Magnetic nanoparticles as biosensing boosters

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Abstract:

Magnetic nanoparticles (MNPs) are a class of nanoparticles that can be manipulated using magnetic fields. They typically range in size from 1 to 100 nanometres and have unique magnetic properties due to their small size and high surface-to-volume ratio. Their applications span through sectors like **industrial & electronic** (Data storage, Catalysis), **environmental** (Pollutant removal, Oil spill cleanup and are widely exploited as **biomedical probes** in Magnetic Resonance Imaging (MRI) as contrast agents to enhance imaging, in Drug Delivery where they are guided to specific sites using external magnets, in Hyperthermia Treatment to deliver specific localized heating to kill cancer cells and in Biosensors and Diagnostics to detect biomolecules via magnetic labelling or to magnetically sort of cells or biomolecules. Their facile remote manipulation via magnetic fields together the non-invasive guidance and retrieval and the easily modified surfaces for targeting are key aspects of their exploitation. Yet, challenges to be addressed are aggregation in solution, potential cytotoxicity depending on composition and long-term biocompatibility and clearance from the body. To perform as biosensing boosters, MNPs, should be incorporated to bio-platforms whereby functionalized surfaces and interfaces on them, provide biorecognition support assist by selective binding of DNA, proteins, or cells. Boosting also corresponds to signal enhancement where magnetic properties are adequately tuned to amplify detection. Thus, MNPs, are currently functionalized with ligands (e.g., antibodies, aptamers) and appear in microfluidic chips, integrated with magnets for sample handling and signal readout, in magnetic-origin sensors to detect magnetic field changes linked to target analyte binding. Their output is highlighted in **high sensitivity** to detect trace amounts of biomarkers, **rapid detection** for fast readout times and suitability for point-of-care (POC) diagnostics, **multiplexing** allowing for multiple targets detection in parallel and **quantitative results** enabling precise concentration measurements. Their clinical practice is currently addressing certain roadblocks and barriers such as **biofouling**: Non-specific binding reduces accuracy, **standardization**: Lack of unified protocols for surface chemistry and biosensor design, **scalability**: challenges in consistent nanoparticle synthesis at industrial scales, **regulatory approval**: complex FDA/EMA pathways for clinical adoption, Biocompatibility & Toxicity: Long-term safety still under scrutiny, **cost of production**: High-purity MNPs and integrated systems remain expensive, **integration with electronics**: Technical challenges in miniaturizing systems for portable use. Since global biosensor market is expected to exceed $40B by 2030; MNP-based systems are growing steadily and expected to become key actors in environmental monitoring, food safety, drug development, wearable biosensors, and AI-integrated MNP platforms.

Funding: This work is supported by the European Union under GA No. 101120706 – project 2D-BioPAD.