GREEN GRAFTING

INNOVATIONS IN POLYMER FUNCTIONALIZATION FOR SUSTAINABLE SOLUTIONS IN THE PHARMACEUTICAL AND HEALTHCARE INDUSTRY

PART 2

Editors:

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Green Grafting: Innovations in Polymer Functionalization for Sustainable Solutions in Pharmaceutical and Healthcare Industry

(Part 2)

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PREFACE

The continuation of Green Grafting: Innovations in Polymer Functionalization for Sustainable Solutions in the Pharmaceutical and Healthcare Industry reflects the expanding scope and significance of sustainable polymer science in modern healthcare and pharmaceutical technologies. While Part I established the foundational principles, mechanisms, and green chemistry approaches in polymer grafting, Part II delves deeper into advanced methodologies, industrial applications, and translational innovations that bridge research and real-world impact.

This volume highlights emerging techniques such as nanotechnology-assisted grafting, mechanochemical and enzymatic green grafting, and the integration of renewable feedstocks for the development of next-generation materials. It also explores the environmental, regulatory, and educational perspectives, emphasizing how sustainable polymer functionalization supports a circular economy, resource efficiency, and global health goals.

By combining scientific innovation with eco-conscious design, the contributors present a comprehensive understanding of how green grafting principles can drive the pharmaceutical and healthcare industries toward carbon neutrality and sustainable manufacturing practices. The chapters included in this part not only extend the scientific dialogue initiated in Part I but also showcase how interdisciplinary collaboration, policy awareness, and educational outreach can accelerate the adoption of greener technologies.

We sincerely thank all authors, reviewers, and contributors for their valuable efforts, insights, and commitment in realizing this second volume. Together, these two parts stand as a consolidated reference for researchers, academicians, and industrial professionals dedicated to building a more sustainable future in material and health sciences.

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CHAPTER 1

Sustainable Grafting for Biodegradable Polymer

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Abstract: Biodegradable polymers such as Polylactic acid (PLA), Polyhydroxyalkanoates (PHA), and starch-based polymers are getting considerable attention for being eco-friendly as the world moves towards sustainability. The mechanical, thermal, and chemical characteristics of these materials can be improved to a greater extent without the need to compromise their biodegradability through the technique known as grafting, *i.e.*, the covalent bonding of polymer chains. This book chapter helps us explore the different sustainable grafting techniques for biodegradable polymers, highlighting recent and ground-breaking approaches and methodologies. With a focus on essential features of grafting, such as green chemistry and principles like the use of non-toxic solvents and catalysts to minimize environmental health risks, this chapter would help to elucidate the different aspects of grafting. Recent studies highlight the potential of these methods to produce high-performance materials suitable for applications in biomedical devices, packaging, and agricultural films, where enhanced properties such as controlled degradation rates and improved biocompatibility are critical. This chapter also focuses on the difficulties faced while scaling up these sustainable practices to industrial levels and other future perspectives.

Keywords: Biocompatibility, Biomedical applications, Environmental health risks, Grafting techniques, Green chemistry, Sustainability.

INTRODUCTION

Biodegradable polymers are one of the new forms of material purposely designed due to the most pressing environmental concerns. Conventional plastics pile up in ecosystems, which is becoming the most argumentative issue due to plastic pollution. On the other hand, biodegradable polymers are designed to decompose

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into innocuous degradation products through naturally occurring mechanisms. Multiple mechanisms by which polymers become biodegradable are based on the molecular structure of the polymer and environmental conditions. These mechanisms include either enzyme degradation, microbiological activity, or simple hydrolysis. Besides the benefits mentioned above for environmental-related uses, biodegradable polymers play a significant role in other applications. Biodegradable polymers are helpful when dealing with materials whose use is temporary in various fields, especially in the pharmaceutical and healthcare industries, packaging, and agriculture [1 - 2].

Biodegradable polymers have a double significance: they solve the problem of waste related to conventional plastics and reduce environmental pressure on items used for a short period. In most healthcare enterprises, materials are often applied only once in order to ensure sterility and safety for the patient. As such, their introduction in a biodegradable form could significantly reduce the quantity of medical waste being generated. Besides this, the biodegradable polymers are biocompatible and, therefore, suitable for use in drug delivery systems, tissue engineering scaffolds, and resorbable sutures. Biodegradable polymers have had much attention over the years due to their interesting properties and wide range of applications [3, 4].

Grafting is a very potent and versatile operation that can be conducted on the polymer surface to change its properties. The main aim of grafting is the development of polymer properties and the extension of their scope of applications. The simplest definition of grafting is the process of the chemical addition of polymer chains or functional groups to the main chain of an existing polymer. This may alter the physical, chemical, and biological properties of the polymer, mainly so that it can be more suitable for some applications [5]. Grafting occurs *via* different methods, which are linked to some benefits and drawbacks. This will mainly depend on the result desired and the nature of the host polymer. The methods of grafting date back to the early 1900s, mainly for modifying the mechanical and thermal properties of polymers. In its early days, the polymer was modified chemically with a required initiator or catalyst; this attached further functional groups to the main structure of the polymer. Early grafted preparations laid a foundation for more advanced work that was going to be performed later and would help meet the need for materials with customised features [6]. Grafting has also been used as a method for the introduction of biocompatibility, antibacterial features, and enhanced biodegradability of polymers. It is in a case where the hydrophilic polymers are attached to the surface of the hydrophobic biodegradable polymers, leading to better compatibility with biological tissues and, hence, applicability in medicine. In addition, the polymers can further be grafted or attached with antimicrobial compounds to come up with some that do not favour bacterial colonisation. This property has been of great use in the production of medical devices and packaging materials. As opposed to synthetic polymers, grafting onto biodegradable polymeric carriers may create an opportunity for the preparation of materials that may be designed to degrade safely under environmental conditions. Such materials can also perform well in advanced biomedical and pharmaceutical applications due to their designed functions [7, 8]. The progress in selective grafting of functional groups into biodegradable polymers is offering design possibilities for material that could potentially cater to the needs of the healthcare industry: from drug release systems where a specific site of interest can be targeted, enabling an interaction of the released drug with the grafted polymer, to tissue engineering scaffolds where the attached polymer can facilitate cell attachment and growth [9].

This chapter provides a comprehensive explanation of sustainable grafting techniques on biodegradable polymers, with a specific focus on their application in the pharmaceutical and healthcare sectors. The general purpose is to demonstrate the potential of grafting to provide biodegradable polymers with functionalities that could enable their use in a versatile manner in both the biomedical and environmental fields. This assumes paramount significance, especially for the pharmaceutical industry and health-related applications. While the latter feature includes rigorous integration of sustainability in performance standards during development, the former would translate to huge problems related to waste management and environmental impacts from high numbers of single-use materials and tight regulatory requirements on both safety and efficacy. Grafting biodegradable polymers can offer potential solutions to this problem. Such materials can be used effectively for various medical applications and can also be degraded safely after application. These grafting techniques offer flexible and realistic methods for modifying biodegradable polymers with the ability to meet the increased demand in the market. For example, grafting can be made to enable targeted drug delivery systems where ligands or other targeting molecules are selectively attached to the polymer, allowing medications to go to certain parts of the body [10]. In tissue engineering, such a tailored system may offer the opportunity to optimise treatment with reduced off-target reactions. It is, therefore, a highly sought-after area of research with respect to the development of improved therapeutics. Surface modification of scaffolds by grafting is one of the methods used within tissue engineering to enhance cell adhesion, proliferation, and differentiation. These bioactive compounds can become grafted onto a biodegradable polymer to design scaffold systems that mimic the natural extracellular matrix, favouring tissue regeneration. This application is crucial in regenerative medicine, in which damaged tissue and organs can be replaced or repaired. These are flexible and pragmatic ways of modification of biodegradable polymers [11]. For example, grafting can be used to achieve a targeted drug

CHAPTER 2

Green Grafting in Industrial Applications

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Abstract: Green grafting is emerging as a transformative approach in various industrial applications. Grafting, which involves the covalent attachment of polymers onto substrates, is used to enhance the properties of a material. By incorporating green chemistry principles, such as waste prevention, safer solvents, energy efficiency, renewable feedstocks, reduction of derivatives, and inherently safer processes, green grafting offers significant environmental and economic benefits. In the polymer and material science industry, green grafting is revolutionizing the production of advanced materials. Techniques like controlled radical polymerization (CRP) and enzyme-mediated grafting offer sustainable alternatives to traditional methods. CRP methods enable precise polymer control with minimal waste, while enzyme-mediated grafting avoids toxic reagents. The textile industry benefits from green grafting by using water-based systems and benign chemicals for treatments like dyeing and finishing. Grafting natural polymers, such as chitosan, onto cotton imparts antimicrobial properties without synthetic biocides, and hydrophobic polymers create water-repellent textiles without harmful chemicals. In the biomedical field, green grafting ensures safer, more biocompatible materials using water and biocompatible catalysts to produce medical devices and drug delivery systems without toxic solvents. Grafting polyethylene glycol onto nanoparticles enhances biocompatibility using eco-friendly processes. Agricultural benefits include improved crop resistance and yield with biodegradable polymers and natural adhesives. This reduces environmental impact and improves soil health. Green grafting also contributes to sustainable packaging by using renewable feedstocks like cellulose to create biodegradable materials. Grafting natural antioxidants onto packaging films extends the shelf life of food, reducing waste. Overall, green grafting offers significant environmental and economic advantages, driving innovation and sustainability across various industries.

Keywords: Bioprinting, Green Grafting, Green Chemistry, Polymer Science, Renewable Energy, Textile Biofinishing.

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INTRODUCTION

Green grafting refers to the use of environmentally friendly methods and materials for grafting processes to reduce the deleterious impact of human activity on the environment [1]. This includes the use of biocatalysts, renewable feedstocks, and eco-friendly solvents, as well as processes that minimize waste and energy consumption. The term “grafting” refers to the process of joining or adding something to an existing structure. For example, in horticulture, it involves placing a bud or scion from one plant onto the stem, root, or branch of another plant in such a way that they unite and grow together as a single organism [2]. The goal of green grafting is to achieve the desired material modifications while reducing the environmental footprint and improving sustainability [3].

Grafting techniques have been widely used in various fields, ranging from agriculture to different industries, due to their benefits in multiple fields. The benefits of grafting techniques in the agricultural field include overcoming biotic and abiotic stress, enhancing plant tolerance, improving disease resistance and fruit quality, and increasing yield, thereby improving the uptake of nutrients in crops [4, 5]. In industrial field, grafting techniques are basically used for sustainable preparation of organic and inorganic material [6], for environment friendly packaging [7], to achieve site specific delivery of drugs [8], for sustainable preparation of green electrospun nanofibers [9], and for obtaining functional textiles, such as antibacterial, water-repellent or flame-retardant textiles [10, 11]. The different types of grafting techniques used in the agriculture field are whip and tongue grafting, cleft grafting, tube grafting, slant-cut grafting, pin grafting, *etc* [12]. The different types of grafting techniques used in industry are microwave-assisted grafting, enzyme-mediated grafting, photochemical grafting, supercritical CO_2 grafting, and ionic liquid-based grafting [13]. There are various factors affecting the grafting of natural polymers, such as the effect of additives, the nature of the polymer backbone, the monomer effect, the solvent effect, the initiator effect, and the temperature effect [14]. Traditional grafting involves the covalent bonding of functional groups or polymers onto a substrate to enhance or modify its properties. Traditional methods often utilize chemical initiators, high temperatures, or harsh solvents. Common techniques include free radical grafting, atom transfer radical polymerization (ATRP), and reversible addition-fragmentation chain-transfer (RAFT) polymerization. These methods can effectively modify materials but often involve environmentally harmful processes. Radiation-induced grafting, known for its ability to create uniform grafts without the need for chemical initiators, uses high-energy radiation sources like gamma rays, electron beams, and UV radiation to generate free radicals on a substrate, initiating graft polymerization. While effective, the need for high-energy radiation sources can pose safety and cost challenges.

Enzyme-mediated grafting uses biocatalysts to initiate and control the grafting process. Enzymes like lipases and peroxidases can facilitate grafting under mild conditions, making this method environmentally friendly. The specificity and mild operational conditions of enzyme-mediated grafting offer significant advantages over traditional chemical methods.

Green grafting techniques help mitigate the adverse environmental effects associated with traditional grafting methods, such as the release of toxic chemicals and high energy consumption. By using renewable and biodegradable materials, green grafting aligns with the principles of sustainability, promoting the development of materials that can be safely integrated into natural ecosystems. Additionally, green grafting provides industries with innovative ways to enhance material properties while adhering to increasingly stringent environmental regulations and consumer demand for eco-friendly products.

Environmental-related problems are increasing day by day, such as global warming, pollution, waste disposal, and greenhouse effects, mainly due to various industries and human activities [15]. To overcome these problems, green grafting techniques have been widely used in various industries, including pharmaceutical, textile, packaging, biotechnology, food, and even the automobile industries. The scope of green grafting is that it teaches us how to protect the environment by using eco-friendly techniques and eco-friendly materials [16]. The objective of this chapter is to study the applications of green grafting in various fields and to utilize it in possible areas, as well as to encourage people to adopt a green concept to reduce environmental-related problems.

Advantages of Green Grafting [17 - 21]:

- Green grafting helps in designing eco-friendly products.
- It facilitates the effective management of waste.
- It assists in making safer and environmentally friendly solvents.
- It also has the potential to reduce global warming, ozone depletion, and smog formation.
- Green grafting is used to improve the quality and quantity of food crops by using bio-pesticides.
- It is effective in treating wastewater using bioflocculants.
- Green grafting techniques are used to stabilize the intrinsic properties of polymers, which are utilized for targeted drug delivery.
- It is used to form an efficient green anti-corrosion coating by using fibrous sepiolite clay for metal substrates.
- Sustainability in packaging can be achieved by using polymers that are directly extracted from natural materials.

CHAPTER 3

Grafting Using Nanoparticles and Nano-concepts

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Abstract: The stability of pharmaceutical formulations and the drug release mechanism are mainly influenced by the type of polymers used in the formulation. Pharmaceutical and biological therapeutics both face challenges like short half-lives, poor bioavailability, and susceptibility to physical and chemical instability. Successfully delivering drugs to a specific target location at a certain concentration for a set period of time depends on using suitable polymers. Consequently, it is not imperative for the polymers currently available to possess all the ideal properties. This necessitates the development of customized polymers with specific characteristics, introducing the concept of grafting to produce novel polymers suitable for employment in various dosage forms.

Several methodologies exist to alter the properties of polymers, including blending, grafting, and curing. Grafting of polymers can be accomplished through various techniques, including polymerization grafting, radiation-induced grafting, photochemical grafting, plasma radiation grafting, and chemical grafting. In contrast to synthetic and chemical grafting, the grafting of natural substances yields a range of tailored polymers with ecological efficiency and eco-friendly advantages like enhanced biodegradability and reduced toxicity. Undeniably, materials based on natural polymers have served humanity for a myriad of applications over centuries. The growing interest in grafting natural biopolymers has been spurred over the past few decades by concerns regarding environmental sustainability. The eco-friendly grafting of natural polymers could establish a foundation for a novel category of environmentally sustainable polymers tailored for the design of dosage forms. The present analysis emphasizes the fundamental concept of grafting, its methodologies, and green grafting alongside their noteworthy pharmaceutical implications.

Keywords: Biodegradable polymers, Drug delivery, Grafting techniques, Green grafting, Pharmaceutical formulation, Polymer grafting.

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INTRODUCTION

Role of Nanotechnology

Conventional pharmaceutical and biological dosage forms often have compliance issues related to poor solubility, extensive first-pass metabolism, reduced bioavailability, and physicochemical instability. Targeting a specific location with a particular amount and time is crucial for achieving a specific therapeutic action. In this regard, nanoscience and nanotechnology are at the forefront of current research in formulating a drug into a novel drug delivery system. It is a rapidly developing scientific area at the intersection of interdisciplinary sciences, including physics, chemistry, materials science, microelectronics, biochemistry, and biotechnology [1, 2].

Nanotechnology enables the synthesis, formulation, analysis, and manufacturing of nanocarriers, including nanostructures, nanodevices, and nanosystems. They are applied for precise drug delivery by regulating the structures and sizes of nanocarriers at the nanometer scale, ultimately enabling us to fabricate tailor-made medications and sensors with enhanced characteristics. Currently, nanotechnology is being utilized and has shown significant interest in various sectors, including agriculture, pharmaceuticals, and medical science [3, 4]. It specifically connects the electronic and biological systems for therapeutic and diagnostic purposes. Subsequently, it involves the use of materials for a specific, targeted tissue or organ in a prolonged or controlled release manner. Recent advancements in this sector enhance the therapeutic efficacy of both new and existing medications by utilizing disease marker molecules [5].

On the other hand, synthetic nanomaterials have shown *in vitro* and *in vivo* toxicity. Various analytical techniques have been employed to analyze and elucidate the structural and functional relationships between nanoparticles and their associated toxicity. The accumulation and localization of nanoentities in cells demonstrated cell-to-cell interaction, resulting in cytotoxic and hemotoxic effects [6, 7]. Therefore, green synthesis techniques are employed to synthesize the nanomaterials using various biological sources that are environmentally safe. In this regard, metal nanoparticles are synthesized using green chemistry, a process known as green nanotechnology, which avoids the use of harmful chemicals in the synthesis [8]. It mitigates the negative externalities associated with environmental and health concerns. It reduces synthetic costs, which improves sustainability [9]. Modern green nanotechnology-based nanocarriers are synthesized from herbs or biological sources. Nanocarriers prepared using green chemistry exhibit remarkable properties, including a wide range of biological and chemical diversity with specific macromolecular structures, as well as lower toxicity. This leads to promising prospects for the discovery of novel drug nanocarriers, encouraging a shift from existing products to new alternatives [10].

Nanoparticle Grafting

Nanocarrier drug delivery systems have enhanced absorption rate, bioavailability, stability, and targeted delivery. For example, polymeric nanocarriers with a diameter of 100-200nm are being explored for their ability to cross the blood–brain barrier. PEGylated nanoparticles significantly increase solubility and stability and improve the blood circulation time of the drug.

However, the problems associated with nanoparticles, such as cytotoxicity, aggregation rates, and physicochemical instability, restrict their use. These problems interrupt the pharmaceutical and biological therapeutic efficacy of drugs. Therefore, there is a need to modify nanoparticles into nanocomposites to improve the effectiveness of drugs and enhance safety by reducing toxicity. Nanocomposites are nanocarrier drug delivery systems composed of two interacting polymeric components combined with one or more drugs.

Nanocomposites exhibit unique interactions between polymers and nanoparticles, possessing combined physicochemical properties of both. This synergy enhances the therapeutic efficacy of the dosage form. However, controlling the spatial dispersion of nanoparticles in a nanocomposite polymeric matrix is difficult. Therefore, altering the polymeric properties used in the nanocomposite is essential. These modified polymers have been tailored to meet specific requirements for targeted drug release. Different methods alter the polymeric properties, including blending, grafting, and curing. In blending, two or more polymers are physically combined to achieve the desired properties of the resulting polymer. Curing involves the polymerization of oligomers to form a coating on the substrate, which helps provide a smooth surface finish. While in grafting, monomers are covalently bonded to existing polymer chains.

Recently, nanotechnology has focused on the polymeric grafting of nanoparticles with different chain lengths and densities of monomers, as shown in Fig. (**1**). The nanoparticles functionalized with polymeric chains are called hairy nanoparticles. The technique used for the synthesis of hairy nanoparticles is known as the graft copolymerization technique. This technique modifies the reactive chemical functional groups and alters the polymeric properties of nanoparticles without converting their integral properties. Therefore, it helps to increase the therapeutic efficacy, stability, and potency of the drug by reducing the side effects. The synthesis of hairy nanoparticles involves three steps: **1** Synthesis of nanoparticles, **2** Synthesis of surface-bound protein (corona), and **3** Attachment of corona to particles.

CHAPTER 4

Coupling Agent Grafting: Types, Methods, and Green Considerations

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Abstract: Coupling agent grafting is a vital process in surface modification that enhances the compatibility and performance of composite materials by introducing functional groups onto substrates. This process involves various types of coupling agents, including silanes, titanates, and zirconates, each offering distinct advantages depending on the material system. Grafting techniques, such as solution grafting, melt grafting, and plasma treatment, are employed to help anchor coupling agents onto substrates. Solution grafting involves dissolving the coupling agent in a solvent and then applying it to the substrate. Melt grafting utilizes heat to graft the coupling agent directly onto the substrate, whereas plasma treatment activates the substrate surface, facilitating the grafting process. The principles of Green chemistry have increasingly influenced the development of environmentally friendly grafting methods. Traditional techniques often involve the use of hazardous solvents and energy-intensive processes, raising concerns about their environmental impact. To address these issues, researchers are exploring solvent-free and low-energy alternatives. Methods such as supercritical fluid grafting and UV-initiated grafting have shown promising results in reducing the ecological footprint of coupling agent grafting. Supercritical fluids, particularly supercritical CO_2, serve as an eco-friendly medium for grafting, eliminating the need for toxic solvents. UV-initiated grafting harnesses ultraviolet light to initiate the grafting reaction, significantly reducing energy consumption. The integration of green chemistry considerations into coupling agent grafting not only aligns with sustainable development goals but also offers potential cost savings and enhanced material properties. Future advancements in this field are expected to focus on optimizing green methods and expanding the range of functional materials.

Keywords: Coupling agent, Environmental sustainability, Functionalization, Green chemistry, Grafting techniques, Surface modification.

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INTRODUCTION

Coupling agents are amphiphilic molecules that possess the ability to bond with both hydrophilic inorganic fillers and hydrophobic resins. These materials undergo chemical bonding processes [1]. They are bifunctional, containing different reactive groups, which enhances interactions at the interface and between polymer chains and filler components, thereby coupling the two constituents [2]. Consequently, coupling agents improve interfacial adhesion, resulting in enhanced performance of the polymer composite [3].

The use of graft copolymers as compatibilizers is also highly significant. These macromolecular structures possess more than two chemical chains, with one chain serving as the backbone and multiple branches formed from macromolecular chains of differing chemical composition than the backbone chain [4]. Graft polymers function as coupling agents by enhancing interfacial interactions between lignocellulosic fibers and the polymer matrix [5].

The crucial role of coupling agents lies in improving interfacial properties between materials, effectively forming a chemical bridge. This process, referred to as coupling agent grafting, involves the attachment of coupling agents to substrates, which modifies their surface characteristics and improves compatibility with other materials. Silane coupling agents are widely used due to their ability to form strong covalent bonds with both inorganic and organic materials [6].

Advantages of Coupling Agent Grafting

In the case of epoxy resin, the increase in mechanical properties and glass transition temperature (Tg) is enhanced by 41K with increased grafting density of the amino silane coupling agent on nano silica. Improvement in homogeneous morphology and tensile strength is achieved by using dry-blending compression moulding and extrusion injection methods, respectively, in the case of poly lactic acid (PLA) biocomposites. Coupling agents are used in applications such as structural components, which leads to an increase in tensile strength by 32% and yield strength by 23%. Improvement in the contact angle, choline resistance, and enhancement in desalination performance in real wastewater treatment. Improvements in the interfacial and interlamellar shear strength values of carbon fibres reinforced with epoxy composite are observed in the case of electrochemical oxidation, which is further followed by the grafting of KH550, a silane coupling agent.

Disadvantages of Coupling Agent Grafting

The thermomechanical properties of epoxy resin are affected by high grafting ratios, resulting in reduced chain mobility [7]. A dosage of 12 mL, a reaction temperature of 80°C, and a hydration degree of 10% are considered optimal reaction conditions for grafting microporous silica onto the silane coupling agent vinyl triethoxysilane. Poor osteogenesis and angiogenesis potential, as well as low mechanical strength and tissue adhesiveness, are limitations associated with current periosteal grafts. To synthesize biomolecule–polymer conjugates, grafting methods such as ATRP, RAFT, or ROMP are used. Modified PAMAM and PAMAM/GO membranes exhibit improved performance in desalination during real wastewater treatment. A water contact angle of 100 is achieved by leading the hydrophobic surfaces to the highest APTMS attachment efficiency in the case of plasma grafting from this approach. New colloidal properties and thermos-reversible aggregation of grafting of poly(N-isopropylacrylamide) onto the cellulose nanocrystals. Enhancement of interfacial adhesion in composites is observed when coupling agents supply active groups onto uniformly grafted, high-density CNTs on the surface of carbon fibres. The highest tensile strength, thermal stability, water vapour barrier properties, and antioxidant potential have been observed in Gallic acid-g-Chitosan (GA-G-Cs) films, which are prepared via the carbodiimide coupling method. Compared to chitosan (Cs) films, these films have rougher surfaces and cross-sections.

TYPES OF COUPLING AGENTS USED FOR GRAFTING

Coupling agents used for grafting are considered to be those compounds that facilitate bonding between different materials, thereby enhancing compatibility and interfacial adhesion. Coupling agents used for grafting are important in various applications, such as composite materials, surface modification, and polymer blends.

Different types of coupling agents are used for grafting, including silane coupling agents, Maleic anhydride (MAH) coupling agents, Titanate and Zirconate coupling agents, Isocyanate coupling agents, Epoxy coupling agents, Acrylate and Methacrylate coupling agents, and sulfur-based coupling agents.

Silane Coupling Agents

The most widely used coupling agents are considered to be silane coupling agents, which can enhance the interfacial properties with different materials, thereby forming strong chemical bonds [8]. These are primarily effective during the grafting process, where they tend to modify the surface characteristics of the

CHAPTER 5

Grafting of Natural Fibers: Techniques and Eco-friendly Aspects

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Abstract: Fibers obtained from natural sources, such as plants and animals, have gained substantial interest due to their versatile applications. This review examines graft copolymerization techniques used for modifying natural fibers, including ring-opening polymerization (ROP), free radical grafting, chemical treatments, and physical treatments. Graft copolymerization enables the introduction of reactive sites, modification of surface morphology, and alteration of hydrophilicity/hydrophobicity as well as chemical and thermal stability in natural polymers. Ring-opening polymerization is a promising method for developing biocomposites with enhanced mechanical properties and improved compatibility. Free radical grafting offers a wider range of solvent options compared to conventional techniques, thereby improving the moisture resistance of fibers. Surface modification through various physical and chemical approaches enhances the strength of fibers. Photocuring is a greener and faster alternative to radiation grafting. Chemical treatments using coupling agents enhance fiber–matrix adhesion, while functionalization improves mechanical properties, resulting in increased stiffness and ductility. Microwave-assisted methods enhance grafting efficiency and increase the moisture resistance of fibers. Various characterization techniques confirm the efficiency of grafting, and the degradation rates of grafted copolymers can be controlled by adjusting grafting efficiency, thereby offering the potential for controlled-release applications. Grafting also reduces the thermal degradation of cellulose nanocrystals, enabling higher processing temperatures and expanding the potential applications of biocomposites. This chapter highlights the significance of grafting techniques and various treatment processes in the context of eco-friendly biocomposites with tailored properties for diverse applications.

Keywords: Biocomposites, Environmental impact, Grafting, Natural fibers, Sustainability.

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INTRODUCTION

Natural fibers encompass a diverse group of materials derived from biological sources, primarily plants and animals, which include protein-based fibers (such as wool and silk) and cellulosic fibers (such as sisal, jute, and cotton). Notably, some regenerated cellulose fibers (acetate, viscose rayon) are derived from wood pulp by chemical processing. Natural fibers are an abundant and cost-effective resource, widely utilized in various commercial sectors, including furniture, geotextiles, insulation materials, and composites [1]. In 2017, global fiber production exceeded 100 million metric tons, with synthetic fibers accounting for approximately 60% of total output. Polyester holds the largest market share at about 51%, followed by cotton at roughly 25%. Artificial cellulosic fibers contribute 6–7%, while wool holds a modest share of 1%. Collectively, different sources from plant fibers such as linen, jute, and hemp constitute the remaining 5%. The dominance of synthetic fibers, which contributes to the environmental impact of fiber production and textile waste generation, necessitates separating economic growth from unsustainable resource consumption [2]. Fig. (**1**) depicts the classification of natural fibers based on their origin. Grafting natural fibers is a technique that enhances fiber–polymer matrix interactions, resulting in biocomposites. Graft copolymerization enables the development of polymers from natural sources with enhanced properties by introducing reactive sites. This alters surface morphology, enhances hydrophilicity/hydrophobicity, and improves chemical and thermal stability. The combination of natural and synthetic polymers provides tailored structure–property relationships (including elasticity, reactivity, glass transition temperature, permeability, and solubility) to meet specific application needs [3]. Graft copolymerization is a prominent method for improving the biocompatibility and degradability by grafting vinyl-based synthetic monomers onto polymers derived from natural fibers, which is particularly relevant for biomedical applications. Starch and its derivatives, due to their inherent properties, are frequently used as matrices in drug delivery systems [4]. This technique modifies the surface of the natural polymer while preserving its core characteristics. Extensive research has explored the grafting of diverse vinyl monomers onto various polysaccharide backbones using different initiators and techniques, achieving promising results. Controlled graft copolymerization of psyllium enables the tailored modulation of properties for specific applications [5, 6]. This versatile technique serves as a powerful tool for chemically modifying natural polymers, with extensive research focusing on polysaccharides such as starch, cellulose, and chitosan. This chapter explores various grafting methods and their eco-friendly implications.

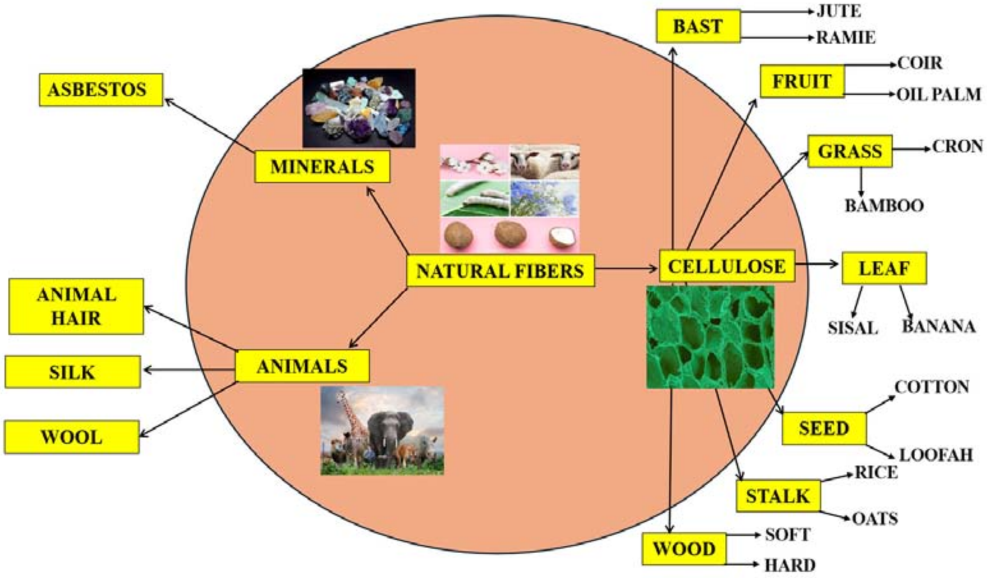

Fig. (1). Categorization of natural fibers.

GRAFTING TECHNIQUES

Graft copolymerization techniques include single-monomer grafting, monomer-mixture grafting, and direct polymer grafting onto fibers. These properties can be tailored by adjusting polymerization parameters. Various copolymerization methods include photochemical initiation, enzyme-mediated grafting, plasma-radiation-induced grafting, free-radical initiation, ionic initiation, living polymerization, and plasma initiation [7]. Polymer grafting onto cellulose is a promising approach for biocomposite development, as it preserves cellulose stiffness while imparting thermoplastic properties.

Ring Opening Polymerization

Ring-opening polymerization (ROP) is notable for its "living" polymerization characteristics, particularly in the conversion of lactide to polylactic acid [8]. ROP improves cellulose grafting by avoiding metal residues, thereby producing cleaner and potentially biocompatible materials, while allowing precise control over molecular weight and distribution [9]. Lönnberg *et al.* covalently grafted ε-caprolactone and lactide onto cellulose *via* the ROP process, using $Sn(Oct)_2$ as a catalyst and benzyl alcohol as the starting material, and demonstrated the versatility of ROP for controlled cellulose modification by regulating the initiator-to-monomer ratio to control grafting density (Fig. (**2a**) [10]. Cordova *et al.* utilized an organic acid catalyst for ROP, which enabled direct poly(ε-

CHAPTER 6

Challenges and Future Directions in Green Grafting

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Abstract: Green grafting, a technique that involves grafting herbaceous scions onto juvenile rootstocks, has emerged as a promising alternative to traditional woody grafting in horticulture. This eco-friendly method offers several advantages, including faster healing, reduced resource requirements, and improved graft compatibility. However, its widespread adoption is still limited by a number of challenges.

This book chapter discusses these challenges and outlines future research directions. Key issues include optimizing scion and rootstock combinations, managing environmental conditions during graft healing, and reducing physiological stress in grafted plants. Progress is further constrained by the absence of standardized protocols and an incomplete understanding of the molecular mechanisms that drive graft union formation.

To overcome these limitations, future research should focus on high-throughput screening methods to identify compatible scion and rootstock combinations, along with advanced imaging techniques to study graft union anatomy. The application of omics technologies can also provide valuable insights into the genetic and metabolic pathways that determine graft success. Additional areas of interest include the role of plant growth regulators, the refinement of hydroponic and aeroponic systems for graft healing, and the potential use of green grafting in climate change adaptation.

By addressing these challenges, green grafting can transform plant propagation practices, support sustainable agriculture, promote biodiversity conservation, and strengthen global food security.

Keywords: Comics technologies, Climate change adaptation, Green grafting, Graft union formation, Herbaceous grafting, Plant propagation, Scion-rootstock compatibility, Sustainable horticulture.

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INTRODUCTION

Polymers derive their name from the Greek roots “poly,” meaning many, and “mero,” meaning parts. They are large molecules with molecular masses ranging from hundreds of thousands to several millions. Synthetic polymers, including plastics, synthetic fibers, and synthetic rubbers, account for nearly 80 percent of the total production in the organic materials industry. A specific form of these structures, known as graft copolymers, is created when segments of one polymer are covalently attached to the backbone of another. A special case is the mikroarm star copolymer, which has a single branch. Both the main chain and the branches, whether composed of homopolymers or copolymers, may vary in chemical composition and topology.

Polymer grafting is a widely used chemical strategy to introduce branching and thereby expand the diversity of homopolymer molecules. In traditional synthesis, branches are often distributed randomly along the backbone with relatively uniform chain size. However, more advanced methods have been developed that allow the production of graft copolymers with evenly spaced and elongated branches. These approaches provide precise control over molecular composition and microstructure. A major focus of research has been understanding the relationship between the structure of graft copolymers and their resulting properties [1].

Polymers, also called macromolecules, are built from smaller units known as monomers that assemble into long chains. Humans have exploited the versatility of polymers for centuries in the form of oils, tars, resins, and gums. The modern polymer industry, however, only emerged during the Industrial Revolution. A landmark achievement was Charles Goodyear’s discovery of vulcanization in the late 1830s, which transformed natural rubber into a durable and practical material [2].Polymer grafting remains a powerful technique for modifying the structure, chemical characteristics, and physical behavior of polymers. Through this method, solubility, biocompatibility, communication at the biological interface, and nanoscale structural properties can be enhanced, while also improving conduction and charge transfer capabilities. Over time, numerous innovative grafting techniques and applications have been reported [3, 4]. By covalently linking new polymer segments as branches onto parent chains, researchers have created novel materials with improved and often unique functional properties [5, 6].

GRAFTING POLYMERS

Improving the mechanical properties, wettability, and biocompatibility of surface polymers is a primary goal of surface modification. Such modifications impart unique characteristics to the material, including enhanced temperature stability, improved performance in physical and multiphase reactions, greater compatibility, flexibility, and stiffness. Surface modification can also alter the solubility of polymers, making them soluble or insoluble as required, while simultaneously creating a more favorable environment for polymer processing. Well-established techniques for polymer modification include blending, cross-linking, composite formation, and grafting [7].

One important method is grafting, which typically involves the attachment of a single monomer to a polymer backbone. Grafting can also be achieved by combining two or more monomers, either sequentially or simultaneously, to tailor the structural and functional properties of the resulting material.

TECHNIQUES OF GRAFTING

Grafting of polymers can be carried out through several techniques, including chemical, photochemical, enzymatic, plasma-induced, and radiation-based methods [8].

Chemical Grafting

Chemical grafting is the most widely applied method for polymer modification. It can be achieved through techniques such as living polymerization, ionic initiation, and free radical formation. In contrast to ionic grafting, which relies on charged species, chemical grafting typically employs an initiator together with a polymer to form the grafted structure. Within these approaches, atom transfer radical polymerization (ATRP) has gained particular importance because of its efficiency and its ability to precisely control polymer architecture [9, 10].

Radiation Grafting

Radiation grafting occurs when macromolecules are exposed to radiation, causing homolytic bond cleavage and the formation of free radicals on the polymer chain. This method does not require any initiator or catalyst and is straightforward, precise, and easily controllable. The energy absorbed by the polymer itself generates the free radicals needed to initiate the grafting process [11].

Photochemical Grafting

Photochemical grafting can be performed with or without a sensitizer. In this process, the chromophore absorbs light and enters an excited state, leading to the formation of reactive free radicals. If bond cleavage alone is insufficient to generate free radicals, photosensitizers such as dyes or benzoin ethyl ether can be

CHAPTER 7

Case Studies: Success Stories in Green Grafting

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Abstract: The current developments in green nanotechnology, which have traditionally been limited to gold nanoparticles (AuNPs) used for *in vitro* biocompatibility testing, have addressed many issues. Researchers are interested in knowing several green nanotechnological protocols and how they are being employed to functionalize gold nanoparticles. Different characterization tools are required to determine the size and physicochemical properties of gold nanoparticles. An overview of the various applications of gold nanoparticles in diagnostic imaging techniques, such as X-ray contrast agents, SPECT imaging, PET imaging, OCT, fluorescence imaging, MRI, SERS, and ultrasound imaging, is of particular interest to researchers. Moreover, this chapter will also focus on drug delivery systems, photothermal therapy, cancer therapy, and molecular imaging, as well as the therapeutic potential of phytochemicals as reducing agents for gold nanoparticles. The systemic toxicity of gold nanoparticles and the strategies to address this toxicity are also important for their effective use in biomedical science. In conclusion, our chapter highlights the numerous potential roles of gold nanoparticles in nanomedicine, while drawing attention to some of the shortcomings associated with their applications. In turn, organic polymers find applications in adhesion, biomaterials, protective coatings, tribology (including friction, lubrication, and wear), advanced composites, and microelectronics, as well as in the rapidly advancing field of thin-film technology. These polymers are important in the plastic industry, but surface modification techniques are used to convert them into useful products. Polymers are suitable for implants and tissue engineering scaffolds because plasma treatment increases cell adhesion, growth, and proliferation in the biomedical field.

Keywords: Biocompatibility testing, Diagnostic imaging, Drug delivery system, Green nanotechnology, Gold nanoparticles, Systemic toxicity.

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INTRODUCTION TO GREEN NANOTECHNOLOGY

Nanotechnology focuses on the design, characterization, production, and application of structures, devices, and systems, with shapes and sizes controlled at the nanometer scale. The term nanotechnology has been defined throughout this book chapter as encompassing structural aspects of materials that measure less than 100 nm. This term is used to describe three types of materials: nanostructures, nanocomposites, and nanoparticle aggregates. Nanomaterials are characterized by size-dependent properties due to their high surface activity, electrical, magnetic, or optical properties, and shape at the nanoscale level.

Synthetic nanomaterials have presented numerous applications and advantages. However, their production and usage were historically expensive and, in some cases, resulted in the generation of toxic byproducts. As a result, the application of synthetic nanostructures in medicine is restricted due to the associated risks and side effects. Researchers are shifting their focus to using environmentally friendly routes to synthesize nanomaterials, which aim to prevent these side effects.

Green nanotechnology involves the use of nanotechnology to minimize costs and potential environmental risks by enhancing the sustainability of processes. The aim is to harness nature's ability to mitigate the risks associated with environmental and human health impacts involving nanomaterials. Finally, it encourages the replacement of existing nanoproducts with more environmentally friendly nanomaterials. Green nanotechnology, as an emerging field, presents potential solutions by serving as a bridge between nanotechnology and sustainable practices. Conventional nanomaterial synthesis and applications pose environmental and health issues, which can be addressed by this technology. Growing awareness of the environmental impact of conventional manufacturing processes is driving a rising demand for sustainable and eco-friendly synthesis methods and their applications.Green nanotechnology involves a variety of techniques designed to reduce the use of hazardous chemicals, decrease energy consumption, and encourage the use of renewable resources. Its potential to revolutionize various industries lies in offering sustainable solutions to critical global challenges.

Green nanotechnology is facilitating the fabrication of biocompatible nanoparticles for drug delivery, diagnostics, and therapeutics with reduced toxicity and enhanced efficacy. This approach signifies a paradigm shift that promotes sustainable practices in the medical field. These nanoparticles are engineered to improve targeting and bioavailability, while minimizing the side effects commonly associated with traditional therapies. Advancements in this area are essential for future innovations in medicine.

Green processes employ non-toxic materials and solvents throughout the synthesis process. Toxic substances from the reactions are completely eliminated, thus preventing the production of harmful byproducts that damage the environment. The aim is to remove all toxic substances from the manufacturing processes.

According to Katti, green nanotechnology refers to the use of phytochemicals as electron-rich reducing agents that facilitate the conversion of metal precursors into diverse functionalized nanoparticles. Phytochemicals derived from natural products such as cumin, cinnamon, tea, grapes, soy, and mango have been successfully employed to synthesize tumor-specific gold nanoparticles through entirely non-toxic methods.

Among the diverse array of metallic nanoparticles that have been subjected to thorough investigation thus far, the gold nanoparticles emerge as particularly noteworthy candidates in the domains of pharmaceutical and biomedical applications, attributable to several salient factors: **1.** The surface atoms intrinsic to gold nanoparticles facilitate the incorporation of a multitude of targeting moieties, which can encompass peptides, proteins, or other biomolecular entities, alongside drug molecules; **2.** The dimensional characteristics of gold nanoparticles can be meticulously engineered, thereby enabling pronounced and efficient cellular uptake, particularly by cancer cells due to their unique permeability and retention characteristics; **3.** Gold nanoparticles, when functionalized, exhibit non-immunogenic properties and demonstrate a tendency towards being non-toxic; and **4.** The properties of gold nanoparticles, such as their magnetic, photophysical, and radioactive properties, enable the development of a diverse array of therapeutic, theranostic, and diagnostic agents aimed at addressing various diseases.

Gold, in the context of nanotechnology, exhibits a distinct characteristic. It stands as the sole element within the periodic table that demonstrates an inertness to oxidation, even when analyzed at the level of nanoparticles.

This chapter will provide a comprehensive summary of the significance of green nanotechnology and its applications, including various synthetic pathways for producing functionalized nanoparticles, highlighting the use of gold nanotechnology, applications in drug delivery and diagnostics, such as computed tomography (CT), photoacoustic imaging, optical coherence tomography (OCT), magnetic resonance imaging (MRI), surface-enhanced Raman spectroscopy (SERS), X-ray and fluorescence imaging, and single photon emission computed tomography (SPECT), and therapeutic applications, including radiotherapy, X-ray therapy, Photothermal/photodynamic therapy, and chemotherapy, which utilize radioactive gold nanoparticles for targeted treatment [1].

CHAPTER 8

Education and Outreach in Green Grafting

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Abstract: Green grafting is an innovative strategy for modifiying polymers that has the potential to promote sustainability in the pharmaceutical and healthcare industries. This chapter highlights the critical importance of education and public outreach in driving the development of such a revolutionary technology. It provides an overview of different approaches and tactics designed to share green graft-handling knowledge with academia, industry key players, and the general public. Through case studies, it is evident how outreach efforts can evoke interest in sustainable practices while inspiring students to become the next generation of scientists and engineers. It underscores that green grafting is interdisciplinary, and to realize long-term beneficial environmental and health effects, research should also be linked to applications, and governance should increase public awareness. It highlights the potential for significant positive impact in the healthcare and pharmaceutical sectors through a holistic approach that combines scientific innovation with strategic outreach. This chapter provides a comprehensive analysis of the impact of education and community engagement on promoting the adoption of green grafting techniques by showcasing successful outreach programs from various regions and discussing the challenges and opportunities in each case.

Keywords: Interdisciplinary research, Green grafting, Green chemistry, Polymer modification, Sustainability.

INTRODUCTION

Green Grafting Technology

Green grafting technology is an initiative to introduce eco-friendly practices into conventional grafting techniques with broad applications in agricultural, biotechnological, and pharmaceutical sectors. Green grafting, when considered for the pharmaceutical industry, means the use of eco-friendly raw materials and

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processes in the development of grafts that are both compatible with the human body and the environment. Green grafting assumes a significant position in drug delivery systems, tissue engineering, regenerative medicine, and many other therapeutic applications. Thus, green grafting does two things. First, it provides efficient and sustainable medical treatment, and it reduces the environmental impact of healthcare practices. Traditionally, pharmaceutical grafting has involved synthetic materials, which are very effective but usually lead to environmental degradation due to the accumulation of their non-biodegradable waste. Green grafting, through materials such as biodegradable polymers and natural biomaterials, works on the paradigm of ensuring they break down safely in the body or environment. This not only reduces the ecological footprint of medical products but also increases patient safety by reducing adverse reactions to synthetic materials. Green grafting derives additional impetus from the fact that it aligns with global trends toward greener healthcare. With the world facing a climate change crisis, pollution, and resource depletion, the healthcare sector has a responsibility to reduce its ecological footprint. One of the crucial innovations that can make high-performance medical products a reality without harming environmental integrity is green grafting. Furthermore, green grafting is also at the core of emerging personalized medicine. As healthcare shifts toward a more individualized concept of treatment plans, so does the need for grafts and delivery systems that can be tailored to address patient-specific needs. Green grafting allows the creation of tailored solutions using a wide range of biocompatible and biodegradable materials that can be tailored to different therapeutic needs [1, 2].

Example: The lead example of the power of green grafting is the development of biodegradable dressings. Conventional dressings are primarily applied to wounds based on synthetic polymers, which, when used in healing, either cause irritation or necessitate surgical removal. In contrast, green grafting uses naturally occurring components, such as chitosan or alginate, which are bioactive, promoting wound healing, and self-degradable, thus avoiding the need for removal and minimizing the potential for infection [3].

Potential Benefits for Sustainability in Pharmaceuticals and Healthcare

The benefits that could be achieved from green grafting technology are massive, ranging from environmental to economic, social, and clinical outcomes. This section elaborates on the benefits of green grafting and how this can contribute to a much more sustainable and effective healthcare system.

Environmental Sustainability: Green grafting ensures a reduced impact on the environment from healthcare. This technology decreases dependency on petrochemical-based products, which are well known for their persistence in the environment, through the use of renewable resources and the production of biodegradable materials. For instance, in tissue engineering, green grafting involves using scaffolds prepared from either polylactic acid or polycaprolactone, both of which are obtained from renewable sources and are completely biodegradable. This minimizes the accumulation of medical waste in the long run, a significant challenge experienced by hospitals and clinics in most parts of the world [4].

Economic Efficiency: On an economic level, green grafting is associated with several benefits. First and foremost, it is very likely that natural renewable products will have a lower production cost compared to their synthetic version, primarily if this material can be sourced locally. Green grafting will also lead to more innovations and create new market openings for using environmentally friendly medical products, thereby opening avenues for expansion within the pharmaceutical and biotech fields. Lastly, the long-term benefits of green grafting include cost savings for healthcare systems, as better patient outcomes that eliminate the need for additional treatments are linked to better cost and implications for the healthcare cycle, waste management, and disposal [4, 5].

Social and Ethical Benefits: In terms of social and ethical benefits, green grafting is particularly profound. As public ecological awareness increased, the demand for solutions leading to sustainable health, giving equal importance to both human and environmental health, also increased. The Corporations, thus, have the responsibility to safeguard their profit-making intentions from causing any damage to society or leading to negative environmental impacts. This corporate social responsibility should be reflected in green grafting [6].

Clinical Progress: From a clinical aspect, green grafting helps to improve the efficacy of quality and treatments. For example, in regenerative medicine, green grafting strategies can design scaffolds that provide mechanical support to tissue development and, in a well-regulated manner, these can act as delivery vehicles for growth factors along with other bioactive molecules. This facilitates effective tissue repair, yielding desirable patient outcomes. The use of biocompatible materials also reduces the risk of immune rejection or other complications, further making green grafting a safer option for a wide variety of medical applications [7].

Example: One of the clinical applications of green grafting is in the field of bioresorbable drug delivery systems. These can be configured and formulated to deliver a therapeutic agent that is extended in a controlled manner, whereby the vehicle degrades into innocuous byproducts. For instance, the preparation of bio-

CHAPTER 9

Advancing Sustainable Polymer Functionalization With Respect to Green Grafting in the Pharmaceutical and Healthcare Industry

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Abstract: In biomedicine, the biocompatible and good physical and chemical properties of polyurethanes are frequently employed in medical devices, such as coronary stents. Despite being a perfect tissue frame in many ways, polyurethane exhibits better compatibility than other polymers, which can be partly attributed to its surface characteristics. Here, we outline a process for functionalizing polyurethane gallows that entails integrating. The primary amine groups thus inserted into the polyurethane surface enable further coupling with dextran and recombinant peptides through reductive amination. Surface analysis is used to confirm the effectiveness of surface functionalization of an aliphatic poly(ether)urethane of medical grade. Polymers are so lightweight, moldable, and adaptable that they are indispensable in modern life; as a result, the human population grows, so will the need for polymers. During their usage, structural and functional polymers save CO_2 and have benefits for sustainability; yet, they pose problems when they reach the end of their useful lives. By utilizing the most recent developments in the field, polymer science and related fields can facilitate the circular economy of polymers by means of biodegradation or recycling. This can be achieved through the implementation of techniques for molecular and system design. Computational material science and advances in polymer chemistry and applications pave the way for a comprehensive approach to resolving these concerns through the design of materials that are biodegradable and recyclable.

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For applications involving controlled medication release, biodegradable polymers can be employed. They break down naturally in the body to produce non-toxic metabolites.

Keywords: Biodegradable, Functionalization, Non-toxic metabolites, Polymer, Polyurethanes.

INTRODUCTION

Green grafting is a relatively new field of polymer functionalization with several potential applications in the pharmaceutical and medical industries. This approach focuses on improving the properties of polymers for a variety of biological applications by changing them using environmentally acceptable methods. The following are crucial aspects of green grafting in the functionalization of polymers. Biocompatibility and biodegradability are the primary mechanisms of green grafted polymers, which possess biocompatible and biodegradable properties that make them suitable for use in medical applications, such as medication delivery systems. Functionalized polymers can enhance a drug's chemical stability, bioavailability, and selectivity, leading to more effective therapies. Sustainability, as opposed to conventional techniques, green grafting minimizes the environmental impact by emphasizing the use of eco-friendly materials and procedures. A polymer is a large molecule composed of repeating structural units, typically bonded together by covalent bonds. These building elements, known as monomers, can vary in structure or be similar, leading to a wide variety of polymers with distinct properties and applications. Examples of polymers include natural polymers, such as proteins, cellulose, natural rubber, and nucleic acids (DNA and RNA). Examples of synthetic polymers are nylon, polystyrene, and polyethylene [1]. They are used in pharmaceuticals for drug delivery systems to control the stability and release of medications. In the healthcare system, it is incorporated into medical devices, tissue engineering, and biocompatible materials. Functionalization is the process of modifying polymers to enhance their suitability for specific applications. Functional groups may be added to improve mechanical strength, drug loading capacity, or biocompatibility.

The structural relationship between monomers and polymers is illustrated in Fig. (**1**), which provides a basic conceptual understanding relevant to subsequent discussions on polymer grafting and functionalization.

A molecule of high relative molecular mass, the structure of which essentially comprises the multiple repetition of units derived, actually or conceptually, from molecules of low relative molecular mass, is the definition of a macromolecule given by the IUPAC Gold Book. Natural polymers comprise the majority of the structures in living tissues, including DNA, protein, starch, and cellulose. Today, synthetic polymers are among the most successful and practical material groups, offering a wide variety of physical characteristics [2].

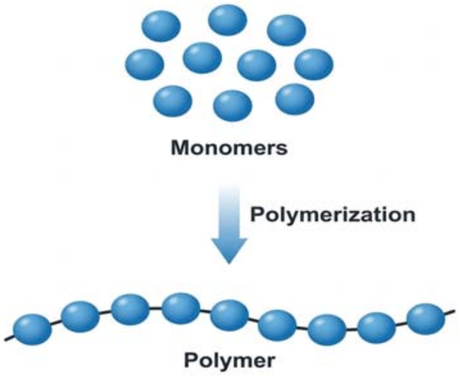

Fig. (1). Monomers and polymers.

TYPES OF POLYMERS

- **Natural Polymers:** These consist of cellulose, proteins, natural rubber, and nucleic acids (DNA, RNA).
- **Synthetic Polymers:** These include nylon, polystyrene, and polyethylene, among others.

APPLICATIONS OF POLYMERS

- **Pharmaceuticals:** Utilized in drug delivery systems to regulate the stability and release of pharmaceuticals.
- **Healthcare**: Utilized as biocompatible materials in tissue engineering and medical devices.
- **Functionalization**: Functionalization is the process of altering polymers to improve their characteristics for particular uses to increase mechanical strength, drug loading capability, or biocompatibility. Functional groups may be added.

ADVANCING SUSTAINABLE POLYMER FUNCTIONALIZATION

The goal of sustainable polymer functionalization is to develop environmentally responsible methods for modifying polymers, enhancing their properties while minimizing their adverse environmental impacts. Here are a few crucial elements. Environmentally friendly products and methods utilize green chemistry principles and renewable resources to produce polymers with a lower environmental impact. Biodegradability of polymers is creating polymers that undergo the natural breakdown process to cut down on pollution and waste. Enhanced Properties are adding active substances or nanofillers to increase the material's electrical

SUBJECT INDEX

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Kuldeep A. Vinchurkar

Dr. Kuldeep A. Vinchurkar, Ph.D. (Pharmaceutical Technology), is a distinguished academician and researcher with over 13 years of teaching and research experience. Currently serving as Professor and Head at Sandip Institute of Pharmaceutical Sciences, Nashik, he specializes in novel drug delivery systems, 3D printing, and green pharmaceutical innovations. Dr. Vinchurkar has authored and edited numerous books with Springer, Elsevier, Wiley, and Bentham, and published extensively in reputed international journals. He holds multiple national and international patents, including innovations in 3D-printed dosage forms. A recipient of several research and innovation awards, he actively contributes to advancing sustainable pharmaceutical sciences.

Satish Arunrao Polshettiwar

Dr. Satish Arunrao Polshettiwar Associate Professor and Academic Coordinator (PG), Dept. of Pharmaceutics, School of Health Sciences & Technology, MIT World Peace University, Pune. M.Pharm, D.I.T (C-DAC), Ph.D. Founder of FormulationAI, the world's first formulation predictive tool. An accomplished pharmacy educator, researcher, and AI trainer with 20+ years of experience in teaching, research, and consultancy. Recipient of multiple national awards and featured in World Scientist Ranking (2021–2025). Authored 60+ research papers, 21 book chapters, 14 patents, and 4 textbooks. Delivered 250+ talks globally. Consultant to leading pharma industries and active in innovation, academic leadership, and student mentoring.

Nilesh M. Mahajan

Dr. Nilesh M. Mahajan is a distinguished Professor and Head of Pharmaceutics at Dadasaheb Balpande College of Pharmacy, Nagpur, with over 22 years of academic and research leadership. A Ph.D. in Pharmaceutical Sciences, he specializes in nanotechnology-driven and targeted drug delivery systems. Dr. Mahajan has successfully executed DBT-BIRAC and AICTE-funded projects of more than 1.2 cr., authored over 75 research publications, contributed to international books, and holds multiple national and international patents. Honored with the Best Researcher Award by RTM Nagpur University, he actively mentor doctoral scholars and serves on prominent scientific and advisory committees, driving innovation and translational research in pharmaceutical sciences.

Yogeshwar Bachhav

Dr. Yogeshwar Bachhav is an accomplished pharmaceutical development expert with over 19 years of experience in the drug discovery, project management, and business development. As a Pharmaceutical Development Consultant, he has led the development of numerous molecules through clinical phases to commercialization. He holds a PhD from Institute of Chemical Technology, an LL.B. from University of Mumbai, and a Global MBA from University of Western Australia. Founder of Adex Pharma, he has authored 17 publications, holds 7 patents, and is an active member of leading scientific societies, advancing global drug innovation.