Biodegradable and Biocompatible Polymer and Their Applications as an antimicrobial Nano Composites

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Abstract:
The antimicrobial activity of nanoparticles prompts their uses in manymedical devices. Chemical dye and natural based antimicrobial biocompatible hyperbranched and linearpolymer nanocomposites have been prepared. Formation of the stable and well-dispersed nanoparticles was confirmed by ultraviolet, X-ray diffractometeric, transmission electron microscopic and Fourier transform infra-red spectroscopic analyses. The enhancement of properties for hyperbranched and linear polymers respectively was observed bythe formation of nanocomposites. The nanocomposites showed biodegradability as conferredfrom the bacterial degradation. The biopolymers can be obtained from different resources such as carbohydrates, animal or plant-derived proteins, and microbialsynthesized and petroleum-based chemicals for food industry applications. The microbial origin biopolymers (polyhydroxyalkanoates, bacterial cellulose, xanthan, curdian, pullan) are biocompatible, eco-friendly, and custom-made, which could be a useful tool for food industry applications. This paper explained various microbial polymer nanocomposites and their effective applications

Keyboard: Antimicrobial Nano-composites, Biodegradability, Biocompatibility,Dye, Polymers.
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Introduction:

There has been an increasing interest for the development of biodegradable polymers forbiomedical applications, such as surgical fixation devices, bio-absorbable surgical suture,and carrier systems for the controlled release of drugs (1-3). The biocompatibility,toxicity, and immunogenicity are fundamental demands for biodegradable materials.Additional requirements for some biomedical applications are predictable rate ofbiodegradation and suitable mechanical properties. To develop new biodegradablepolymers which have appropriate mechanical property and biodegradability for thedesired applications, many efforts have been made. One of the effective methods ismolecular architecture by which tailored mechanical properties as well as biodegradationcan be obtained, e.g., copolymers and polymer blends are derived from this method.

High molecular weight macromolecules known as polymers are either organic or inorganic and formed up of recursive monomer units.

An in-depth knowledge of polymers' structure and characteristics is necessary for their development into medication delivery systems.

For instance, it has been discovered that the swelling of polycarbophil (polyacrylic acid cross-linked with divinyl glycol) is reduced if the carboxylic acid groups in the molecule are unionised, whereas in the case of a high concentration of ionised groups, there is a greater influx of water and the particles are highly swollen.

Classification of polymers:

Polymers can be categorised in a number of ways.They are simply divided into natural and synthetic polymers for pharmacological usage.Drug delivery systems are further divided into two subgroups: biodegradable and non-biodegradable due to the significant (essential) role that biodegradability plays in these systems.

Polymers as Pharmaceutical Excipients:

Pharmacy technicians have been using polymers in many facets of their work with pharmaceutical items for many years.Polyethylene and polyolefin bottles, polystyrene vials, rubber closures, rubber and plastic tubing for injection sets, and flexible polyvinyl chloride bags to hold blood and intravenous fluids are a few examples of such polymers.Polymers were initially only used for packing purposes rather than for the delivery of drugs in the early phases.The introduction of polymers in the design and development of drug delivery systems resulted from the fusion of polymer research and pharmaceutical science (DDS) [3-5].

The main intension of these polymeric drug delivery systems was to achieve controlled or sustained drug delivery. Hydro gels, liposomes, bioadhesives, nanoparticles and tissue engineering are some of the most applications of polymers.

Many other polymers which are used as excipients are microcrystalline cellulose (MCC), sodium carboxymethyl cellulose (NaCMC), hyddroxypropulcellulose (HPC), polyethylene glycol (PEG) and povidone are used to coat tablets. Cellulose acetate phthalate, hydroxymethylcellulose phthalate and copolymers of methacrylic acid and its esters, Eudragit are also used for enteric coating of tablets. Targeting of drugs to the colon following oral administration has been done by using biodegradable polysaccharides. Cross-linked guar gum was used as a vehicle in delivery systems for localized delivery to the distal portions of the bowel as its having reduced swelling properties due to the cross-linking.

Polymers used in Electronics:

Biodegradable polymers which can be used for electronic gadgets may be an effective solution for E-waste management, since they canbe degraded or dissolved into the surrounding environment with no pollution. This endows theelectronics with environmental safety and disposability [6 –8], by simultaneously decreasing the costfor recycling operations and the health risks associated with harmful emissions [9–12].Additionally, biodegradable materials are usually biocompatible, which enables electronics to beused in implantable biomedical applications. Biocompatibility allows the materials to directly contacttissues or skin without generating adverse effects [13– 17]. Furthermore, electronics which are bothbiodegradable and biocompatible can be dissolved or resorbed safely by human body at controlledrates after treatment or diagnosis is completed. Eliminating the need for a second surgery to retrievethe device simultaneously decreases the associated infection risks [18].Besides biodegradability and biocompatibility, some other characteristics, including flexibility,mechanical properties, electric conductivity, and gas and vapor barrier properties, are also essentialmfor specific applications in electronics. However, many polymers cannot completely meet theseperformance requirements. Therefore, recent research has focused on incorporating nanofillers withexcellent properties into polymers so as to improve their performance capabilities [19–22].

This paper aims to carefully demonstrate the development and potential of the biodegradable andbiocompatible nanocomposites in electronic applications. It will first review emergent biodegradableand biocompatible polymers used as insulators or (semi)conductors, and then highlight specificexamples of nanocomposites used in electronics as substrates, conductors, semiconductors, anddielectrics, as well as electronic packaging [23].

1. **Biodegradable and Biocompatible Polymers:**

1.1 Biodegradable Polymers

1) Biodegradable polymers are defined as polymers consist of monomers

linked to one another through functional groups and have unstable links in the backbone.

2) They are broken down into biologically acceptable molecules that are metabolized and removed from the body via normal metabolic pathways.
3) The American Society for Testing of Materials (ASTM) and the International Standards Organization (ISO) define degradable polymers as "those which undergo a significant change in chemical structure under specific environmental conditions".
4) These changes result in a loss of physical and mechanical properties, as measured by standard methods.
5) Biodegradable polymers undergo degradation from the action of naturally occurring microorganisms such as bacteria, fungi, and algae.
6) Between October 1990 and June 1992, confusion as to the true definition of "biodegradable" led to lawsuits regarding misleading and deceitful environmental advertising.
7) Thus, it became evident to the ASTM and ISO that common test methods and protocols for degradable polymers were needed.
8) To be considered compostable, three criteria must be met:
   a) biodegradation—it has to break down into carbon dioxide, water and biomass at the same rate as cellulose;
   b) disintegration—the polymer must become indistinguishable in the compost; and
   c) non-toxicity.
9) Most international standards (such as ISO 17088) require at least a 60% biodegradation of a product within 180 days, along with other factors, in order to be called compostable.

Biopolymers are the basis of biodegradable and biocompatible nanocomposites. They can beclassified as natural-based polymers and synthetic polymers [13]. Natural-based polymers refer tothose which come from nature. Table 1 shows an overview of biodegradable and biocompatiblepolymers used to fabricate electronics. In this section, biodegradable and biocompatible polymers willbe introduced according to their conductivity, since the electrical property directly determines theirapplication directions.

2.1.1 Types of Biodegradable Polymers

Biodegradable Polymers are basically divided into two main classes based on the source :-

1. Naturally Occurring Biodegradable Resins
2. Biodegradable Synthetic Resins.

1. Naturally Occurring Biodegradable Resin

This category of material includes:

•Polysaccharides e.g.- Starch from potatoes and corn.

•Proteins e.g. – Gelatin, Casein from Milk, Keratin from silk and wool, Zein from corn

•Polyesters – Polyhydroxy Alkanoates formed by Lignin, Shellac, Prolactic Acid

•Materials such as jute, flux, cotton, silk.

2. Biodegradable Synthetic Resin

•While there are number of degradable synthetic resins, including: Polyalkylene , Esters, Polylactic Acid Polyamide Esters, Polyvinyl Acetate, polyvinyl alcohol, Polyanhydrides.

•The materials mentioned here are those that exhibit degradation promoted by micro-organisms.

2.2) Biocompatible Polymer:

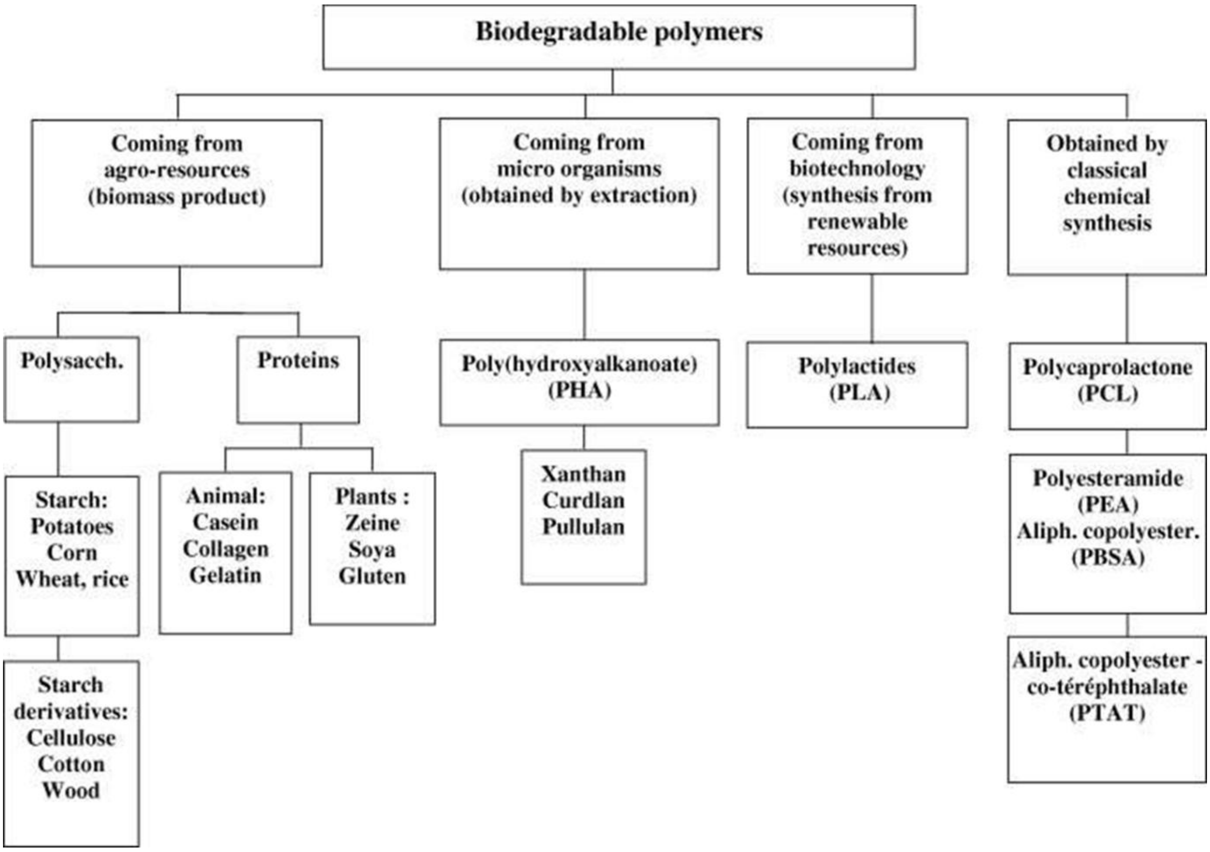


Table 1 Tables shows the physical properties of different polymers

Polymer	Melting Point (°C)	Glass-Transition Temp (°C)	Modulus (Gpa)	Tensile Strength (MPa)	Degradation Time (months)
PGA	225—230	35—40	7.0	NA	6 to 12
LPLA	178	60—65	2.7	48	>24
DLPLA	Amorphous	55—60	1.9	35	12 to 16
PCL	58—63	(-60)	0.4	16	>24
PDO	N/A	(—10— 0)	1.5	NA	6 to 12
PGA-TMC	N/A	N/A	2.4	NA	6 to 12
85/15 DLPLG	Amorphous	50—55	2.0	NA	5 to 6
75/25 DLPLG	Amorphous	50—55	2.0	NA	4 to 5
65/35 DLPLG	Amorphous	45—50	2.0	NA	3 to 4
50/50 DLPLG	Amorphous	45—50	2.0	NA	1 to 2

Table 2: Natural and Synthetic Polymer biodegradability and biocompatibility

Category	**Natural Polymer**	**Synthetic Polymer**		
Polymer Material	Cellulose, Silk, Gelatin	Poly(vinyl alcohol) (PVA), Polydimethylsilicane (PDMS), Polyactide (PLA), Polycaprolactone (PCL), Poly(glycerol-co-sebacate) (PGS), Poly(lactic-co-glycolic acid)(PLGA),		Polyaniline (PANI), Polypyrole (PPy), Poly(3,4-ethylenedioxythiophene) PEDOT
Electrical Property	Insulator	Insulator,		Conductor (doped)
Biodegradable/Biocompatible	Both	Both	Biocompatible	Biocompatible
Application	Substrate, Dielectric	Substrate, Dielectric		Conductor

3. Types of Biodegradable Materials and its Application:

3.1 Synthetic Biodegradable Polymers:

3.1.1 Aliphatic poly(esters)

These are prepared by ring opening and polymerization of cyclic ester.Aliphatic polyesters include:

a) POLY (GLYCOLIC ACID)
b) POLY (LACTIC ACID)
c) POLY (CAPROLACTONE)

a) Polyglycolic Acid

Polyglycolide or Polyglycolic acid (PGA) is a biodegradable, thermoplasticpolymer and the simplest linear, aliphatic polyester.Due to its hydrolytic instability its use has been limited. It has a glass transition elevated degree of temperature between 35-40 ^{0}C, crystallinity, around 45.Its melting point is in the range 55%, thus resulting in of 225-230 ^{0}C insolubility in water.polyglycolide is degraded by hydrolysis, and broken down by certain enzymes.

APPLICATIONS

- Used to deliver drugs in the form of microspheres, implants etc.,
- Examples of drugs delivered include steroid hormones, antibiotics, anti-cancer agents etc.,

b) Polylactic Acid

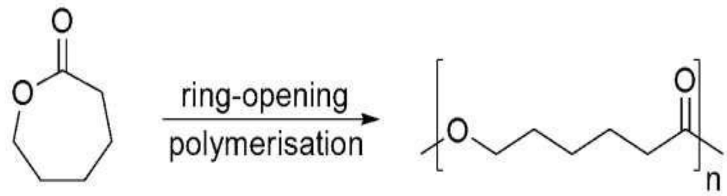
Polylactic acid or polylactide (PLA) is a thermoplastic aliphatic polyester derived from renewable resources, such as corn starch, tapioca products (roots, chips or starch) or sugarcane.It can biodegrade under certain conditions, such as the presence of oxygen, and is difficult to recycle.Polylactic acid have highly crystalline, high melting point, low solubility.Bacterial fermentation is used to produce lactic acid from corn starch or sugarcane.

APPLICATIONS

- PLA is used in the preparation of sutures or orthopaedic devices.

c) Polycaprolactone

Polycaprolactone (PCL) is biodegradable polyester.It has a low melting point of around 60 C.It has a glass transition temperature of about −60 C.slower degradation rate than PLA. It remains active as long as a year for drug delivery.



APPLICATIONS

Drug delivery applications of PCL includes:

- Cyclosporin in the form of nanoparticles
- Ciprofloxacin in the form of dental implants

3.1.2 Poly anhydrides

- Highly reactive and hydrolytically unstable.
- Degrade by surface degradation without the need for catalysts.
- Aliphatic (CH2 in backbone and side chains) polyanhydrides degrade within days.
- Aromatic (benzene ring as the side chain) polyanhydrides degrade over several years.
- Excellent biocompatibility.
- Drug loaded devices prepared by compression molding or microencapsulation.
- Suitable for short term drug delivery.
- Used for vaccination and localized tumor therapy.

3.1.3 Polyphosphazenes

- Its hydrolytic stability/instability is determined by change in side group attached to macromolecular backbone.
- Used in the construction of soft tissue prosthesis, tissue like coatings, as material for blood vessel prosthesis.
- Used for immobilization of antigen or enzyme.
- Use for drug delivery under investigation

Based on side chain these are of 3 types:

I. Hydrophobic phosphazenes
II. Hydrophilic phosphazenes
III. Amphiphilic phosphazenes

3.1.4 Polyaminoacids

- Aminoacid side-chains offer sites for drug attachment.
- Low-level systemic toxicity owing to their similarity to naturally occurring amino acids.
- Investigated as suture materials.
- Artificial skin substitutes.
- Limited applicability as biomaterials due to limited solubility and processibility.
- Drug delivery (difficult to predict drug release rate due to swelling)
- Polymers containing more than three or more amino acids may trigger antigenic response.
- Tyrosine derived polycarbonates developed as high-strength degradable orthopaedic implants.

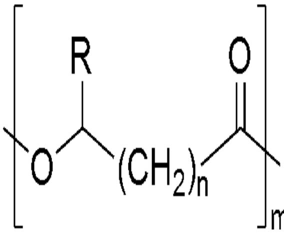
3.1.5 Poly (hydroxy alkanoates)- PHAs

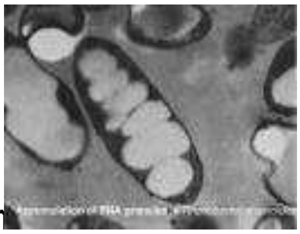
PHAs are produced by a wide range of microorganisms, including Pseudomonas, Bacillus, Rhodobacter, cyanobacteria and marine algae, using a range of carbon sources. PHAs degrade via a variety of mechanisms:

i. in bacteria: enzymatic hydrolysis
ii. in animals or in the environment: enzymatic or

iii. Chemical hydrolysis

iv. Accumulation of PHA in rhodobacter sphaeroides





R = C1–C13alkyl group (all Rstereochemistry), n = 1 –4, m = 100 –30,000

The generation of synthetic biopolymers, which we refer to as neobiopolymers, that mimic natural biopolymers could have profound applications

a. in disease prevention and treatment, as well as

b. in the elucidation of biological mechanisms.

These applications are predicated on the development of new methods for the controlled synthesis of these materials.

3.2 Natural Biodegradable Polymers

Natural polymers are an attractive class of biodegradable polymers as they are:

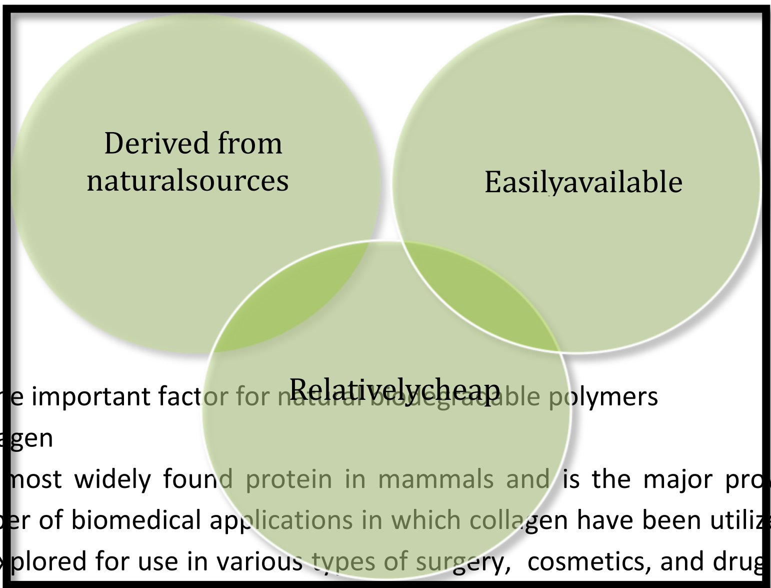


Figure1 shows the important factor for natural biodegradable polymers

3.2.1 Collagen

Collagen is the most widely found protein in mammals and is the major provider of strength to tissue.The number of biomedical applications in which collagen have been utilized is too high;it not only has been explored for use in various types of surgery, cosmetics, and drug delivery, but also in bioprosthetic implants and tissue engineering of multiple organs as well. It is used as sutures, Dressings, etc.

Disadvantages

- Poor dimensional stability. Variability in drug release kinetics.
- Poor mechanical strength.

APPLICATIONS

Majorly used in ocular drug delivery system

3.2.2Albumin

- It is a major plasma protein component.
- It accounts for more than 55% of total protein in human plasma.
- It is used to design particulate drug delivery systems.

APPLICATIONS

Albumin micro-spheres are used to deliver drugs like Insulin, Sulphadiazene, 5-fluorouracil, Prednisolone etc. It is mainly used in chemotherapy, to achieve high local drug concentration for relatively longer time.

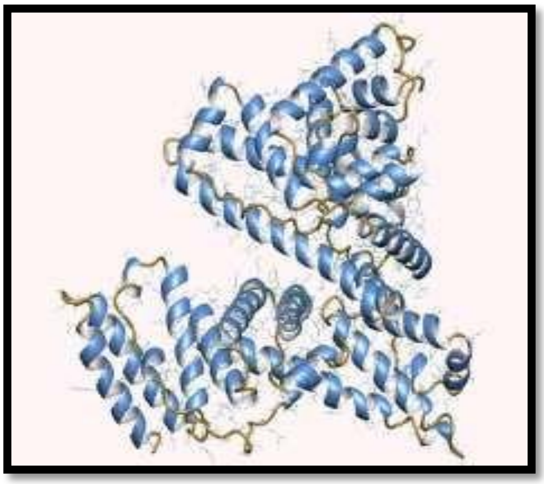


Figure 2 shows chemotherapy process

3.2.3 Dextran

Dextran is a complex branched polysaccharide made of many glucose molecules joined into chains of varying lengths. It consists of α-D-1,6-glucose-linked glucan with side-chains linked to the backbone of Polymer. Its Mol.wt ranges from 1000 to 200,000 Daltons.

APPLICATIONS

- Used for colonic delivery of drug in the form of gels.
- Replacement of Blood loss.
- Thrombosis Prophylaxis.
- Improvement of Rheology.

3.2.4 Chitosan

- It consists of β-1-4 linked 2 amino-2-deoxy gluco –pyranose moieties.
- Commercially manufactured by N-deacetylation of Chitin which is obtained from Mollusc shells.
- It is soluble only in acidic pH i.e. when amino group is protonated.
- Thereby it readily adheres to bio membranes.
- It is degraded mainly by Glycosidases & lysozymes.

ADVANTAGES

Free availability, Biocompatibility, Biodegradability, Bioadhesive, unique properties.

3.2.5 Gelatin

Gelatin is a mixture of peptides and proteins produced by partial hydrolysis of collagen, extracted from the boiled bones, connective tissues, organs and some intestines of animals. Gelatin is an irreversible hydrolyzed form of collagen. Its physicochemical properties depends on the source of collagen, extraction method and thermal degradation.

APPLICATIONS

- Employed as coating material.
- Gelatin micropellets are used for oral controlled delivery of drugs.

3.3 FACTORS AFFECTING BIODEGRADATION OF POLYMERS

a) Morphological factors

- Shape & size
- Variation of diffusion coefficient and mechanical stresses

b) Chemical factors

- Chemical structure & composition
- Presence of ionic group and configuration structure

- Molecular weight and presence of low molecular weight compounds

c)Physical factors

- Processing condition
- Sterilization process

ADVANTAGES OF BIODEGRADABLE POLYMERS

- Localized delivery of drug
- Sustained delivery of drug
- Stabilization of drug
- Decrease in dosing frequency
- Reduce side effects
- Improved patient compliance
- Controllable degradation rate

3.4 APPLICATIONS OF BIODEGRADABLE POLYMERS

1) Polymer system for gene therapy.
2) Biodegradable polymer for ocular, tissue engineering, vascular, orthopedic, skin adhesive & surgical glues.
3) Bio degradable drug system for therapeutic agents such as anti tumor, antipsychotic agent, anti-inflammatory agent.
4) Polymeric materials are used in and on soil to improve aeration, and promote plant growth and health.
5) Many biomaterials, especially heart valve replacements and blood vessels, are made of polymers like Dacron, Teflon and polyurethane.

4. Conclusion:

A rich and active area of study is using antimicrobial nanocomposites to create new biodegradable and biocompatible systems.Since antimicrobial nanocomposites are a highly biocompatible substrate, their ability to adsorb and encapsulate ions, molecules, and polymers is of paramount interest.On the other hand, antimicrobial nanocomposites can function as a secondary agent that significantly adds value features to the primary system in biodegradable and biocompatible systems.In this overview, representative research areas where antimicrobial nanocomposites are important have been summarised. First, it has been observed that biocomposites improved bone regeneration when combined with chitosan derivatives, with antimicrobial nanocomposites contributing to the improvement of the mechanical characteristics.Second, by altering the operating parameters, technologies like electrospinning show the enormous variety of biocompatible systems that are possible. Additionally, the electrospinning technology enables the control of the performance of polymeric fibres that contain bioactive and antibacterial nanocomposites.Third, any antimicrobial method that might provide long-term protection from biofilm formation is appealing and should be investigated, given the importance of the fight against biofilm formation on the surface of implanted medical devices.Antimicrobial nanocomposites, which may include both ions and molecules with antimicrobial activity, are a polyvalent substrate that can be used to coat such implants. Fourth, the importance of imaging technology in the realm of medical diagnosis cannot be overstated.Such techniques can only develop exponentially, in our opinion.When combined with biomarkers, biocompatible nanosubstrates, including antimicrobial nanocomposites, are strong options for examining the genesis and progression of illnesses.Fifth, non-viral transfecting agents based on antimicrobial nanocomposites are getting more attention due to the lack of side effects, even if gene therapy is still in the development stage.

The outcomes of intensive study to improve transfection efficiency are still encouraging but not entirely adequate.The advancement of gene therapy will significantly benefit from the investigation of molecular mechanisms relating to dissolution and transfection using antimicrobial nanocomposites. The ability to distribute medications after they have crossed biological barriers and attacked the root of the disease is expected to open up new therapeutic avenues.Since antimicrobial nanocomposites draw researchers from several disciplines, it is essential to establish a shared body of knowledge.This review adds to the multidisciplinary effort to shed light on the effectiveness of antimicrobial nanocomposites in the context of biodegradable and biocompatible systems.

References:

1.Zhang,X.: Wyss,U. P.;Pichora D. and Goosen,M. F. A.; “A mechanistic study of antibiotic release from biodegradable poly(d,1-lactide) cylinders,Journal of Controlled Release, 1994, 31 (2), 129-144,

2. LangerR. and Peppas,N. “Chemical and Physical Structure of Polymers as Carriers for Controlled Release of Bioactive Agents: A Review”, J. Macromol. Sci.-Rev. Macromol. Chem. Phys., C23, 61 (1983).

3. Sung Y. K. and Song, D. K. “Biodegradable Polymers for Biomedical Applications”, Polym. Sci. Tech.,5(6), 551 (1994).

4. Kumar, S.; Shankar,B.; Saxena, S.; Tomar, R.; Singh, M.; Sahu D. K.; and Srivastava, A. K.;“Intrinsically conducting polymer nanocomposite as the vigorous material for the health monitoring”,International Journal of Health Sciences, 2022, 6(S3), 8446.

5. Kumar,S.; Shankar, B.;Tomar, R.; Singh,M.;Sahu D. K. and Saxena,S.; “Synthesis and Optical Properties of Eu@ AcPEG Polymer”, International Journal of Mechanical Engineering, 2022, 7(5), 1087–1094.

6. Tafazoli, S.; Rafiemanzelat, F.; Hassanzadeh, F.; Rostami, M. Synthesis and characterization of novelbiodegradable water dispersed poly(ether-urethane)s and their MWCNT-AS nanocomposites functionalizedwith aspartic acid as dispersing agent. Iran. Polym. J. 2018, 27, 755–774.

7. Salehpour, S.; Jonoobi, M.; Ahmadzadeh, M.; Siracusa, V.; Rafieian, F.; Oksman, K. Biodegradation andecotoxicological impact of cellulose nanocomposites in municipal solid waste composting. Int. J. Biol. Macromol. 2018, 111, 264–270.

8. Rao, K.M.; Kumar, A.; Rao, K.S.V.K.; Haider, A.; Han, S.S. Biodegradable Tragacanth Gum Based SilverNanocomposite Hydrogels and Their Antibacterial Evaluation. J. Polym. Environ. 2018, 26, 778–788.

9. Gao, X.; Huang, L.; Wang, B.; Xu, D.; Zhong, J.; Hu, Z.; Zhang, L.; Zhou, J. Natural Materials Assembled,Biodegradable, and Transparent Paper-Based Electret Nanogenerator. ACS Appl. Mater. Interfaces 2016, 8,35587–35592.

10. Ko, J.; Nguyen, L.T.H.; Surendran, A.; Tan, B.Y.; Ng, K.W.; Leong, W.L. Human Hair Keratin for BiocompatibleFlexible and Transient Electronic Devices. ACS Appl. Mater. Interfaces 2017, 9, 43004–43012.

11. Lee, D.; Lim, Y.W.; Im, H.G.; Jeong, S.; Ji, S.; Kim, Y.H.; Choi, G.M.; Park, J.U.; Lee, J.Y.; Jin, J.; et al. BioinspiredTransparent Laminated Composite Film for Flexible Green Optoelectronics. ACS Appl. Mater. Interfaces 2017, 9, 24161–24168.

12. Song, Y.; Kim, S.; Heller, M.J. An Implantable Transparent Conductive Film with Water Resistance andUltrabendability for Electronic Devices. ACS Appl. Mater. Interfaces 2017, 9, 42302–42312.

13. Armentano, I.; Dottori, M.; Fortunati, E.; Mattioli, S.; Kenny, J.M. Biodegradable polymer matrixnanocomposites for tissue engineering: A review. Polym. Degrad. Stab. 2010, 95, 2126–2146.

14. Pinto, V.C.; Costa-Almeida, R.; Rodrigues, I.; Guardao, L.; Soares, R.; Guedes, R.M. Exploring the in vitro andin vivo compatibility of PLA, PLA/GNP and PLA/CNT-COOH biodegradable nanocomposites: Prospects

fortendon and ligament applications. J. Biomed. Mater. Res. Part A 2017, 105, 2182–2190.

15. Abd El-Kaream, S.A.; Abd Elsamie, G.H.; Abd-Alkareem, A.S. Sono-photodynamic modality for cancertreatment using biodegradable bio-conjugated sonnelux nanocomposite in tumor-bearing mice: Activatedcancer therapy using light and ultrasound. Biochem. Biophys. Res. Commun. 2018, 503, 1075–1086.

16. Li, Y.N.; Guo, Y.; Niu, W.; Chen, M.; Xue, Y.M.; Ge, J.; Ma, P.X.; Lei, B. Biodegradable Multifunctional BioactiveGlass-Based Nanocomposite Elastomers with Controlled Biomineralization Activity, Real-Time BioimagingTracking, and Decreased Inflammatory Response. ACS Appl. Mater. Interfaces 2018, 10, 17722–17731.

17. Sha, L.; Chen, Z.; Chen, Z.; Zhang, A.; Yang, Z. Polylactic Acid Based Nanocomposites: Promising Safe andBiodegradable Materials in Biomedical Field. Int. J. Polym. Sci. 2016, 2016, 1–11.

18. Feig, V.R.; Tran, H.; Bao, Z. Biodegradable polymeric materials in degradable electronic devices. ACS Cent. Sci. 2018, 4, 337–348.

19. Chivrac, F.; Pollet, E.; Averous, L. Progress in nano-biocomposites based on polysaccharides and nanoclays.Mater. Sci. Eng. R Rep. 2009, 67, 1–17.

20. Lim, L.-T.; Auras, R.; Rubino, M. Processing technologies for poly (lactic acid). Prog. Polym. Sci. 2008, 33, 820–852.

21. Reddy, M.M.; Vivekanandhan, S.; Misra, M.; Bhatia, S.K.; Mohanty, A.K. Biobased plastics andbionanocomposites: Current status and future opportunities. Prog. Polym. Sci. 2013, 38, 1653–1689.

22. Sun, J.Y.; Shen, J.J.; Chen, S.K.; Cooper, M.A.; Fu, H.B.; Wu, D.M.; Yang, Z.G. Nanofiller ReinforcedBiodegradable PLA/PHA Composites: Current Status and Future Trends. Polymers 2018, 10, 505.

23. Bettinger, C.J.; Bao, Z. Biomaterials-based organic electronic devices. Polym. Int. 2010, 59, 563–567.