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Nucleic acid based polymer and nanoparticle conjugates: Synthesis, properties and applications

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Nucleic acid based fabrication of nanomaterials has fascinated scientists since the past two decades and exciting challenges have been surmounted. Recently, nucleic acid is successfully combined with other nanometre-scale entities, sometimes by modifying with chemical functional groups, to obtain a wide range of nanomaterials which in certain cases have been characterized with atomic level precision. These nanomaterials are highly focused due to their new physico-chemical properties, which confer several advantages in multidisciplinary field of research leading to advanced technologies. This review highlights the systematic advances in the synthesis, properties (optical and electronic) and versatile applications of nucleic acid based nano-biomaterials produced from polymer and metal or semiconductor nanoparticles.

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1. Introduction

Deoxyribonucleic acid (DNA), one of the important constituent of nucleic acid family, has attracted irredeemable interest not only to the biologists and physicians but also to the chemists and physicists, even theorists since DNA was first identified in the late 1860s by Swiss chemist Friedrich Miescher [1]. The recent era have experienced stout developments in the nucleic acid based research especially on DNA, since Watson and Crick reached their ground-breaking conclusion in 1953, that the DNA molecule exists in the form of a three-dimensional double helix [2] and indeed, the double helix has become a cultural icon of our modern civilization. DNA plays a fundamental role in all living organisms for its key function in storage, duplication, realization of genetic information and these applications occur through the double strands of DNA, produced from the hydrogen bonded base pairing between specific nucleobases; adenine (A)-thymine (T) and guanine (G)-cytosine (C). This unique base-pairing can cause hairpin or loop structures in single-stranded DNA (ssDNA) or can make double-stranded DNA (dsDNA) from two complementary ssDNA segments. Again, dsDNA can exist in right handed double helical structures (B-DNA, A-DNA); among which, the B-DNA is the most common form and can also have a left-handed double-helical form named Z-DNA. Polymorphic self assembled DNA structures such as i-motif and G-quadruplex are obtained by manipulating the conventional Watson-Crick base pairings. In 1982 an eminent scientist, Seeman launched a new promising research area using the DNA, presently popular as 'structural DNA nanotechnology.' It involves the formulation of artificial nano-architectures using synthetic DNA branched junction motifs (flexible) mainly containing three and four arms which utilizes DNA's molecular recognition properties [3]. These designed DNA strands with specific sequences have been utilized as a synthon in structural DNA nanotechnology due to its exquisite specificity of base pairing. Seeman also explored this field employing DNA double-crossover molecules (termed as DX molecules) as building blocks [4] for the assembly of two-dimensional (2D) DNA crystals [5] as well as self-assembled, three-dimensional (3D) DNA crystal based on the DNA tensegrity triangle [6]. On the contrary, Yan et al. [7] arranged the DX tiles into barcode-patterned lattices, with the help of long single-stranded DNA chain, whereas, another group designed a long ssDNA to construct 3D wire-frame octahedron by controlled folding using simple denaturation-renaturation procedure [8] which may be thought as a precursor of 'single-stranded DNA-origami'. But, the major revolution came in 2006 when Rothenmund [9] introduced the concept of 'DNA origami', a new programmed DNA assembly system based on the folding of a long ssDNA (named as 'scaffold strand') with the help of hundreds of sequence-designed complementary short strands (called 'staple strands'). It provides a wide variety of 2D structures of around 100 nm in size, including rectangles, triangles and even a smiley face and five-pointed star. Though the structural DNA nanotechnology became enormously popular to design several nano-architectures but the synthesis protocol is relatively complex since, multiple reaction steps and purifications are utmost necessary which in turn results low yield of desired DNA nanostructure. This major difficulty can now be circumvented due to the emergence of DNA origami technology since it permits precise placement, shape variations as well as provides detailed DNA sequence information from all the positions of the designed nanostructure. This novel technique has become promising in nanotechnology and the progressive ideas of scientists have geared up this particular field to take a commanding position. The history and state of art in structural DNA nanotechnology have been widely reviewed by various research groups [10–16]. Apart from designing DNA nanoarchitectues, DNA nanotechnologies have also found versatility in the fabrication of DNA nanomachines like 'tweezers' and 'walkers' which are made by self-assembly technique that rely on the sequence specific interactions and bind complementary oligonucleotides together in a double helix [17–22].

On the other hand, ribonucleic acid (RNA), which also resembles DNA but contains pyrimidine-derived base uracil (U) instead of thymine, is usually single stranded [23,24]. RNA is another widely recognised biomolecule which plays several important roles: a carrier of genetic information from DNA to proteins, a messenger between DNA and protein synthesis complexes as well as a carrier molecule of amino acids for protein synthesis [25]. Like DNA, RNA can also be designed and manipulated to produce wide variety of nanostructures. The idea of RNA nanotechnology arrived in the late 20th century and the very first confirmation for the construction of RNA nanostructures through the self-assembly of several re-engineered natural RNA molecules were reported in 1998 [26]. Although, the folding properties of RNA and DNA are not exactly the same due to the base-pairing rules, the fundamental principles in DNA nanotechnology are applicable to RNA