OPEN ACCESS
Islamic Research, Pages 185 – 200, Vol. 8, No. 2, 2025
DOI: 10.47076/jkpis.v8i2.368
E-ISSN: 2654-3974
www.islamicresearch.id

ISLAMICRESEARCH
The International Journal of Islamic Civilization Studies

Review

Antibacterial-enhanced Synthetic Stainless Steel, Hydroxyapatite, and Polylactic Acid in Bioactive Screw Systems for Safe Bone Healing

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ARTICLE INFO

Keywords
Antibacterial biomaterials, Bioxcrew, Bone fractures, Osteointegration, Polylactic acid–hydroxyapatite (PLA–HA)

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Article History
Received 01 July 2025
Accepted 22 September 2025
Published online 18 October 2025

ABSTRACT

Bone fractures are rising worldwide due to aging populations and increased trauma, creating demand for implants that overcome infection, delayed healing, and poor osteointegration. Multifunctional biomaterials, especially PLA–HA Bioxcrew systems, offer integrated mechanical support with antibacterial, anti-inflammatory, and osteogenic functions while remaining biocompatible. Implant-associated infections driven by *Staphylococcus aureus* and Gram-negative bacteria persist because of biofilm formation and chronic inflammation. Bioxcrew advancements address these barriers through metal-ion doping, nanoscale surface engineering, and incorporation of antimicrobial agents into biodegradable polymer matrices, enabling controlled ion release, immune modulation, stem-cell recruitment, and improved bone regeneration. Stainless steel provides strength, hydroxyapatite enhances biological integration, and PLA enables safe degradation and localized drug delivery, making their hybridization ideal for next-generation implants. Using a narrative–integrative review of peer-reviewed literature from 2018 to 2025, this study synthesizes trends in antibacterial strategies and regenerative performance. Findings show that hybrid Bioxcrew platforms significantly reduce infection risk and enhance functional bone healing.

1. INTRODUCTION

Bone fractures remain a major global health challenge, affecting individuals across all age groups and imposing substantial burdens on healthcare systems, national economies, and community well-being (Liu et al., 2023). Multiple factors drive the rising incidence of fractures (Wang, 2020). Aging populations are more susceptible due to diminished bone mineral density and slower fracture healing, making older adults particularly vulnerable (Soysal, 2021). Exposure to high-risk environments, such as areas prone to falls or road traffic accidents, further contributes to fracture incidence, with falls being a leading cause among the elderly. The economic impact is profound: healthcare systems bear high costs for hospitalization, surgical intervention, and long-term care, while national economies are affected by lost productivity and ongoing support for dependent individuals. Fractures also significantly reduce quality of life, often leading to functional impairment, permanent institutionalization, and elevated morbidity and mortality, particularly among older adults with comorbidities (Quevedo et al., 2020). Rising global trends underscore the need for preventive strategies, including fall prevention, osteoporosis management, and integrated orthopedic-geriatric care models, to mitigate both clinical and socioeconomic burdens (Bol & Broos, 2006; Wu et al., 2021).

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Younger individuals often sustain fractures from high-energy trauma such as traffic accidents and sports injuries, whereas older adults experience fragility fractures linked to osteoporosis and decreased bone mineral density.

Hip fractures, particularly prevalent among the elderly, have profound consequences, often resulting in long-term disability, loss of independence, and elevated mortality risk (Mukherjee & Dweck, 2017). Following a hip fracture, many patients experience significant physical impairments, with only around 60% regaining pre-injury mobility, and up to 20% requiring permanent institutional care (Vestergaard, 2010). Complications such as venous thromboembolism, infections, and delirium further increase morbidity and mortality. These fractures also contribute to higher rates of depression, cardiovascular disease, and other comorbidities, compounding the individual and societal burden (Barry & Maday, 2021). As global populations age, especially in regions undergoing rapid demographic transitions, the incidence of hip fractures is projected to rise sharply, from approximately 1.26 million in 1990 to 4.5 million by 2050 (Veronese & Maggi, 2018). The economic impact is substantial, encompassing hospitalization, rehabilitation, and long-term care costs. Effective prevention and management strategies, including early surgical intervention, fall prevention, osteoporosis treatment, and targeted public health programs, are essential to reduce the clinical, functional, and socioeconomic burden of hip fractures worldwide (Bryan, 2010). The burden of fractures extends beyond direct health implications. Millions of people worldwide live with long-term physical limitations due to fracture-related conditions. The economic consequences include substantial medical expenditures for surgical procedures, hospitalization, rehabilitation, and long-term care. Indirect costs, such as reduced workforce participation, productivity losses, and caregiver strain, further amplify the societal impact (Kao et al., 2025). Despite the magnitude of the problem, many individuals remain under-treated or inadequately managed, especially those at high risk of recurrent fractures. Gaps in secondary prevention, such as fall-prevention programs, dietary optimization, physical activity interventions, and bone-health monitoring, contribute to persistent cycles of injury, disability, and escalating healthcare demands (Radosavljevic et al., 2014).

Traditional fracture management relies heavily on metallic fixation devices, including plates, screws, and rods, due to their high strength, stiffness, and reliable mechanical stability (Hayes & Richards, 2010). However, these implants have notable limitations. Their higher stiffness compared to bone can cause stress shielding, reducing load transfer to surrounding tissue and potentially compromising bone healing (Yang et al., 2025). Metallic implants may also exhibit suboptimal osteointegration, limiting their ability to promote natural bone regeneration (Al-Tamimi et al., 2020). Long-term implantation carries risks of corrosion and metal ion leaching, which can lead to local or systemic toxicity. Additionally, metallic surfaces are susceptible to bacterial colonization, resulting in postoperative infections that may require revision surgery, further increasing patient risk and healthcare costs (Prasad et al., 2024). To overcome these challenges, emerging alternatives include polymeric composites such as PLA and PCL, which can be combined with bioactive substances like hydroxyapatite to enhance osteogenic support (Li et al., 2020). Bioabsorbable implants, bone adhesives, and hybrid implants with bioactive or porous structures are also being developed to reduce stress shielding, promote integration, and eliminate the need for secondary surgeries, offering promising directions for future fracture management (Huang et al., 2020; Huang et al., 2021).

Advances in biomaterials research have enabled the development of bioscrews composed of polylactic acid (PLA) and hydroxyapatite (HA), offering a promising alternative to traditional metal-based fixation devices. These composites combine structural integrity with biological functionality while addressing limitations of metallic implants (Prasad et al., 2023). PLA is a biodegradable polymer that gradually metabolizes into lactic acid, eliminating the need for hardware removal and reducing long-term complications. Incorporating HA, a major component of natural bone, enhances mechanical strength, biocompatibility, and osteoinductive properties, promoting better cell adhesion, proliferation, and differentiation for effective bone healing (Kim et al., 2020). PLA/HA composites also have an elastic modulus closer to native bone, reducing stress shielding and supporting natural remodeling. Challenges include optimizing HA content to balance bioactivity with mechanical performance and controlling degradation rates to match healing. Advanced manufacturing techniques, such as 3D printing and microinjection molding, allow precise tailoring of composite architecture and properties (Elrefaei et al., 2025; Prasad et al., 2017). PLA is a biodegradable polymer that gradually breaks down into lactic acid, which the body naturally metabolizes (Backes et al., 2021). This eliminates the need for hardware removal, reducing both patient discomfort and healthcare expenditures. HA, a mineral found abundantly in natural bone, enhances the integration of the implant with surrounding tissue. Its osteoconductive properties provide a favorable environment for new bone formation, ensuring more harmonious healing (Xia et al., 2022).

Recent advancements have transformed PLA–HA (polylactic acid–hydroxyapatite) bioscrews from purely structural devices into multifunctional therapeutic platforms . By incorporating antimicrobial agents, such as silver

nanoparticles or embedded antibiotics, these implants can deliver localized antibacterial activity, effectively reducing the risk of surgical site infections, including those caused by multidrug-resistant bacteria (Bee et al., 2021; Kumar et al., 2025; Piecuch et al., 2023). Anti-inflammatory compounds, including phytochemicals like curcumin or magnesium particles, help minimize postoperative swelling and promote tissue regeneration (Ebenezer et al., 2025; Wang et al., 2022). Furthermore, bioactive molecules such as growth factors and hydroxyapatite nanoparticles enhance osteointegration, accelerate healing, and stimulate angiogenesis (Lee et al., 2024). Additional multifunctional coatings, like bioactive glasses, provide controlled release of therapeutic ions, further supporting bone regeneration and inhibiting bacterial colonization (Bodylska et al., 2024; Galarraga-Vinueza et al., 2017). These innovations enable PLA–HA bioscrews to combine mechanical support with targeted antimicrobial, anti-inflammatory, and regenerative functions, representing a significant advancement in orthopedic biomaterials and offering improved outcomes for fracture healing (Mondal et al., 2023). Furthermore, bioactive molecules such as growth factors can be integrated to stimulate osteogenic processes, accelerating the rate and quality of bone regeneration (Hsu et al., 2025). These advances represent a transformative approach to orthopedic biomaterials, enabling implants to actively participate in the healing process rather than serving merely as passive mechanical supports (Vinod Kumar et al., 2024).

Integrating advancements in orthopedic biomaterials with Islamic ethical principles provides a holistic framework for evaluating biomedical innovation (Vaishya & Ghosh, 2025). Islamic bioethics, grounded in the maqāṣid al-sharī'ah (*higher objectives of Islamic law*), emphasizes the preservation of life (*ḥifẓ al-nafs*), prevention of harm (*daf' al-ḍarar*), and pursuit of public benefit (*jalb al-maṣlaḥah*) (Ibrahim et al., 2019). In this context, biocompatible and biodegradable implants support life preservation by enhancing recovery and quality of life, while innovations such as nanobiomaterials and bioactive coatings minimize harm through improved osteointegration and reduced postoperative complications (Alias et al., 2024; Xia et al., 2025). Moreover, patient-specific implants and multifunctional materials promote public benefit by improving surgical outcomes and reducing healthcare burdens (Baharuddin et al., 2016). Islamic bioethics also encourages sustainability, rigorous safety testing, and equitable access to medical technologies (Christenson et al., 2007). By aligning orthopedic innovations with these principles, biomedical advances can achieve both clinical efficacy and ethical integrity, fostering patient-centered care and societal well-being (Mahmud et al., 2023). These principles form the ethical backbone upon which contemporary medical technologies, such as antibacterial-enhanced Bioxcrew systems can be evaluated (Erzen et al., 2025). When biomedical innovations reduce infection, enhance healing, prevent disability, and improve overall patient well-being, they directly align with these overarching goals (Misir, 2025).

The principle of preserving life (ḥifẓ al-nafs) is central to Islamic law. The Qur'an declares:

﴿وَمَ ٥ن أ ٥حيَاهَا فَكَأَنَّمَا أ ٥حيَا ٱلنَّاسَ جَيِعًا﴾

"Whoever saves one life, it is as though he saved all of humanity." (Al-Mā'idah 5:32)

Biomedical implants designed to reduce mortality from postoperative infection, accelerate fracture healing, and restore mobility embody this Qur'anic mandate. When multifunctional biomaterials—such as PLA–HA Bioxcrews with antibacterial enhancements—help prevent fatal complications like sepsis, they become instruments of life preservation. Thus, using or developing such technologies falls not merely within the permissible realm but within the commendable acts encouraged by the shariah.

Islamic ethics also emphasizes the prevention of harm (lā ḍarar wa lā ḍirār), a maxim derived from a well-established hadith of the Prophet ﷺ:

« لَ ضَرَرَ وَلَ ضِرَارَ »

"There should be neither harm nor reciprocating harm."

This principle supports innovations that minimize risks associated with traditional implants, such as infection, implant failure, or the need for secondary surgeries. Antibacterial Bioxcrew systems, through controlled release of antimicrobial agents, surface modifications, and biofilm-preventing technologies, directly address these harms. Their ability to degrade safely inside the body without requiring hardware removal fulfills the Islamic imperative of avoiding unnecessary procedures that may expose patients to additional danger or prolonged suffering.

Closely related is the Islamic obligation to pursue public benefit (maṣlaḥah). The Shariah fundamentally seeks what is beneficial for individuals and communities. Allah says:

﴿يُرِيدُ ٱللَّ بِكُمُ ال ٥يُ ٥سَ وَلَ يُرِيدُ بِكُمُ ال ٥عُ ٥سَ﴾

"Allah intends ease for you and does not intend hardship." (Al-Baqarah 2:185)

Modern biomaterials that shorten recovery time, reduce disability, and decrease the economic burden on families and healthcare systems clearly promote societal welfare. Reducing hospital stays, avoiding costly revision surgeries, and enhancing long-term outcomes are all ways to ease hardship—both medical and financial. These outcomes resonate with the maqāṣid framework, which views public benefit as a legitimate basis for adopting new technologies when they do not contradict foundational Islamic principles.

Islam further encourages seeking treatment and medical innovation as part of responsible stewardship over the human body, which is considered an amanah (trust) from Allah. The Prophet ﷺ said:

« تَدَاوَ ºوا عِبَادَ اللّٰهِ، فَإِنَّ اللّٰهَ لَ ºمْ يَضَ ºعْ دَاءً إِلَّا وَضَعَ لَهُ دَوَاءً »

"Seek treatment, O servants of Allah, for Allah has not created a disease except that He created its cure."

This hadith not only legitimizes medical intervention but also encourages scientific research and discovery. Developing antibacterial biomaterials that address infections—one of the most dangerous complications of orthopedic surgery—is a direct manifestation of the quest for these cures. Innovating materials that integrate osteogenic, antimicrobial, and anti-inflammatory properties reflects the human effort to uncover the cures Allah has placed in His creation.

Another principle relevant to biomedical innovation is easing human suffering. The Prophet ﷺ stated:

« مَ ºنْ نَفَّسَ عَ ºنْ مُ ºؤْمِنٍ كُ ºرْبَةً مِ ºنْ كُرَبِ الدُّنْ ºيَا نَفَّسَ اللّٰهُ عَنْ ºهُ كُ ºرْبَةً مِ ºنْ كُرَبِ يَ ºوْمِ الْ ºقِيَامَةِ »

"Whoever relieves a believer from hardship, Allah will relieve him from a hardship on the Day of Resurrection."

Reducing the burden of postoperative complications, chronic infection, or prolonged immobility is a direct form of relieving suffering. Biomaterials that promote faster healing and reduce pain, thus contribute to fulfilling this prophetic encouragement. Scientists, engineers, and clinicians involved in developing such technologies also participate in this virtuous endeavor.

Moreover, the Islamic legal principle *"al-mashaqqah tajlib al-taysīr"* (hardship brings facilitation) supports biomedical innovations that reduce the burden on patients. Traditional metallic implants often require removal surgeries, which can impose new physical, emotional, and financial hardships. By contrast, biodegradable implants like PLA–HA Bioxcrews, especially those enhanced with antibacterial properties, naturally dissolve, eliminating the need for secondary operations (Tejhashwini et al., 2024). This aligns with the Islamic directive that legal and ethical solutions should minimize hardship whenever possible.

Finally, Islamic ethics requires avoiding materials or methods prohibited in shariah, unless there is necessity (*ḍarūrah*) and no permissible alternatives. In the context of antibacterial biomaterials, if metal ion doping, polymer composites, and antimicrobial agents are derived from materials that do not involve prohibited substances, their usage becomes straightforwardly permissible. Even if specific components required Islamic scrutiny, the principle of necessity, based on the Qur'anic verse:

﴿ فَمَنِ ا ºضْطُرَّ غَ ºيْرَ بَاغٍ وَلَا عَادٍ فَلَا إِثْ ºمَ عَلَيْ ºهِ ﴾

"If one is compelled by necessity, without willful disobedience or transgression, there is no sin upon him." (Al-Baqarah 2:173)

would allow their use when essential for life-saving or critical healing purposes, provided they are regulated and justified by medical experts.

Another essential consideration is the purity and lawful origin (*ṭahārah and ḥalāl*) of the materials used in medical devices, especially those intended for use inside the human body. Hydroxyapatite may be derived from bovine or marine sources, raising potential concerns for Muslim patients if the origin is unclear or not compliant with Islamic guidelines. Prioritizing synthetic or non-animal-derived HA supports both scientific standardization and religious acceptability (Tejhashwini et al., 2024). Similarly, transparency regarding the sourcing of antimicrobial agents and polymer components respects patients' moral and spiritual integrity and strengthens trust in biomedical innovations. Ensuring that materials are biocompatible, ethically sourced, and free from contaminants fulfills Islamic ethical expectations regarding bodily sanctity.

Islamic ethics also emphasize justice, accessibility, and societal welfare. Fracture-related disabilities disproportionately affect vulnerable populations, including older people and individuals with limited economic resources. Technologies such as antibacterial Bioxcrews that reduce complications, minimize hospital stays, and improve rehabilitation outcomes promote social welfare and reduce the burden on healthcare systems. Aligning biomedical progress with principles of equity and compassion reflects the Islamic vision of medicine as a means of serving humanity (Darjee et al., 2025).

In light of the rising incidence of fractures, the persistent challenges associated with traditional fixation devices, and the growing demand for safe and effective biomaterials, this review examines recent developments in antibacterial-enhanced Bioxcrew systems. The discussion covers the nature of postoperative infections, the importance of antibacterial functionality, the mechanisms that confer antimicrobial effects, and the comparative advantages of different biomaterial components. By integrating scientific advancements with ethical considerations rooted in Islamic principles, this review aims to contribute to the development of biomaterials that are not only effective and innovative but also ethically grounded and socially responsive.

2. RESEARCH METHODS

This study employs a narrative–integrative review approach designed to synthesize recent scientific developments in antibacterial-enhanced biomaterials, Bioxcrew systems, bone-regeneration technologies, and postoperative orthopedic infections, while embedding the discussion within the ethical principles of Islamic bioethics (Deccó & Zuchuat, 2016). To achieve this, an extensive literature search was conducted across major scientific databases, including PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar, focusing on publications from 2018 to 2025 to reflect up-to-date findings. Foundational studies published earlier were included when they contributed essential mechanistic insights into bone healing or biomaterial behavior. The search utilized combinations of keywords such as *"orthopedic implant infection," "bioscrew," "Bioxcrew," "hydroxyapatite antibacterial," "PLA composite," "metal-ion doping," "surface modification," "plasma treatment,"* and *"Islamic bioethics."* Only peer-reviewed articles, high-quality reviews, and relevant conference papers were selected, while non-peer-reviewed sources and preprints were excluded to ensure scientific accuracy.

All retrieved articles underwent a two-stage screening process. During title and abstract screening, studies were included if they discussed antibacterial biomaterials for orthopedic or dental applications, mechanisms of antibacterial enhancement such as metal-ion release or polymer–metal interactions, orthopedic infection epidemiology, or relevant regenerative mechanisms associated with PLA–HA hybrid systems (Lin et al., 2017). Full-text screening further refined the dataset to include only articles with empirical or mechanistic evidence of antibacterial effects, biofilm inhibition, polymeric drug-delivery capabilities, ion-doping strategies, surface engineering techniques, osseointegration performance, or clinically relevant data on bone infection risk and healing outcomes. Studies limited to non-orthopedic applications, lacking an antibacterial focus, or providing insufficient scientific detail were excluded.

The extracted data were synthesized using a thematic approach. Recurring scientific themes, such as the epidemiology of implant-associated infections, antibacterial mechanisms of modified biomaterials, osteoinductive behavior of PLA–HA composites, mesenchymal stem-cell recruitment, inflammatory modulation, and comparative evaluation of stainless steel, hydroxyapatite, and PLA, were identified and analyzed collectively. These themes were then used to construct an integrated understanding of how antibacterial enhancement strategies intersect with structural, biological, and regenerative requirements of orthopedic implants. Specific attention was given to analyses of ion-doped materials (silver, copper, zinc), surface topography engineering, plasma treatments, nanotextured surfaces, and controlled-release polymer matrices, and to their impact on both bacterial inhibition and bone tissue regeneration. This synthesis enabled a multifaceted evaluation of hybrid Bioxcrew concepts as next-generation orthopedic solutions (Huang et al., 2020).

Although the narrative–integrative approach allows for deep, qualitative synthesis across fields, it carries inherent limitations. The methodology depends on published literature, which may omit negative results or long-term safety data for new biomaterials. Narrative interpretation lacks the quantitative rigor of meta-analysis, and the rapidly evolving nature of biomaterial science means that some experimental findings may not yet be validated in long-term clinical settings. Additionally, interpretations of Islamic ethical principles may vary among different schools of jurisprudence, though the central objectives of maqāṣid al-sharīʿah remain consistent across traditions (Ibrahim et al., 2019). Despite these limitations, the method provides a robust and comprehensive foundation for evaluating

antibacterial-enhanced Bioxcrew systems and their alignment with contemporary scientific challenges and Islamic bioethical imperatives.

3. RESULTS AND DISCUSSION

3.1 Postoperative Infections and the Need for Antibacterial-Enhanced Materials

Postoperative orthopedic infections, particularly those associated with implantable devices such as bioscrews, remain one of the most persistent and costly complications in musculoskeletal surgery (Ling et al., 2025). These infections can severely disrupt the healing cascade, trigger chronic osteomyelitis, increase morbidity, and necessitate implant removal or revision surgery (Boyle & Duquin, 2018). The pathophysiology of implant-related infections is primarily driven by rapid bacterial adhesion to biomaterial surfaces and subsequent biofilm formation, which protects pathogens from host immunity and systemic antibiotics. Because biofilms can become resistant to antibiotic concentrations far beyond clinically safe levels, preventing bacterial colonization at the implant–tissue interface has become a central focus of orthopedic biomaterials research (Lin et al., 2017). Developing implants with inherent or engineered antibacterial properties significantly improves healing outcomes, reduces hospitalizations, minimizes the risk of repeated surgical interventions, and helps combat the rise of antimicrobial resistance by reducing dependence on systemic antibiotics.

Advances in biomaterials science have expanded the options available for antibacterial enhancement, with hydroxyapatite (HA), polylactic acid (PLA), stainless steel, and engineered polymer composites demonstrating promising results (Atesok et al., 2020). HA, a key mineral component of bone, is widely used for its biocompatibility and osteoconductive properties. Modern approaches involve doping HA with antibacterial metal ions such as silver, copper, zinc, or magnesium (Huang et al., 2020). These ions disrupt bacterial cell membranes, interfere with metabolic pathways, and inhibit biofilm maturation, all while maintaining levels that remain safe for surrounding osteogenic cells. Precision engineering has enabled controlled ion release profiles, providing long-term antibacterial protection without compromising bone regeneration or mechanical stability.

PLA has also gained attention as a biodegradable platform capable of delivering localized antibacterial therapy (Xia et al., 2022). In contemporary designs, PLA-based screws and scaffolds are infused with bioactive agents such as magnesium particles, tricalcium phosphate, antimicrobial peptides, or encapsulated antibiotics (Wang et al., 2022). These agents are released gradually as the polymer degrades, providing sustained antimicrobial action exactly where needed. The ability to combine PLA with osteoinductive fillers enhances not only infection resistance but also bone regeneration, making PLA–HA hybrids a leading candidate for next-generation bioscrews. Moreover, the degradability of PLA eliminates the need for secondary surgical removal, which further reduces patient risk (Emadian et al., 2017).

Stainless steel, valued for its mechanical strength and affordability, is now being optimized with surface-engineered antibacterial coatings. Advances in plasma treatment, sol-gel techniques, and nanoscale surface modifications allow stainless steel implants to be coated intraoperatively or during manufacturing with antimicrobial layers such as silver nanoparticles, quaternary ammonium compounds, zinc–polymer hybrids, or hydrophilic nanofilms. These coatings inhibit initial bacterial adhesion, modify surface energy, and can be tailored to remain stable throughout the early postoperative period, the window when infection risk is highest (Hatz et al., 2016). Notably, these surface modifications can be applied without disrupting existing manufacturing protocols or regulatory standards, enabling realistic clinical translation.

In parallel, natural and synthetic polymers are being developed for antimicrobial delivery and tissue integration. Chitosan, hyaluronic acid, poly(ethylene imine), and poly(methyl methacrylate) are being engineered to respond to environmental signals such as pH changes, enzymatic activity, or oxidative stress (Yang et al., 2025). These “smart” polymers release antibacterial molecules only when infection risk is detected, optimizing therapeutic efficiency and preventing unnecessary drug exposure. In addition to antimicrobial functions, many of these polymers enhance osteogenesis and angiogenesis by supporting stem-cell attachment, modulating inflammatory pathways, and improving integration at the bone–implant interface.

Collectively, these innovations illustrate a shift toward multifunctional orthopedic implants that provide mechanical stability while simultaneously preventing bacterial invasion and promoting bone regeneration (Deccó & Zuchuat, 2016). The integration of bioactive materials, responsive polymers, and advanced surface engineering represents a significant leap toward safer, more effective fracture fixation systems.

3.2 Epidemiology of Orthopedic Infections

Understanding the epidemiological burden of orthopedic infections is essential for advancing antibacterial biomaterials that can meaningfully improve clinical outcomes. Orthopedic surgical site infections (SSIs) continue to represent a significant global health concern, with incidence rates varying widely depending on the type of procedure, fracture classification, perioperative practices, and healthcare infrastructure. In technologically advanced healthcare systems, SSIs after orthopedic operations generally fall within a low percentage range, yet these values increase substantially in resource-limited regions where aseptic facilities, surveillance protocols, and access to prophylactic antibiotics may be inconsistent. Even within high-performing hospitals, closed fracture surgeries can show infection rates of several percent, and reports from the past decade indicate that infection-related readmissions remain a persistent challenge (Erivan et al., 2024). Such variability underscores the complexity of maintaining infection control and the necessity for antimicrobial implant strategies that operate directly at the biomaterial–tissue interface.

The epidemiological burden becomes even more pronounced in procedures involving prosthetic joints and trauma-related fixation. Prosthetic joint infections, although relatively infrequent after primary hip or knee replacement, carry substantial long-term implications and occur far more often in revision surgeries where prior implants have failed or surrounding tissues have been compromised. Similarly, open reduction and internal fixation (ORIF) procedures involving high-energy trauma exhibit sharply elevated infection rates due to tissue devitalization, contamination at injury, and prolonged surgical manipulation. In some severe open fracture patterns, infection rates can escalate to alarming levels, particularly where the soft tissue envelope has been severely disrupted. Across these contexts, the leading pathogens remain remarkably consistent: Staphylococcus aureus, including methicillin-resistant strains; coagulase-negative staphylococci associated with biofilm formation; and a range of Gram-negative bacteria, such as Pseudomonas aeruginosa and members of the Enterobacterales family. These organisms are highly adept at colonizing foreign surfaces and forming biofilms rapidly, making them particularly difficult to eradicate once established.

The socioeconomic burden of orthopedic infections underscores the urgency of developing improved antibacterial biomaterials. These infections consistently lead to extended hospital stays, heightened need for revision surgeries, increased antibiotic usage, and greater long-term rehabilitation requirements. Hospitalizations may be prolonged by several weeks, and postoperative mortality, although generally low, remains a notable concern in vulnerable populations. The cumulative financial impact on healthcare systems continues to rise, driven by aging populations, the growing prevalence of comorbidities, and the increasing number of orthopedic procedures performed worldwide. These realities highlight the clinical and economic necessity of implants that can resist bacterial attachment and interrupt biofilm formation at the earliest stages.

In response to this burden, modern biomaterial engineering has shifted toward enhancing antibacterial performance across multiple classes of orthopedic implant materials (Lin et al., 2017). Stainless steel, widely used for its mechanical durability, naturally forms a passive chromium oxide layer but exhibits significantly improved antibacterial properties when surface-modified with silver nanoparticle coatings, plasma-based treatments, or nanoscale texturing. These modifications disrupt bacterial adhesion while maintaining structural integrity. Hydroxyapatite (HA), although highly favored for its osteoconductive and bioactive properties, benefits greatly from functionalization. Metal-ion doping with silver, copper, zinc, or magnesium introduces vigorous antibacterial activity without compromising cytocompatibility (Wang et al., 2022). Emerging composite approaches incorporating natural bioactive molecules further enhance HA's capacity to inhibit pathogenic microorganisms.

Polylactic acid (PLA), a biodegradable polymer widely used in resorbable orthopedic devices, naturally generates a mildly acidic microenvironment upon degradation, which can discourage some bacterial species. However, its antibacterial performance is significantly enhanced by incorporating agents such as silver nanoparticles, chitosan, or carbon-based nanomaterials. These composite PLA scaffolds have demonstrated exceptionally high inhibition levels against common orthopedic pathogens and simultaneously promote tissue regeneration. Because PLA resorbs naturally in the body, such modifications make it highly suitable for resorbable screws and drug-delivery platforms that eliminate the need for secondary removal surgeries.

Taken together, stainless steel remains optimal for high-load applications, HA is best suited for surface coatings and bone-interfacing regions requiring bioactivity, and PLA excels in degradable systems and localized antimicrobial delivery. Across all material groups, the integration of silver nanoparticles, antibacterial ions, and bioactive additives has emerged as a versatile and highly effective strategy for reducing infection risk and enhancing the overall performance of orthopedic implants.

3.3 Importance of Antibacterial Properties in Bone Healing

Antibacterial properties in bone-healing technologies hold significant importance not only from a biomedical perspective but also within the framework of Islamic ethical evaluation (Fu et al., 2008). Infection is one of the most critical obstacles to bone regeneration, as postoperative pathogens such as *Staphylococcus aureus* (including MRSA), *Escherichia coli*, and *Pseudomonas aeruginosa* can rapidly colonize implant surfaces, initiate biofilm formation, and complicate healing (Lewandowski, 2025). These clinical risks underscore the need for antipathogenic biomaterials that maintain sterility at the implant interface, reduce reliance on prolonged systemic antibiotics, and improve osseointegration. From an Islamic bioethical standpoint, such innovations fall under the objectives of *maqāṣid al-sharī'ah*, particularly *ḥifẓ al-nafs* (preservation of life) and the prevention of harm. The Prophet ﷺ emphasized the principle of avoiding damage, as expressed in the foundational hadith:

«لَ ضَرَرَ وَلَ ضِرَارَ»

"There should be neither harm nor reciprocating harm," narrated by Ibn Mājah and others.

Technologies that reduce the incidence of osteomyelitis, implant loosening, and surgical failure, therefore, align directly with the Islamic imperative to remove harm and facilitate healing.

The integration of antibacterial mechanisms, whether through ionic doping of hydroxyapatite with Ag, Cu, or Zn ions, or through polymer–ceramic composites engineered for localized drug delivery, serves to both protect patients and enhance regenerative outcomes. These developments resonate with the Qur'anic directive:

﴿وَلَ تَ ۡقتُلُوا أَن ۡفُسَكُ ۡم إِنَّ ٱللَّ كَنَ بِكُ ۡم رَحِيمًا﴾ (al-Nisā' 4:29),

Which scholars interpret as an injunction against exposing oneself to unnecessary harm or risk. By minimizing postoperative infection, these materials fulfill the Islamic ethical value of *maṣlaḥah* (public benefit), as they help shorten recovery time, reduce medical burdens, and improve overall patient well-being. Furthermore, the Qur'an enjoins believers to proactively seek means of healing, as reflected in the verse:

﴿فِيهِ شِفَا ء لِلنَّاسِ﴾ (al-Naḥl 16:69)

Traditionally understood as a general affirmation that Allah provides avenues of cure through natural and human-developed means. Thus, antibacterial biomaterials that enable safer and more reliable bone regeneration can be regarded as part of the legitimate pursuit of therapeutic solutions encouraged in Islamic ethics.

At the same time, Islamic jurisprudence also stresses balance and responsibility, principles reflected in the material design challenge of ensuring antimicrobial efficacy without compromising biocompatibility. Excessive ion release or cytotoxic responses would contradict the ethical requirement to prevent additional harm. This aligns with the Qur'anic guidance:

﴿وَلَ تُل ۡقُوا بِأَي ۡدِيكُ ۡم إِلَ ٱلَت ۡهلُكَةِ﴾(al-Baqarah 2:195)

This prohibits self-destructive or negligent actions. Therefore, the development of biomaterials that are both antibacterial and osteogenic, and that safely and sustainably function within the body, is consistent with the Islamic mandate to seek treatments that minimize risk and maximize benefit. Taken together, antibacterial functionalization in bone-healing materials is not only a scientific necessity but also an ethically commendable advancement within an Islamic framework that prioritizes life, safety, and human flourishing.

3.4 Antibacterial-Enhanced Bioxcrew Systems and Infection Challenges in Bone Implants

Implant-associated infections remain one of the most significant challenges in orthopedic and reconstructive surgery, as bacterial adhesion to implant surfaces can rapidly initiate biofilm formation, leading to chronic, recurrent infections. Once established, these biofilms create a protective matrix that shields bacteria from immune clearance and drastically reduces the effectiveness of systemic antibiotics. Clinically, this manifests as delayed bone union, chronic osteomyelitis, implant loosening, and, in severe cases, the need for implant removal or limb amputation. *Staphylococcus aureus* and *Staphylococcus epidermidis* remain the predominant pathogens, while trauma-related cases increasingly involve resilient Gram-negative organisms such as *Pseudomonas aeruginosa*. Due to the difficulty of eradicating mature biofilms, particularly on metallic or polymeric implant interfaces, the development of next-generation scaffolds and fixation systems with inherent antibacterial functionality has become a significant focus in modern biomaterials engineering (Pan et al., 2024).

Bioxcrew systems enhanced with antibacterial properties represent one of the most promising solutions to these persistent complications. These systems integrate antimicrobial strategies directly into the scaffold matrix or onto its surface, enabling early protection against bacterial colonization during the critical postoperative period. Common approaches include embedding controlled-release reservoirs of antimicrobial ions, such as silver, copper, or zinc; incorporating antimicrobial peptides that disrupt bacterial membranes; or engineering nano-patterned surface topographies that mechanically inhibit bacterial attachment without compromising osteoblast adhesion. Recent advancements also explore the use of bioinspired nanostructures that mimic natural bactericidal surfaces, such as those found in insect wings, to achieve contact-based bacteriolysis. These innovations provide a dual advantage: they suppress the early stages of infection while simultaneously creating a biologically favorable environment that supports osteogenic cell activity, extracellular matrix deposition, and mineralization.

Beyond their antibacterial design, Bioxcrew scaffolds function as highly versatile platforms that support the fundamental phases of bone regeneration. Their porous architecture and biochemical cues facilitate the recruitment of periosteal stem cells and mesenchymal stem cells, guiding their differentiation into osteoblasts that orchestrate new bone formation. Through a combination of mechanical support and targeted bioactivity, these scaffolds promote the transition from early matrix formation to organized lamellar bone. They also help regulate the inflammatory environment, helping maintain the balance necessary for appropriate tissue remodeling while promoting angiogenesis to ensure adequate oxygenation and nutrient exchange. Biomarkers of bone turnover, including osteocalcin, alkaline phosphatase, and procollagen derivatives, are increasingly used alongside imaging techniques to evaluate scaffold-mediated regeneration, reflecting the field's shift toward precision monitoring of implant performance.

Modern Bioxcrew technologies also act as sophisticated localized drug-delivery systems. Their tunable architectures enable sequential release profiles, starting with fast-acting antibacterial agents to mitigate early infection risk, followed by sustained delivery of osteogenic growth factors or signaling molecules to accelerate bone healing. Innovations such as injectable hydrogels, shape-memory polymers, 3D-printed lattices, and composite nanofiber matrices provide structures that closely resemble the native extracellular matrix while ensuring prolonged antibacterial function (Tang et al., 2025). This targeted delivery approach reduces the need for systemic antibiotics, lowers the likelihood of antimicrobial resistance, and shortens rehabilitation time, yielding both clinical and socioeconomic benefits.

By integrating antibacterial activity, osteogenic stimulation, and localized therapeutic delivery, Bioxcrew systems offer a comprehensive response to the long-standing challenges posed by implant-associated infections. By preventing early bacterial adhesion, promoting robust bone regeneration, and enabling precise control over drug release, these multifunctional scaffolds hold substantial potential to improve outcomes across diverse patient populations, particularly those at elevated risk of complications (Yıldıran et al., 2025).

3.5 Mechanisms of Antibacterial Enhancement

The mechanisms underlying antibacterial enhancement in modern Bioxcrew systems rely heavily on the strategic incorporation of bioactive metal ions, which provide potent, multifaceted antimicrobial activity while supporting bone regeneration. Silver, zinc, and copper ions remain the most widely explored due to their broad-spectrum efficacy and compatibility with advanced scaffold architectures. Silver ions exhibit strong reactivity toward thiol-containing proteins within bacterial membranes and cytoplasmic enzymes, disrupting essential metabolic pathways and destabilizing structural proteins. Their interaction with membrane components increases permeability, leading to rapid cell lysis, while intracellular accumulation disrupts respiratory chains and accelerates reactive oxygen species production. These combined effects damage bacterial nucleic acids, proteins, and lipids, making silver particularly effective against both planktonic bacteria and mature biofilms. Nanostructured silver formulations amplify these benefits by functioning as long-lasting ion reservoirs, enabling sustained antibacterial action and enhanced penetration into biofilm matrices that typically resist conventional therapies.

Zinc ions contribute a complementary antibacterial mechanism by disturbing multiple pathways vital for bacterial survival. Their binding to thiol groups in metabolic enzymes compromises respiratory activity, while elevated intracellular zinc levels trigger oxidative stress that damages DNA and proteins. Zinc can also disrupt metal homeostasis, a key component of bacterial regulatory networks, causing metabolic imbalance and growth arrest. One of the defining advantages of zinc-enhanced scaffolds is their dual functionality. While suppressing bacterial proliferation, zinc simultaneously promotes osteogenic differentiation by activating signaling cascades associated with bone formation. This makes zinc particularly advantageous for regenerative applications where maintaining a balance between antibacterial protection and tissue compatibility is essential.

Copper ions further reinforce the Bioxcrew system's antibacterial arsenal through redox cycling, generating abundant reactive oxygen species that rapidly compromise bacterial walls, membranes, enzymes, and genetic material. Copper also interacts with bacterial metalloproteins, displacing essential cofactors and disrupting enzymatic processes indispensable for survival. Nanostructured copper materials enhance the speed and magnitude of these effects due to their high surface area, facilitating rapid ion release and multilevel antibacterial action. Importantly, monovalent copper species often exhibit more potent antimicrobial activity than their divalent counterparts, especially in acidic microenvironments, every day in infected bone lesions, making copper particularly effective in conditions where bacterial resilience is heightened.

Current developments in antibacterial biomaterials increasingly emphasize synergistic combinations of metal ions to magnify bactericidal performance. These dual-ion systems, such as silver–copper or zinc–silver composites, leverage complementary mechanisms to achieve enhanced antibacterial activity. Copper can accelerate the release of silver ions while simultaneously enhancing oxidative stress, resulting in significantly greater antimicrobial potency than single-ion scaffolds. Such multifunctional composites have demonstrated potent activity against both Gram-positive and Gram-negative bacteria, including those that exhibit multidrug resistance, while maintaining compatibility with osteoblasts and mesenchymal stem cells. This synergy underscores a growing design trend in next-generation scaffolds: optimizing antibacterial performance without compromising biocompatibility or osteogenic potential.

Collectively, these metal-ion mechanisms, membrane disruption, enzymatic inactivation, oxidative stress induction, and interference with metabolic pathways form the biochemical foundation of antibacterial enhancement in Bioxcrew systems. Their integration into bone scaffolds provides a powerful strategy to address the persistent challenges of implant-associated infections, particularly in orthopedic procedures where the risks of postoperative contamination and biofilm formation remain high. As research continues to refine the balance between antimicrobial strength and regenerative support, metal-ion–augmented scaffolds stand at the forefront of advanced biomaterial design for infection-resistant bone healing.

3.6 Surface Modification: Surface Coating and Plasma Treatment

Surface modification through advanced coating strategies and plasma-based treatments has become a central approach in enhancing the antibacterial performance of Bioxcrew systems and modern orthopedic implants (De Pace et al., 2025). These methods are designed to modulate surface chemistry, topography, and surface energy to make bacterial adhesion energetically unfavorable while simultaneously supporting osteoblast attachment and host tissue integration (Yıldıran et al., 2025). Antibacterial coatings today are increasingly engineered to be multifunctional, combining metal ions, polymeric matrices, and bioinspired compounds to generate surfaces that kill bacteria on contact, inhibit early colonization, or release antimicrobial agents in a controlled manner. Hydrophilic polyphenol coatings, for example, create hydration shells that limit protein adsorption, a prerequisite for bacterial attachment, while also serving as reservoirs for antibacterial molecules. At the same time, nanostructured coatings incorporating silver, zinc, or copper particles create microscale and nanoscale landscapes that physically hinder bacterial settlement and promote membrane destabilization. These surfaces provide continuous antibacterial activity while maintaining compatibility with osteogenic cells, allowing implants to support early bone regeneration even in microbe-rich environments.

A parallel development involves engineering nanotopographies that mimic the natural antimicrobial surfaces found on insect wings and plant leaves. Such nanostructures can mechanically rupture bacterial membranes via stretching, puncturing, or shear forces, while leaving mammalian cells largely unaffected due to their greater elasticity. This mechanical bactericidal effect has gained substantial attention because it reduces reliance on chemical agents, thereby minimizing risks associated with ion toxicity and antimicrobial resistance. Additionally, engineered surfaces capable of generating reactive oxygen species under physiological conditions have emerged as promising platforms for reducing biofilm formation. These coatings use catalytic nanostructures or redox-active materials to induce localized oxidative stress, which disrupts bacterial DNA replication, enzyme activity, and membrane integrity. By concentrating antimicrobial activity at the implant–tissue interface, ROS-generating coatings reduce the need for systemic antibiotics and help maintain a sterile microenvironment during the critical early stages of healing.

Plasma treatment technologies further expand the possibilities for surface modification by enabling precise, uniform deposition of ultrathin antibacterial layers while preserving the underlying material's bulk properties. Plasma processing can introduce functional groups that improve wettability, enhance protein selectivity, and tailor interactions with both bacteria and host cells. It can also be used to deposit plasma-polymerized films or inorganic layers, such as silver oxide or diamond-like carbon, that provide long-lasting antibacterial functionality (Campoccia

et al., 2023). Plasma-assisted nanostructuring creates micro- and nanoscale features that mechanically disrupt bacterial membranes while simultaneously activating bone-forming pathways within host cells. Newer plasma-derived coatings, including hybrid organosilicon or silicon–hydrogen films, have demonstrated the ability to suppress biofilm formation and reduce inflammatory signaling without compromising cell viability. These ultrathin layers are particularly beneficial for load-bearing implants where maintaining mechanical strength is critical.

Increasingly, research is moving toward hybrid strategies that combine plasma functionalization with ion-releasing coatings to create synergistic effects. Plasma treatment enhances surface bonding, improving the stability and longevity of antibacterial coatings, while controlled release of metal ions provides sustained antimicrobial defense. Altogether, surface modification through chemical functionalization, nanostructuring, and plasma-engineered coatings is reshaping the design of orthopedic biomaterials. By integrating long-term antibacterial protection with enhanced tissue compatibility, these innovations are improving clinical outcomes, reducing infection-related complications, and extending the lifespan of implantable devices.

3.7 Incorporation of Antimicrobial Agents into Polymer Matrices

The incorporation of antimicrobial agents into polymer matrices has become a central strategy for advancing Bioxcrew systems for orthopedic applications, offering a powerful means to prevent infection while maintaining the biocompatibility required for bone regeneration (Sui et al., 2024). Polymers engineered with cationic functionalities, such as amine, guanidine, or quaternary ammonium groups, exert antibacterial effects primarily through strong electrostatic interactions with the negatively charged bacterial membrane surfaces (Monia & Ridha, 2024). Once attached, these polymers disrupt the structural organization of phospholipid bilayers by mechanisms often described through the carpet, toroidal pore, or barrel-stave models. These interactions lead to the formation of nanoscale membrane defects, allowing uncontrolled leakage of cellular contents and ultimately causing bacterial lysis. Beyond membrane damage, some cationic polymers can penetrate bacterial cells, where they interfere with DNA condensation, inhibit protein synthesis, and suppress metabolic pathways essential to bacterial survival. This multi-layered antimicrobial mechanism makes polymer matrices particularly effective in preventing early colonization of implant surfaces, which is critical for avoiding biofilm formation.

To enhance antibacterial capabilities, polymer matrices are increasingly engineered to incorporate metallic ions and nanoparticles, particularly silver, copper, and zinc (Wang et al., 2022). These additions introduce complementary bactericidal pathways: metal ions disrupt respiratory enzymes, promote oxidative stress via reactive oxygen species, and damage essential biomolecules, including proteins and nucleic acids. Nanoparticles further enhance these effects through their large surface-to-volume ratio, which facilitates sustained ion release and improves interactions with bacterial cells and biofilms. Such polymer–metal nanocomposites have been shown to provide long-term antibacterial activity while simultaneously promoting osteogenic differentiation, reflecting the growing trend toward multifunctional implants that couple infection control with bone regeneration.

Organic antimicrobial agents, such as phenolic derivatives, benzoic acid compounds, and N-halamine structures, are also being incorporated into polymer matrices to provide stable, prolonged antibacterial performance (Campoccia et al., 2023; Lee et al., 2024). These compounds function through several mechanisms, including the generation of oxidative microenvironments, disruption of bacterial metabolic pathways, and the creation of surfaces that resist bacterial adhesion. Their incorporation enables fine control over release kinetics, especially when combined with polymers that degrade gradually or swell in response to physiological conditions. The material properties of the polymer matrix, hydrophilicity, porosity, degradation rate, and chemical compatibility, play a crucial role in determining the diffusion of antimicrobial agents and, consequently, the duration and magnitude of antibacterial action. Increasingly, advanced polymer designs feature interconnected porous networks or hydrophilic domains that facilitate sustained diffusion, enabling implants to maintain antibacterial potency during the critical early weeks of healing.

Hybrid systems that combine antimicrobial-loaded polymers with bioactive ceramics or metals represent another emerging direction. Composite structures integrating titanium, hydroxyapatite, or calcium phosphate with antibiotic-releasing polymers provide synergistic benefits by supporting both infection prevention and osteointegration. These multifunctional platforms are particularly valuable for patients at high risk of postoperative complications, including those with diabetes, immunosuppression, or severe trauma. Altogether, antimicrobial polymer matrices within Bioxcrew systems bring together electrostatic membrane disruption, intracellular inhibition, oxidative stress induction, and tailored release mechanisms to create a versatile and robust approach for protecting implants against infection while promoting reliable bone healing (Monia & Ridha, 2024).

3.8 Comparative Analysis of Materials

Stainless steel, hydroxyapatite, and poly(lactic acid) represent three material classes that together define much of the contemporary landscape in antibacterial bioimplant design for bone repair. Each material offers distinct mechanical, biological, and antibacterial advantages, and their comparative performance has become increasingly crucial as implant-associated infections continue to challenge clinical outcomes. Medical-grade stainless steels, including conventional 316L and newer copper-bearing variants, remain indispensable for load-bearing applications owing to their high tensile strength, corrosion resistance, and elastic modulus comparable to those of traditional orthopedic metals. When stainless steel is enhanced with copper addition or engineered with antibacterial surface treatments, it can suppress bacterial colonization while preserving the cytocompatibility required for stable bone fixation. These developments enable stainless steel implants to maintain structural reliability while actively contributing to infection control, addressing a key limitation of earlier generations of inert metallic hardware.

Hydroxyapatite, a biomaterial prized for its chemical similarity to bone mineral, occupies a different niche by supporting osteoconduction, bone–implant integration, and extracellular matrix deposition (Lin et al., 2017). Although hydroxyapatite lacks the mechanical robustness required for major load-bearing roles, it functions exceptionally well as a biologically active coating or composite component. Modern engineering approaches have strengthened its antibacterial functionality through ionic substitution, nanoparticle incorporation, and the development of multifunctional composites that simultaneously promote vascularization and bone formation. These innovations enable hydroxyapatite to serve as both a structural cue for osteoblast activity and a passive or active barrier against pathogenic colonization. Such dual functionality is critical in significant or contaminated bone defects, where both osteointegration and infection resistance determine long-term healing success (Sui et al., 2024).

Poly(lactic acid) offers additional advantages as a degradable, biocompatible polymer suitable for temporary scaffolding, fixation devices, and drug-delivery systems. Although its native antibacterial activity is minimal, PLA can be transformed into a potent antimicrobial platform by incorporating metallic nanoparticles, metal oxides, chitosan derivatives, or bioactive peptides. These strategies allow PLA-based devices to inhibit common pathogens while providing controlled, localized release of therapeutic agents during the early post-implantation window when infection risk is highest. PLA degradation can further enhance antibacterial effects by lowering local pH, creating an environment that suppresses microbial proliferation while gradually transferring the load to the regenerating tissue. This makes PLA particularly valuable for resorbable systems that aim to eliminate the need for secondary implant removal procedures.

When considered together, these materials highlight a spectrum of design priorities in modern orthopedic and dental implant engineering. Stainless steel provides mechanical strength and procedural reliability; hydroxyapatite enhances biological integration and directs bone regeneration; and PLA provides temporary structural support, with tunable antibacterial and pharmacological functions. Persistent challenges include balancing antimicrobial potency with host-cell compatibility, preserving mechanical integrity after modification, and ensuring long-term stability of antibacterial effects in vivo. As a result, hybrid material systems have gained prominence, integrating metallic cores for stability, hydroxyapatite interfaces for osteointegration, and polymer reservoirs for sustained antimicrobial release. Such integrated approaches increasingly define next-generation Bioxcrew systems, emphasizing structural performance, biological harmony, and enduring protection against infection within a single multifunctional platform.

4. CONCLUSION

The integration of antibacterial-enhanced materials into Bioxcrew systems represents a decisive advancement in orthopedic biomaterials, addressing long-standing challenges associated with postoperative infections, biofilm formation, and impaired bone regeneration. As demonstrated across stainless steel, hydroxyapatite, and polylactic acid platforms, modern engineering strategies, including metal-ion functionalization, nanostructured surface modification, responsive polymer design, and hybrid composite architectures, provide robust mechanisms to inhibit early bacterial adhesion while simultaneously supporting osteogenesis. These innovations reduce dependence on systemic antibiotics, lower revision-surgery rates, and improve long-term fracture-healing outcomes, positioning multifunctional implants as essential tools for contemporary orthopedic practice. By targeting the critical interface where bacteria first colonize implant surfaces, antibacterial-enhanced Bioxcrew systems enhance mechanical stability and biological compatibility, meeting clinical priorities for safety, durability, and patient-centered healing. Furthermore, the ethical significance of these advancements remains evident when viewed through the lens of harm reduction and life preservation, reinforcing their importance within broader biomedical and societal contexts.

Future developments in antibacterial-enhanced Bioxcrew systems will likely evolve along three major trajectories: personalization, synergistic multifunctionality, and intelligent therapeutic responsiveness. Personalized implants, enabled through patient-specific imaging, 3D printing, and biomarker-guided design, promise to optimize mechanical geometry, drug-release profiles, and antimicrobial potency based on individual risk factors such as diabetes, immunodeficiency, or trauma severity (Tang et al., 2025). Research is also expected to intensify in multifunctional scaffolds that integrate antibacterial action with immunomodulation, angiogenic stimulation, and controlled osteoinductive signaling, creating implants that do far more than provide structural support. Meanwhile, intelligent, stimulus-responsive biomaterials capable of sensing infection-related changes in pH, oxidative stress, temperature, or enzymatic activity will usher in a new generation of smart implants that release antimicrobials only when necessary, minimizing toxicity and the development of resistance.

At the same time, emerging fields such as bioinspired nanomechanics, peptide-engineered coatings, and living biomaterials employing probiotic or bacteriophage-based strategies offer promising antimicrobial approaches that move beyond conventional metal-ion release. Long-term in vivo studies will also be critical to determining the stability, degradation kinetics, and host-tissue interactions of these advanced systems under real physiological conditions. Finally, future interdisciplinary collaboration among materials scientists, clinicians, microbiologists, and ethicists will be essential to ensuring that innovations remain safe, accessible, and aligned with holistic principles of patient welfare. As global orthopedic needs expand, driven by aging populations, rising trauma incidence, and increasing surgical complexity, antibacterial-enhanced Bioxcrew technologies will remain at the forefront of efforts to design implants that heal effectively, resist infection, and support sustained quality of life.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support for this research from Riset Kolaborasi Indonesia, under grant number 2140/UN40.R4/PT.01.01/2025.

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