IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Biodegradable Polymer-Based Pharmaceutical Packaging and Digital Technology for Waste Circularity: An Integrative Review

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ABSTRACT: Environmental problems throughout the world have gotten worse due to the pharmaceutical industry's reliance on non-biodegradable plastic packaging. This comprehensive review investigates pharmaceutical packaging made of biodegradable polymers and how it combines with digital technology to promote sustainability and waste circularity. The PubMed, ScienceDirect, and Scopus databases were used to conduct a thorough literature review and data synthesis from 2015 to 2025. The review highlights the favourable mechanical, barrier, and biodegradability properties of polymers including polylactic acid (PLA), polyhydroxyalkanoates (PHA), polyhydroxybutyrate (PHB), and polybutylene succinate (PBS). Pharmaceutical supply chains may benefit from intelligent lifecycle evaluation, real-time monitoring, and traceability through the combination of artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT), blockchain, and RFID devices. Results show that the Circular Pharmaceutical Economy (CPE) is developed and waste management efficiency is improved by integrating green materials with digital optimization frameworks. This multidisciplinary strategy provides a revolutionary route to intelligent, ecological, and legal pharmaceutical packaging solutions.

KEYWORDS: Biodegradable polymers, Pharmaceutical packaging, Artificial Intelligence, Internet of Things, Circular economy, Smart packaging, Waste management, Sustainability.

INTRODUCTION

Today's plastic is ultimate disposability or recyclability is not considered much throughout the design process. The impact that these materials have on the environment when they end up in the waste stream after being used for their intended functions is therefore causing concern to develop globally. Particularly concerning are polymers used in single-use, disposable plastic applications.[1] Plastics are affordable, lightweight, robust, and easy They are disposable and incredibly durable. These characteristics of strength and indestructibility, however, are exactly what cause problems when these materials find their way into the waste stream. as well as energy efficient. Their barrier qualities are good. They are difficult for the natural elements of the environment and waste management techniques like composting to break down and integrate into the biological carbon cycle of our ecosystem. As a result, dangerous chemicals build up irreversibly in the ecosystem, endangering marine life and leaving beaches and landscapes scarred. Plastics are resistant to biological decomposition because bacteria lack the enzymes needed to break down and use the majority of synthetic polymers.[2] For many years, the pharmaceutical packaging business has used traditional packaging materials and petroleum-based byproducts. These include polyvinyl chloride (PVC), polystyrene (PS), polypropylene (PP), polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and linear low-density polyethylene (LLDPE). An estimated 50% to 70% of all plastic waste is made up of these typical plastic compounds, which together account for approximately 90% of the total volume of plastics utilized in industry.[3]

Businesses will not be able to thrive in today's competitive market if these duties are completed by hand, and the lead time for any product would be lengthy. Using intelligent AI and ML-based packaging solutions reduces total lead time and ensures package quality, increasing consumer loyalty and brand exposure. Emerge Research projected that the global AI packaging market will be valued at $2.31 billion USD in 2022.[4] Every business uses AI and ML models to analyze vast quantities of complex, high-quality data in order to discover the best pack aging solution. The primary goal of using a sizable product dataset to train machine learning models is to decrease packing waste in online sales. Nevertheless, biodegradable packaging materials have a number of difficulties, including affordability, food safety, and longevity. AI and nanotechnology may provide important solutions. Thanks to AI's capacity to evaluate data and streamline processes, manufacturers may create materials of higher quality, forecast performance, and increase production speed.[5]

This review article outlines the major producers, their current production and application status, and their capacity in the global biodegradable and bioplastics market. The technology behind commercial biopolymers now available on the market has also been debated in detail. Applications for package quality inspection, supply chain management, and customer interaction have been reviewed, after a brief introduction to artificial intelligence (AI), machine learning (ML), natural language processing, computer vision, and image processing. The industry is being transformed by this technological integration, which also forces it to adopt more sustainable practices. Combining AI and nanotechnology in food packaging can overcome current issues with environmental impact and food safety. This not only speeds up the process of finding novel materials, but it also enables researchers to more accurately and effectively modify the characteristics of materials for certain uses. The panorama of biodegradable AI and ML-based materials discovery is consolidated in this paper, with an emphasis on representative materials like as natural and synthetic polymers, AI in waste management, and integration of these materials, which are the foundation of every electronic device.[6]

A. Global Environmental Concerns in Packaging Waste

The negative environmental consequences of medicines are caused by three reasons. The carbon footprint of medicines because of the carbon inherent in their production and transportation, the packaging waste, the chemical effects of the drugs themselves, and the burning of unnecessary drugs and their original containers are a few of these. Now, let's examine each of these separately. The main way that drugs impact the environment is through their carbon footprint. The carbon footprint of pharmaceuticals in public hospitals is significant. For example, in 2010, 4.4 million tons of CO2 emissions, or 22% of NHS England's overall carbon footprint, came from medications. This represents 3% of the total carbon footprint of the UK.[7] Direct chemical effects on the environment are the second way that drugs affect the ecosystem. The issue of drugs in the environment has been an increasing worry for the scientific community and the general public for over 20 years. The National Packaging Covenant was established in 1999 with the intention of altering corporate culture in order to decrease packaging waste, boost recycling rates, and create more ecologically friendly packaging.[8]

It was renamed the Australian Packaging Covenant (APC) in 2010. Government, industry, and community groups have agreed to use the APC to address packaging sustainability issues. The APC aims to reduce the environmental impact of consumer packaging by encouraging the recovery and recycling of used packaging and supporting the design of packaging that is more recyclable and resource efficient. In order to encourage companies to join the APC, Australian state governments require companies with annual sales exceeding $5 million to either sign the APC or abide by the "National Environmental Protection Measure (Used Packaging Materials) 2011." While many pharmaceutical manufacturers and suppliers have offices in Australia, several of the largest suppliers of generic drugs to Australia are based in India and are not signatories to the APC. The keys to reducing the environmental impact of medications are maximizing resource efficiency to reduce the actual amount of waste created and ensuring that this pharmaceutical waste is disposed of in the most environmentally responsible way.[9]

B. Pharmaceutical Packaging: Current Materials and Limitations

Because plastic is robust, chemically stable, and widely used in pharmaceutical packaging, it is now mostly employed for packaging. Because plastic is clear, flexible, and has superior heat-sealing properties, it guarantees a safe and speedy packing closure. Plastics have several advantages, but they can also have major drawbacks, such plasticizer migration. Plasticizers are frequently applied during manufacturing to plastic polymers like PVC.[9]

These chemicals might then wind up in medications, posing health risks, especially with regard to children's endocrine and reproductive development. Children who eat fragments of broken plastic packaging might potentially suffer injuries.[10] To ensure drug safety, plastic materials used in pediatric pharmaceutical packaging must undergo extensive testing. According to Yuan et al.'s systematic analysis of the structural properties and applications of biodegradable plastics, polybutylene succinate (PBS) is a safe and eco-friendly option for pharmaceutical outer packaging. Despite not being biobased, PBS's biodegradability removes the long-term environmental hazards associated with traditional plastic waste. describes the key procedures and system boundaries of the life cycle model, such as the production of materials, the packing procedure, the delivery of waste from pharmaceutical packaging to pharmacies and distribution hubs, and the elimination of end-of-life goods.[11]

C. Bio-degradable polymer/material

Definition: A substance made of biomass, or organic matter, that may break down in the environment without leaving behind leftovers or harming the ecosystem while simultaneously fostering the growth of nature by restoring the ecosystem's depleted biomass. This material is referred to as biodegradable material. A substance or product that is made fully or in part from biomass (plants) is called "biobased." Biomass from sources such as cellulose, maize, and sugarcane is used to make bioplastics. For example, if the polyethylene produced from ethylene monomer is obtained by dehydrogenating alcohol, which was produced from biomass, it may be called biobased or bio-polyethylene even if it won't be biodegradable or compostable.[12]

D. Biodegradation Process Overview

Any physical or chemical change in a substance brought on by biological activity is referred to as biodegradation. It is a bio-chemical process wherein environmental microorganisms transform hydrocarbons, such as polymers, into organic materials including compost, carbon dioxide, water, and methane. Whether the process is anaerobic or aerobic determines the breakdown product. Environmental factors (such as temperature or location), substance, and application all affect the biodegradation process.[12]

Table no 1.1: Classification of biodegradable polymers based on their source.

Bio-Based Polymers					
Synthetic Biodegradable Polymers			Natural Biopolymers Extracted from Biomass		Polymers Produced by Microorganisms
From Biomass	From Petrochemicals	Polysaccharides	Lipids	Proteins	Microbial
PLA	PCL PVA PGA	Starch Cellulose Alginate Carrageenan Chitosan	Glycerides Waxes	Gelatin Casein Whey protein Soy protein Zein Wheat gluten	Bacterial cellulose PHAs PHB PHV PHBV

Lactic acid monomers are used to make PLA. These lactic acid monomers are created when starch or any other carbohydrate-rich material (wheat, corn, sugarcane, kitchen scraps, etc.) undergoes fermentation. PLA, the most used synthesis method, is made by polymerizing lactic acid produced by lactide monomers. Among PLA's many important advantages are its high mechanical resilience, nontoxicity, biodegradability, renewability, high sealability at low temperatures, capacity to serve as a flavour and odor barrier, low energy consumption and carbon emissions, and minimal manufacturing waste. Several pathogens and microorganisms, such as Salmonella species, Escherichia coli, Listeria monocytogenes, Staphylococcus aureus, and Micrococcus lysodeikticus, have been shown to be protected against by PLA surface coatings when various nanoparticles (cellulose nanocrystals, lysozyme, and sophorolipids) are added.[13]

PHARMACEUTICAL PACKAGING

A. What is a Pharmaceutical Package?

A pharmaceutical package container is an item or apparatus that holds a pharmaceutical product; the container may or may not come into direct contact with the substance within it. A sturdy container is essential for pharmaceutical applications.[1]

B. Types of Pharmaceutical Package

a. **Primary Packaging:** This is the initial packing envelope that comes into contact with the equipment or dosage form. The packaging must be designed to prevent medication interactions and ensure that drugs are properly contained. E.g. blister, strip, and other packaging.

b. **Secondary Packaging:** This is a sequential covering or packaging that holds medicinal packets for grouping purposes. E.g. Cartons, boxes, etc.

c. **Tertiary packaging:** This is to handle and transport medications in bulk from one location to another. E.g. Containers, barrels, etc.[14]

C. Types of Pharmaceutical packaging materials

Pharmaceutical packaging is made of five different types of materials: Paper, Cardboard, Metal, Plastic, and Glass. Pharmaceutical packaging is designed to shield medications and formulations from external influences, preventing contamination of the product.[10]

Primarily two types of containers are used for packaging:

I. Glass Containers
II. Plastic Containers

I. Glass Containers

These must be sturdy, stiff, impermeable, and chemically inert in order to receive FDA approval. The pharmaceutical sector uses four kinds of glass.

a. **Type I (Borosilicate glass):** Glass that is chemically inert and extremely resilient. Boron and/or aluminum and zinc are used in place of glass's alkalis and earth cations. These are used to hold strong alkalis and acids. E.g. Parenteral preparations, injectables, ampoules, vials, lyophilized products.[15]
b. **Type II (Treated soda-lime glass**): Compared with Type I glass, these are more chemically inert. The "sulphur treatment" de-alkalizes the glass surface, preventing bottles from weathering or blooming. E.g. Aqueous injections, buffers (not for strong alkalis).[12]
c. **Type III (Soda-lime glass):** Untreated soda lime glass with average chemical resistance. E.g. Oral solids, topical products, powders, tablets.
d. **Type IV (General purpose glass:** General Purpose soda lime glass is only used for items meant to be applied topically or taken orally; it is not utilized for parenteral administration. E.g. External use liquids, ointments, non-critical products.[11]

Colored glass effectively shields contents from light because it blocks ultraviolet rays. For this, amber and red-colored glass are utilized. Glass's fragility and weight are two of its main drawbacks as a packaging material.[15]

II. Plastic Containers

High-quality plastic containers with a variety of patterns are readily produced. There is very little chance of these products breaking or leaking.

The following polymers are primarily used to make plastic containers,

a. **Polyethylene (PE):** It provides a decent barrier against moisture, however it is not very effective against gasses like oxygen. Four fundamental properties of a container are determined by the density of the polymer employed: stiffness, moisture vapor transfer, stress cracking, and clarity or translucency. High density polyethylene is utilized, with a density ranging from 0.91 to 0.96.
b. **Polypropylene (PP):** Polypropylene does not stress crack under any circumstances, and it shares characteristics with polyethylene. The packaging is softened using hot aromatic or halogenated solvents. It is appropriate for boilable containers and items that require sterilization due to its high melting point. Its main drawback is brittleness at low temperatures. [4]
c. **Polyvinyl Chloride (PVC):** Crystal clear clarity can be made, and it will offer rigidity and an excellent gaseous barrier. Further improving the quality of PVC was the decrease in leftover vinyl chloride monomers. PVC is used to provide a shatter-resistant covering for glass bottles.[10]
d. **Polyethylene Terepthalate (PET):** Terepthalic acid or dimethyl terepthalic acid reacts with ethylene glycol to create condensation polymer. It is a handy container for mouthwashes, cosmetics, and other goods because of its exceptional strength and ability to offer a barrier against gas and smell.[8]

Although the FDA has authorized several packaging materials, it should be noted that the FDA only approves the material being used, not the container. Substances that the FDA deems "Generally Recognized As Safe (GRAS)" are included. The manufacturer is in charge of obtaining FDA clearance and demonstrating the safety of a packaging material. According to the FDA's specific regulation for drugs, "Containers, closures, and other component parts of drug packages, to be suitable for their intended use, must not be reactive, additive, or absorptive to the extent that identity, strength, quality, or purity of the drug will be affected." Manufacturers may use materials not listed in GRAS, but before that manufacturer need to test the material and send the report to FDA for New Drug Application (NDA).[16]

D. Ideal Qualities of a Pharmaceutical Package

- It must be mechanically strong enough to endure handling, filling, closing, and shipping.
- It shouldn't react with the things that are kept within.
- It should have an appealing form that makes it easy to read the contents.
- It shouldn't cause the contents' alkali to leach.
- The container shouldn't encourage the formation of Mold.
- When sterilizing, the container must withstand the heat.
- It is important that the container does not absorb its contents.
- The container should be made of an inert or neutral substance.
- The container and closure should not react with one another in any way.
- The closure needs to be nontoxic and chemically stable with the contents of the container.
- The intended level of defense against environmental dangers should be provided.[14]

E. Importance of Pharmaceutical Packaging

The active components in pharmaceutical packaging are protected against vibration, stress, compression, and temperature fluctuations. Additionally, it protects inside items from deterioration caused by dust, water vapor, and ambient oxygen. In secondary packing, batch packaging makes shipping easier. Important details like the internal product and its storage, transportation, batch number, product name, expiration date, manufacture date, etc. are disclosed in order to communicate with buyers and marketers. The security risk is reduced by seal authentication. The packaging is simple to use and reuse, circulate, approach, display, and sell. There are several reasons why the specifics of pharmaceutical packaging are crucial.[17]

F. Functions of Packaging

a. **Physical Protection:** Its goal is to shield pharmaceutical dosage forms from physical damage.

b. **Barrier Protection:** Changes in moisture, light, oxygen, and temperature are just a few of the unfavourable external elements that might alter the product's properties. Pharma-grade barrier films and environmentally friendly Halogen-free films, which are used in blister packaging, can provide this type of protection.

c. **Biological Containment Protection:** The protection against biological contaminants is its main objective.

d. **Information Communication:** Pharmaceutical packaging should contain information on the ingredients, provenance, side effects, warnings, and the correct usage of dose forms. Its objective is to identify the item.[16]

e. **Marketing:** It is commonly used as a marketing strategy to differentiate a product from rivals, highlight the therapeutic qualities for consumers, and/or convey a certain message or brand image.

f. **Security:** Pharmaceutical packaging contains specific features to prevent counterfeiting. Additionally, it denies young infants access to formulation materials.

g. **Convenience:** Packaging must be easy to use in order to increase consumer access to the product and make handling, marketing, and distribution of the product easier.[15]

Since environmentally friendly packaging is a fundamental requirement, the majority of pharmaceutical businesses are prepared to accept this as their primary duty. Because of this, pharmaceutical companies have started using recycled materials for their packaging and have made it easier to recycle their packaging.[17]

BIODEGRADABLE POLYMERS FOR PHARMACEUTICAL PACKAGING

Bioplastics are made from biological or biodegradable ingredients, such as feed scraps, maize starch, or even agricultural residue. Plastic derived from biomass and petroleum both break down more readily in the environment.[14] In contrast, hydrocarbons are taken from natural gas or crude oil, which are used to make polymers.[15] Monomers, catalysts, and additives including plasticizers, stabilizers, and colorants are used to further polymerize the hydrocarbons.[16] After processing the liquid or semi-solids by extrusion and inclusion into certain molds, the product is cooled before being finished, packaged, and distributed. Corn, sugarcane, or other plant starches are used to make bioplastics. Sometimes plant-based sugars are fermented by microorganisms like bacteria or yeast to produce lactic acid or another bio-based monomer, which may then be extracted straight from the plant. It also goes through a polymerization, cooling, processing, and finishing process.[18]

Bioplastics	Sources	Applications	Advantages over plastics
Polylactic acid (PLA)	Plant-based materials such as corn, sugarcane, cassava, sugar beet pupl and fermented plant starch	Medical devices, food packaging, 3D printing, textiles, automotive, personal protective equipment	Renewable resources, biodegradable, carbon footprint, compostable, mechanical strength, cost effective, sustainable
Poly-3-hydroxybutyrate	Microorganisms, bacteria and mangrove ecosystems	Biomedical applications, food packaging	Biodegradability, renewable resources, non-toxic, physical properties, barrier performance
Polyamide II or nylon II	Fermented corn or sugar beets	Food packaging, clothing items	Biodegradability, mechanical strength, renewable resources, recyclability and reusability, versatility
Poly-hydroxyurethane	Vegetable oils, sugars, starches, methane and waste water	Coatings and adhesives, sustainable packaging materials, biocompatible medical devices, textiles and fibers	Biodegradability, low carbon footprint, energy efficiency, versatility
Cellulose- based biopolymers	Cotton linters and wood pulp	Packaging, textiles, agriculture, water treatment	Renewable resources, lower carbon footprint, biodegradability, energy efficiency, versatility, improved food safety
Protein and lipid-based biopolymers	Plant and animal-based proteins such as wheat gluten, soy protein, whey protein, zein, casein, collagen and gelatin	Food packaging, wound dressings and other biomedical uses	Shows better mechanical and tensile properties in the films
Polyhydroxy alkanoate	Microorganisms (bacteria, algae and fungi), renewable resources and agricultural by-products	Packaging, agriculture, textiles, medical and healthcare, toys and environmental remediation	Biodegradability, renewable resources, reduced carbon footprint, biocompatibility, barrier properties, hydrophobicity and mechanical flexibility
Cellulose acetate	Kapol fiber	Film base, eyeglass frames, coating component, synthetic fiber, wrapping	Biodegradability, low carbon footprint, energy efficiency, biocompatibility, chemical and thermal stability, low cost, transparency

Bioplastics	Sources	Applications	Advantages over plastics
Bio-based polyethylene terephthalate	Renewable raw materials such as ethanol from sugarcane and monothylene glycol from renewable plant resources	Make bottles for beverages, food packaging, coatings, textile fiber, PET barrels	Sustainability, biodegradability, recyclability, reduced waste, carbon neutrality

Table no. 2: A brief introduction of various types of bioplastics along with their sources, applications and advantages over plastics.

Material Properties Required for Pharmaceutical Packaging

A. Criteria for Choosing Packaging Types and Materials

The following factors are employed in the selection of packaging and the various packaging materials used in pharmaceutical products,

- In terms of the facilities that are available, some products like pressure dispensers need specific equipment in order to be filled.
- Determining whether a product will be used by trained professionals in a medical environment or if it must be appropriate for people to use in their homes is crucial when thinking about its final application.
- Since the substance might come in solid, semisolid, liquid, or gaseous dose forms, its physical shape should also be considered.
- Another important consideration is the delivery route, which might be external, parenteral, or oral.
- Furthermore, the material's stability needs to be considered. A number of variables, including moisture, oxygen, carbon dioxide, sun exposure, trace metals, temperature, and pressure, may be harmful to the product.

Other considerations when selecting a pharmaceutical packaging item include its resistance to moisture, resistance to corrosion from acids or alkalis, resistance to grease, protection from salt, defense against microorganisms, deterrence of insects and rodents, tolerance to temperature changes, protection against light exposure, fire hazards, and theft, retention or prevention of odors, aesthetic appeal, and overall cost.[19]

B. Ideal Requirements for Packaging

The product's stability and safety depend on the optimum specifications for its individual packaging, among other criteria, some of which are covered in the section that follows,

- Make sure the product maintains its original character by not reacting with the material.
- To avoid any possible breakage or damage, keep the dosage form safe.
- Environmental factors were kept out of the preparation. Don't give the product any Flavors or smells. FDA-approved and nontoxic.
- Put up with the fast-paced packaging production machine.[20]

A number of essential elements are included in the optimal pharmaceutical packaging quality to guarantee the goods' integrity, safety, and effectiveness. First and foremost, it should offer sufficient defense against external elements that might deteriorate the quality of medications, such as light, moisture, oxygen, and temperature changes. Using materials that are appropriate for the particular drug and its storage needs is part of this. The container should be made with simplicity of use in mind, with labeling and instructions that are easy to read and comprehend for both patients and medical professionals. Important characteristics including the drug's name, dose, administration guidelines, expiration date, lot number, and manufacturer should all be included on the label. Accurate dosing should also be made easier by the container, whether this is done with premeasured dosages or, for liquid drugs, with obvious dosage markings.[20]

Bioplastic

Polymers made from natural resources are known as bioplastics. The majority of bio-based polymers are nontoxic, biodegradable, and renewable. Biological systems including plants, animals, and microorganisms can create biopolymers, or they can be chemically manufactured from biological starting ingredients like sugar, starch, oils, and natural lipids.[21]

The carbon impact is reduced because the renewable biomass feedstock used to make bioplastics absorbs carbon dioxide. Bioplastics made from renewable agricultural resources can cut CO2 emissions by 30-80%, whereas synthetic plastics made from petroleum are projected to produce 3-6 kg of CO2.[21]

Enzymes, bacteria, and fungus help biodegrade bioplastics when their useful lives are coming to an end. Commercial composting facilities may handle biodegradable bioplastic items for disposal; but smaller household compost piles have not been shown to be an efficient place for them. The fundamental difference still lies in temperature; for composting to be efficient, a considerable amount of heat is needed to help break down molecules, and only commercial composting facilities typically provide this amount of heat.[21]

Biobased renewable source of poly (alkylene 2,5-thiophenedicarboxylate) and 2,5-TDCA-dimethyl ester and glycol, as well as polycondensation of 2,5-TDCA. A variety of qualities could be covered by adjusting the quantity of CH2 groups in the glycol portion alone. This was especially useful for materials that are appropriate for the manufacturing of rigid films and their packaging applications.[19]

A. Physicochemical properties bioplastics

Depending on the kind of bioplastic, the physicochemical properties may differ; nonetheless, the following general features are covered,

a. Mechanical properties: It encompasses the hardness, elasticity, flexibility, and tensile strength of particular bioplastics. The tensile strength of bioplastics is lower than that of polyethylene or PP. Bioplastics made of starch are less elastic and more brittle, while bioplastics made of poly-hydroxyalkonates are more elastic and flexible. Polylactic acid is comparatively hard, but poly-hydroxyxbutyrate is more likely to be fragile.

b. Thermal Properties: When compared to polymers derived from petroleum, bioplastics often have poorer thermal characteristics. For example, PLA, a popular bioplastic, has a glass transition temperature (Tg) of around 60°C and a melting point of 150-180°C, which restricts its heat resistance. Because of their lower Tg than traditional polymers, bioplastics like PLA may become softer or lose their structural integrity at lower temperatures. Furthermore, compared to their petroleum-based equivalents, bioplastics frequently have lesser thermal stability, which means they might break down or lose their mechanical qualities more easily at high temperatures.[5]

c. Barrier properties: The efficacy of bioplastics in packaging applications that call for moisture barriers is limited by their high-water permeability, especially when it comes to starch-based polymers. Furthermore, some bioplastics like PLA have poor gas barrier qualities, such as high permeability to carbon dioxide and oxygen, which makes them less appropriate for long-term food packaging where maintaining product quality is crucial.

d. Biodegradability and compostability: The capacity of bioplastics to break down spontaneously in particular environmental circumstances is one of its main benefits. PHB and PLA, for instance, can biodegrade in soil or marine settings, however PLA can only be composted in industrial composting facilities. Furthermore, under the correct circumstances, many bioplastics like those made of starch can decompose completely in a matter of months, minimizing their negative effects on the environment.

e. Chemical resistance: When compared to traditional plastics, bioplastics often show less chemical resistance. PLA, for instance, may disintegrate or deteriorate in response to certain solvents or high temperatures.

f. Optical properties: Certain bioplastics, like PLA, are transparent, which makes them perfect for uses where product visibility is crucial, such food packaging. PLA is translucent and glossy, both of which can be advantageous in packaging due to its visual appeal.[22]

Biodegradation Mechanisms of Packaging Polymers

a. Abiotic involvement: Biological activity is the main element that explains the phenomena of "biodegradation." However, nature's biotic and abiotic elements work together to breakdown the organic materials.[22] Biodegradable polymers can change in a variety of ways when exposed to external factors like weather, age, or burial, including mechanical, chemical, light, and thermal forms. The biodegradable polymers perform worse as a result of this exposure. The macromolecular structure of biodegradable polymers is often weakened by abiotic interaction, which promotes decomposition. Additionally, these abiotic factors could be helpful in starting the biodegradation process. As a result, one should not overlook the role of abiotic factors.[24]

b. Biotic involvement: Physical biodegradation is one of the three primary biodegradable processes of biodegradable polymers that have been identified thus far. Microorganisms degrade polymers, which are then eliminated by cell development.[22] Through the direct action of biological enzymes, microorganisms break down the polymer chain, causing chemical biodegradation and depolymerization. Typically, there are two stages to biochemical breakdown. In the first stage, materials' surfaces are acted upon by extracellular enzymes, or exoenzymes, which break down polymer chains and produce tiny molecules (such as acids, esters, etc.) with molecular weights under 500 daltons. The microbes absorb the small molecule chemicals through metabolic pathways in the second stage, converting them into biomass and bioenergy until the end products of CO2 or CH4 and water are produced.[9] The second stage is typically concurrent with the first; new macromolecules are created when bacteria and polymers interact. Typically, a complex interplay of biophysical, biochemical, and physicochemical processes breaks down polymers rather than a single mechanism.[25]

In order for the polymer to acquire a biodegradable characteristic, enough humidity is always required since microorganisms are crucial to the biodegradable process. Polymers can undergo further biodegradation in anaerobic or aerobic environments, or both. With CO2, water, and microbial biomass as the end products, aerobic microorganisms aid in the breakdown of polymeric materials when oxygen is present. The aerobic biodegradation mass balance equation is illustrated in equation (1). In contrast, biodegradable polymers may be broken down by anaerobic microbes in an anaerobic environment. Microbial biomass, water, CH4 or other hydrocarbons, or CO2 will be the end products. The equation for total carbon in anaerobic biodegradation is shown in equation (2). Degradation is referred to as mineralization when the main metabolites are inorganic species, such as salts, CO2, H2O, N2, etc.[25]

$$CT + O2 \rightarrow CR + CB\ldots\ldots. \ (1)$$

$$CT \rightarrow \ CH4 + CO2 + CR + CB\ldots\ldots. \ (2)$$

Where, CT is the total carbon content of biodegradable polymers, CR is any residual products of polymers left or any by-products produced during the degradation process, gaseous CO2 is a measurable product and CB is the microbial biomass from the reproduction and growth of microorganisms.[25]

Compatibility of Biodegradable Polymers with Drug Formulations

The number of medications, drug treatments, and disorders that need for various formulations utilizing innovative production methods and altered release kinetics is always growing. No one polymer is able to meet each of these needs.[27] As a result, biodegradable polymer technology has advanced significantly during the past 30 years. Biodegradable polymers can help prolong the drug's release for weeks or months, and they eliminate the need to remove the device from the patient at the conclusion of the therapy session. Furthermore, they provide benefits in terms of stabilizing drug molecules in polymeric matrix and delivering the medicine precisely.[28]

A biodegradable polymer that has been thoroughly investigated and documented due to its superior tissue compatibility, biodegradable nature, and human safety profile.[28] Using polyvinyl alcohol and magnesium, a new composite material with good drug release qualities that is biodegradable and biocompatible may be created. Adding magnesium, a biodegradable metal with proven biocompatibility, to polyvinyl alcohol (PVA) creates a new composite with qualities superior to those of the polymer (polyvinyl alcohol) and constituent metal (magnesium).[29]

Manufacturing and Scalability Challenges

The low thermal and mechanical endurance of biodegradable polymers present considerable challenges for their implementation in process intensification.[30] For example, the brittleness and low melting point (~160°C) of polylactic acid (PLA) limit its application in high-temperature or high-stress situations. Although they are more flexible, polyhydroxyalkanoates (PHA) lose stability when they hydrolyse in humid environments. These qualities can be improved by mixing or adding composites, but doing so raises prices and complicates manufacturing, making widespread adoption difficult.[31]

Scalability problems and high production costs further prevent biodegradable polymers from being widely used. PLA is more expensive to produce (~USD 2.50 per kilogram) than traditional polymers like polyethylene (~USD 1.20 per kilogram). Reliance on agricultural feedstocks and a limited global production capacity (~1.2 million metric tons yearly) make these problems worse, and supply risks are introduced by seasonal variations. Increased barriers to entry for sectors result from the substantial infrastructural expenditure needed to scale up production.[32]

The problems of biodegradable polymers are compounded by environmental concerns about their lifetime and end-of-life management. Many may fail because they need industrial composting conditions, which are not accessible in conventional waste systems. Furthermore, the advantages they provide to the ecosystem may be undermined by the production of greenhouse gasses like methane due to their decomposition. Sustainability is an issue since attempts to improve material performance, such the addition of nanofillers, can lead to trade-offs between improved qualities and decreased biodegradability. Additionally, industry and end-user reluctance impedes adoption. Overcoming misconceptions of decreased reliability and adapting current infrastructure to biodegradable polymers are major challenges. Building trust and easing the shift to these sustainable materials requires educating stakeholders about the long-term advantages and providing proof of successful implementations.[33]

ARTIFICIAL INTELLIGENCE IN MATERIAL AND PROCESS OPTIMIZATION

Many tests require a large number of costly instruments, in addition to more time and effort. Modern technology must thus be used to get the data and minimize the number of tests. Numerical software methods for estimating the properties of composites are available commercially, however these programs are computationally intensive. The use of AI methods for data creation, manufacturing, analysis, and post-processing has become more and more common in recent years. In order to solve difficult mathematical problems with the available data, artificial Intelligence (AI) is inspired by the organic nervous system. By needing fewer experimental data, the AI-assisted approach reduces labor costs and time. AI has several subcategories, including Machine Learning (ML) and Deep Learning (DL). AI is being used extensively in smart manufacturing. In DL, human players play a less significant role than in ML. Furthermore, although ML is used to predict the properties of composites, DL architecture comprises several hidden layers with non-linear combinations of multi-layers. In ML, step-by-step training in each module is frequently necessary, but in DL, several parameters may be learnt collectively.[34]

AI-Assisted Polymer Screening and Selection

AI has paved the way in several domains and functions similarly to machine learning models in process improvement. Recently, researchers have demonstrated a tendency to combine Taguchi with ML frameworks for process parametric prediction and optimization, resulting in more complex search parameters and selection criteria. They are often contrasted to evaluate the accuracy and effectiveness achieved with these alternative methods. Using a nonlinear machine learning model, employ the desirability strategy to set the FFF parameters as ideally as feasible. In another research, the Taguchi Design of Experiments was combined with a two-layer neural network (NN) of 15 neurons and an L25 orthogonal array. To speed up the process, the parameters were adjusted for tensile and compressive strength.[35]

The infill density was the largest contributor to both compressive and tensile strength. With little prediction error, the Artificial Neural Network (ANN) model proved to be reliable; this dependability could only be increased by gradually improving the results using additional test data.[5,36]

AI-Enabled Quality Control in Biodegradable Packaging Manufacturing

Machine learning applications have shown great promise in quality control, as demonstrated by the following examples: Fadhilah et al. used convolutional neural networks (CNNs) to detect non-Halal substances in packaged foods, reaching a character recognition accuracy of over 98%; Ribeiro et al. developed a deep learning powered computer vision system to automatically verify use-by dates on packaging; the solution demonstrated impressive detection accuracies of 98% and 97% across several datasets, effectively addressing mislabeling concerns that could endanger customers' health; and AI also makes it easier to follow nutritional recommendations.[6,37]

AI-powered predictive models are able to predict the rate at which biodegradable materials will decompose, allowing manufacturers to choose the best component combination for the intended result. These models may replicate the behavior of different packaging materials over time under different conditions to ensure that the packaging remains intact throughout the supply chain, especially for perishable commodities [37]. Furthermore, AI improves cold chain management for biodegradable products by employing smart sensors and RFID technology to monitor temperature and humidity levels, reducing spoiling and ensuring that only safe, high-quality products are shipped to clients.[38]

Including AI and nanotechnology in biodegradable packaging materials is fraught with difficulties, especially when it comes to consumer acceptability and understanding. Incorrect reading of product labels, such as "best by," "best before," and "expiration date," is a major problem that leads to a significant amount of waste worldwide. Because consumers are confused by these labeling, they frequently discard food that is still edible and fresh, underscoring the need for creative solutions like clever packaging.[34,39]

A major challenge is finding a balance between economic and environmental factors and technical performance. Creating biodegradable materials with nanotechnology-enhanced qualities, such better mechanical strength and barrier functions, that are affordable and scalable is a difficult task. Furthermore, real-time monitoring systems driven by AI require a significant infrastructure for data processing, which presents questions regarding integration and cost across global supply chains.[40]

AI IN WASTE MANAGEMENT AND PHARMACEUTICAL PACKAGING

Together, AI and life-cycle assessment analyze trade-offs between production efficiency and waste effect. By ensuring that waste reduction also promotes long-term profitability, strategic asset and liability management further combines sustainability with financial resilience. Together, these techniques demonstrate how the pharmaceutical business may be able to mitigate the consequences of industrial waste and byproducts through the use of circular resource usage, technology integration, and operational analytics.[41]

AI-Powered Sorting and Recycling of Polymer Waste

AI makes it possible for systems to make data-driven judgments, which improves the precision and effectiveness of MSW management tasks including garbage sorting and route planning. AI-driven algorithms, for instance, may evaluate intricate datasets to optimize collection schedules, reducing the number of collections while maintaining the ability to empty bins before they overflow and prevent the needless emptying of underutilized bins.[42]

IoT technology is revolutionizing MSW management with real-time monitoring capabilities that enable trash cans and collection vehicles to communicate their position, status, and capacity levels to central management systems. Sensors integrated inside trash cans monitor fill levels, while GPS-enabled vehicles monitor routes and operational efficiency. These systems communicate using sophisticated protocols like LoRaWAN and NB-IoT, which provide seamless data flow to centralized platforms. IoT-enabled solutions use data analysis to decide the optimal course of action, reducing unnecessary travel, fuel consumption, and operational costs. Combining IoT with AI makes it even more revolutionary. AI systems may analyze data from the Internet of Things to improve resource allocation and dynamically adjust collection schedules, in addition to predicting trends in garbage generation in metropolitan environments. For example, by employing machine learning algorithms to forecast peak rubbish volumes during events or certain seasons, communities may take precautionary action. Furthermore, AI-powered automated sorting systems may significantly reduce landfill contributions and improve recycling efficiency by correctly identifying rubbish.[42]

The world's waste production is expected to reach 3.40 billion tons by 2050, necessitating improved rubbish sorting to promote recycling and advance the circular economy. This transformation requires increased production, more efficiency, and higher sorting intensity through heightened methods. While smaller facilities usually use positive sorting to collect recyclables, larger firms use automated techniques in addition to manual sorting. The application of negative sorting removes impurities and improves material quality. The development of manual sorting, however, has stagnated. The advancements in AI and machine learning have the potential to drastically alter waste management, with digitalization and better recycled materials becoming leading issues. These advancements notwithstanding, most people still consider manual sorting to be a digital mystery.[43]

Real World Applications of AI Waste Management Systems

Artificial intelligence (AI)-driven systems provide useful data on waste management practices, enabling more precise and sustainable practices. Real-world examples demonstrate how AI technology may revolutionize landfill operations and encourage more environmentally responsible waste management practices. Long-term sustainability objectives and landfill-related environmental problems will be addressed with the further advancement of AI in this field.[44]

A ground-breaking method of ensuring sustainability and safety in landfill operations is to use AI to track environmental hazards. By using advanced AI technologies, landfill operators may reduce environmental concerns by improving real-time monitoring, identifying issues like methane accumulation and soil instability early, and implementing preventive actions. This proactive approach ensures rigorous adherence to environmental rules while also improving safety. Using AI to manage landfills is a significant step in resolving environmental problems and safeguarding public health.[41,45]

FUTURE DEVELOPMENT

The combination of digital intelligence, biodegradable materials, and IoT-driven traceability systems is set to revolutionize pharmaceutical packaging and waste management in the coming ten years. The future of intelligent, sustainable, and circular pharmaceutical systems will be determined by the integration of artificial intelligence (AI), machine learning (ML), and Internet of Things (IoT) technologies, even if biodegradable polymers have already demonstrated their ability to lessen environmental effect.[40]

A. IoT-Based Pharmaceutical Waste Management Systems

The development of IoT technology makes it possible to track, monitor, and separate pharmaceutical packaging waste in real time as it moves from production to disposal. It is anticipated that future systems would use

- IoT-enabled collection networks and smart bins with RFID, NFC, or QR sensors that automatically distinguish between biodegradable and non-biodegradable trash.
- AI systems can forecast trash creation trends, improve recycling routes, and save operating costs through data-driven logistical optimization.[44]
- Blockchain enabled traceability, complete transparency in trash management, decreased illicit dumping, and enhanced adherence to regulations.
- Intelligent composting and biodegradation tracking devices that can keep an eye on temperature, humidity, and microbial activity to regulate the breakdown of biodegradable packaging.[40]

A Circular Pharmaceutical Economy (CPE), where data analytics, Internet of Things (IoT) sensors, and digital twins work together to reduce waste leakage and increase recovery, will be built atop this networked waste management infrastructure.[41]

B. Next-Generation Biodegradable Polymers for Pharmaceutical Packaging

Future studies in materials science will concentrate on creating biodegradable polymers that combine sustainability, durability, and safety with pharmaceutical-grade performance.

- Functional biopolymers (such as chitosan composites, PLA-PHB blends, and cellulose nanofibers) are made to satisfy mechanical, sterility, and drug barrier specifications.
- AI-aided molecular design and polymer informatics, enabling predictive modeling of polymer properties and degradation rates for specific drug formulations.[42]
- Using genetically altered microbes, bioengineered microbial polymers create customized PHAs or polyesters with enhanced purity and regulated molecular weight.
- Antioxidants, antimicrobials, and oxygen scavengers are integrated into active biodegradable packaging to improve product stability.
- Nanosensor integrated smart biodegradable sheets that track pollution, pH, and oxygen levels in real time while being stored and distributed.

These developments will combine sustainability and performance excellence by enabling biodegradable materials to take the place of traditional polymers, even in sterile and high-barrier pharmaceutical applications.[43]

C. Integration of AI and IoT for Smart Packaging and Waste Circularity

Packaging will be redefined beyond its conventional function as a confinement medium by combining AI and IoT technology, becoming a system that generates data and keeps track of itself. Potential future developments might include,

- IoT microchips incorporated in intelligent packaging labels allow for real-time monitoring of product condition, temperature, and humidity.
- AI-based lifecycle assessment (AI-LCA) technologies that may continually monitor packaging materials' environmental performance from production to disposal.
- predictive analytics for recyclability and degradation, in which machine learning algorithms forecast how things would deteriorate in certain storage or climate scenarios.
- Each batch of packaging has a digital product passport (DPP) that contains unique information on the material composition, biodegradability, and regulatory compliance.

By using these advances, pharmaceutical packaging will create a feedback loop between waste management and production, protecting the medicine while also communicating, adapting, and reporting its environmental state.[45]

D. Industrial and Policy-Level Transformations

Coordination between business, academia, and regulatory agencies is crucial to achieving these technical breakthroughs. Future frameworks ought to contain:

- standardized certification procedures for biodegradability that are in line with those of the FDA, EMA, CDSCO, and ISO.
- IoT-based waste tracking and national pharmaceutical waste databases are integrated via digital compliance systems.
- incentive-based policies that use extended producer responsibility (EPR) credits and tax breaks to encourage the development of biodegradable packaging.
- collaborative digital ecosystems that link recyclers, pharmaceutical firms, packaging makers, and AI developers for lifecycle optimization and data exchange.

In pharmaceutical packaging, this alignment will hasten the transition from a linear "produce use dispose" paradigm to a closed-loop circular economy, guaranteeing both commercial viability and environmental accountability.[30]

E. Vision for the Future

IoT connection, AI analytics, and biodegradable polymer technology are coming together to create smart, sustainable pharmaceutical packaging ecosystems. In this hypothetical future, every medication packaging will be digitally identified, traceable, and biodegradable. Intelligent IoT networks will handle waste management by interacting with centralized composting and recycling systems. Through AI-driven insights, material deterioration, quality, and recycling efficiency will be continually enhanced. By achieving net-zero plastic waste, the pharmaceutical supply chain will contribute to the advancement of global sustainability goals including the UN SDG-13 (Climate Action) and SDG-12 (Responsible Consumption and Production). In essence, future developments will transform pharmaceutical packaging from a passive containment system into an active, intelligent, and sustainable component of healthcare one that harmonizes material innovation, environmental stewardship, and digital intelligence for a cleaner, smarter planet.[37]

CONCLUSION

The pharmaceutical sector is reducing its reliance on non-biodegradable packaging as a result of the worldwide trend toward sustainability and the concepts of the circular economy. Although there are still difficulties in achieving stringent mechanical, barrier, and sterilization criteria, this analysis emphasizes biodegradable polymers such PLA, PHA, PBS, and starch-based blends as possible environmentally acceptable substitutes. Strategies including surface modification, polymer mixing, and nanocomposite integration have the ability to get beyond these restrictions.

Technologies like artificial intelligence (AI), machine learning (ML), and the internet of things (IoT) are transforming waste management and material design. Predictive modeling and property optimization for polymer creation are made possible by AI, while circular packaging solutions are made possible by IoT-based systems that improve waste traceability, sorting, and lifecycle monitoring.

Building on these discoveries, my research strategy for the future is on creating cutting-edge biopolymers for pharmaceutical packaging that offer pharmaceutical-grade performance together with sustainability. The main goal will be to create and manufacture biodegradable polymers with regulated rates of breakdown, which will guarantee stability during the product's shelf life and permit full biodegradation after disposal. This will entail altering the composition of polymers, functionalizing their surfaces, and combining them with nanocomposites to improve their mechanical, thermal, and barrier qualities while adhering to legal requirements for pharmaceutical packaging. Through the use of cutting-edge coating technologies, attempts will also be made to shield these biopolymers from environmental stressors including humidity, temperature changes, and UV radiation.

IoT-enabled technologies like RFID and smart labeling will be included into the package design to guarantee authenticity and traceability. This will enable real-time monitoring of the product's integrity across its supply chain. AI-based analytical tools will also be used to better control post-consumer waste, forecast degradation behavior, and enhance polymer performance. The goal of this interdisciplinary approach is to develop a new generation of environmentally responsible, intelligent pharmaceutical packaging materials that can successfully replace traditional plastics while preserving product performance, safety, and environmental responsibility.

However, there are other barriers to wider implementation, such as exorbitant expenses, a dearth of data, and the absence of standardized biodegradability tests. Pharmaceutical packaging's future depends on multidisciplinary cooperation to combine digital intelligence and innovative materials. A smart, sustainable, and circular healthcare ecosystem that strikes a balance between environmental responsibility, safety, and performance will be fostered by this kind of collaboration.

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