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# Introduction to theranostic nanoplatforms for biomedicine

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Sylvie Begin

*Sylvie Begin-Colin is Professor at the Ecole Européenne d'Ingénieurs en Chimie, Matériaux et Polymères (ECPM) at the University of Strasbourg and was Director of ECPM from 2014 to 2021. Her* *research at the Institute of Chemistry and Process for Energy Environment and Health focuses on the synthesis, functionalization and organization of oxide nanoparticles for biomedical, energy and environmental applications, and she heads the "Chemical engineering of hybrid nanomaterials for environment and health" team. A great part of her research activity is devoted to the design of oxide nanoparticles as these nano-objects are highly sought after for their applications in the biomedical field and are also considered as the building blocks of the future nanotechnological devices in the fields of sustainable development or energy. Most of these studies are made in collaboration with organic chemists, biologists and physicists. Sylvie Bégin has obtained AOARD, ANR, INCA, Labex, MICA, ARC, INTERREG, and Alsace contre le Cancer grants and has participated and participates as partner to different European programs (Euronanomed, Marie Curie…). She has produced 218 publications and 13 book chapters, 3 patents, more than 200 oral communications and 90 invited lectures/seminars. Her work has been rewarded by the "Jean-Rist" prize of the French Society for Metallurgy and Materials and Scientific Excellence Award and by a "Chevalier dans l'ordre des palmes académiques".*

Sophie Laurent

*Sophie Laurent studied at the University of Mons-Hainaut (UMH), Belgium, from which she graduated with a master degree in chemistry in 1989. She obtained her PhD in 1993 from the same University where she was successively appointed assistant, lecturer, associate professor, professor and full professor. She joined the Prof R. N. Muller's team and was involved in the development (synthesis and physicochemical characterization) of contrast agents (paramagnetic lanthanide complexes and superparamagnetic iron oxide nanoparticles) for magnetic resonance imaging (MRI). She is co-author of 390 publications in international journals such as Chemical Reviews and more than 650 abstracts in international conferences (h factor: 68, citations: more than 30 000). She collaborates actively with the Center for Microscopy and Molecular Imaging (CMMI) in Gosselies, Belgium. Since October 2016, she* *has been the head of General, Organic and Biomedical Chemistry Unit in the University of Mons and of the UMONS part of the CMMI. She is the scientific co-director of the CMMI.*

Teresa Pellegrino

*Teresa Pellegrino is a tenured team leader of the group of Nanomaterials for Biomedical Applications at Italian Institute of Technology, Genoa (Italy) since 2014 and a Mildred Dresselhaus Guest Professorship at University of Hamburg since July 2025. She received her MSc degree in Chemistry in 2000 and her PhD in Chemical Synthesis in 2005 from the University of Bari (Italy). During her PhD, she started working in the field of nanoscience at the University of California, Berkeley, focusing on the study of the interaction of quantum dots with tumor cells. Later she moved with a Marie Curie fellow to the Center for Nanoscience in Munich (Germany), developing water-soluble and biocompatible coating for nanocrystals of different materials. In 2005 she was appointed as a postdoctoral fellow at the National Nanotechnology Laboratory of CNR-INFM, Lecce, Italy. In 2010, she became permanent staff scientist researcher at the Nanoscience Institute of CNR, Lecce, Italy working on stimuli-responsive magnetic nanoparticles. Her current research interests focus on the development of inorganic nanostructures for drug delivery, magnetic hyperthermia, photo-thermal treatment and radiotherapy applications. Currently, she is the recipient of an ERC consolidator grant, named GIULIa, focused on magnetic hyperthermia of metastasized tumours and of an investigator grant of the AIRC -Italian association of cancer research- project focused on magnetic hyperthermia-mediated immune therapy.*

Nguyen Thi Kim Thanh

*Professor Nguyen Thi Kim Thanh, MAE, FRSC, FInstP, FAPS, FIMMM FRSB (https://www.ntk-thanh.co.uk) held a prestigious Royal Society University Research Fellowship (2005–2014). She was appointed a full professor in nanomaterials in 2013 at the University College London. She leads a very dynamic group conducting cutting-edge interdisciplinary and innovative research on the design and synthesis of magnetic and plasmonic nanomaterials, mainly for biomedical applications. In 2019, she was honoured for her achievements in the field of nanomaterials and was awarded the highly prestigious Royal Society Rosalind Franklin Medal. She was RSC Interdisciplinary Prize winner in 2022. She was awarded the SCI/RSC Colloids Groups 2023 Graham Prize Lectureship to recognise an outstanding mid-career researcher in colloid and interface science. She is one of 12 recipients globally of the 2023 Distinguished Women in Chemistry/Chemical Engineering Awards, bestowed by the International Union of Pure and Applied Chemistry (IUPAC). Currently, she is Vice Dean for Innovation and Enterprise at the Faculty of Maths and Physical Sciences. She was elected as a member of Academia Europaea in April 2024. She is Editor-in chief of the Royal Society of Chemistry book series Nanoscience and Nanotechnology, and an Associate Editor for the Nanoscale and Nanoscale Advances Journals. She edited 8 theme issues including: Magnetic Nanoparticles: From Massart Method to a Cascade of Innovations (Nanoscale, RSC, 2025); Design and scaling up of theranostic nanoplatforms for health: towards translational studies (Nanoscale, RSC, 2023); Theranostic nanoplatforms for biomedicine (Nanoscale, RSC , 2021); Multifunctional nanostructures for diagnosis and therapy of diseases (Interface Focus, The Royal Society, 2016). She is the sole editor of two seminal books on Magnetic Nanoparticles from Fabrication to Clinical Applications (https://tinyurl.com/y5bgxb3r) and Clinical Applications of Magnetic nanoparticles (https://tinyurl.com/yyjawnz2).*

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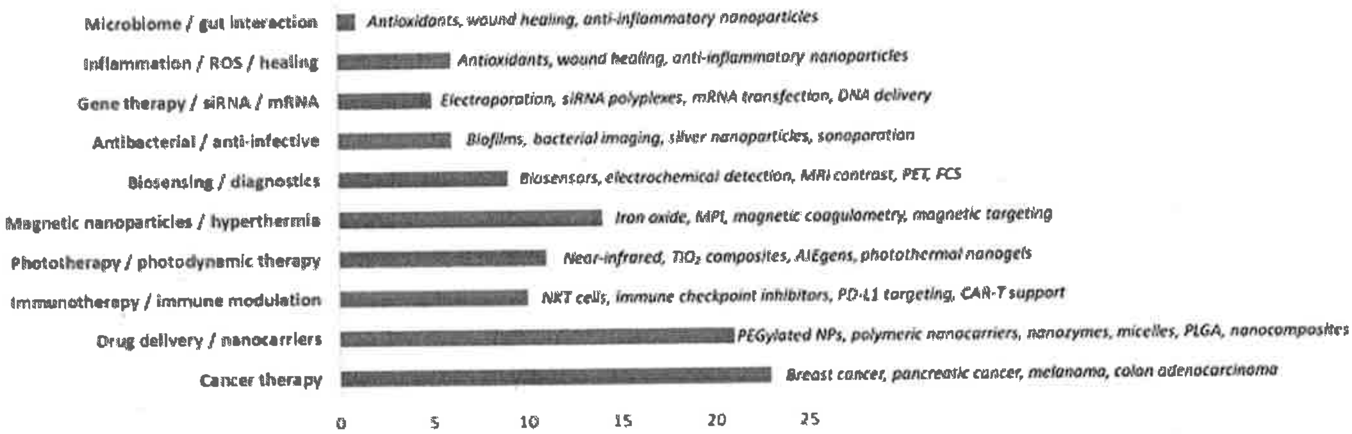
**Challenges in theranostic nanoplatforms for biomedicine**

Theranostic nanoplatforms, which integrate diagnostic and therapeutic functions into a single nanoscale system, represent a promising advancement in personalized medicine. However, several significant challenges slow down their development and clinical translation. An important one is the complex design and synthesis of these multifunctional systems. Incorporating therapeutic agents, imaging components, and targeting ligands into a single platform increases manufacturing complexity and can compromise reproducibility. Additionally, biocompatibility and toxicity remain major concerns. Many nanomaterials used in these systems have unclear long-term effects and may trigger immune responses or accumulate in untargeted organs.

Achieving precise targeting and favorable biodistribution is also difficult. While theranostic platforms aim to deliver drugs directly/locally to diseased cells or tumors, they often exhibit off-target accumulation in organs such as the liver and spleen, reducing efficacy and increasing the risk of side effects. Similarly, ensuring controlled and stimuli-responsive drug release at the target site is technically challenging, particularly when relying on internal or external triggers like pH changes or light exposure.

On the diagnostic side, imaging sensitivity and resolution must be high enough to provide accurate data without being compromised by the therapeutic elements. Furthermore, these systems face regulatory and manufacturing hurdles, as their dual-function nature complicates classification and approval processes. Scaling up production while maintaining quality and consistency is also a significant barrier.

Finally, despite encouraging preclinical results, clinical translation of theranostic nanoplatforms remains limited. Issues such as poor *in vivo* stability, unpredictable pharmacokinetics, and a lack of standardization contribute to the slow transition from laboratory to clinical settings.




***Analysis of the themed collection: frequency of representative topics.***

In that challenging context, this themed collection on Theranostic Nanoplatforms for Biomedicine with 65 accepted articles including 3 minireviews and 13 reviews shows the great, very active and high-level research activities conducted in that field and reports on promising researches showing progress in the design of theranostic nanoplatforms and in nanotechnology-based biomedical applications. Most of papers deal with oncology and multimodal imaging and therapy. For this collection as shown in the figure, cancer therapy (20%) and drug delivery systems (20%) are more frequently reported-on topics than are photo- and photodynamic therapy and magnetic systems (9–13%).

An important group of articles reported on biomimetic and functionalized nanomaterials. Inspired by biological systems, these nanoparticles—ranging from cell membrane-coated structures to protein-based and glycopolymer-engineered systems—demonstrate enhanced biocompatibility, immune evasion, and targeting specificity. Functionalization with targeting ligands such as RGD peptides, antibodies, and hyaluronic acid improves precision targeting to tumor markers and disease-associated receptors.

The design of hybrid and multimodal nanostructures consisting of combining materials such as metal–organic frameworks, silica shells, and biodegradable polymers is also outlined here. These complex architectures enhance functionality, enabling combined therapies (*e.g.*, chemo-gene or photodynamic therapy (PDT)–photothermal therapy (PTT)), advanced imaging capabilities, and tunable physicochemical properties.

The theranostic integration, where diagnostic and therapeutic functionalities are combined within a single platform, remains an active and challenging research area. Multifunctional nanostructures are demonstrated to now enable simultaneous imaging and treatment, particularly for cancer. Magnetic nanoparticles, graphene quantum dots, and aggregation-induced emission (AIE) luminogens are being applied in real-time tumor imaging, PTT, and magnetic hyperthermia, offering more precise and minimally invasive interventions.

Another strong trend presented here is the design of stimuli-responsive drug delivery systems. These smart nanoplatforms are capable of releasing therapeutic agents in response to specific internal (*e.g.*, pH, enzymatic activity) or external (*e.g.*, light, ultrasound, magnetic fields) stimuli. Such responsiveness allows for spatiotemporally controlled therapies that minimize off-target effects while maximizing therapeutic impact.

The application of nanotechnology is also broadening beyond oncology. Notable advancements are seen in the treatment of infectious diseases, pulmonary disorders, cardiovascular conditions, and autoimmune diseases, as well as in gene therapy and immunotherapy. Biomaterial-based enhancements of CAR-T therapy, bacterial infection imaging, and even wound healing through smart sutures and hydrogels highlight this expanding scope.

Technological advances in manufacturing and characterization techniques are shown to play a pivotal role. Microfluidics, nanoimprint lithography, and Bayesian optimization are being used to achieve greater control over nanoparticle uniformity, loading efficiency, and structural precision. Complementary tools such as PET, fluorescence correlation spectroscopy, and machine learning simulations are deepening our understanding of biodistribution, cellular uptake, and target interactions.

Finally, as clinical translation becomes increasingly important, there is growing attention to toxicity, systemic interactions, and regulatory challenges. Biodegradable, food-grade, and naturally-derived materials are thus detailed as well as nanoparticle interactions with the gut microbiome, immune system, and metabolic pathways.

Collectively, these articles and reviews reflect a shift toward more personalized, targeted, and integrative approaches in nanomedicine. As technologies mature, the synergy between diagnostics and therapeutics holds the potential to reshape how diseases are detected, monitored, and treated in the near future.

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