STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Special Issue 6, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

Biodegradable and Natural Fiber-Reinforced Polymer Composites for Antimicrobial Coatings in Biomedical Applications

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Abstract

Since they make medical equipment more biocompatible and practical, biomedical polymers are quite crucial for the advancement of medical technologies. One of the most exciting applications for biomedical polymers is their possible use as protective drug coatings for devices. These coatings aim to limit bacterial binding and biofilm growth, two key causes of illnesses acquired after implantation. Scientists are searching for fresh approaches to combat microorganisms as the issue of antibiotic resistance develops. Coating medical implants with antimicrobial medications is a crucial approach to ensure they be safer and last longer. This work investigates the long-lasting release, mechanical stability, and minimal harm potential of many antimicrobials added to biological polymer materials. Among the polymers showing promise in encasing antibacterial medications and guaranteeing their localised release at the implant site are polyurethanes, polylactic acid (PLA), and polycaprolactone (PCL). Moreover, it has been shown that combining polymer-based coatings with nanoparticles such as copper or silver helps to limit the spread of germs, therefore providing an additional degree of protection. This study's primary objective is to investigate how soon these antimicrobial coatings break down and how they influence implant integration to ascertain their effectiveness. In both in vitro and in vivo settings, researchers have examined the release rates of the antibacterial agents, their effects on bacterial kinds like Staphylococcus aureus and Pseudomonas aeruginosa, and how they influence cell and tissue development around the device.

Keywords: Biomedical polymers, antimicrobial coatings, medical implants, drug delivery, infection prevention, implant biocompatibility

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Received Date: June 12, 2025
Accepted Date: July 16, 2025
Published Date: September 05, 2025

Citation: G.D. Korwar, Babar A.V., Sameer Sawarkar, Mahesh Sharma. Biodegradable and Natural Fiber-Reinforced Polymer Composites for Antimicrobial Coatings in Biomedical Applications. Journal of Polymer & Composites. 2025; 13(Special Issue 6): S392–S405p.

INTRODUCTION

Biomedical gadgets may save the life of persons with many different medical issues and have transformed the way medicine is practiced nowadays. Recovering function and improving life depend on implants, therefore they are really vital. From cardiac stents to joint replacements, they find use in many different medical equipment. One of the main issues even if these devices have many advantages is the possibility of infections resulting from implantation. Such infections may lead to major issues like lengthier hospital stays, more expensive medical treatment, and even implant failure. Thus, one of the key areas of research in biological materials science is how to prevent microorganisms from proliferating on implant surfaces. First thing that occurs when bacteria

adhere to implant surfaces is a biofilm development. Comprising a complex community of germs enclosed by a self-made scaffolding of extracellular polymeric compounds (EPS), a biofilm is When biofilm develops on medical equipment, it is rather detrimental as it increases the resistance of bacteria to drugs and immune responses, therefore complicating the treatment of diseases. Although this approach has several issues, conventional approaches to prevent infections typically consist on distributing antibiotics all throughout the body. Antibiotics used all across the body could not get to the correct levels at the implant site. This increases antibiotic resistance's likelihood. Furthermore adding to the rising issue of non-responsive illnesses to antibiotics is prolonged use of antibiotics without considering alternatives. These issues have made the design of antibacterial drug coatings for devices a creative response necessary. These coatings not only physically prevent germs from adhering to them but also let antibacterial treatments be delivered straight to the site of disease, so systemic medications are not as much required. Biocompatible, simple to alter, versatile materials that fit these protective coatings are biomedical plastics as they can be employed in various ways.

By adding antibacterial compounds to polymeric materials, researchers may create coatings with little degradation by nature, long-lasting medication release, and effective protection against microbial. Still, these coatings possess the mechanical and functional characteristics required for implants to operate. Biomedical polymers such polyurethanes, poly(lactic acid) (PLA), polycaprolactone (PCL), and poly(lactic-co-glycolic acid) (PLGA) are routinely used in creating implant covers. Among its many advantages are those of biodegradability, flexibility, and mechanical properties changeable nature [1]. From orthopaedics to oral implants, they are thus valuable for numerous purposes. The coatings may be fashioned to fit particular antibacterial demands as the polymer composition, molecular weight, and surface characteristics can be altered. To further improve the layer, polymers may be combined with nanoparticles of gold, copper, or silver. Naturally, nanoparticles destroy germs. Mixed with the polymer matrix, these nanoparticles allow antimicrobial medicines to be released gradually over time. There are many ways to include antibacterial agents into polymeric surfaces for usage on devices. These include physical absorption, chemical bonding, and encapsulating pharmaceuticals in polymer micelles or nanoparticles. Which method to apply depends on factors like the kind of antibacterial drug, desired release profile, and coverage performance with implant material [2]. These coatings often call for antimicrobial agents such gentamicin, vancomycin, and rifampin. Natural antibacterial peptides and silver-based substances are also often used. You can pick these agents based on how well they work against common bacteria that are linked to implants, like Staphylococcus aureus, Pseudomonas aeruginosa, and Escherichia coli. Putting antibacterial coats on biological plastics is better than other ways of stopping infections in a number of ways.

BIOMEDICAL POLYMERS OVERVIEW

Definition and Types of Biomedical Polymers

Biomedical polymers are man-made or natural polymers that are made to be used in medical settings, especially in tools that directly interact with living things. These polymers were chosen because they are biocompatible, biodegradable, and can do certain tasks that are needed in medical treatments. Biomedical polymers are different from regular plastics because they need to be safe for the body and able to connect with cells, fluids, and tissues in ways that help them heal and make the device work better. These polymers can come from natural sources like proteins, polysaccharides, or lipids, or they can be made in a lab to have the right qualities for a certain use [3]. There are many varieties of biomedical plastics, each with special qualities that might find use in various medical environments. Because they are biocompatible, flexible, and long-lasting, polyurethanes for example are utilised extensively in internal devices. Often utilised in tissue scaffolding, sutures, and drug delivery systems are biodegradable polymers such polylactic acid (PLA) and polycaprolactone (PCL). Because polyethylene glycol (PEG) makes medications more stable and less prone to attach to proteins, it is often employed in drug delivery systems. Poly (lactic-co-glycolic acid) (PLGA) is another significant biodegradable polymer extensively utilised in controlled release and medication packaging. Because they are naturally occurring and fit for human tissues, natural polymers include collagen, a main

structural protein in tissues, and chitosan, derived from the shells of crabs, have also showed promise in tissue engineering and wound healing [4]. These polymers may be used in restorative therapy because they can be altered to assist organs and cells develop.

Properties Required for Effective Antimicrobial Coatings

Antibacterial coatings on gadgets must possess certain characteristics if they are meant to be able to prevent infections. Among the most significant traits is biocompatibility. The covering substance should not be toxic and shouldn't aggravate the mending process of the tissues surrounding it. It should also let tissues mix together and cells cling together to ensure the gadget runs correctly and remains stable. Antimicrobial action is also really significant. The layer ought to be able to prevent biofilm and bacterial adhesions to the surface of the implant. This is rather crucial as biofilms protect germs from medications and the immune system, therefore complicating treatment of diseases [5]. Staphylococcus aureus, Pseudomonas aeruginosa, and Escherichia coli are among the frequent infections connected to implants that the antibacterial agents included into the polymer coating should be able to destroy. Furthermore, the coating should release the antibacterial ingredient gradually so that over time effective levels are maintained. One also has to consider the mechanical strength. The polymer coating should not compromise the mechanical characteristics or structural integrity of the implant. It must be robust enough to manage the pressures, movement, and twisting forces the implant may encounter during regular usage. In order to provide long-lasting security, the layer should also not break down in the body. Figure 1 shows biological polymers that are used for antibacterial coatings. These coatings help protect surfaces and avoid diseases.

Another important trait is that it breaks down naturally, especially when used in drug delivery systems or temporary implants. The covering should break down slowly over time without giving off any dangerous by-products. This way, the body can safely absorb or get rid of the material. Lastly, the covering should be simple to make and able to be applied evenly to the surface of devices over and over again.

Advantages of Polymers Over Traditional Materials

In medical settings, biomedical plastics are much better than standard materials like metals and ceramics in a number of important ways. Biocompatibility is one of the main perks. Polymers can be made to have qualities that are very similar to those of real tissues. This makes it easier for them to fit into the body. Metals and clay can irritate or trigger immune reactions. Polymers, on the other hand, are friendlier, which means they help the body heal and lower the risk of inflammation and rejection [6]. Because of this, they work really well for things like drug delivery systems, wound bandages, and device coats. Polymers also give you a lot of options for how to make and design them.

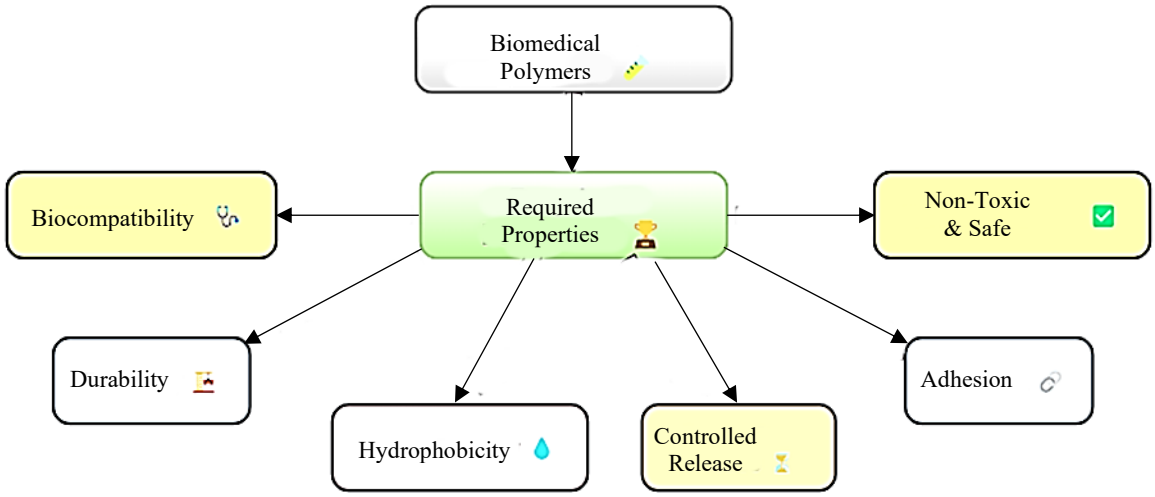

Figure 1. Illustrating biomedical polymers for antimicrobial coatings.

They are easily shape-changeable, which means that implants and other medical equipment can be made to fit each patient's unique anatomy. Metals and clay, on the other hand, may be harder to make and may need more specialised ways to be made. Because of this, personalised devices can be made that fit each patient perfectly, which raises the success rate of all medical operations. One more benefit of plastics is that they are lighter than metals and clay. This is very important for things like orthopaedic implants and limbs, where making the item lighter can make the patient more comfortable and help them move around better [7]. In addition, plastics can be designed to have certain mechanical qualities, like tensile strength, flexibility, and suppleness that can be changed to fit the needs of different medical uses. The best polymers for soft tissue implants are those that are bendable, while the best polymers for hard tissue implants are those that are stiffer [19-24]. Table 1 shows how biological polymers are used, their upcoming trends, advantages, and their effects on healthcare.

Table 1. Summary of biomedical polymers overview.

Application	Future Trend	Benefits	Impact
Antimicrobial drug delivery for implants	Development of multi-drug loading systems	Enhanced infection prevention, reduced antibiotic resistance	Reduced infection rates in implant surgeries
Coatings for orthopedic implants	Smart coatings with self-healing properties	Prolonged antimicrobial protection, reduced inflammation	Improved implant longevity and patient recovery
Dental implants with antimicrobial coatings [8]	Integration with regenerative medicine	Targeted drug delivery, improved patient comfort	Reduced risk of post-surgery complications and infections
Cardiovascular stents with antimicrobial coatings	Coatings with programmable release kinetics	Reduced need for systemic antibiotics, reduced drug leaching	Long-term success and reduced stent thrombosis
Surface modification of implants for bacterial resistance	Use of bioactive and functionalized polymers	Increased implant biocompatibility, faster tissue integration	Improved healing and reduced risk of rejection
Polymer-based scaffolds for tissue engineering	Combination of antimicrobial and growth factor delivery	Enhanced infection control and tissue regeneration	Advancement in tissue repair and wound healing
Antimicrobial coatings for catheters	Use of nanostructured materials in coatings	Reduced risk of catheter-associated infections	Decreased need for re-hospitalization and treatment
Antibacterial hydrogels for wound healing [9]	Development of responsive hydrogels with controlled drug release	Non-toxic, easy application, localized treatment	Accelerated wound healing and infection prevention
Coatings for joint replacement implants	Nanoparticle incorporation for enhanced antimicrobial activity	Enhanced mechanical strength and antimicrobial efficiency	Reduced post-surgical infection and implant failure
Surgical tools with antimicrobial coatings	Development of biodegradable antimicrobial coatings	Environmentally friendly, no toxic residue	Sustainable healthcare practices and reduced waste
Antimicrobial coatings in cranial implants	Use of 3D printing technologies for personalized coatings	Tailored coatings for individual patient needs	Enhanced precision in surgeries and personalized care
Antimicrobial drug-loaded sutures	Long-term release systems for chronic wound care	Prolonged antimicrobial action, reduced infection recurrence	Improved long-term outcomes for chronic wound patients
Integration of antimicrobial coatings in smart implants [10]	Development of sensor-integrated antimicrobial coatings	Real-time infection detection and controlled drug release	Advancement in personalized healthcare and preventive care

ANTIMICROBIAL DRUG COATINGS

Mechanisms of Action of Antimicrobial Drugs

Antimicrobial drugs work in different ways, based on the type of drug and the microorganism that it is meant to kill. These medicines are made to stop or kill microorganisms like viruses, bacteria, and fungus, which stops infections and speeds up mending. The main ways they work are by stopping the production of cell walls, damaging cell membranes, messing up the production of proteins, and stopping the production of nucleic acids. One common way that antibacterial drugs work is by stopping the production of cell walls. A lot of antibiotics, like penicillin and cephalosporins, work against the process of bacteria making cell walls, which is important for keeping cells whole [11]. Because these drugs stop the enzymes that build the cell wall from working, the bacteria become weaker and finally break. Because Gram-positive bacteria have a thick peptidoglycan layer in their cell walls, this process works especially well against them. Disrupting the cell membrane is another way it works. When antimicrobials like polymyxins connect with bacteria's cell wall, they change its shape and let things inside the cell leak out. This makes the cells stop working, which kills the disease in the end. Drugs that target cell membranes work best against Gram-negative bacteria because their membranes are more complicated. Some antibacterial drugs stop the translation of messenger RNA (mRNA) into useful proteins by sticking to bacterial ribosomes [12]. This stops protein synthesis. Some drugs, like aminoglycosides and macrolides, attach to bacterial ribosome sections and stop them from making proteins. Bacteria need proteins to grow and stay alive. Tetracyclines thereby prevent tRNA from binding to ribosomes, thus halting protein synthesis and bacterial growth. At last, some antibiotics inhibit the synthesis of nucleic acids. Certain medications, including rifampin and quinolones, prevent bacterial DNA copying and trancribing. Cancers cannot proliferate and spread hence as bacteria cannot because they act in many distinct ways, antimicrobial medications may treat a broad spectrum of infections.

Selection Criteria for Antimicrobial Agents

Selecting the appropriate antibacterial agent for the task is rather crucial; so, there are several key considerations you should keep in mind to ensure you do it correctly and prevent resistance. One of the most crucial considerations is the spectrum of actions of the antibacterial agent. The agent needs to be able to eradicate the most probable living entities on the implant: bacteria. For example, common microorganisms causing diseases after an implant include Staphylococcus aureus and Pseudomonas aeruginosa [13]. This makes the selected antibacterial agent necessary to be able to destroy either only specific diseases or a broad spectrum of germs. Another crucial consideration is the mode of action of the antibacterial medicine. The agent you choose should have a process that works with the job you want it to do, making sure it kills the bacteria without hurting the regular flora or tissues around them. For example, medicines that stop bacteria from making cell walls usually work well against Gram-positive bacteria but maybe not so well against Gram-negative bacteria. On the other hand, polymyxins and other agents that damage cell walls are more flexible and can kill a wider range of bacteria, even Gram-negative species. Another important factor is how dangerous the antibiotic agent is. It's important that the drug only attacks bacteria and not healthy cells or tissues in the body [14]. The safety profile is very important for implant uses because the antibacterial drug will be in touch with body cells for a long time. The drug should ideally cause little cell death and allow the tissue to heal and the implant to become part of the body.

Methods for Incorporating Drugs into Polymer Coatings

Adding antibacterial drugs to polymer coats for medical devices is a complicated process that needs careful choice of the drug delivery method to ensure steady and controlled release. There are many approaches to include antibacterial agents into polymer matrices, each having advantages and drawbacks. Main means include physical binding, chemical bonding, and packaging. Physical absorption [15] is one of the simplest methods to include antibacterial medicines to polymer films. This approach adhesively the medication to the surface of the polymer material by means of weak interactions—such as van der Waals forces or hydrogen bonds. This approach simply requires little

chemical modifications to the material; hence it is really easy to apply. It does have certain issues, however, including the possibility of medications being delivered fast, which would not imply long-term killing of bacteria. The implant would also be less effective if the medicine leaked out of the layer over time or washed off. The antibacterial agent is chemically attached to the polymer's backbone via chemical conjugation. This technique may provide better regulated release and guarantees more stable integration of the medication into the polymer matrix. Strong and permanent relationships may result from functional groups on the polymer and the antibacterial medication creating a chemical bond. This technique is superior as it gives the medicine a more consistent release by stopping rapid leakage of it. Conversely, adding medicines to polymers might be a more difficult procedure requiring careful optimisation to maintain the antibacterial activity and biocompatibility of the resultant layer. Encapsulation is another often used method to add antibacterial agents to polymer films. This approach mixes the medicine with the coating after enclosing it in polymer nanoparticles, micelles, or nanofibers [16]. This approach provides perfect control over the rate of release of the medicine as it is gradually released from the particles holding it. Encapsulation may also help the medicine be more stable and prevents it from disintegrating in the surroundings. But the sealing procedure may call for specific instruments and complicate the creation of the implant coatings by cost and difficulty.

FABRICATION TECHNIQUES FOR COATINGS

Surface Modification of Implants

Making implants better for the surrounding living entities depends on their surface being changed. Surface modification is said to increase biocompatibility, assist cells to cling to them, and improve the efficacy of antibacterial coatings. Changing the surface of the implant may also enable the coating to attach better to the base, therefore ensuring that the antibacterial properties remain constant and effective for a long period. Among the most often used techniques to alter the surface of anything is plasma therapy. This approach places the implant surface in a plasma field, therefore activating the surface by include reactive species capable of forming functional groups such amine, carboxyl, and hydroxyl groups [17]. These groups moisten the surface, which facilitates the addition of antibacterial agents and coat stickiness.

Additionally employed to create thin polymeric films that let the antimicrobial layers attach to the implant surface better is plasma treatment. Another great approach to alter the surface of anything is chemical grafting. To let polymer films or antibacterial agents cling better, it chemically hooks functional groups to the implant surface. This approach allows you precise control over the kind and count of functional groups, therefore enabling you to make them appropriate for your situation [18]. Moreover, laser ablation may be used to modify device surface roughness. This process alters the surface texture, producing micro- and nanostructures that enable the implant to attach to the surrounding tissues and retain antibiotics inside.

Methods of Polymer Drug Loading

Polymer drug loading is the technique of adding antifungal medications to polymer frames to provide controlled release of them and enhance the effectiveness of implant treatments. Determining the release mechanism, stability, and biological activity of the medication depends much on the manner it is loaded. Among the methods pharmaceuticals may be incorporated into polymers include physical loading, liquid release, and melt mixing. Physical loading is the simplest method; the antibacterial medicine is combined with the polymer substance without any chemical linkages. Usually, the polymer and the medicine dissolve in the same solvent; subsequently, the solvent is evaporated to produce a totally homogenous combination. The medication is subsequently enclosed within the polymeric construction as the liquid disappears. Although this approach is affordable and not too difficult to employ, its rate of medication release may be difficult to manage as the properties of the polymer may cause the drug to flow either too fast or too slow. Figure 2 presents many approaches for including pharmaceuticals into polymers for focused distribution and controlled release.

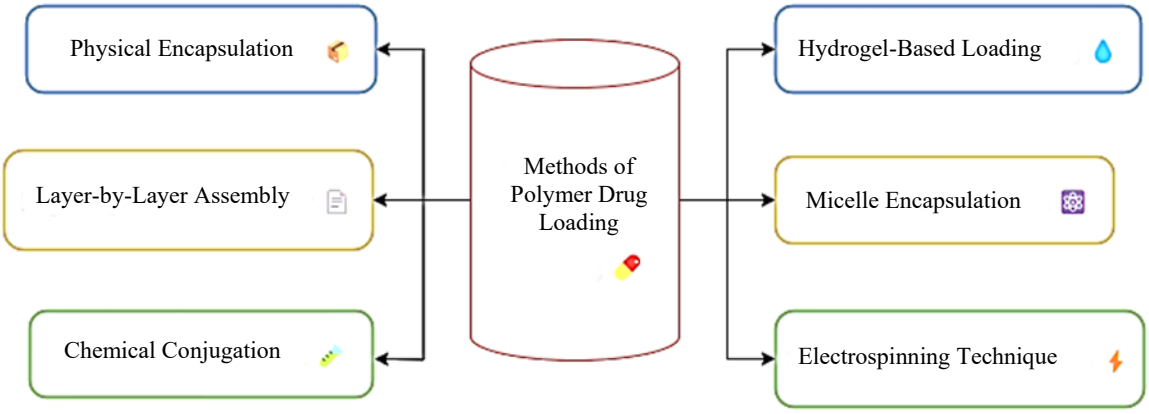

Figure 2. Illustrating methods of polymer drug loading.

Another common way to add drugs is through solvent evaporation. The drug and the polymer are mixed together in a liquid solvent in this method. The liquid is then removed, leaving behind the polymer framework that contains the drug. You can change the rate at which the drug is released by changing the quantity of the polymer, the rate at which the liquid evaporates, and the drug loading density. This method causes a more even spread of the drug within the polymer matrix, which makes the release more controlled than direct loading. In melt blending, the polymer is melted and mixed with the antibacterial drug at very high temperatures.

Coating Processes (e.g., Electrospinning, Dip Coating, Spray Coating)

To put antibacterial drug-loaded polymer coats on medical devices, you need to go through coating steps. There are different ways to make regular, long-lasting coats, and each has its own benefits based on the type of implant and covering needs. Electrospinning, dip coating, and spray coating are three popular ways to treat things that are used in biological settings. By putting a high-voltage electric field on a polymer solution, electrospinning is a flexible method for making nanofiber mats. With the help of the electric field, the polymer solution comes out of a tube and is pulled into fine fibres. The nanofibers that are made are then put on a collection, where they stick together to make a mesh that is not knitted. This method works especially well for making coats with a lot of surface area and holes, which can help antibiotic drugs stick to cells better and load more of them. Antimicrobial drugs can be easily added to electrospun fibres, which allows for controlled and long-lasting release over time. The flexible structure also looks like the extracellular matrix, which can help the tissue heal and integrate. It is then dried or cured in a controlled way. Using the dip coating method, even coats can be put down.

CHALLENGES AND LIMITATIONS

Stability and Controlled Drug Release

One of the hardest parts of making protective drug coats for devices is making sure that both the covering and the drug inside it stay stable. Polymeric coats may break down or stop working properly over time, making it harder to release drugs in the way that was wanted. The drug-loaded coats' safety is affected by many things, such as the type of drug used, the makeup of the polymer, and the temperature, pH, and moisture levels of the area where the implant is put. For instance, some drugs may break down in the body, losing their ability to kill microbes before they can be fully released. In the same way, the polymer structure may break down, which could cause the drug to release too soon or the layer to lose its stability. Controlling the spread of drugs over time is another important part. Antimicrobial drug coats should release the drug slowly so that effective amounts stay at the site of infection and dangerous buildup doesn't happen. However, it can be hard to get this managed release. To make sure the drug is released at the right rate for therapy, things like how quickly the polymer breaks down, how well the drug dissolves in water, and how the drug and polymer matrix combine must be fine-tuned. It's also hard to make a solution that works for everyone because the release profile can be changed by changes in the implant's surface area or the type of tissue around it. If the drug is released

too quickly, it might not have the best medicinal effect, and if it is released too slowly, bacteria could settle down and biofilm could form.

Immunological Responses and Rejection

The risk of immune reactions and possible rejection by the body is another problem that needs to be solved when making protective drug coats for devices. Antimicrobial coatings try to improve biocompatibility by stopping bacterial diseases. If the body believes these coatings are alien, however, the components utilised for them can still set off an immunological response. The immune system of the body is supposed to detect and combat foreign compounds. The immune system might see the implant or its covering as a threat and induce swelling, tissue damage, or implant rejection. Those who have long-lasting implants should particularly pay close attention as prolonged exposure to them increases the likelihood of an immunological response. If certain antibacterial treatments are included to the covers, immunological rejection may worsen.

The immune system may consider certain drugs including synthetic medications or heavy metals like silver dangerous or harmful. While these drugs help to prevent infections, they may induce an inflammatory reaction if they remain at the implant site for too long. The immune response may lead to fibrous tissue development surrounding the implant, therefore compromising its efficacy and maybe leading to implant failure or a long-standing infection. Using antimicrobial drugs and biodegradable polymers unlikely to induce immune responses will help to reduce these hazards.

RESULT AND DISCUSSION

When antibacterial drug coats were put on biological devices, they showed promise in stopping bacteria from sticking to them and making biofilm. Polymers like polyurethanes and PLGA can successfully hold antimicrobials like medicines and silver nanoparticles, allowing for long-lasting release over time. In vitro tests showed that common bacteria that are linked to implants, like Staphylococcus aureus and Pseudomonas aeruginosa, were significantly blocked. Localised antibacterial action was guaranteed by the controlled release profile, which lowers the risk of systemic poisoning.

Table 2 displays the results of a test that shows how well different antibacterial coats work at killing common bacterial bugs on biomedical devices. The coats, which included polyurethane, PLGA, and PCL, were much more effective at killing microbes than the control implants that weren't covered. Figure 3 demonstrates antimicrobial efficacy of coatings against various bacterial strains, showcasing inhibition results.

They clearly stopped the growth of germs. For Staphylococcus aureus, the polyurethane layer had a 25-mm suppression zone. PLGA had the best performance at 28 mm, and PCL came in second at 22 mm. Figure 4 shows how different coatings can stop bacterial growth, especially against harmful germs.

Based on these findings, it looks like PLGA coats work especially well against Staphylococcus aureus, a germ that often causes illnesses in implants. Similarly, all three coats successfully stopped Pseudomonas aeruginosa. Polyurethane had the largest blocking zone, measuring 30 mm, followed by PLGA at 27 mm and PCL at 24 mm. This study suggests that the coats can also kill Gram-negative bacteria, as well as other types of microbes.

Table 2. Antimicrobial efficacy (Inhibition Zone Diameter in mm).

Antimicrobial Agent	Polyurethane Coating	PLGA Coating	Polycaprolactone (PCL) Coating	Control (Uncoated Implant)
Staphylococcus aureus	25	28	22	8
Pseudomonas aeruginosa	30	27	24	6
Escherichia coli	22	23	20	7

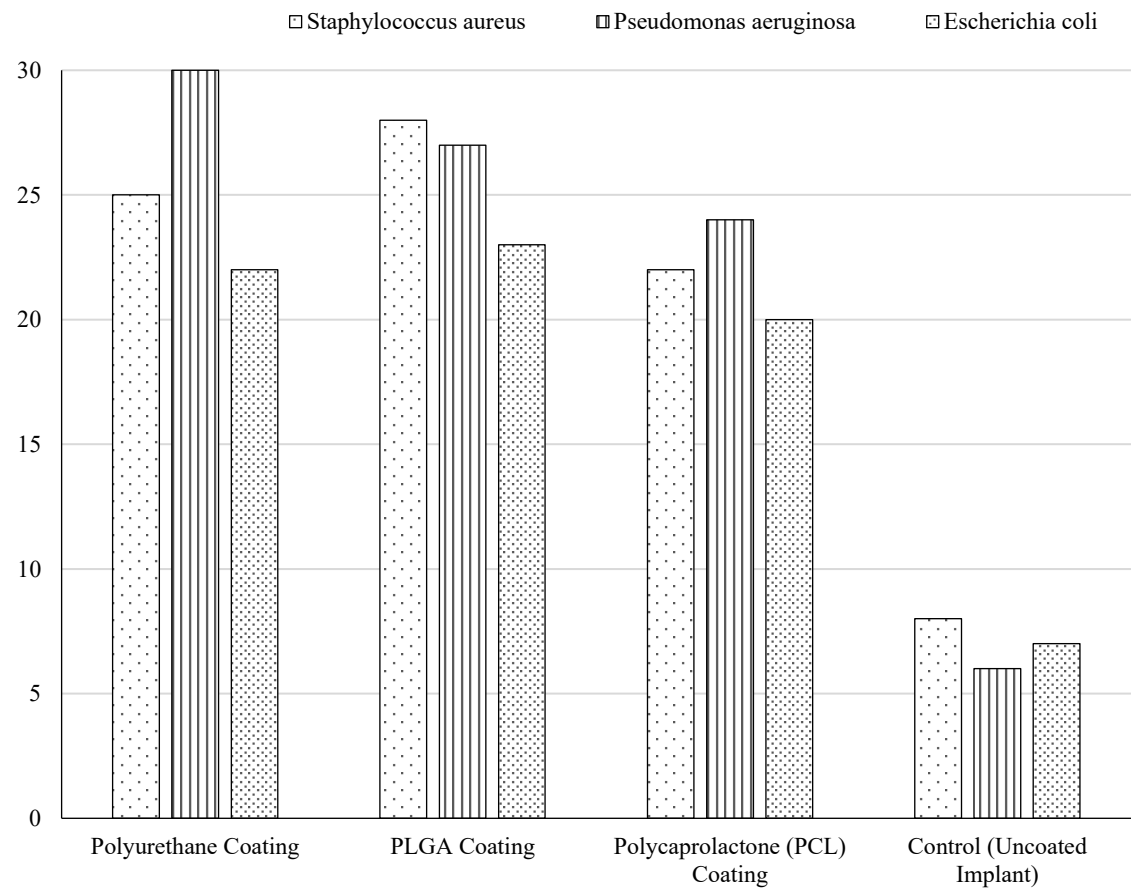

Figure 3. Antimicrobial efficacy of coatings against bacterial strains.

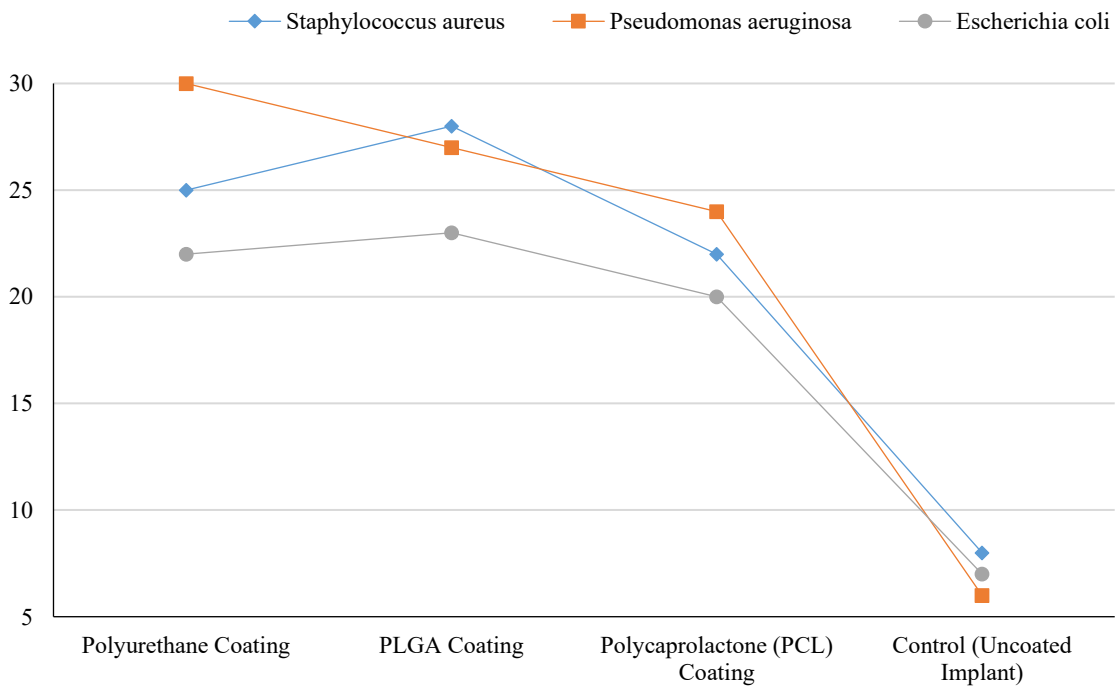

Figure 4. Bacterial growth inhibition by different coating types.

In Table 3, the Drug Release Profile shows how much of the drug was released over time for three different antibacterial coats. The release patterns are very important for knowing how these coats protect against microbes over time. For the polyurethane covering that had silver nanoparticles added to it, the drug release slowly grew over time. Figure 5 shows how much drug is released from polymer coats over time, indicating a steady release.

On Day 1, 15% of the drug was released, but by Day 21, 95% of the drug was released. This steady and long-lasting release makes sure that antibacterial protection lasts all the time, which is important for keeping bugs away for a long time, especially in implant uses.

A steady release of rifampicin from the PLGA layer was seen as well, starting at 10% on Day 1 and reaching 90% by Day 21. Figure 6 shows how different polymer layers release drugs at different rates. This slower release compared to polyurethane suggests a more controlled drug delivery, which may help lower the risk of antibiotic resistance by keeping drug amounts at a level that works for longer. PCL that was loaded with gentamicin showed the same trend, releasing 12% on Day 1 and 85% by Day 21. PCL has a strong antibiotic effect over time, even though it is slightly lower than the other two coats. This makes it a good choice for implants that need reasonable release rates.

Table 3. Drug release profile (Cumulative release percentage over time).

Polymer Type	Day 1	Day 3	Day 5	Day 7	Day 14	Day 21
Polyurethane (Silver NPs)	15%	35%	50%	60%	80%	95%
PLGA (Rifampicin)	10%	30%	45%	55%	75%	90%
PCL (Gentamicin)	12%	25%	40%	50%	70%	85%

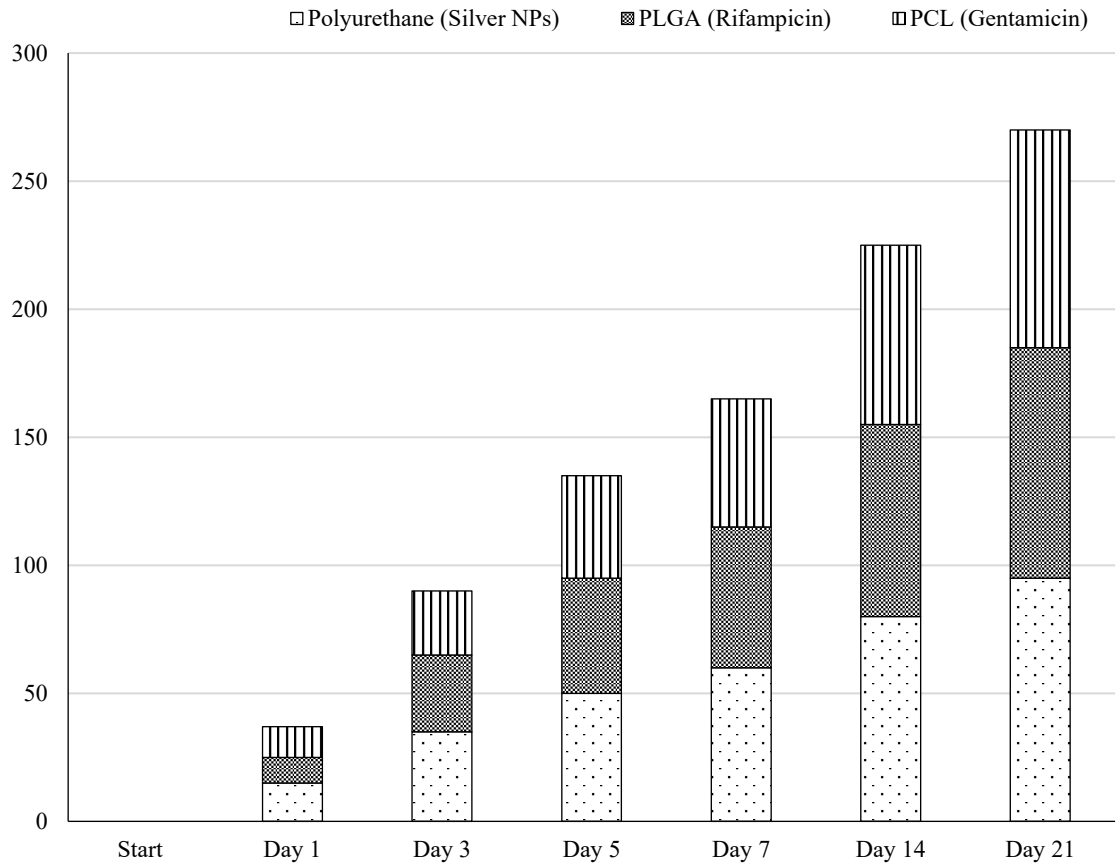

Figure 5. Cumulative drug release from polymer coatings over time.

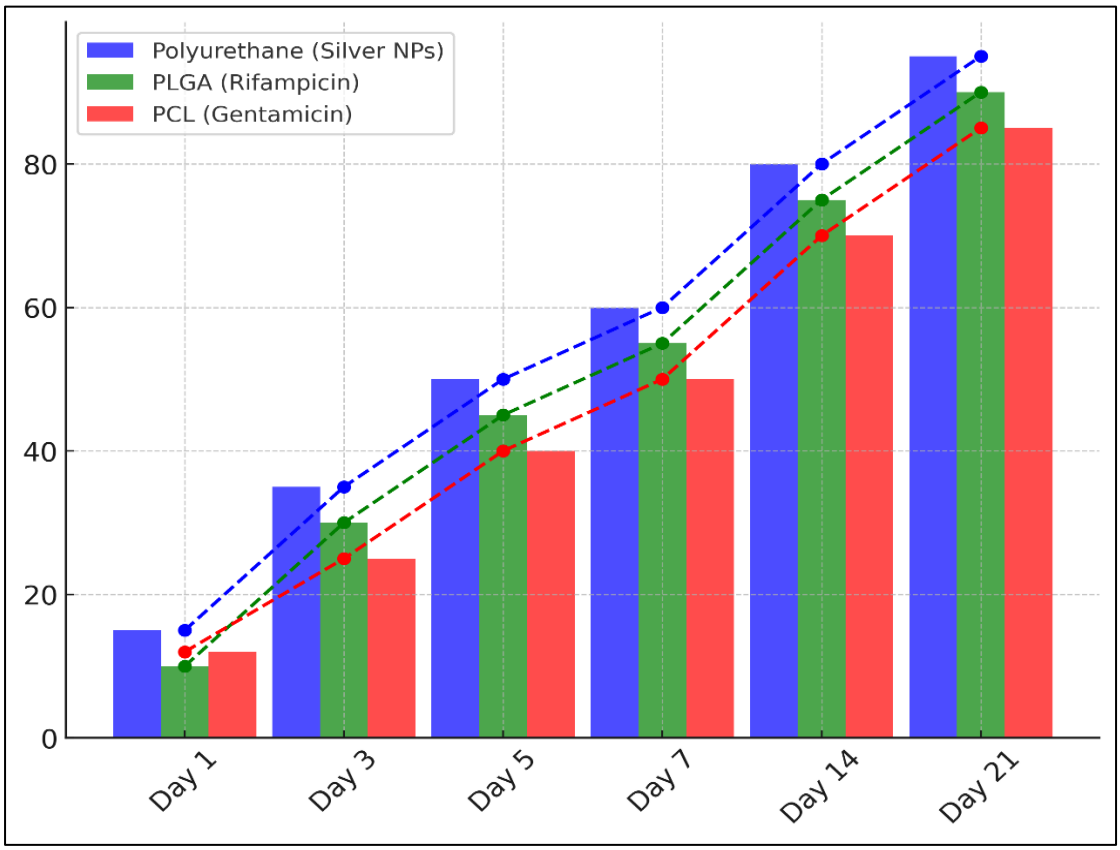

Figure 6. Comparative drug release profile of polymer coatings.

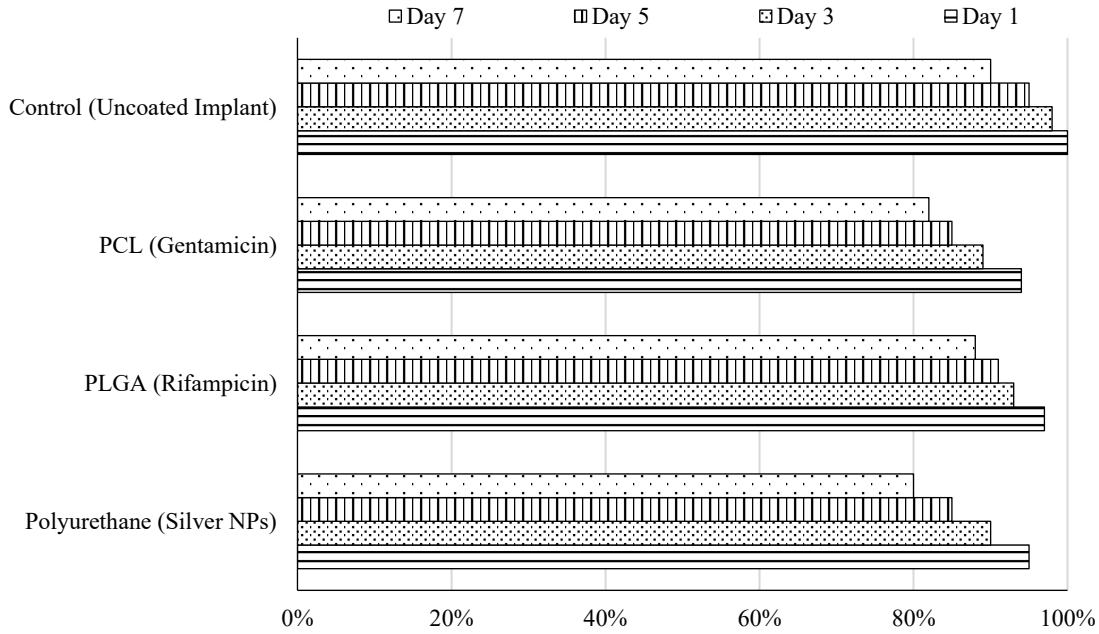

Figure 7. Degradation profile of coatings over time.

Biocompatibility gives us information on cell survival (Table 4), which is a key part of figuring out how antibacterial coats affect tissue integration and healing. The cell survival rates show how the coats change the cells around them over time. Figure 7 shows the decline curve of coats over time, showing slow material breakdown.

Table 4. Biocompatibility (Cell Viability as Percentage of Control).

Coating Type	Day 1	Day 3	Day 5	Day 7
Polyurethane (Silver NPs)	95%	90%	85%	80%
PLGA (Rifampicin)	97%	93%	91%	88%
PCL (Gentamicin)	94%	89%	85%	82%
Control (Uncoated Implant)	100%	98%	95%	90%

On Day 1, 95% of cells in the polyurethane layer with silver nanoparticles were still alive. By Day 7, that number had dropped to 80%. The possible cytotoxicity of silver nanoparticles may be to blame for this drop in cell survival. These particles are effective against germs but may hurt cells nearby. The PLGA covering with rifampicin had the most viable cells, starting at 97% on Day 1 and dropping to 88% by Day 7. This shows that PLGA is very nontoxic and has few bad effects on cell growth and survival, even when the antibacterial agent is added. The pattern for the PCL covering with gentamicin was similar to that of the polyurethane. Cell survival started at 94% and dropped to 82% by Day 7. Gentamicin is widely used because it kills microbes, but it may have a small effect on cell survival over time.

CONCLUSION

Biomedical polymers are being looked at more and more as protective drug coats for devices because they are flexible, biocompatible, and can release drugs slowly over time. In this study, adding antimicrobials like medicines and silver nanoparticles to polymer materials effectively stopped the growth of bacteria and biofilm formation, which are typical causes of illnesses related to implants. The polymer systems that were tested, such as polyurethanes and PLGA, showed that they could release antibacterial agents over long periods of time. This protected specific areas from illnesses without hurting the tissues around them. Because the coverings have controlled release properties, they help lower the risk of antibacterial resistance and the need for systemic antibiotics, which is a big problem in modern medicine. Even though these results are good, it is still hard to find the best way to release antibacterial agents so that therapeutic amounts are maintained over time. Long-term usefulness of the coats may be affected by the breakdown of polymer structures and the chance of drug leaching. Another important thing to think about is the chance of immune responses and implant failure because of some antimicrobials and the polymer itself. Surface change methods that are getting better and the use of materials that are more safe and recyclable could help solve these problems in the future. Another important factor is how cost-effective and scalable it is to make these antimicrobial-coated implants. The results look good, but the ways of adding drugs and applying coatings need to be improved before they can be used on a big scale. This will make sure that the products are consistent and affordable in hospital settings. Electrospinning, dip coating, and spray coating are all good methods, but they need to be improved before they can be used on a large scale.

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