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Original Article

Innovations in Biodegradable Materials for Consumer Products

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ABSTRACT

The growing volume of plastic waste and its long-term environmental impact have intensified global interest in biodegradable materials for consumer products. Conventional petroleum-based plastics, while durable, contribute to persistent pollution, microplastic formation, and ecosystem damage. In response, biodegradable materials offer a sustainable alternative, as they can decompose naturally under controlled conditions while maintaining acceptable mechanical and functional properties. This review examines recent innovations in biodegradable materials, including bio-polymers, natural fiber-reinforced composites, starch-based plastics, polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and bio-nanocomposites. It explores their design principles, synthesis methods, processing technologies, and degradation mechanisms. The study highlights key advancements, performance trade-offs, and application challenges identified in existing literature. A methodological framework is proposed to evaluate these materials based on mechanical strength, biodegradability, lifecycle impact, and economic feasibility. The analysis identifies critical challenges such as high cost, limited scalability, and consumer acceptance. The paper concludes by emphasizing future research directions, including material hybridization, nano-engineering, and the integration of circular economy principles to accelerate the adoption of biodegradable materials in mainstream consumer products.

KEYWORDS

Biodegradable Materials, Biopolymers, Sustainable Consumer Products, Polylactic Acid, Natural Fiber Composites, Circular Economy.

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1. INTRODUCTION

1.1. Background

The endemic and long-term reliance on synthetic plastics has become a significant ecological issue of the international concern, which is preconditioned by the widespread usage of the materials in the whole gamut of consumer goods. Polyethylene and polypropylene plastics are more recommended due to their durability, low cost as well as versatility but the same properties have made them remain in the environment several decades. Consequently, it can be seen that plastic wastes are accumulated in landfills as well as in the natural ecosystems where there are overflowing landfills, marine pollution and damage to the ecology in the long term. Consumer goods such as packaging material, single-use ware, and disposable household waste can offer a sizable fraction of the overall amount of plastic waste produced annually, in large part because these products have a short service life and are consumed at a significant rate. The inadequate disposal of the plastic waste also increases the issue since lightweight plastic products are easily shipped to waterways and oceans, where they are torn into microplastics and become a significant threat to marine life and human health. Other than waste build-up, making, and disposal of traditional plastics lead to significant emission of greenhouse gases, which aggravates the problems of climate alteration. Such increasing environmental issues demonstrate the necessity of having a sustainable alternative to the conventional plastics and explain why it is necessary to create biodegradable materials that can be used as consumer products.

1.2. Importance of Innovations in Biodegradable Materials

Fig 1 - Importance Of Innovations in Biodegradable Materials

1.2.1. Environmental Sustainability

The use of biodegradable materials technology is important in light of the emissions that are posed to the environment by traditional plastics. Using biodegradable alternatives will reduce the accumulation of waste in landfills and natural ecosystems over the long-term, since the materials can disintegrate into non-toxic elements in natural or controlled environments. Such novelty approaches directly solve the pollution of the seas and the formation of micro plastics, contributing to the ecosystem maintenance and environmental safety.

1.2.2. Reduction of Carbon Footprint

Biodegradable materials are commonly based on renewable materials like agricultural crops, biomass, or bio-waste and this factor has a lower carbon footprint in relation to petroleum-based

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plastics. The technologies of material synthesis and processing have also enhanced higher energy efficiency and less emissions of greenhouse gases throughout the product life cycle. This renders biodegradable materials to be a significant resource in combating climatic changes that are attributed to the production and disposal of plastic.

1.2.3. Advancement of Circular Economy

Biodegradable material innovations will facilitate the change to circular economy as they ensure safe material flows and end-of-life management. These materials may be compostable, recyclable or biodegradable so that it can be used again in the natural or the industrial processes. This kind of development lowers the reliance on non-renewable resources and promotes the maintenance of a sustainable pattern of consumption and production.

1.2.4. Enhanced Material Performance

The mechanical, thermal and barrier properties of the biodegradable materials have improved greatly due to new studies that have made them useful in consumer products. Such innovations as bio composites and bio-nan composites allow biodegradable materials to fulfil performance needs of traditionally held by conventional plastics. This is a critical performance improvement on top of building confidence in the industry to expand the market adoption.

1.2.5. Regulatory and Market Drivers

The pressure on sustainable materials has been increasing due to the increasing environmental standards and the growing awareness of the consumer. Biodegradable materials promote innovations in marketing, enabling manufacturers to meet standards in regulation as well as satisfying consumers with greener products of the company. These innovations provide environmental and economic benefits regardless, as a new differentiator on the market is sustainability.

1.3. Biodegradable Materials for Consumer Products

Biodegradable plastics have become an exciting development as alternatives to the traditional plastic material in the application of plastic in consumer product production due to growing concern with the environment and the need to have a more sustainable material. These materials are supposed to break down into permanent components that are natural and non-toxic that can be broken down through biological means through microorganisms, enzymes, and environment factors including moisture and temperature. Popular biodegradable polymers present in consumer goods are biopolymers (polylactic acid (PLA), polyhydroxyalkanoates (PHAs), starch plastics, and cellulose plastics. The short life and disposable packaging containers of consumer goods, such as packaging materials, kitchenware, shopping bags and containers of personal care products, are especially appealing owing to their renewable nature and less environmental endurance. Biodegradable materials can be of great benefit in the consumer packaging sector because it solves the problem of waste management related to single-use plastics. Compostable packaging can cut down the amounts of landfills and contribute to the organic waste treatment systems when they are disposed of. On the same note, biodegradable kitchenware and household disposables offer viable performance and reduced

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adverse effects on the environment in the long run. The strength, bending, and strength of these materials have also been enhanced through the progress of material formulations which include; the blending of polymer, and reinforcement with natural fiber, together with this, the material succeeded in addressing the real-life demands of everyday consumers.The introduction of biodegradable materials in consumer goods however beneficial as it is, has some challenges. Most of the biodegradable polymers have a disadvantage like low thermal resistance, sensitivity to moisture and cost of production compared to the traditional plastics. Moreover, biodegradation would rather require particular environmental conditions, e.g. industrial compost facilities, which cannot always be found everywhere. The awareness of consumers and correct disposal procedures also is very important as a key to realizing the benefits of such materials on the environment. Continued research and innovation are used to overcome these difficulties through the improvement of material performance, the minimization of costs, and infrastructure end-of-life. With the growth of technological development and the rise of the sustainability policy, biodegradable materials will become the part of creation of environment-conscious consumer products.

2. *LITERATURE SURVEY*

2.1. Biopolymers in Consumer Applications

Renewable biopolymers including corn starch, sugarcane, and cellulose have also enjoyed much consumer popularity because of rising environmental awareness and the failure to utilize fossil based plastics. The benefits of these materials are that they are biodegradable and renewable and have a reduced carbon footprint in their life cycle. One of the most diverse biopolymers in terms of research and commercial implementation is polylactic acid (PLA). PLA is characterized by high transparency, stiffness and plastic can be easily processed by the conventional polymer manufacture methods of extrusion and injection molding. That has made it to find a lot of application in packaging materials, disposable cutlery, food containers and the packaging of personal care products. Nevertheless, irrespective of these strengths, weaknesses like brittle strength and poor thermal conductivity persist in motivating material-modification and blend approaches research to increase its areas of use.

2.2. Natural Fiber-Reinforced Bio composites

Natural fiber-reinforced bio composites are materials of significance as sustainable materials, whereby biodegradable polymer matrixes are reinforced with plant-fibers like jute, hemp, flax and bamboo. These fibers are appealing because they are of low density, renewable, biodegradable and moderately good mechanical properties. It has been demonstrated that an addition of natural fibers to biopolymers has a positive effect on tensile strength, stiffness, and impact resistance priority over neat polymer matrices. Also, the fibers lead to cost reduction and improved environmental performance. It has been established by numerous investigations that fiber surface treatment and optimization of fibers-matrix surfaces bonding is very essential in ensuring the attainment of optimum mechanical results. Consequently, natural fiber-reinforced biocomposites are being put into consideration to find their ways into consumer goods, interior parts of the automotive industry and lightweight structural items.

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2.3. Starch-Based and Cellulose-Based Materials

The most studied biodegradable polymers are starch-based and cellulose-based polymers because of their abundance, low costs and complete biodegradation. In the short life consumer product and packaging sector, especially plastics that are based on starch are appealing. They are however very susceptible to moisture due to their hydrophilic nature thus low mechanical and mechanical stability, and low level of durability in wet environments. In order to address these difficulties, the recent studies have paid attention to the utilization of plasticizers, chemical changes, and polymer hybrid procedures to contribute to the flexibility, moisture resistance, or mechanical stability. Equally, cellulose based materials are very promising with regard to their mechanical properties and thermal stability, however, processing challenges and insufficient solubility is a challenge. The development of technologies of the material formulations and processes are further enhancing the performance and usage of starch- and cellulose-based bioplastics in the consumer market.

2.4. Bio-Nanocomposites

The concept of bio-nanocomposites has come by as an encouraging new stride in sustainable development of materials through the introduction of nanoscale fillers to biodegradable polymer matrices. The nanofillers: nanocellulose, layered silicate clays, and the bio-based nanoparticles (or nanoparticles) greatly increase mechanical, thermal stability and barrier properties even at low filler content. The excellent interfacial contribution and high surface area between the nanofillers and polymer matrices have assisted in the provision of improved performance over traditional biocomposites. These applications in theory have been identified by literature as potential uses of bio-nanocomposites: use in packaging of food to ensure gas barrier properties are improved, and also in electronic consumer products where weight reduction and thermal stability are of primary importance. The issues surrounding the inability of nanoparticles to be dispersed, as well as their scalability and cost, are some of the main topics of the current research despite their potential.

3. METHODOLOGY

3.1. Material Selection Framework

Fig 2 - Material Selection Framework

3.1.1. Renewability of Raw Materials

The sustainable choice of materials is significantly determined by the renewability of the raw materials, which is the main factor as it also has a direct effect on the environmental impact and the

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availability of resources in the long run. Sources of materials that are weakly renewable like plant waste or bio-fibers like agricultural crops are better than those based on fossil. Renewable feedstocks can help to reduce emissions of greenhouse gases and facilitate a circular economy by reducing reliance on non-renewable resources.

3.1.2. Mechanical Performance

Mechanical performance is the key element in making sure that the material offered has the capacity to resist service loads and fulfills operational demands of consumer goods. Attributes like tensile strength, stiffness, impact resistance, durability among others are tested to see if they are fit to be used in the target situations. The chosen material should have good balance of mechanical strength and flexibility without compromising on performance with that of standard plastics.

3.1.3. Biodegradation Rate

Biodegradation rate is a measure of the degradation rate of a material under natural or industrial compost requirements, once the material has served its purpose. Preferably controlled and predictable biodegradation behavior of materials is sought to avoid environmental build-up in the long run. The criterion is followed to guarantee that the material can break down to non-toxic by-products in a realistic time frame, which is in line with the objectives of sustainability and waste management.

3.1.4. Processing Compatibility

Processing compatibility is trained in processing the material through the testable methods of the current industrial processing procedures like extrusion or injection and compression molding. Mediums that can be adapted with minimum changes in the standard machinery are preferred since they cut the costs of production and enable the extensive implementation. Good thermal stability and processability are needed to achieve the same quality in each manufacturing.

3.2. Experimental Evaluation Parameters

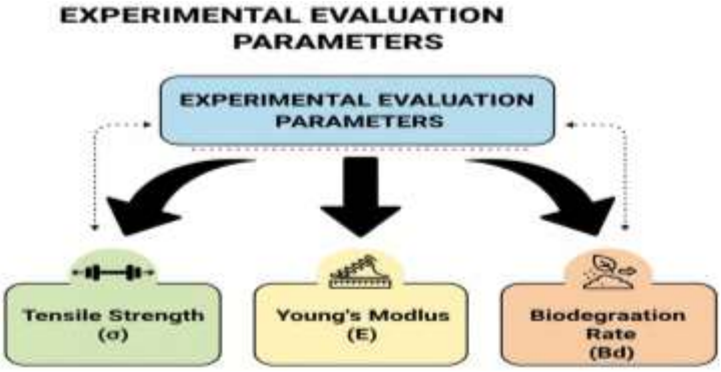

Fig 3 - Experimental Evaluation Parameters

3.2.1. Tensile Strength (σ)

Tensile strength is an essential mechanism characteristic that shows the maximum tension that a material can bear under uniaxial tensile loading before it breaks. It shows the load carrying ability of the material and is very important to measure whether it can be used in structures and consumer

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structures or not. An illustration of better tensile strength values is an internal resistance to deformation and fracture during service.

3.2.2. Young's Modulus (E)

The modulus of the material is the stiffness of the material, and this factor determines connection between occurrence of stress and elastic strain in the linear domain of deformation. It gives an idea regarding the rigidity of the material and its stability to the load in its dimensions. Youngs modulus of materials used as elements of a building creates materials whose elastic deformation is lower and this parameter is vital whenever one is needed in a use that needs structural integrity and shape retention.

3.2.3. Biodegradation Rate (Bd)

Biodegradation rate is used to measure the degree and rate of material degradation that occurs in the biological or environmental environment. This parameter is measured by recording the mass loss, structural change or microbial activity within a specific time. The rate of biodegradation should be controlled such that it will guarantee the material to retain its operational functionality in the process of its use without losing its usefulness and at the same time be biodegraded conveniently after the end of its life cycle.

3.3. Lifecycle Assessment Approach

Lifecycle assessment (LCA) is a scientific and regularized way of researching of the environmental effects of a product in its entire cycle of existence, addressing the extractions of the raw materials in addition to the discarding of the final product. LCA is used in this study to evaluate the sustainability of bio-based materials and also, to facilitate a holistic comparison between the bio-based and traditional petroleum-based plastics. The analysis is conducted on a cradle-to-grave basis, which involves important processes in acquiring raw materials, processing, manufacture of products, distribution, use and disposal or recycling of products at the end. LCA analyzes every stage of the product life cycle and gives the understanding of cumulative environmental impacts, instead of concentrating on one part of the process. The LCA framework commences with goal and scope definition, which provides system barriers, the functions, and categories of impacts of the system in a clear way. This makes biopolymers and traditional plastics consistent and comparably similar. The inventory analysis step entails the process that entails gathering of data in terms of energy use, raw materials used, emissions, and waste produced in every stage of the life cycle. Primary experimental data and secondary information in the form of the available life cycle databases is done to ensure accuracy and reliability. The impact assessment will then reduce the inventory data to the environmental markers of potential global warming, energy demand, water usage, and impact on the ecosystem. Specific attention is paid to end-of-life situation, such as biodegradation, composting, recycling, and landfill disposal, because of its strong effect on the overall environmental performance. Biodegradable substances are assessed with regard to the lessening of environmental persistence and waste build-up on a long term basis as compared to the traditional plastics. Lastly, the interpretation of LCA outcomes contributes to the recognition of hotspots of critical impacts and possible aspects of

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the material selection and processing improvements. This integration will aid in making wise decisions, encourage responsible material formulation based on the environment, and endorse the environmental benefits of sustainable alternatives in the consumer applications.

3.4. Process Flow

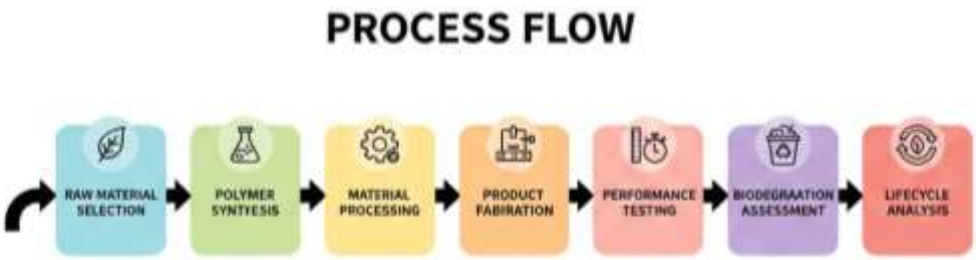

Fig 4 - Process Flow

3.4.1. Raw Material Selection

This is initiated by ensuring a proper choice of raw materials that are renewable and sustainably obtained. The availability, renewability, environmental impact and consistency in quality are considered factors that enable to ensure the selected feedstocks meet the performance requirements as well as the sustainability requirements. This measure forms the basis of coming up with green materials.

3.4.2. Polymer Synthesis

The stage of polymer synthesis involves the chemical or biological transformation of the raw materials into polymeric materials by either fermenting, polymerizing, or modifying the materials in a chemical reaction. The process parameters are set to ensure desired material properties, purity and molecular weight. The most effective synthesis processes should be developed to limit the use of energy and environmental emissions.

3.4.3. Material Processing

Material processing entails a process of transforming synthesized polymers in into usable forms by utilizing traditional methods of extrusion, injection molding, or compression molding. Processing variables such as temperature, pressure and residence time are strictly maintained in order to maintain consistency in the structure of the material and to avoid thermal decomposition. This is done to make sure that it is compatible with the industrial manufacturing practices.

3.4.4. Product Fabrication

In product fabrication the processed materials are formed into final consumer products (or even test items) in line with the designed specifications. It focuses on realising dimensional accuracy, surface quality and functional performance. This phase proves the viability of application of bio-based materials in the actual consumer performance.

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3.4.5. Performance Testing

Mechanical, thermal and physical tests are performed to test the products that have been fabricated. The parameters like tensile strength, stiffness, and durability are determined by standardized testing. The measurements present the important information on the material appropriateness and stability under service situations.

3.4.6. Biodegradation Assessment

Biodegradation testing involves the behaviour of the material with regard to the decomposition in controlled environmental or composting conditions. Monitoring the degradation efficiency is followed by changes in mass, structure and mechanical properties with time. This measure confirms the ecological advantages of biodegradable substances at the lifecycle and the end-of-life stages.

3.4.7. Lifecycle Analysis

The last phase consists of the lifecycle analysis that will help to estimate the total environmental consequences of the material and product. All past stages are incorporated in order to assess the energy consumption, emissions and waste. The result of this analysis allows the comparison with traditional plastics and making the decisions to develop the sustainable materials.

4. RESULTS AND DISCUSSION

4.1. Comparative Material Performance

Table 1: Comparative Material Performance

Material Type	Tensile Strength (%)	Biodegradability (%)	Cost (%)
PLA	80%	60%	60%
PHAs	60%	90%	90%
Starch-based	40%	95%	40%
Bio-nanocomposites	95%	65%	60%

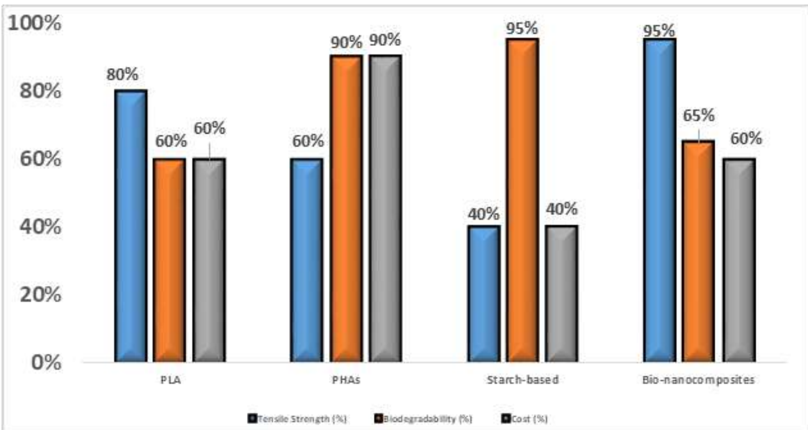

Fig 5 - Comparative Material Performance

4.1.1. Polylactic Acid (PLA)

Polylactic acid (PLA) has relatively high tensile strength with a level of 80 to 80, thereby implying that it is applicable in as many consumer applications as possible including packaging and

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disposable products. It is moderately biodegradable with an approximate of 60 percent implying that PLA is biodegradable, though in many instances, it requires controlled industrial composting environments in order to degrade effectively. The price of PLA is medium (60%), the manifestation of a compromise between the advantages of performance and cost-effectiveness in relation to the conventional plastics.

4.1.2. Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoates (PHAs) have mediocre tensile strength approximated to be 60, which restricts their application in weight bearing applications. Nevertheless, PHAs are highly biodegradable with high percentage of about 90; this is because they can easily decompose in soil, and marine ecosystems. The major weakness of PHAs is the fact that they have a high cost of production (90%), thus limiting their widespread commercial application despite its high environmental benefits.

4.1.3. Starch-Based Materials

In low stress and short-life applications such as packages to be discarded and farm films, starch-based materials are preferable since they have low tensile strength of about 40%. Conversely, they are extremely biodegradable (95 percent) and hence decompose very quickly in natural environmental conditions. Starch based materials are economically favourable owing to their low cost (40%); most importantly in the case where mechanical performance is not a major consideration.

4.1.4. Bio-Nanocomposites

The tensile strength of bio-nanocomposites compares with the highest tensile strength of the materials which have been compared as it reaches about 95 percent as a result of nanoscale fillers reinforcing effect. Their bio-degradability is mediocre at about 65 because the incorporation of nanofillers may alter the degradation pattern. Bio-nanocomposites have a medium level of cost (60 percent), and therefore, represent an appealing compromise between high-performance and low cost in terms of mechanical performance, so they can be used in high-end consumer product applications that demand the use of superior material properties.

4.2. Discussion of Trade-Offs

The comparative analysis of bio-based materials indicates that there are major trade-offs in the mechanical performance, biodegradability, and economy of some materials and this should be put into consideration when choosing materials to be used by the consumer. The use of nanoscale reinforcements such as nanocellulose or layered silicate clays has contributed to the fact that, bio-nanocomposites have superior mechanical properties, which include high tensile strength, stiffness, etc. Such nanofillers improve the movement of loads and limit the mobility of polymer chains leading to better structural performance. Nevertheless, interactions that help in promoting high mechanical strength may also impede the biodegradation. Nanoparticles could decrease the exposure of polymer chains to moisture and microorganisms, postponing the breakdown rate of the enzymes and the loss of the mass during the degradation process. This presents difficulty to the application where post-use degradation is a priority. Starch based materials on the other hand are highly bio-degradable because

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they tend to be hydrophilic in nature and therefore would be susceptible to microbial attack and enzyme degradation occurring in natural environment. This is what makes them extremely appealing in short life product like disposable packages and use in agriculture. They are however, limited in tensile strength and moisture resistance making them less suitable in terms of load carrying or long bearing application. In their non-modified form, starch material is usually brittle with low dimensional stability and low durability. In order to limit these constraints, fiber addition, polymer blending or chemical modification strategies of reinforcement are regularly adopted. Though these strategies enhance mechanical performance, they could swell up material cost, and, in certain situations, adversely influence biodegradability. The issue of performance/environmental impact trade-off necessitates optimization of material with respect to their application. Intermediate solutions to materials like PLA and PHAs are used in many cases that provide a compromise between mechanical strength, biodegradation rate, and cost. Finally, the process of bio-based material choice must involve a more comprehensive evaluation of the requirements on the functional level, environmental performance, processing limitations, and end-of-life behavior. This knowledge of these trade-offs can lead to an informed choice and help in designing sustainable materials in applications to a particular consumer product.

4.3. Consumer Product Implications

Innovation in the consumer product market and especially in areas like packaging, kitchenware and personal care products has been enabled by the development of biodegradable and bio-based products. The development of biopolymers, biocomposites, and bio-nanocomposites has allowed producers to come up with products that have satisfied the functionalities and minimized environmental impact. Biodegradable materials can be better used in packaging, as it can provide more effective methods of waste treatment by allowing the elimination of the long-term accretion of plastics and encouraging composting programs. Equally, bio-based products in the case of kitchen ware and disposable consumer products offer safe, light weight, and renewable options to traditional plastics that do not affect the usability and appearance of the product. In personal care products, biodegradable packaging improves brand sustenance practices and conforms with increasing regulatory and consumer pressure and demand of environmentally responsible products. Along with such technological development, consumer perception still is a key factor affecting market adoption. The biodegradable materials have a negative association with most consumers as they perceive that it reduces performance or has a reduced lifespan. Issues of heat resistance, strength and shelf life tend to influence buying behaviors, especially where such characteristics are compulsory. There also needs transparent communication, labeling and performance validation that will help to build consumer trust and acceptance. Moreover, the poor knowledge on the conditions of biodegradability among the public like distinction between industrial composting and natural degradation can cause misunderstandings and improper disposal thus lessening the environmental benefits of such materials. The other significant impediment to mass adoption is cost competitiveness. Bio-based materials hence tend to be more expensive to produce than the conventional plastics because of raw materials procurement, the complexity of their processing, and low economies of scale. These increased expenses can be translated to high prices on the product and that can put off consumers who are price sensitive. Nevertheless,

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costs should be minimized with time due to the further development of technologies, the growth of the production volume, and supportive policy actions. The solution is necessary to the issue of perception by the consumer as well as economic issues to facilitate the introduction of biodegradable material and its effective implementation in the market of conventional consumer products.

5. CONCLUSION

One such solution is the use of innovations in biodegradable materials to solve environmental problems in general with the consumption use of conventional petroleum based plastics in typical consumer products. The paper has discussed in detail the significant biodegradable material categories that include biopolymers, natural fiber-reinforced biocomposites, starch-based and cellulose-derived materials, and bio-nanocomposites with their properties, strengths, and weaknesses. The trends in recent research indicate that such materials can help to go a long way in cutting down environmental impact using renewable resources and decreasing carbon emissions, as well as enhancing end-of-life disposal with biodegradability and composting processes. The systematic methodology of assessment outlaid in this research including material selection criteria, mechanical performance examination, biodegradation examination, and an analysis of lifecycle offers a rigorous system through which the biodegradable substitutes to conventional plastics can be evaluated in the context of consumer utilization. In spite of these innovations, pivoting on the significant progress of the biodegradable materials, some problems still remain as obstacles to the universal implementation of these materials. Consistency in performance is a major issue with bio-based materials with most bio-based materials showing variability in mechanical performances as well as degradation behavior because of variations in sources of raw materials and other variability in processing conditions. Also, mass production poses both technical and economic risks, such as shorter processing time, sensitivity to moisture and temperature, and fit with the existing industrial facilities. Another critical obstacle that can create is economic feasibility because production expenses of biodegradable materials are usually too high when compared to those of conventional plastics hence they cannot compete with them in price sensitive consumer markets. The development of hybrid material systems with the potential to fuse the robustness of several biodegradable components should be the future research activity to advance towards producing balanced mechanical performance and controlled degradation rates. Engineering nano-based technologies, including the use of bio-based nanofillers, provide good opportunities to improve the properties of materials without reinforcing the sustainability concept. In addition, innovation of processing technology as well as a secondary raw material or waste usage can also result in a cost-cut and higher scalability. Incentives that are guided by policies, such as subsidies, environmental laws and producer responsibility schemes that have a longer period will also be very important in catalyzing industrial uptake finally, to attain environmental sustainability in the long term, it is necessary to focus on the successful introduction of biodegradable material into the cyclical economy models. The biodegradable material can facilitate the reuse, recycling, composting, and disposal in order to close the loop between production and consumption. This cooperation between researchers, industry stakeholders, policymakers and consumers in the past to continue will be important in driving material innovations towards practical, scalable, and environmentally friendly consumer products.

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