different candidate materials.

4.2 Cost of the panel

The total cost (C_t) of a panel is the summation of the cost of material, cost of manufacturing and finishing, cost over the entire life of the component (running cost), and cost of disposal and recycling.

4.2.1 Cost assumptions

The cost of the material in the panel is based on its weight and the price of material per unit weight. The manufacturing cost is roughly estimated based on the assumption that compression molding is used. According to Farag, the life of a car could be estimated to be 5 years, a total of 200,000 km traveled, \$3/gal of fuel, and 8.62 km/L for a 1782 kg vehicle; the total fuel cost savings of the vehicle is approximately \$6.6/kg. This amount can also be taken as the share in the running cost of a component weighing 1 kg over the entire life of the vehicle. Finally, the cost of disposal and recycling is estimated as being proportional to the weight of the panel and its material. Synthetic composites and matrices are difficult to dispose; thus the cost is assumed as \$0.7/kg, while natural composites are relatively easier, and the cost of disposal is assumed to be \$0.5/kg.

Finally, the cost of pure synthetic polymers is considered to be easy and estimated to be \$0.3/kg., while biodegradable natural fibers are easiest to dispose of with a cost of 0.15/kg.

4.3 Environmental considerations

Motorcar weight reduction is considered as the most important factor in reducing the negative impact on the environment. This is related to the reduction in fuel consumption and the reduction in carbon dioxide emissions [47]. Therefore, this study assumes that the environmental impact of the panel is directly proportional to its weight.

4.4 Comparison of candidate materials using the compound objective function method

Table 7 gives the normalized values for each of the computed cost and weight of the panel. The performance index of a panel made of a given material is taken as

Material	E (GPa)	ρ (g/cc)	t (mm)	Cost of material /kg (\$)	Cost elements (\$)				Total cost of panel (\$)	Weight of panel (Kg)
					Materials	Manufacturing	Running	Disposal		
PVC	2	1.3	3.7	1.375	3.3	2	15.84	0.72	21.86	2.4
PP and 40% GF	7.75	1.78	2.36	3.46	7.3	2	13.86	1.47	24.60	2.1
PP and 40% flax	4.65	1.34	2.8	1.04	2	2	12.4	0.94	17.34	1.88
Starch and 50% flax	4.5	1.4	2.82	0.34	0.7	2	13	0.3	16	1.97

Table 6.
Material properties and cost elements of candidate materials.

Material	Total cost of panel (\$)	Normalized cost	Weight of panel as a measure of environmental impact	Normalized environmental impact	Performance index			
					Scenario 1	Rank	Scenario 2	Rank
PVC	21.86	73.2	2.4	78.33	75.8	3	90.9	3
PP and 40% GF	24.60	65	2.1	89.5	77.2	4	74.8	4
PP and 40% flax	17.34	92	1.88	100	96	2	95.2	2
Starch and 50% flax	16	100	1.97	95.4	97.7	1	98.16	1

Table 7.
Ranking of candidate materials.

the weighted sum product of the normalized values of its cost and environmental impact. Using the objective function method, two scenarios are considered: in the first scenario, the cost of the panel and its environmental impact are given equal weight, and in the second scenario, the cost of the panel is considered less important and is given a weight of 40%, and the environmental impact is considered more important and is given a weight of 60%. Both scenarios give the starch-flax composite the first rank. Its low cost more than compensates for its moderate weight.

5. Conclusion

Conventional plastics are designed with little consideration for their ultimate disposability or recyclability. Accordingly, this has led to the growing environmental awareness and notion toward the use of alternatives to petrochemical-based polymers. Given the ubiquity of plastic use in everyday life, substantial progress was made in the development of a reliable substitute, and in recent years, significant advancement was achieved in the production of alternative biodegradable materials based on renewable resources, which can offer equivalent functionality and physical properties similar to their petrochemical-based counterparts. Products that are based on such materials can be designed to biodegrade at the end of their useful life using the design for a life approach which entails that the material used in making a given product will not last long after the end of its useful life. However, the challenge is to design polymers to provide the required functionality during use and naturally degrade after. Consequently, this chapter has elucidated the advancement achieved by researchers in fabricating biodegradable alternatives from starch-based composites.

Abbreviations

T _g	glass transition temperature
T _m	melting temperature
UTS	ultimate tensile strength
E	Young’s modulus
ε	elongation
ρ	density

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