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Systematic Review

Nanotechnology-based strategies in orthopaedic surgery: implications for osseointegration, infection prevention and bone regeneration

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ABSTRACT

Orthopaedic surgery continues to face challenges related to delayed bone healing, implant loosening, and implant-associated infection, despite advances in surgical techniques and biomaterials. Conventional implant materials are primarily mechanically reliable but biologically passive, limiting their ability to promote osseointegration or actively resist bacterial colonization. Nanotechnology has emerged as a promising strategy to enhance biological performance at the bone–implant interface by modifying material properties at the nanoscale. A systematic review was conducted to synthesise experimental, translational, and early clinical evidence on nanotechnology-based applications in orthopaedic surgery. A structured literature search was conducted using PubMed, Google Scholar, and Web of Science for studies published between 2015 and 2025. Evidence was thematically analysed and organized into three domains: nanostructured implant surfaces and osseointegration, antimicrobial nanocoatings for infection prevention, and nanofibrous or nanocomposite scaffolds for bone regeneration. Across the reviewed studies, nanoscale surface modifications consistently demonstrated enhanced osteoblast adhesion, early mineralization, and increased bone–implant contact compared with conventional surfaces. Antimicrobial nanocoatings and nanoparticle-based delivery systems showed effective local inhibition of bacterial adhesion and biofilm formation while maintaining cytocompatibility. Nanofibrous and nanocomposite scaffolds that mimic the native bone extracellular matrix support cellular infiltration, osteogenic differentiation, and mineral deposition in preclinical models. However, most available evidence remains preclinical or early translational. Nanotechnology-enabled strategies offer promising biological advantages for enhancing osseointegration, reducing implant-related infections, and promoting bone regeneration in orthopaedic surgery. While current findings support their potential clinical value, widespread adoption is limited by the lack of large-scale clinical trials, long-term safety data, and standardised regulatory pathways. Further high-quality clinical studies are required to validate these technologies and define their role in routine orthopaedic practice.

Keywords: Nanotechnology, Orthopaedic implants, Osseointegration, Antimicrobial nanocoating, Bone regeneration, Biomaterials

INTRODUCTION

Orthopaedic surgery continues to face substantial challenges related to bone regeneration, implant integration, and implant-associated complications. Despite advances in surgical techniques, fixation methods, and biomaterial engineering, delayed fracture healing, implant loosening, and infection remain leading causes of morbidity, prolonged disability, and revision surgery worldwide.[1,2] Conventional orthopaedic materials, while mechanically reliable, are largely biologically passive and often fail to provide the microenvironmental cues required to promote osteogenesis or resist microbial colonisation at the active bone–implant interface. These limitations are particularly evident in trauma, tumour reconstruction, and complex reconstructive procedures, where early biological fixation and durable integration are critical for functional recovery.[3]

Bone is a hierarchically organised tissue characterised by nanoscale structural features that regulate cellular adhesion, differentiation, and matrix mineralisation. Traditional implant surfaces and graft substitutes, which are predominantly smooth or micro structured, do not adequately replicate this native architecture. As a result, increasing attention has been directed toward strategies that better mimic bone's biological and structural properties while maintaining mechanical stability. Nanotechnology has emerged as a promising interdisciplinary approach capable of addressing these challenges by manipulating material properties at the nanometre scale.[4]

Role of nanotechnology in orthopaedic materials

Nanotechnology enables precise control over surface topography, chemistry, and material composition, allowing targeted modulation of protein adsorption, cell behaviour, and host–implant interactions. In orthopaedics, nanoscale modifications have been applied to implant surfaces, antimicrobial coatings, and scaffold-based bone regeneration systems to enhance biological performance without compromising mechanical integrity.[5-7]

Nanostructured implant surfaces have been shown to influence early cellular responses following implantation. Surface features at the nanometre scale enhance osteoblast adhesion, proliferation, and differentiation, while also regulating the adsorption of serum proteins that mediate cell attachment and signalling.[8] Compared with smooth or purely microtextured surfaces, nanoscale topographies provide increased surface area and more favourable biological interactions, potentially resulting in faster osseointegration and improved early mechanical stability. These effects are particularly relevant in trauma and reconstructive orthopaedics, where delayed fixation or impaired integration may lead to non-union or implant failure.[9]

Infection prevention and antimicrobial strategies

Implant-related infection remains one of the most serious and costly complications in orthopaedic practice. Bacterial adhesion and biofilm formation on implant surfaces significantly impair host immune responses and reduce the effectiveness of systemic antibiotics, frequently necessitating prolonged treatment, staged revision procedures, or implant removal.[10] Consequently, innovative strategies to prevent bacterial colonisation at the implant interface have become a primary focus of orthopaedic biomaterials research.

Nanotechnology-based antimicrobial approaches include surface-bound antibacterial coatings and nanoparticle-enabled drug delivery systems designed to provide localised antimicrobial activity. By concentrating antibacterial effects directly at the implant surface, these strategies aim to reduce bacterial burden while minimising systemic exposure and toxicity.[11,12] Recent advances have emphasised the importance of maintaining biocompatibility and preserving osteogenic potential, recognising that excessive antimicrobial activity may compromise bone healing. The development of multifunctional coatings that balance antibacterial efficacy with support for osseointegration represents a critical translational objective.[13]

Nanofibrous and nanocomposite scaffolds for bone regeneration

Beyond implant surface modification, nanofibrous and nanocomposite scaffolds have garnered increasing attention due to their role in bone regeneration. These scaffolds are designed to replicate key features of the bone extracellular matrix, providing a high surface-area framework that supports cell migration, proliferation, angiogenesis, and osteogenic differentiation. Nanofibrous architectures more closely simulate the native bone microenvironment, while nanocomposite designs incorporate bioactive inorganic phases to enhance mechanical strength and osteoconductivity.[14,15]

Polymer–ceramic nanocomposites, particularly those incorporating nanohydroxyapatite or bioactive ceramic phases, have demonstrated favourable interactions with bone tissue and enhanced mineral deposition in experimental models.[16] Hydrogel-based nanocomposites offer additional versatility, providing hydrated matrices that support cellular viability, facilitate the controlled delivery of growth factors, and promote osteogenic activity. These scaffold-based strategies are especially relevant for large bone defects, established nonunions, and reconstructive procedures following tumour resection, where conventional autografting or allografting may be inadequate.[17]

Scope and rationale of the review

Given the breadth of applications and heterogeneity of available evidence, a systematic review is necessary to integrate findings across experimental, translational, and early clinical studies. Current literature spans multiple disciplines, including materials science, immunology, microbiology, and orthopaedic surgery, yet remains fragmented with respect to clinical relevance and translational readiness.

This review focuses on three interrelated domains: nanostructured implant surfaces and their role in enhancing osseointegration, antimicrobial nanocoatings and nanoparticle-based systems for preventing infections, and nanofibrous and nanocomposite scaffolds designed to support bone regeneration.

By consolidating evidence across these domains, this article aims to provide clinicians and researchers with a comprehensive overview of the biological rationale, translational potential, and current limitations of nanotechnology-enabled strategies in orthopaedic surgery, with particular emphasis on their implications for fracture healing, implant longevity, and infection prevention.

METHODS

Study design

This article was designed as a systematic review to synthesise emerging evidence on nanotechnology-based strategies in orthopaedic surgery. A narrative approach was selected because the available literature is highly heterogeneous, encompassing in vitro experiments, animal models, translational investigations, and limited early clinical studies. The variability in nanomaterial composition, surface modification techniques, scaffold designs, and reported outcome measures precludes meaningful quantitative pooling or meta-analysis. Instead, a narrative framework enables the integration of mechanistic insights with clinically relevant observations, providing a comprehensive overview of the field that is well-suited to an evolving, multidisciplinary domain.

Search strategy

A structured literature search was conducted to identify relevant studies published between January 2015 and March 2025. Electronic databases searched included PubMed, Google Scholar, and Web of Science. The search strategy combined controlled vocabulary and free-text terms related to nanotechnology and orthopaedic applications. Key search terms included combinations of: "nanotechnology," "nanostructured implant surfaces," "orthopaedic implants," "osseointegration," "antimicrobial nanocoatings," "implant-related infection," "bone regeneration," "nanofibrous scaffolds," and "nanocomposite biomaterials." Reference lists of selected articles and relevant review papers were also manually screened to identify additional pertinent studies.

Eligibility criteria

Studies were considered eligible for inclusion if they met the following criteria: addressed nanotechnology-based materials or surface modifications relevant to orthopaedic or musculoskeletal applications; reported outcomes related to osseointegration, infection prevention, or bone regeneration; involved in vitro experiments, animal models, translational research, or human clinical observations; and were published in peer-reviewed journals in English. Articles focusing exclusively on non-musculoskeletal systems, purely theoretical modelling without biological validation, or non-orthopaedic biomedical applications were excluded (Figure 1).

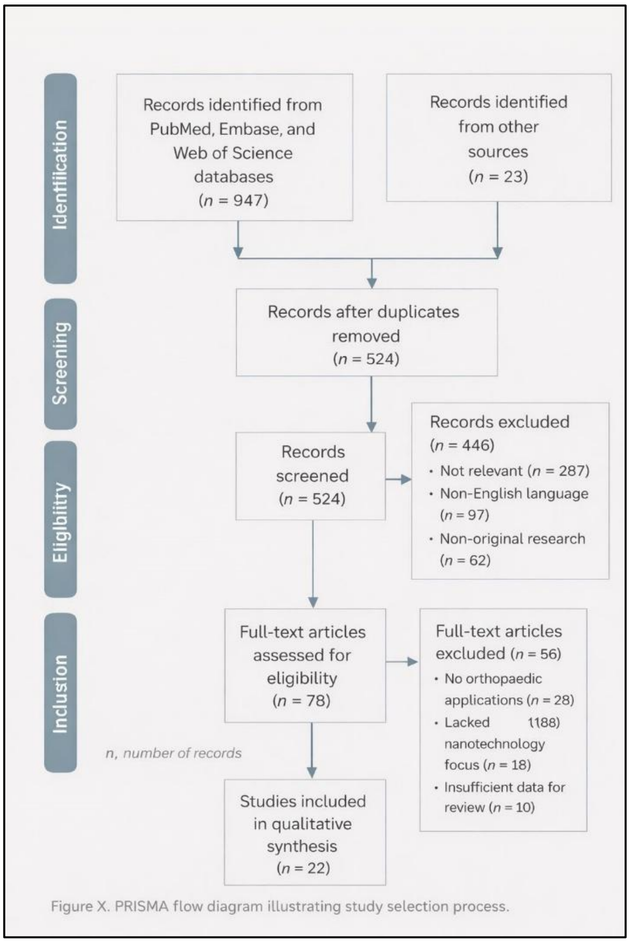

Figure 1: Flowchart of eligibility criteria of articles.

Data extraction and synthesis

Data were extracted qualitatively from included studies, focusing on material type, nanostructural characteristics, study design, biological or clinical outcomes, and translational relevance. Given the diversity of methodologies and outcome measures, findings were synthesised thematically rather than quantitatively. The results were organised into three principal domains reflecting the significant areas of application in orthopaedic nanotechnology: nanostructured implant surfaces and osseointegration, antimicrobial nanocoatings and nanoparticle systems for infection prevention, and nanofibrous or nanocomposite scaffolds for bone regeneration.

RESULTS

Nanostructured implant surfaces and osseointegration

Across the reviewed literature, the nanoscale modification of orthopaedic implant surfaces has been consistently associated with enhanced biological responses at the bone–implant interface when compared with conventional smooth or purely microtextured materials. Review-level evidence indicated that nanoscale surface topography influences early protein adsorption and downstream cellular signalling pathways, thereby regulating osteoblast adhesion, proliferation, and differentiation.[18,19] Experimental investigations have demonstrated that nanorough, nanoporous, and nanotubular titanium surfaces promote improved osteogenic differentiation and accelerate early bone formation compared to unmodified surfaces (Figure 2).[20-22]

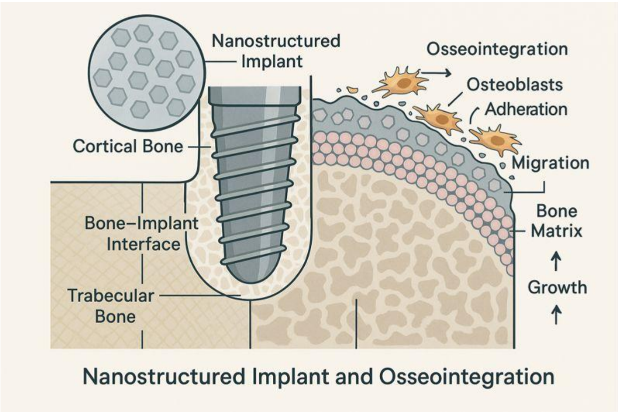

Figure 2: Nanostructured implant and osseointegration.

Representative schematic illustrating the role of nanostructured implant surfaces in promoting osseointegration. Nanoscale surface features on the orthopaedic implant enhance protein adsorption and facilitate osteoblast adhesion, migration, and differentiation at the bone–implant interface. These cellular interactions promote early bone matrix deposition and progressive integration of the implant with surrounding cortical and trabecular bone. Improved nanoscale surface–cell interactions accelerate bone–implant contact and enhance mechanical stability compared with conventional smooth or microtextured implant surfaces. Animal model studies further reported increased bone–implant contact and superior mechanical fixation parameters, including higher pull-out strength and torque resistance, suggesting more robust early osseointegration.[20]

Antimicrobial nanocoatings and nanoparticle systems

Implant-related infection remained a prominent focus across the included studies, with multiple nanotechnology-based strategies developed to reduce bacterial adhesion and biofilm formation at implant surfaces. Surface-bound antimicrobial nanocoatings and nanoparticle-enabled drug delivery systems were the most frequently reported approaches.[11,13,17] Review articles emphasised that antibacterial efficacy was determined not only by the antimicrobial agent itself, but also by surface chemistry, nanoscale architecture, and controlled-release characteristics (Figure 3).[11-17]

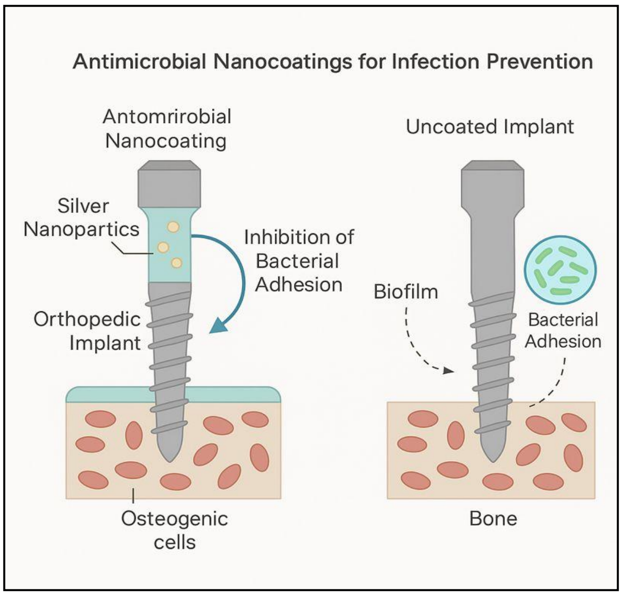

Figure 3: Antimicrobial nanocoatings for infection prevention.

Representative schematic illustrating the role of antimicrobial nanocoatings in preventing implant-associated infection. The nanocoated orthopaedic implant (left) is shown with a surface-bound antimicrobial nanolayer, such as silver or drug-eluting nanoparticles, which inhibits bacterial adhesion and disrupts early biofilm formation while maintaining compatibility with surrounding osteogenic cells. In contrast, the uncoated implant surface (right) permits bacterial attachment and biofilm development at the bone–implant interface, increasing the risk of implant-related infection. Localised antimicrobial activity at the implant surface may reduce dependence on systemic antibiotics and improve implant longevity, particularly in trauma and revision surgery. Experimental studies have demonstrated that controlled-release nanocoatings provide sustained antibacterial activity against common orthopaedic pathogens while maintaining cytocompatibility with osteogenic cells.[13-23] Several investigations have described multifunctional coatings that combine antibacterial and osteogenic properties, thereby supporting both infection prevention and bone healing at the implant interface.[24] Collectively, these findings suggest that nanotechnology-based antimicrobial strategies can provide adequate localised protection while reducing dependence on prolonged systemic antibiotic therapy.

Nanofibrous and nanocomposite scaffolds for bone regeneration

Nanofibrous and nanocomposite scaffolds have been widely reported as promising platforms for bone regeneration in both experimental and translational studies. The review highlights evidence that nanofibrous architectures closely mimic the extracellular matrix of bone, offering a high surface area and interconnected porosity that support cell migration, angiogenesis, and osteogenic differentiation.[18,19,21] Polymer–ceramic nanocomposites, particularly those incorporating nanohydroxyapatite or bioactive ceramic phases, consistently demonstrated enhanced osteoconductivity and increased mineral deposition (Figure 4).[21-24]

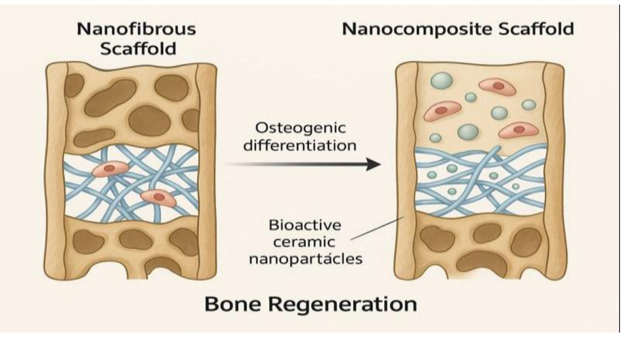

Figure 4: Nanofibrous and nanocomposite scaffolds for bone regeneration.

Representative schematic illustrating nanofibrous and nanocomposite scaffold-based strategies for bone regeneration. The nanofibrous scaffold (left) mimics the extracellular matrix of native bone, providing a high-surface-area architecture that supports osteogenic cell adhesion, migration, and proliferation. The nanocomposite scaffold (right) incorporates bioactive ceramic nanoparticles within a polymeric matrix, and enhancing osteogenic differentiation, mineral deposition, and mechanical stability. Together, these scaffold designs facilitate cellular infiltration and bone tissue formation, highlighting their potential utility in managing significant bone defects, non-unions, and complex reconstructive orthopaedic procedures.

Experimental investigations have further demonstrated that biomimetic membranes, which combine polymer matrices with nanoscale ceramic components, enhance osteogenic activity and improve scaffold integration within host bone.[25] Hydrogel-based nanocomposites also supported cellular viability and osteogenic potential, suggesting adaptability for irregular or complex bone defects.[17] Translational and early clinical observations underscored the importance of scaffold mechanical stability and biological activity in achieving successful union in significant defects and non-union scenarios, reinforcing the need for constructs that combine structural support with bioactivity.[20]

Summary of findings

A summary of nanotechnology-based strategies evaluated in the included studies, along with their primary biological effects and orthopaedic applications, is presented in Table 1. Collectively, the reviewed evidence demonstrates that nanoscale material modifications can enhance osseointegration, reduce the risk of infection, and support bone regeneration through biologically active and mechanically compatible design strategies.

Table 1: Summary of nanotechnology-based strategies in orthopaedic applications with clinical relevance.

Ref.	Author, year	Nanotechnology application	Material/system	Study type	Key findings	Potential clinical relevance
1	Xia et al, 2025[18]	Nanostructured implants, antimicrobial systems, scaffolds	Nano-engineered implant surfaces and composites	Review	Demonstrated improved biocompatibility, osseointegration, and infection control concepts	May inform future implant designs aimed at improving early fixation and reducing infection risk
2	Hamza et al, 2025[19]	Nano-enhanced orthopaedic implants	Nanotechnology-modified implant materials	Review	Highlighted enhanced implant performance and longevity	Supports clinical adoption of nano-modified implants to improve long-term survivorship
3	Brochu et al, 2024[21]	Bio ceramic nanocomposites for bone regeneration	Calcium phosphate–based nanoceramics	Review	Reported improved osteoconductivity and bone bonding	Potential application in bone defect reconstruction and non-union management
4	Ji et al, 2021[20]	Structural bone reconstruction	Pasteurised tumour bone with fibular support	Clinical /experimental	Demonstrated graft viability and union in significant bone defects	Relevant for limb salvage and post-tumour reconstruction cases
5	Li et al, 2020[22]	Nanocomposite scaffold for bone regeneration	Gelatin/nanohydroxyapatite/ PLLA membrane	Experimental	Enhanced osteogenic activity and mineral deposition	May improve outcomes in segmental defects and delayed union

Continued.

Ref.	Author, year	Nanotechnology application	Material/system	Study type	Key findings	Potential clinical relevance
6	Huang et al, 2020[17]	Nanocomposite hydrogel scaffold	Biopolymer-based nanocomposite hydrogel	Experimental	Maintained cell viability and supported osteogenic potential	Potential use in irregular or complex bone defects
7	Chen et al, 2023[11]	Antimicrobial nanocoatings	Nano-engineered antibacterial implant coatings	Review	Reduced bacterial adhesion and biofilm formation	May lower early postoperative infection rates in high-risk implants
8	Chouirfa et al, 2019[13]	Antibacterial titanium surface modification	Coated and modified titanium surfaces	Review	Inhibited bacterial colonisation on implant surfaces	Applicable to trauma and arthroplasty implants
9	Jahanmard et al, 2020[24]	Controlled-release antibacterial coating	Drug-eluting nanocoating system	Experimental	Provided sustained local antibacterial activity	Potential adjunct to systemic antibiotics in infection prevention
10	Zhou et al, 2024[25]	Hybrid antibacterial–osteogenic nanocoating	Zinc oxide nanostructured coating	Experimental	Combined antibacterial efficacy with osteogenic support	Particularly relevant for trauma and revision surgery with high infection risk

This table summarises representative review, experimental, translational, and limited clinical studies evaluating nanotechnology-based approaches in orthopaedic surgery. The listed studies encompass three major application domains: nanostructured implant surfaces for enhanced osseointegration, antimicrobial nanocoatings and nanoparticle systems for infection prevention, and nanofibrous or nanocomposite scaffolds for bone regeneration. While the majority of evidence remains preclinical, the findings highlight potential clinical relevance in trauma surgery, revision arthroplasty, extensive bone defect reconstruction, and infection-prone orthopaedic procedures. The table is intended to provide a clinically oriented overview rather than a comprehensive systematic comparison.

DISCUSSION

This review synthesises current evidence on nanotechnology-enabled strategies in orthopaedic surgery, focusing on their potential to address persistent clinical challenges related to implant integration, infection prevention, and bone regeneration. Despite advances in implant design and surgical technique, complications such as delayed osseointegration, implant loosening, and implant-associated infection continue to contribute substantially to patient morbidity and revision surgery.[2,3] The reviewed literature suggests that nanoscale modification of orthopaedic materials offers biologically active solutions that extend beyond the capabilities of conventional, mechanically focused biomaterials.[4-7]

Clinical implications of nanostructured implant surfaces

One of the most clinically relevant findings across the reviewed studies is the consistent enhancement of osseointegration associated with nanostructured implant surfaces. Unlike traditional smooth or microtextured implants, nanoscale surface features interact directly with proteins and cells involved in the early stages of bone healing.[7,8] Experimental and translational studies demonstrate that nanorough, nanoporous, and nanotubular surfaces promote improved osteoblast adhesion, proliferation, and differentiation, which are critical determinants of early implant stability.[8,9,26]

From a clinical perspective, improved early fixation has essential implications for trauma and reconstructive orthopaedics. Early biological stability may reduce the risk of micromotion at the bone–implant interface, thereby lowering the likelihood of nonunion, implant loosening, and delayed weight-bearing.[5-9] These effects are particularly relevant in high-risk scenarios such as osteoporotic bone, complex periarticular fractures, and revision surgery, where compromised bone quality often limits fixation success.[1,27] Although most supporting evidence remains preclinical, the biological consistency observed across studies suggests that nanostructured surfaces may offer a meaningful adjunct to existing implant technologies.

Infection prevention and implant longevity

Implant-associated infection remains one of the most challenging complications in orthopaedic surgery, often resulting in prolonged hospitalisation, multiple surgical procedures, and increased healthcare costs.[10-12] Nanotechnology-based antimicrobial strategies aim to intervene at the earliest stages of bacterial adhesion and biofilm formation, a phase during which conventional systemic antibiotics are least effective.[11-13]

The reviewed evidence indicates that antimicrobial nanocoatings and nanoparticle-based delivery systems can significantly reduce bacterial colonisation at the implant surface while preserving cytocompatibility with osteogenic cells.[11,13,24] Controlled-release nanocoatings, in particular, offer sustained local antimicrobial activity without the systemic toxicity associated with prolonged antibiotic therapy.[24-28] From a clinical standpoint, such localised strategies could complement established infection prevention measures, including perioperative antibiotics and sterile technique, rather than replace them. Multifunctional coatings that combine antibacterial and osteogenic properties are of particular interest, as they address the dual goals of infection control and bone healing.[25-29] If validated in clinical settings, these technologies may reduce early postoperative infection rates and improve long-term implant survival, particularly in trauma cases and revision arthroplasties, where the risk of infection is elevated.

Role of nanofibrous and nanocomposite scaffolds in bone regeneration

Large bone defects resulting from trauma, tumour resection, or complex revision surgery continue to present significant reconstructive challenges. Autografting and allografting, while effective, are limited by donor site morbidity, availability, and variable biological performance.[27-30] Nanofibrous and nanocomposite scaffolds offer a biologically inspired alternative by mimicking the nanoscale architecture of native bone extracellular matrix.[14,15]

The reviewed studies demonstrate that nanofibrous scaffolds support cellular adhesion, migration, and osteogenic differentiation, while nanocomposite designs incorporating bioactive ceramics enhance mineralisation and mechanical competence.[16,21,22] Clinically, these properties are particularly relevant for segmental defects and non-union, where both biological stimulation and structural support are required.[20] Hydrogel-based nanocomposites further expand reconstructive options by enabling adaptation to irregular defect geometries, potentially improving graft–host integration.[17]

Although clinical application remains limited, these scaffold-based strategies may ultimately reduce reliance on repeated grafting procedures and improve outcomes in patients with compromised healing potential. Careful consideration of mechanical stability, degradation kinetics, and integration with fixation systems will be essential for successful clinical translation.

Translational considerations and future directions

Despite promising biological and experimental data, several barriers must be addressed before nanotechnology-based strategies can be widely adopted in routine orthopaedic practice. Long-term biocompatibility and durability data are limited, particularly for permanent implants incorporating nanoscale modifications.[4,6] Manufacturing reproducibility, cost-effectiveness, and regulatory approval pathways also represent significant challenges that must be navigated to ensure safe and scalable clinical implementation.

Future research should prioritize well-designed clinical trials that evaluate not only radiographic and histological outcomes but also patient-centered measures, such as functional recovery, complication rates, and implant survival.[1-18] Standardised reporting of nanomaterial characteristics and outcome measures will be essential to facilitate comparison across studies and support evidence-based adoption.

Broader clinical relevance

Innovation in orthopaedic nanotechnology is increasingly global, with contributions emerging from both high- and middle-income settings.[19,31] This broader research engagement highlights the potential for nanotechnology-based solutions to be adapted to diverse healthcare environments. Continued interdisciplinary collaboration between clinicians, material scientists, and regulatory bodies will be critical to ensure that these technologies are translated responsibly and equitably.

Overall, the findings of this review support the view that nanotechnology represents a clinically relevant and evolving adjunct to contemporary orthopaedic practice. While further validation is required, nanoscale strategies have the potential to enhance implant integration, reduce infection-related complications, and improve bone regeneration outcomes in carefully selected clinical scenarios.

Limitations

This review has several limitations that should be acknowledged. First, the majority of evidence evaluating nanotechnology-based strategies in orthopaedic applications is derived from in vitro experiments and animal models. While these studies provide essential mechanistic insights, their findings may not fully translate to clinical outcomes in human patients. Differences in biomechanics, immune responses, and healing environments between experimental models and clinical settings limit direct generalisation.

Second, there is substantial heterogeneity in material composition, nanoscale design parameters, experimental protocols, and outcome measures across studies. Variations in surface chemistry, nanoparticle size, scaffold architecture, and antimicrobial agents complicate direct comparison between investigations and preclude quantitative synthesis. As a result, conclusions are based on qualitative trends rather than pooled effect estimates.

Third, clinical evidence remains limited, with relatively few prospective human studies or randomised trials assessing long-term outcomes such as implant survival, infection recurrence, or functional recovery. Most available clinical data are from early-phase or observational studies, which restrict definitive conclusions regarding safety, durability, and cost-effectiveness.

Finally, this narrative review did not include a formal risk-of-bias assessment or meta-analysis due to the diverse nature of the available literature. While this approach allows broad synthesis across disciplines, it may introduce selection bias. These limitations underscore the need for cautious interpretation and highlight priorities for future research.

Clinical implications

From a clinical perspective, nanotechnology-based orthopaedic strategies should currently be viewed as adjunctive innovations rather than replacements for established surgical principles. Mechanical stability, meticulous surgical technique, and appropriate patient optimisation remain the foundation of successful fracture healing and implant survival.

Nevertheless, the reviewed evidence suggests that nanoscale material modifications may enhance early biological responses that are critical in high-risk clinical scenarios, including complex fractures with compromised biology, revision surgeries with poor bone stock, large bone defects and non-union, and patients at increased risk of implant-related infection.

Antimicrobial nanocoatings and localised drug delivery systems may complement standard infection prevention strategies, particularly where biofilm formation poses a significant risk. However, until robust clinical trial data are available, the widespread routine use of this approach should be approached cautiously and guided by regulatory approval and institutional protocols.

CONCLUSION

Nanotechnology represents a transformative yet evolving approach in orthopaedic biomaterials, with the capacity to enhance osseointegration, reduce implant-related infections, and support bone regeneration. Continued interdisciplinary collaboration between clinicians, materials scientists, and translational researchers will be essential to translate these advances into safe, effective, and clinically scalable solutions that improve patient outcomes in orthopaedic surgery.

Future directions and research priorities

Future research should prioritise well-designed translational and clinical studies that bridge the gap between experimental promise and clinical implementation. Key areas for further investigation include:

Standardisation of nanoscale material design, including surface topography, coating thickness, and release kinetics, to improve reproducibility and comparison across studies. Prospective clinical trials evaluating osseointegration, fracture union rates, infection prevention, and long-term implant survival. Safety and biocompatibility assessments, particularly regarding long-term nanoparticle exposure and potential systemic effects. Cost-effectiveness analyses to determine the feasibility of large-scale clinical adoption. Integration with host biology, including immune modulation and patient-specific risk stratification. Interdisciplinary collaboration between orthopaedic surgeons, materials scientists, microbiologists, and regulatory bodies will be essential to ensure that nanotechnology-enabled solutions are both clinically effective and safely translated into practice.

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REFERENCES

1. Khan SN, Cammisa FP, Sandhu HS, Diwan AD, Girardi FP, Lane JM. The biology of bone grafting. J Am Acad Orthop Surg. 2005;13(1):77-86.
2. Giannoudis PV, Dinopoulos H, Tsiridis E. Bone substitutes: an update. Injury. 2005;36(3):S20-7.
3. Jacobs JJ, Roebuck KA, Archibeck M, Hallab NJ, Glant TT. Osteolysis: basic science. Clin Orthop Relat Res. 2001;(393):71-7.
4. Mazaheri M, Eslahi N, Ordikhani F, Tamjid E, Simchi A. Nanomedicine applications in orthopedic medicine: state of the art. Int J Nanomedicine. 2015;10:6039-53.
5. Jones CF, Quarrington RD, Tsangari H, Starczak Y, Mulaibrahimovic A, Burzava ALS, et al. A novel nanostructured surface on titanium implants increases osseointegration in a sheep model. Clin Orthop Relat Res. 2022;480(11):2232-50.
6. Hou C, An J, Zhao D, Ma X, Zhang W, Zhao W, et al. Surface modification techniques to produce micro/nano-scale topographies on Ti-based implant surfaces for improved osseointegration. Front Bioeng Biotechnol. 2022;10:835008.
7. Gittens RA, Olivares-Navarrete R, Schwartz Z, Boyan BD. Implant osseointegration and the role of microroughness and nanostructures: lessons for spine implants. Acta Biomater. 2014;10(8):3363-71.
8. Balasundaram G, Webster TJ. Increased osteoblast adhesion on nanograined Ti modified with KRSR. J Biomed Mater Res A. 2007;80(3):602-11.
9. Salou L, Hoornaert A, Louarn G, Layrolle P. Enhanced osseointegration of titanium implants with nanostructured surfaces: an experimental study in rabbits. Acta Biomater. 2015;11:494-502.
10. Besinis A, De Peralta T, Handy RD. Inhibition of biofilm formation and antibacterial properties of a silver nano-coating on human dentine. Nanotoxicology. 2014;8(7):745-54.
11. Chen X, Zhou J, Qian Y, Zhao L. Antibacterial coatings on orthopedic implants. Mater Today Bio. 2023;19:100586.

12. Hasan J, Crawford RJ, Ivanova EP. Antibacterial surfaces: the quest for a new generation of biomaterials. Trends Biotechnol. 2013;31(5):295-304.
13. Chouirfa H, Bouloussa H, Migonney V, Falentin-Daudré C. Review of titanium surface modification techniques and coatings for antibacterial applications. Acta Biomater. 2019;83:37-54.
14. Laurencin CT, Ashe KM, Henry N, Kan HM, Lo KW. Delivery of small molecules for bone regenerative engineering: preclinical studies and potential clinical applications. Drug Discov Today. 2014;19(6):794-800.
15. Carbone EJ, Jiang T, Nelson C, Henry N, Lo KW. Small molecule delivery through nanofibrous scaffolds for musculoskeletal regenerative engineering. Nanomedicine (Lond). 2014;10(8):1691-9.
16. Nukavarapu SP, Kumbar SG, Brown JL, Krogman NR, Weikel AL, Hindenlang MD, et al. Polyphosphazene/nano-hydroxyapatite composite microsphere scaffolds for bone tissue engineering. Biomacromolecules. 2008;9(7):1818-25.
17. Huang K, Gu Z, Wu J. Tofu-incorporated hydrogels for potential bone regeneration. ACS Biomater Sci Eng. 2020;6(5):3037-45.
18. Xia L, Zhou C, Li Q, Liu L, Jiang C, Dai H, et al. Nanotechnology in orthopedic care: advances in drug delivery, implants, and biocompatibility considerations. Int J Nanomed. 2025;20:9251-74.
19. Hamza HM, Malik MM, Asad M, Ali S, Awan AA. Advances in orthopedic implants: the role of nanotechnology in enhancing performance and longevity. Regener Med Rep. 2025;2(1):15-21.
20. Ji T, Li Y, Xing Z, Tang X, Yang R, Guo W. Assessment of the viability and union feature of diaphysis reconstruction using pasteurized tumor bone and intramedullary free fibular after tumor resection. J Pediatr Orthop. 2021;41(9):e833-40.
21. Brochu BM, Sturm SR, Kawase De Queiroz Goncalves JA, Mirsky NA, Sandino AI, Panthaki KZ, et al. Advances in bioceramics for bone regeneration: a narrative review. Biomimetics. 2024;9(11):690.
22. Li B, Chen Y, He J, Zhang J, Wang S, Xiao W, et al. Biomimetic membranes of methacrylated gelatin/nanohydroxyapatite/poly(L-lactic acid) for enhanced bone regeneration. ACS Biomater Sci Eng. 2020;6(12):6737-47.
23. Jahanmard F, Dijkmans FM, Majed A, Vogely HC, van der Wal BCH, Stapels DAC, et al. Toward antibacterial coatings for personalized implants. ACS Biomater Sci Eng. 2020;6(10):5486-92.
24. Jahanmard F, Croes M, Castilho M, Majed A, Steenbergen MJ, Lietaert K, et al. Bactericidal coating to prevent early and delayed implant-related infections. J Control Release. 2020;326:38-52.
25. Zhou J, Wang H, Virtanen S, Witek L, Dong H, Thanassi D, et al. Hybrid zinc oxide nanocoating on titanium implants: controlled drug release for enhanced antibacterial and osteogenic performance in infectious conditions. Acta Biomater. 2024;189:589-604.
26. Zhao H, Huang Y, Zhang W, Guo Q, Cui W, Sun Z, et al. Mussel-inspired peptide coatings on titanium implant to improve osseointegration in osteoporotic condition. ACS Biomater Sci Eng. 2018;4(7):2505-15.
27. Li K, Liu S, Hu T, Razanau I, Wu X, Ao H, et al. Optimized nanointerface engineering of micro/nanostructured titanium implants to enhance cell–nanotopography interactions and osseointegration. ACS Biomater Sci Eng. 2020;6(2):969-83.
28. Pan C, Zhou Z, Yu X. Coatings as the useful drug delivery system for the prevention of implant-related infections. J Orthop Surg Res. 2018;13(1):220.
29. Lian Q, Zheng S, Shi Z, Li K, Chen R, Wang P, et al. Using a degradable three-layer sandwich-type coating to prevent titanium implant infection with the combined efficient bactericidal ability and fast immune remodeling property. Acta Biomater. 2022;154:650-66.
30. Hollister SJ. Porous scaffold design for tissue engineering. Nat Mater. 2005;4(7):518-24.
31. Khalid MH, Muzammil S, Siddique MH, Ashraf A, Arooj I, Saqalein M, et al. Breaking barriers: antimicrobial nanocoatings as a revolutionary approach to combat biofilm infections. Prog Org Coat. 2025;209:109571.

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